Bond strength of prestressed CFRP strips to concrete substrate: comparative evaluation of EBR and EBROG methods

Niloufar MOSHIRI [1,2], Christoph CZADERSKI [2], Davood MOSTOFINEJAD [1], Masoud MOTAVALLI [2]

[1] Isfahan University of Technology (IUT), Isfahan, Iran
[2] Empa, Swiss Federal Laboratories for Materials Science and Technology, Structural Engineering, Dübendorf, Switzerland

Contact e-mail: niloufar.moshiri@cv.iut.ac.ir
nilou.msh@gmail.com

ABSTRACT: Application of Fiber Reinforced Polymer (FRP) for rehabilitation of existing concrete structures is well-known nowadays. Externally Bonded Reinforcement (EBR) method is usually used to apply FRP composites on the concrete surface. However, a premature debonding failure mode may occur prior to achieving the full capacity of the FRP. The newly developed Externally Bonded Reinforcement On Groove (EBROG) method was shown to extensively postpone the debonding failure mode.

In this paper, bond behavior of prestressed FRP to concrete was investigated. Concrete blocks were strengthened with EBR and EBROG methods using prestressed Carbon FRP (CFRP) strips. The prestressing force was gradually decreased until the CFRP strip was debonded from the concrete substrate. Through these prestress force-releasing tests, the bond resistances of prestressed FRP to concrete were measured. Experimental results showed that EBROG method increased the bond resistance twice the EBR method. This high increase is attributed to the failure mode of the specimens. While the debonded layer in EBR method was a few millimeters beneath the FRP strip, it was deep and wide in the concrete substrate for EBROG method.

1 INTRODUCTION

Application of fiber reinforced polymer (FRP) composites for strengthening concrete structures is widely accepted all over the world. In this regard, using prestressed FRP for strengthening has several advantages compared to non-prestressed FRPs, such as improving the serviceability state of the structure, increasing the cracking and ultimate load, decreasing the deflections and crack widths and improving the fatigue behavior. However, proper bond between FRP and concrete is even more important. A newly introduced method called externally bonded reinforcement on groove (EBROG) was used to investigate the bond behavior of prestressed FRP to concrete structure, and compared with conventional method of externally bonded reinforcement (EBR).

1.1 Externally bonded reinforcement (EBR)

Usually externally bonded reinforcement method is used to bond FRP strips to the concrete structures. Surface preparation is first applied to the substrate (e.g. by grinding the surface as in this research), and then the strips are bonded to the substrate by using proper adhesive. By using EBR method, one cannot use prestressed FRP for strengthening the structure, and usually mechanical anchorage is needed. In current research, a bond area of 300 mm length and 50 mm width were initially ground and the adhesive was then applied on the surface, followed by bonding the strip on the surface. The prestressing procedure is described below.

1.2 Externally bonded reinforcement on grooves (EBROG)

The new introduced method, externally bonded reinforcement on grooves, was first proposed by Mostofinejad and Mahmouadabadi (2010) at Isfahan University of Technology (IUT). It was shown that the bond strength of unstressed FRP to concrete structure using EBROG method increased significantly compared to EBR method (Hosseini and Mostofinejad 2013, Ghorbani et al. 2017, Mostofinejad et al. 2018, Moshiri et al. 2018, Tajmir-Riahi et al. 2018, Moshiri et al. 2019, Tajmir-Riahi et al. 2019). In the current research, the effect of EBROG method on bond strength of prestressed FRP to concrete is studied. Two longitudinal grooves with 10×10 mm dimensions in cross section were initially cut in the concrete cover, then filled with epoxy adhesive, and a thin layer of adhesive was applied on the surface, followed by bonding the strip on the surface. No surface preparation was made in EBROG method.

2 EXPERIMENTS

2.1 Test setup

For investigating the bond behavior of prestressed CFRP strips to concrete, prestress force-release tests as firstly presented in Motavalli et al. (2011) and Czaderski (2012) were performed. To do so, three main steps were followed: prestressing, curing, and releasing. The strip was initially prestressed up to a determined value, F_p, by increasing the oil pressure in a hydraulic jack, and then bonded to concrete using the epoxy adhesive. During curing of the adhesive, the prestressing force was kept constant. After 5 to 7 days of curing, the prestressing force was gradually released from one side of the strip until debonding of strip from concrete occurred and failure happened. Two load cells on the two unbonded lengths of the strip recorded the force during all steps. In-plane and out-of-plane deformations were measured using a 3D digital image correlation (DIC) measurement system. The test setup is demonstrated in Figure 1.

