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Investigating the effects of concrete compressive strength, CFRP thickness and groove depth on CFRP-concrete bond strength of EBROG joints

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HIGHLIGHTS

- Effects of different parameters on CFRP-concrete bond strength of EBROG joints were investigated.
- PIV was used to investigate strain distribution in CFRP-to-concrete joints.
- Effective bond length of EBROG joints is relatively smaller than that of the EBR joint.
- Effective bond length of EBROG joints were relatively smaller than that of the EBR.
- Highest bond capacity of EBROG joints achieved for grooves of 10 mm deep.

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ABSTRACT

Dominant efficacy of the new developed "externally bonded reinforcement on grooves" (EBROG) technique in comparison with "externally bonded reinforcement" (EBR) method has been previously shown when fiber reinforced polymer (FRP) composites are used for strengthening. Current experimental study presents the effects of different parameters such as concrete compressive strength, carbon FRP (CFRP) thickness and groove depth on the bond shear strength between FRP and concrete, failure mode, and strain distribution of CFRP composites attached to the concrete substrate through EBROG in FRP-concrete joints using a single lap-shear test, and compares the results with those of the EBR joints. In total, 84 concrete prism specimens with three different compressive strengths were cast. CFRP sheets with three different thicknesses were then adhered on the side faces of the specimens using both EBR and EBROG techniques. Finally, the specimens were subjected to single lap-shear test, while a 2D digital image correlation (DIC) system was used to monitor all the tests. The experimental results revealed great improvement in bond strength of EBROG joints, as their ultimate load capacity were increased up to 71% compared to those of the EBR joints; while the observed failure mode in most of the EBROG specimens with groove depths equal to 5, 10 and 15 mm was CFRP tensile rupture. The DIC results revealed that the effective bond length of EBROG joints is relatively smaller than that of the EBR joint, although providing a higher bond capacity.

1. Introduction

Owing to their advantageous properties, such as high durability under harsh environmental conditions, high tensile strength, and ease of transport, fiber reinforced polymer (FRP) composites have attracted much attention by designers for strengthening concrete structures [1]. Externally bonded reinforcement (EBR) technique is the method most commonly used for applying FRP composites to strengthen reinforced concrete (RC) elements. Unlike most features of the technique such as simplicity and rapid application, the main problem which has greatly hampered the use of EBR technique is the premature debonding of FRP composite from the concrete substrate before reaching the tensile strength of the material [2–5].

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To further understand the behavior of adhesively bonded composite sheet to concrete joints, Chajes et al. [6] conducted an experimental research in which they investigated the effects of concrete surface preparation, adhesive resin type, and concrete strength on the bond strength. Other research studies (Chen and Tang [7], Ueda et al. [8], Yuan et al. [9], and Lu et al. [10]) have shown that concrete compressive strength, f'_c; effective bond length, L_θ; axial stiffness of FRP composites, $E_p t_p$; width of the reinforcement per width of the concrete substrate ($\frac{b_p}{b_c}$); and shear modulus of adhesive, G_a, are the main factors influencing the bond behavior between the concrete and the FRP sheet.

Concrete compressive strength is an important and effective parameter influencing the bond strength. To investigate the impact of concrete compressive strength on debonding load, some studies have suggested that the bond strength is proportional to $\sqrt{f'_c}$ while others proposed a factor of $f^{\frac{2}{3}}$ [11]. Based on the equation proposed by Chen and Teng [7], the relationship between the load capacity and concrete compressive strength is captured by $\sqrt{f'_c}$. Moreover, the equation proposed by Seracino et al. [12] the effect of concrete compressive strength on load capacity is equal to $f_c^{0.33}$.

In order to evaluate the effect of concrete compressive strength on the load capacity of FRP-concrete interface, Sharma et al. [13] used a single lap-shear test to investigate the bond strength of both FRP and steel plates adhesively bonded to concrete substrate. In their experiments, they used specimens reinforced with the EBR method. It has been reported that the axial stiffness and ultimate strength of the reinforcement, as well as the concrete compressive strength had significant effects on the bond strength of externally bonded FRP or steel sheets to concrete [13]. Introducing the single lap-shear test as a potential candidate for a standard test to evaluate the bond capacity of FRP-to-concrete, Yao et al. [14] investigated such parameters as FRP sheet length, the ratio of sheet width to that of concrete element, specimen free height, and initial loading angle, in order to examine the single lap-shear test as a potential candidate for a standard test to evaluate the bond capacity of FRP-to-concrete and to verify the accuracy of the Chen and Teng's bond strength model [7]. They concluded that the single lap-shear test can be considered as a standard test due to its simplicity and reliability; also that the Chen and Teng's bond strength model can acceptably predict the experimental results, despite being conservative in limiting the ratio of FRP plate width to width of concrete substrate.

