EBROG method to strengthen heat-damaged concrete with CFRP sheets

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ABSTRACT: Externally bonded reinforcement on groove (EBROG) method is recently becoming more popular for strengthening concrete structures with fiber reinforced polymer (FRP) composites. Its capability to increase the bond strength of FRP to concrete substrate and to postpone debonding of FRP, has made it an appropriate substitute to conventional externally bonded reinforcement (EBR) method.
Concrete structures in some industrial constructions such as steel companies may be exposed to high temperatures during their lifetime. FRP composites can be used for strengthening heat-damaged concrete in such structures. However, bond properties of FRP to heat-damaged concrete should be investigated. In the current research, EBROG method is used to study the bond behavior of FRP to heat-damaged concrete substrate. To do this, concrete blocks were first subjected to different temperatures of 300, 400 and 500˚C or maintained in room temperature (25˚C). They were then strengthened with carbon FRP sheets using EBR and EBROG methods. Eight single lap-shear tests were conducted. 2D Digital Image Correlation (DIC) measurement system was utilized to measure full-field displacements. Experimental results showed that although the concrete strength decreased when subjected to high temperatures, bond strength of heat-damaged concrete strengthened with EBROG method increased significantly compared to those of EBR joints that were maintained in room temperature. A two-fold increase was observed experimentally for EBROG joints. Heat-damaged EBROG joints experienced a bilinear behavior in terms of load-slip diagrams and reached high slips at final stage.

1 INTRODUCTION

Corrosion, application changes, and construction/design errors would engender the need for retrofitting and strengthening the existing structures. There are different ways for strengthening the civil structures such as buildings and bridges. Application of fiber reinforced polymer (FRP) composites are extensively recognized for retrofitting concrete structures. Due to different applications of the structure, i.e. steel company, it may have been subjected to elevated temperatures. Since re-construction of the structure or even, the weak structural member is not always possible, retrofitting the structural member with FRPs would be a fast and easy solution.

There are several studies investigating the effect of high temperatures on the behavior of FRP-strengthened structures; such as Ahmed and Kodur (2011), Dai et al. (2012), Firmo et al. (2015), Gallego et al. (2017), Hajiloo et al. (2017). However, FRP-strengthening of post-heated concrete is rarely found in the literature. In other words, the behavior is unknown for the cases that the concrete structure is initially subjected to high temperatures, and then retrofitted with FRPs. The first step is to examine the bond behavior of FRP to post-heated concrete. Premature failure in terms of debonding of FRP from concrete surface may occur before achieving the full capacity of the FRP material. A new introduced method called externally bonded reinforcement on groove (EBROG) was proposed as an alternative to common method of externally bonded reinforcement (EBR) to improve the bond behavior of FRP to concrete, Mostofinejad and Mahmouadabadi (2010). Previous research works on EBROG method demonstrated that it can significantly improve the bond behavior by increasing the bond strength and postponing the debonding. It was shown by Mostofinejad and Shameli (2013), Hosseini and Mostofinejad (2013), Ghorbani et al. (2017), Moghaddas and Mostofinejad (2018), Moshiri et al. (2018), Mostofinejad et al. (2018), Tajmir-Riahi et al. (2018), Moshiri et al. (2019), Tajmir-Riahi et al. (2019). Therefore, in current research the EBROG method is used to investigate the bond behavior of FRP to concrete structures. For this purpose, single lap shear tests were performed on concrete blocks that were strengthened with FRP sheets by using EBR or EBROG method. A two-dimensional digital image correlation (2D DIC) measurement system was utilized to monitor the full-field displacements.

2 EXPERIMENTS

2.1 Materials

Concrete blocks with 150×150×350 mm dimensions and 55.9 MPa concrete compressive strength were constructed. Unidirectional carbon fiber sheets, which is commercially called SikaWrap-230C, with a thickness of 0.131 mm, elastic modulus of 238 GPa, and ultimate tensile strain of 1.8 % were used for strengthening the concrete. An epoxy adhesive, which is named Sikadur-330, with an elastic modulus of 4.5 GPa, ultimate tensile strain of 1.5 %, and ultimate tensile strength of 30 MPa was used in all steps of strengthening.