2.2 Materials

Concrete blocks with 250×473×1000 mm dimensions were cast with cylindrical compressive strength of 41.8 MPa and maximum aggregate size of 32 mm. CFRP strips, S&P C-Laminate type SM (150/2000) Austria production, with a thickness of t_f=1.4 mm, width of b_f=50 mm, and elastic modulus of E_f=172500 MPa were used for strengthening the blocks. A two-part epoxy adhesive, S&P 220, was used to bond the strips to the concrete blocks as well as to fill the grooves in the EBROG method. CFRP strips and epoxy adhesive were delivered from the S&P Clever Reinforcement Company AG, Switzerland.

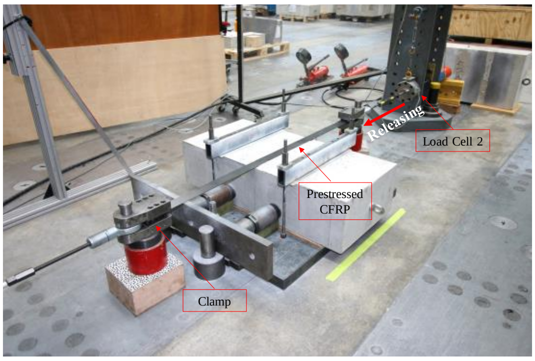


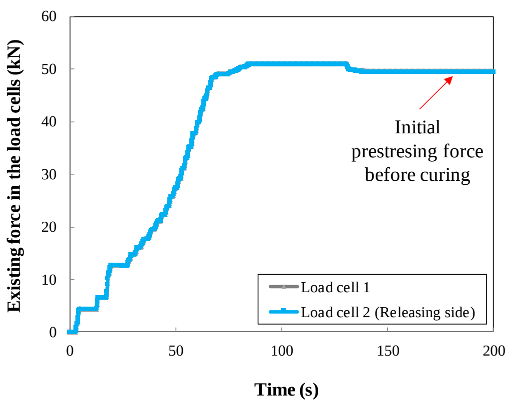
Figure 1. Test setup for the prestress force-release tests.

2.3 *Test program*

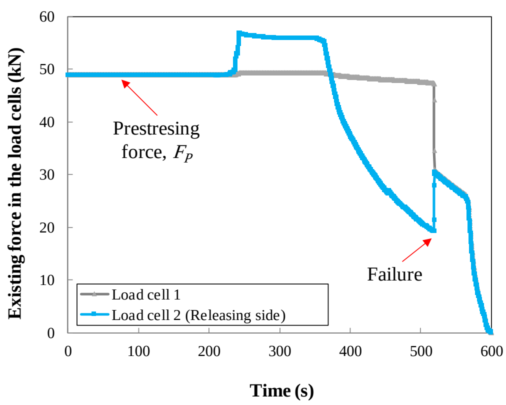
The overview of the test program is given in Table 1. Four prestress force-release tests were conducted. Two specimens were strengthened with EBR and two with EBROG method. Specimens' labels start with letter "*R*" indicating the type of the experiment (release test), followed by the name of the strengthening method, and at the end the number 1 or 2 showing the repetition of similar tests. In the EBROG method, two longitudinal grooves with 10 mm width, 10 mm depth, and 15 mm free space were used.

Table 1. Test program.

Specimen label	Strengthening method	Test type	Number of longitudinal grooves	Groove dimensions	
				Width, b_g (mm)	Depth, h_g (mm)
R-EBR -1 *R-EBR-2*	EBR	Prestress force-release test	-	-	-
R-EBROG-1 *R-EBROG-2*	EBROG	Prestress force-release test	2	10	10



(a) Prestressing



(b) Releasing

Figure 2. Prestressing and releasing procedure in a prestress force-release experiment (diagrams of specimen *R-EBR-2*).

3 RESULTS AND DISCUSSION

3.1 Bond strength

The existing force in the strip at each stage was recorded by two load cells on two sides of the strip. In order to better understand the test procedure, the existing force on both sides of the strip in a prestress force-release test is shown in Figure 2 for specimen *"R-EBR-2"* as an example. It can be observed that during prestressing, the forces in two load cells on the two sides of the strip, increased equally up to the selected prestressing force. After curing and during the releasing, the existing force in one side of the strip was manually released until failure. Differences between the prestressing force, F_p, and the force in the strip at the releasing end at final stage (i.e. at failure), $F_{R,u}$, is determined as the bond strength (bond strength= F_p - $F_{R,u}$), and demonstrated in Table 2. It can be seen that the bond strength of EBR specimen was 39.2 and 29.6 kN for the two repetitions. EBROG specimens, however, achieved much higher strengths of 79.1 and 83.1 kN for two similar tests. It is, therefore, concluded that using EBROG method increased tremendously the bond capacity of prestressed FRP strips to concrete. It is worth mentioning that since the bond behavior of prestressed FRP is not a pure shear mode and is a mixed mode behavior, it is recommended to compare the bond strengths rather than the bond stresses

Table 2. Experimental results.