Recent research efforts to postpone or eliminate FRP debonding from the concrete surface have led to the development of the two novel methods of externally bonded reinforcement on grooves (EBROG), and externally bonded reinforcement in grooves (EBRIG) [15,16]. In these research studies, concrete beam specimens were strengthened in flexure using CFRP sheets, applied on longitudinal grooves, to find that the methods would not only completely prevent the debonding of CFRP sheets but would also increase the ultimate loads up to 80% compared to the specimens strengthened via the EBR method [15]. Mostofinejad et al. [17] carried out further investigations on the performance of the grooving methods in flexural strengthening of RC beams using multilayer CFRP sheets, and demonstrated the great advantages of the methods in enhancing the efficiency of CFRP strengthening.

In the same line of research, Hosseini and Mostofinejad [18] used single lap-shear tests, performed on CFRP sheets attached to concrete specimens using EBR and EBROG techniques. They compared the experimental results of 16 lap-shear tests to demonstrate that the debonding failure, which is commonly observed in EBR specimens, was completely eliminated when the EBROG technique was used. They also reported that the bond capacity in EBROG joints increased by up to 55.5% compared to the specimens strengthened using the EBR technique [18]. In another study, Hosseini and Mostofinejad studied the effects of groove depths of 2, 5, 10 and 15 mm on EBROG-strengthened concrete prism specimens with a compressive strength of 46 MPa through a set of single lap-shear tests. The authors found that both the interfacial fracture energy (G_f) and the peak interfacial shear stress (τ_f) can be significantly increased with increasing groove depth. More specifically, they reported that EBROG specimens having grooves with a depth of 15 mm exhibited enhancements in terms of G_f and τ_f by 66.7% and 112.4%, respectively, compared to the same parameters in EBR specimens [19].

Ghorbani et al. carried out an in-depth investigation on the FRP-concrete bond behavior using specimens strengthened via the EBR and EBROG methods under positive and negative angles of the single lap-shear test. They found out that the rupture mode in the EBR-strengthened specimens occurred through the debonding of the CFRP sheets off the bond surface while in most of the EBROG ones occurred in the form of CFRP sheet rupture. They also observed a considerable increase in the load carrying capacity of all the EBROG specimens as compared with the EBR ones such that all the EBR specimens achieved higher load carrying capacities when the effective bond length was increased from 100 to 150 mm. However, increased bond length in the EBROG ones was found to have no considerable effect on their load-carrying capacities since the CFRP sheets had already reached their maximum tensile strength at a bond length of 100 mm [20,21].

Since the EBROG is a contemporary method, currently not a lot of research is devoted to investigating the effect of different parameters and variables on its efficacy in FRP-to-concrete bond strength. In other words, despite the benefits of the novel grooving method in postponing and/or eliminating the undesired debonding failure, only few studies have been devoted to the investigation of the behavior of FRP-to-concrete bonded joints treated with this method. It is obvious that, further development of this method can only become possible by conducting studies focused on the joint behavior to identify the parameters affecting the bond strength. Along these lines, the present study aims to use the single lap-shear test to determine the effects of concrete compressive strength, CFRP thickness and grooves depth on the bond shear strength between FRP and concrete, failure mode, and strain distribution of CFRP composites attached to the concrete substrate using a single lap-shear test in specimens strengthened with the EBROG technique and control specimens strengthened with the conventional EBR method. For this purpose, 84 single lap-shear tests were carried out on CFRP-to-concrete adhesively bonded joints with different concrete compressive strengths, CFRP thicknesses and grooves depth. A full-field digital image correlation (DIC) technique was used to comprehensively investigate the strain fields along the CFRP laminates. The experimental results are reported as values of bond strength in the EBROG and EBR specimens, failure modes, as well as the evolution of strain fields along the CFRP laminates with respect to the applied load. Furthermore, the effects of concrete compressive strength, CFRP thickness, and grooves depth on the bond strength of EBROG joints have been studied.

2. Experimental program

2.1. Specimen details and material properties

To evaluate the bond strength of CFRP laminates adhesively bonded to concrete through EBR and EBROG joints, 84 concrete prism specimens were constructed, each $150 \times 150 \times 350$ mm (width $\times$ height $\times$ length) in dimensions as commonly proposed for the test [14]. Three concrete cylinders having dimensions of 150×300 mm (diameter $\times$ height) were used to measure the