2.2 Specimen preparation

To investigate the FRP-strengthened heated-concrete, the concrete blocks were first heated up to different temperatures of 300, 400 and 500˚C and then strengthened with unidirectional carbon fiber sheets by using the EBROG method. As the control specimens, two concrete blocks, which were kept in room temperature (25˚C), were strengthened with carbon fiber sheets by using the EBR method

The heating protocol was as follows:

- Drying the concrete blocks at 110˚C temperature for 24 hours to avoid probable concrete spalling in the succeeding high temperatures in next step.
- Exposing the concrete blocks to high temperatures (300, 400 or 500˚C) for 40 minutes, followed by a break to manually turn around the blocks in the furnace, and exposing them to high temperatures for another 40 minutes. Heating was performed by putting the concrete blocks in a furnace with a heating rate of 10˚C/min.
- Turning off the furnace for cooling the concrete blocks for 24 hours.

After heating and cooling the concrete blocks, they were strengthened with EBR or EBROG methods. Steps in each method are summarized as follows:

EBR method:

- Grinding the surface of concrete blocks by a circular saw for surface preparation.
- Impregnating the fiber sheets with epoxy adhesive.
- Bonding the FRP sheets on the concrete blocks by applying a thin layer of epoxy onto the surface.

EBROG method (Figure 1):

- Cutting one longitudinal groove with dimensions of 10×10 mm in cross section.
- Filling the groove with epoxy adhesive.
- Impregnating the fiber sheets with epoxy adhesive.
- Bonding the FRP sheets on the concrete blocks by applying a thin layer of epoxy onto the surface.

After curing of the adhesive, the specimens are ready for the test.

2.3 Test layout

The test program is demonstrated in Table 1. Eight single lap shear tests were conducted in which specimens number 1 and 2 were the reference specimens that were kept in room temperature and strengthened with EBR method. Specimens number 3 to 8 were first subjected to the temperature T (˚C) and then strengthened by using EBROG method. In all EBROG specimens one groove with 10×10 mm cross-sectional dimension was used. Labels start with the name of strengthening method, follow by the groove dimension (if EBROG method), the temperature, and number 1 or 2 to indicate the repetition of similar experiments. Bond length and FRP width were 200 mm and 48 mm for all specimens. The bond are started 35 mm far from the concrete edge to prevent stress concentration.

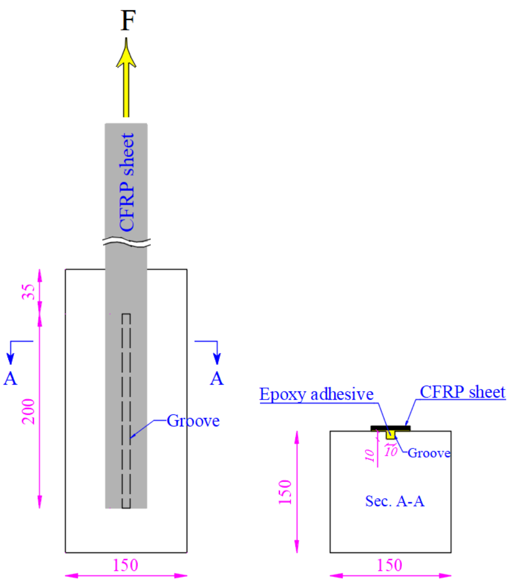


Figure 1. Schematic view of the specimen in EBROG method (dimensions are in mm).

2.4 Test procedure

Single lap shear tests were conducted at Isfahan University of technology (IUT) by using a 300 kN testing machine. Tests were performed in displacement-controlled mode with a rate of 2 mm/min. A two-dimensional digital image correlation (2D DIC) measurement system was utilized to monitor the full-field displacements, Tajmir-Riahi et al. (2019). Force was measured by using a 50 kN load cell. The maximum force in each test was called the bond strength of FRP-to-concrete joint are is reported in Table 1.

