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Bond characteristics of straight- and headed-end, ribbed-surface, GFRP bars embedded in high-strength concrete

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HIGHLIGHTS

- Bond characteristics of both straight- and headed-end GFRP bars are studied experimentally.
- 180 pullout tests were conducted to cover 30 parameters.
- Empirical equation is proposed for the development length calculation of GFRP bars.
- Development lengths based on experimental results are compared with the available design standards.
- CSA S6-06 showed the closest development length results to the experimental findings.

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ABSTRACT

Glass Fiber Reinforced Polymer (GFRP) bars as a proper substitute for traditional reinforcing steel bars not only eliminate the durability problem due to corrosion of reinforcing steel, but also provide remarkably enhanced capacity due to their high tensile strength compared to that of the steel bars. This paper presents the experimental findings of 180 pullout tests conducted on GFRP bars embedded into high-strength concrete blocks covering different parameters. The studied parameters were bar diameter size (12 or 16 mm), embedment length (4 or 6 times the bar diameter), bar end condition (straight and headed), and concrete cover (1.5, 2.5, and 5 or 7 times bar diameter for straight bars and 8 or 10.5 times bar diameter for headed bars) in addition to a case of no embedment length except the head length for headed-end bars. In total, 30 variables were studied, while each variable was conducted on 6 identical specimens in order to increase the reliability of the results. Based on the results of the parametric study, the bond stress was shown to be inversely proportional to the embedment length and bar diameter as expected. In addition, the smaller concrete cover appeared to have significant effect on bond stress, leading to side blow-out failure rather than bar pullout or concrete splitting in the case of headed-end GFRP bars. In addition, the GFRP bar with headed-end showed significant increase in pullout strength compared to that for the straight-end bars. Finally, an empirical expression was proposed to calculate the development length of GFRP bars with either straight or headed-end, and then compared with the available design standards such as CSA-S806-02, CSA S6-06, ACI 440-1R-06, and JSCE-97. The comparison showed that the results developed by CSA S6-06 standards was the closest to the experimental findings showed about 2% safety margin exceeding the obtained development length by the proposed expression.

1. Introduction

Fiber Reinforced Polymer (FRP) bars have desirable characteristics which give them more advantages over traditional reinforcing steel bars. These characteristics include high tensile strength, corrosive resistance, light weight, electric insulation and fatigue resistance [1]. Therefore, in the recent years, FRP bars have been introduced as a competent alternative to traditional reinforcing steel bars for different concrete structures subjected to severe environmental conditions such as waste water treatment and chemical plants, floating decks, sea walls and water structures [2–7]. In addition, it has been found that FRP bars can eliminate durability problem associated with corroded reinforcing bars [8–11]. However, direct replacement of the reinforcing steel bars

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with the FRP bars has many concerns due to various differences in the manifested behavior of the two materials under different loading conditions. For instance, FRP exhibits linear elastic behavior up to failure which means that it exhibits limited ductility. In addition, FRP bars have anisotropic material properties while steel bars have isotropic properties, which make the bond behavior dubious. Furthermore, higher cost of the FRP bars compared to that of steel bars and lack of familiarity with the new technology resulted in slow adaptation of FRP as concrete reinforcement [12].

As the transfer of stresses between the concrete and the reinforcement is mainly dependent on the quality of bond, the force transfer mechanism is always a serious issue of the structural design regardless of the type of reinforcement [11,13–16]. Hence, the force between the reinforcement and concrete should be transferred efficiently through the bond between the two materials in order to ensure strain compatibility and composite action in reinforced concrete members. The transfer of forces between a reinforcing bar and concrete is attributed to three different mechanisms, namely: (i) chemical adhesion; (ii) friction and (iii) mechanical interlocking arising from the textures on the bar surface as illustrated in Fig. 1(a). The resultant of these forces can be resolved into an outward component (radial splitting force) and a shear component, parallel to the bar that is the nominal bond force as shown in Fig. 1(b). For traditional steel reinforcement, bond failure is attributed to bearing causing side splitting or shearing of concrete. On the other hand, bearing stress of the GFRP bars can exceed the shear strength between the surface deformations and the bars core resulting in a bond failure at this interface as depicted in Fig. 2(a) [17]. For real structures, it is unusual for a pure pullout or pure splitting failure to occur, mostly a combination of the two modes occurs as shown in Fig. 2(b).