Specimen label	Prestressing force*, F_p (kN)	Prestressing level**	Bond strength, F_p- $F_{R,u}$ (kN)
R-EBR -1	51.8	26%	39.2
R-EBR-2	48.8	25%	29.6
R-EBROG-1	100.0	51%	79.1
R-EBROG-2	101.9	52%	83.1

* Immediately before start of the prestress release test.

** With respect to the ultimate capacity of CFRP strip (196 kN).

3.2 Load-separation behavior

Czaderski (2012) showed that the failure mode in prestressed FRP-to-concrete is a mixed mode I/II failure. It was found that out-of-plane deformations are of the most interest in prestress force-release tests. Relative out-of-plane deformations of the strip with respect to the concrete substrate is called separation. Load-separation behavior of the release end on FRP strip is depicted in Figure 3. It can be observed that the EBROG specimens experienced very high separation and force compared to EBR specimens. EBROG specimens reached to 8.7 mm and 10.6 mm separation at ultimate forces of 79.1 kN and 83.1 kN, while the corresponding values for EBR joints were 1.8 mm for both test repetitions at ultimate forces of 39.2 and 29.6 kN. The slop of the load-separation behavior was the same for both EBR and EBROG. However, a gradually deceasing slope was observed for EBROG, while EBR specimens experienced one or two horizontal plateau before ultimate which means local debonding occurred.

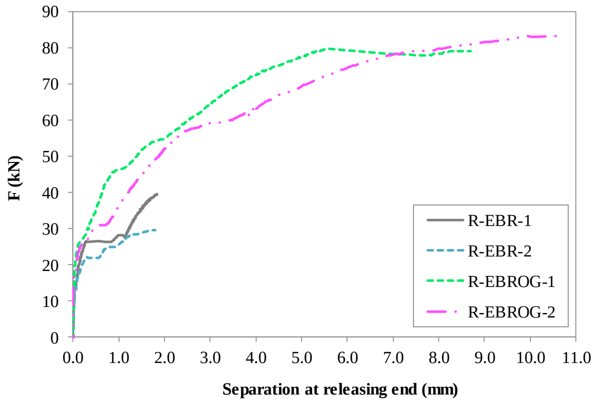
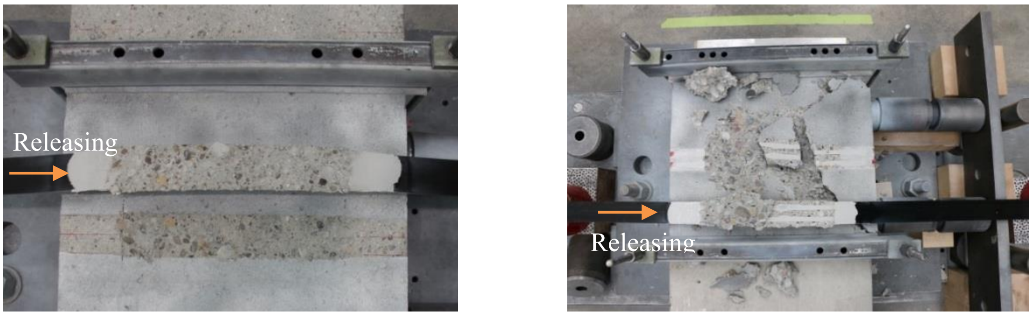


Figure 3. Load-separation behavior (separation at releasing end means the maximum out-of-plane separation, compared to concrete block, at the end of the bond zone on the loading side).



R-EBR-1 *R-EBROG-1*

Figure 4. Failure mode of EBR and EBROG.

3.3 Failure mode

The failure modes of EBR and EBROG specimens are illustrated in Figure 4. Debonding in a thin layer of concrete beneath the CFRP strip was observed in the EBR joints. In EBROG joints, surprisingly, the debonding layer was deep in the concrete substrate, and expanded perpendicularly to the sides of the strip. A large area of concrete was cracked and debonded in EBROG method contributing to a high fracture energy, and a high bond strength.

4 CONCLUSION

In this paper, a preliminary study on bond behavior of prestressed FRP strips to concrete structures bonded through a recently introduced method is presented. The so-called externally bonded reinforcement on grooves (EBROG) method was compared with conventional EBR technique.

Using EBROG method for strengthening of concrete blocks with prestressed CFRP strips, improved the bond strength with a factor of 2.4 over the EBR method, on average. Bond resistance was 81.1 kN for EBROG specimens on average, while it was 34.4 kN on average for EBR joints.

Very high separations could be developed in EBROG joints. Separation at released end at ultimate was 9.6 mm for EBROG specimens, on average, while it was only 1.8 mm for EBR.

The observed failure modes showed impressively large concrete volume which debonded in the EBROG method and extended in depth and width of the substrate, indicating a high bond strength.

5 ACKNOWLEDGMENTS

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