3 RESULTS AND DISCUSSION

3.1 Bond strength

It can be observed in Table 1 that the bond strengths of EBR joints, of which the concrete blocks were kept in room temperature, were 7.17 and 7.46 kN. Cylindrical concrete compressive strength, f_c', shown in Table 1 demonstrates a significant decrease when the blocks were subjected to elevated temperatures. f_c' was 42.5, 31.8 and 26.8 MPa for 300, 400 and 500˚C temperatures, respectively; while it was 55.9 MPa for the room temperature. Although f_c' reduced greatly for elevated temperatures, the bond strength of FRP-to-concrete joints that were strengthened by using EBROG method did not decrease. In fact, using EBROG method improved the bond strength tremendously so that the bond strengths were even higher than those of EBR joints in room temperature. Specimens subjected to 300, 400 and 500˚C temperatures which were retrofitted with the EBROG method, had bond strengths of 13.36, 14.59, and 13.80 kN, respectively. It can be concluded that the EBROG method was able to increase the bond strength in heat-damaged concrete. However, in 500˚C, the EBROG method was not as efficient as it was in 400˚C, since the concrete was greatly damaged and the concrete strength was very low compared to 500˚C.

Table 1. Specimens' details and experimental results.

Test No.	Specimen	Strengthening method	T (˚C)	f_c' (MPa)	Bond strength, F_{max} (kN)	Average bond strength, $F_{max,avg}$ (kN)	Increase in $F_{max,avg}$
1	EBR-25-1	EBR	25	55.9	7.17	7.31	-
2	EBR-25-2	EBR	25	55.9	7.46		
3	EBROG-10×10-300-1	EBROG	300	42.5	12.76	13.36	83%
4	EBROG-10×10-300-2	EBROG	300	42.5	13.97		
5	EBROG-10×10-400-1	EBROG	400	31.8	15.20	14.59	100%
6	EBROG-10×10-400-2	EBROG	400	31.8	13.99		
7	EBROG-10×10-500-1	EBROG	500	26.8	13.35	13.80	89%
8	EBROG-10×10-500-2	EBROG	500	26.8	14.26		

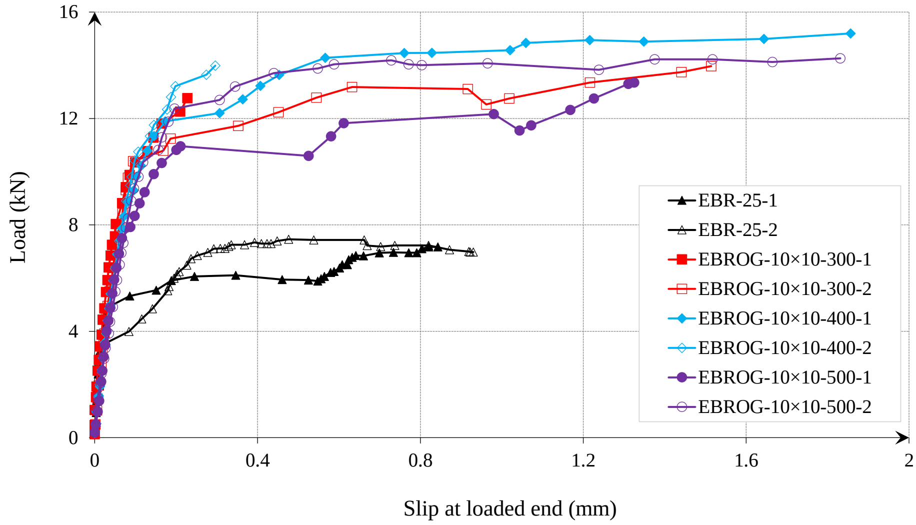


Figure 2. Load-slip behavior.

3.2 Load-slip behavior

General bond behavior of all specimens are illustrated in Figure 2 in terms of load-slip at the loaded end of the FRP. A bilinear behavior can be observed for all specimens. However, EBROG joints achieved much higher slips at ultimate. The point at which the load-slip diagram turns into horizontal and no further increase in load is observed, is referred to be the stage of initiation of debonding. The slip at this stage is very close to each other for all EBROG joints.