Generally, bond behavior between concrete and reinforcing steel bar can be assumed constant, however this assumption is less valid for GFRP bars due to their relatively lower stiffness compared to that of steel bars. This results in greater slip values at the loaded end than at the free end [15]. Thus, the free end slip will be reduced to almost zero once the embedment length is greater than the development length as depicted in Fig. 3(a). Adopting the same concept, the bond stress distribution for headed-ended GFRP bars maybe assumed as shown in Fig. 3(b).

Previous research showed that bond behavior of FRP bars in concrete is influenced by several geometric and material-related factors [2,15,18–23,11,24–27]. Regression manipulation on different experimental results indicated that good correlation exists between bond strength and the square root of the compressive strength of concrete [12,20,28]. In addition, bond failure mechanism of FRP bars in concrete is influenced by concrete cover around the reinforcing bar by virtue of its confining effect [18,19]. Bond failure occurs through splitting of the concrete when the member does not have adequate concrete cover [28]. On the other hand, when enough concrete cover is provided, splitting failure is prevented or delayed while the pullout failure is dominating [29].

Experimental investigations revealed that bond strength of FRP bars increases with decrease in the bar diameter, which is the same results obtained for steel bars [2,9,11,12,30]. Hao et al. [1] and Tighiouart et al. [11] verified that when the diameter of the bar is larger, more bleeding water is trapped beneath the bar. Consequently, there is a greater chance of creating voids around the bar which will eventually decrease the contact surface between the concrete and the bar and thus, reduces bond strength. It was also observed that the maximum average bond stress decreased with an increase in the embedment length as exhibited by steel bars [2,10,11,15,23]. Due to the nonlinear distribution of the bond stress along the length of the reinforcing bar, as the embedment length increases, the stress is distributed over a longer length and henceforth, the bond strength decreases.

Bond between reinforcement and concrete can be described by means of a constitutive bond stress-slip relationship that can be introduced in the solution of problems, such as the calculation of bar development length [22]. Although numerous existing formulations for steel bars exist and are well-established, FRP bars still require extensive research effort to determine an analytical model of the bond stress-slip constitutive law. Malvar [31] established the first modeling of the bond behavior in the case of FRP bars with various deformation geometries and radial confining stresses. Cosenza et al. [22] investigated the bond stress-slip behavior of FRP bars and proposed a modification to the bond prediction evaluation (BPE) model to account for the FRP characteristics. Diverse efforts were dedicated in order to develop more refined bond-slip model to cover various surface treatments, shear and axial stiffness, bar diameter, bond length, confinement applied to the FRP bars due to concrete shrinkage or external loads, and swelling of FRP bars due to temperature variation and moisture absorption [32–42].

For many years, bond strength was represented in terms of the shear stress at the interface between the reinforcing bar and the surrounding concrete treating bond as a material property [43]. It is now understood that bond, anchorage, development, and splice strength, are structural properties that are dependent on not only the materials, but also on the geometry of the reinforcing bar and the structural member itself.

Glass Fiber Reinforced Polymer (GFRP) bars are commonly used in various projects in North America such as bridge deck slabs traffic barrier and parking garages as a substitute of steel reinforcing

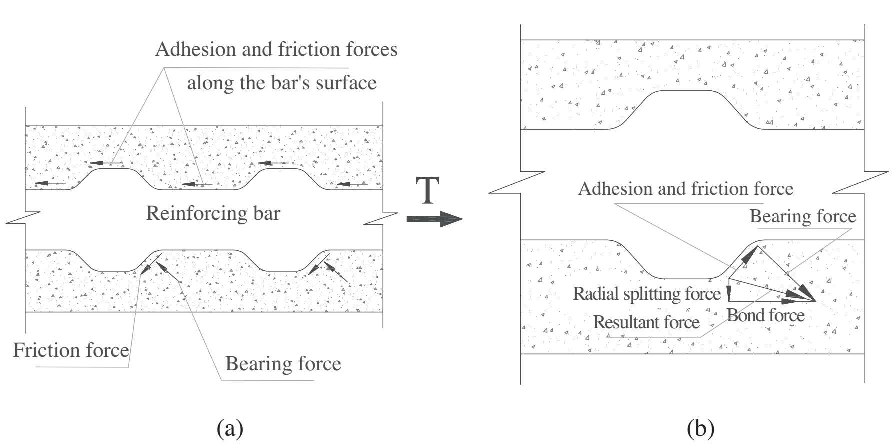

Fig. 1. Bond force transfer mechanism.