3.3 Failure mode

The failure modes of specimens are demonstrated in Figure 3. As it was expected, EBR specimens failed by debonding in a thin layer of concrete. Failure mode in EBROG joints in the case of heat-damaged concrete was a combination of debonding in concrete layer, a kind of delamination in which a thin layer of FRP sheets was remained on the concrete surface or in some cases on the groove, and failure in the adhesive.

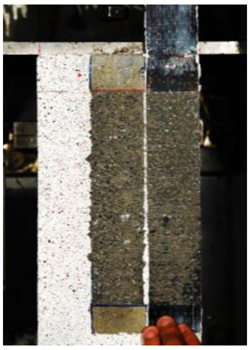
4 CONCLUSION

In this paper, a preliminary study on bond behavior of FRP sheets to heat-damaged concrete was presented. A recently introduced method, called externally bonded reinforcement on grooves (EBROG) method was used to strengthen heat-damaged concrete and compared with EBR method. Concrete blocks were subjected to 300, 400 and 500˚C temperatures and compared with the ones remained at room temperature (25˚C).

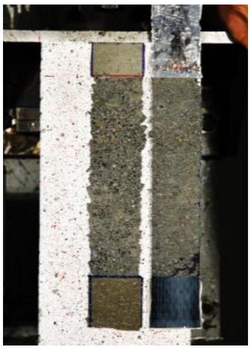
Based on the experimental results, it was shown that although the concrete compressive strength decreased significantly by exposing to high temperatures, using EBROG method increased the bond strength.

Bond strength of EBROG joints, of which the concrete blocks were subjected to 300, 400 and 500˚C, respectively, increased 83%, 100%, and 89% compared to EBR joints kept in 25˚C.

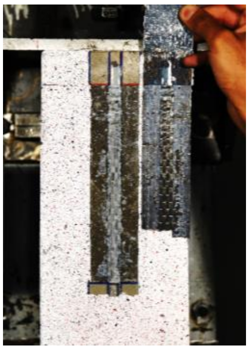
A bilinear load-slip behavior was observed for all specimens, though the maximum slip at ultimate was higher for EBROG joints.



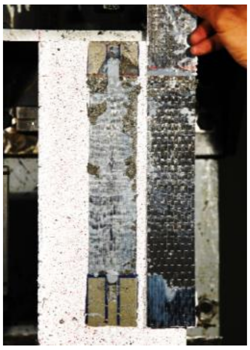
EBR-25-1



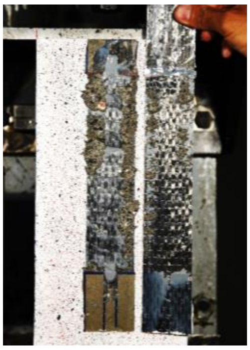
EBR-25-2



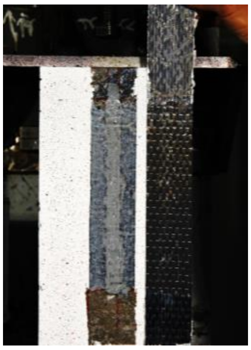
EBROG-10-10-300-1



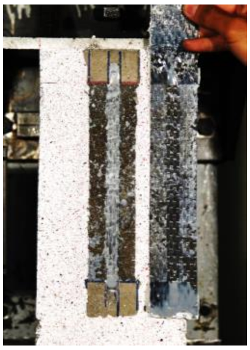
EBROG-10-10-300-2



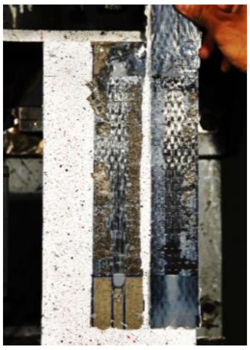
EBROG-10-10-400-1



EBROG-10-10-400-2



EBROG-10-10-500-1



EBROG-10-10-500-2

Figure 3. Failure modes.

The observed failure modes in EBROG joints of heat-damaged concrete demonstrated a combination of different failure modes like debonding in concrete layer, delamination in a thin layer of FRP sheets, and failure in the adhesive. More investigation is suggested by using the precured FRP strips, based on authors' experience.

5 ACKNOWLEDGMENTS

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