Alexandria Engineering Journal (2014) **xxx**, xxx–xxx

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Bond behavior and assessment of design ultimate bond stress of normal and high strength concrete

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Received 11 January 2014; revised 15 March 2014; accepted 27 March 2014

KEYWORDS

Bond strength;
Single and double pull-out test;
High strength concrete;
Design ultimate stress

Abstract The aim of this work is to assess the ultimate bond stress of normal and high strength concrete. This study contains two phases. The first phase included the studied bond behavior using two different models. In the first model, single pull-out test (SPOT), the concrete section of specimen was subjected to compressive stresses. In the second model, double pull-out test (DPOT), the concrete section of specimen was subjected to tensile stresses. So this phase of study aimed to make a comparison between the single pull-out test and the double pull-out test. To compare the behavior of these models, different levels of compressive strength were considered through the use of different coarse aggregate types, different W/C ratios and different cement contents. The second phase focused on the study of bond strength of high strength concrete using double pull-out test to assess design ultimate bond stress. In this phase, the effect of concrete compressive strength, bar diameter, concrete cover, embedded length, and pre-flexural crack length was studied. Based on the test results, a proposed concept to assess design ultimate stress of normal and high strength concrete was adopted. Equations to calculate the design ultimate bond stress, and required development length were suggested.

1. Introduction

Bond refers to the interaction between reinforcing steel and the surrounding concrete, which allows transferring of tensile stress from the steel into the concrete. It is the mechanism that allows the anchorage of straight reinforcing bars and influences many other important features of structural concrete such as crack control and section stiffness [1]. Similarly the bond between concrete and development length of reinforcing steel is essential for composite action in reinforced concrete construction [2,3]. It is well known that the use of deformed bars can greatly enhance the steel–concrete bond capacity. Three main components determine the bond strength between the adjacent ribs of a reinforcement bar. These components are shear stresses due to adhesion along the bar surface, the bearing stresses against the faces of ribs (mechanical interlock), and the friction between bars with concrete in the rib dales and

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

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http://dx.doi.org/10.1016/j.aej.2014.03.012

the surrounding concrete. The highest contribution to bond strength comes from mechanical interlock [4].

Adequate bonding between reinforcing bars and concrete is essential for the satisfactory performance of reinforced concrete structures. In the absence of sufficient bond strength, effective beam action, as required by codes of practice, cannot be achieved, and hence, the specified design equations are no longer valid. Loss of strain compatibility at the depth of a reinforcement results in a redistribution of stresses in the reinforced concrete element, which may lead to excessive service deflections and altered load capacities [5]. One way to evaluate the steel–concrete bond is to investigate the bond stress–slip evolution generally obtained through classical pull-out tests [6]. Even if these tests are not totally satisfactory due to boundary conditions or stress state [7] and replaced by other experimental setups (direct tension-pullout bond test [7]), they remain the most convenient and simplest experiment to achieve a global estimation of the bond effect. The main characteristics of the bond stress–slip evolution and especially the maximum bond stress are found to be clearly dependent on material, geometrical or loading parameters. The positive effect of the spacing and height of ribs was investigated by Hamad [8] and Castel et al. [9]. The confinement was defined as one of the key parameters which influenced the value of the maximum bond stress. This point is of great concern especially in the case of structures which are reinforced with stirrups or submitted to a tri-axial state of stress [10,11]. Torre-Casanova et al. showed [12] that the splitting and pull-out failures depend on the concrete cover (splitting failure for low concrete covers and pull-out failure for others cases).

Also some factors affect negatively the bond strength such as epoxy coating. This effect is due to reduction in adhesion and frictional components along the smooth epoxy surface [13]. Compared with uncoated bars, the decrease in bond strength was found to range from 15% to 50% depending on several factors such as the coating thickness, bar size and location, deformation patterns, concrete properties, and casting conditions [14–16]. Therefore, to compensate such loss, design codes stipulated an increase in the development length of the bars. For example, in ACI 318, the development length is multiplied by a factor of 1.5 for epoxy-coated bars with a cover of less than 3 d_b or clear spacing between bars less than 6 d_b (where d_b is the bar diameter), and a factor of 1.2 for other cases [17]. In the AASHTO bridge specification, these factors are 1.5 and 1.15, respectively [18].

The bond strength of high strength concrete is improved significantly. Many researches have been conducted to give the best expression of the bond strength of this type of concrete. Zsutty [19] found that $\acute{f}_c^{1/3}$ provided an improved match with data compared to $\acute{f}_c^{1/2}$. Darwin et al. [20] combined their own test results with large international database and observed that a best fit with existing data was obtained using $\acute{f}_c^{1/4}$ to represent the effect of compressive strength on development and splice length. Zuo and Darwin [21] also observed that $\acute{f}_c^{1/4}$ provides the best representation for the effect of compressive strength contribution to bond strength. For bar confined by transverse reinforcement, Zuo and Darwin [21] found that $\acute{f}_c^{1/2}$ significantly under-estimates the effect of concrete strength on the additional bond strength provided by transverse reinforcement.

The aim of this study is to make a comparison between the single pull-out test and the doubled pull-out test. Also proposed equations are constructed to assess the design ultimate stress of normal and high strength concrete.

2. Experimental program

2.1. Materials

The experimental program includes two phases. In the first phase (I), three types of coarse aggregate, 19 mm crushed pink limestone, 12 mm gravel and 19 mm crushed dolomite with specific gravity of 2.48, 2.65 and 2.70, respectively were used. Natural siliceous sand with fineness modulus of 2.57 and specific gravity of 2.63 was used. The used aggregates meet ASTM C33 requirements. Silica fume of 10% cement replacement meeting the requirements of ASTM C 1240 was used in some mixes of dolomite concrete. Different cement contents, water cement ratios and type F high range water reducing with different doses presented in Table 1 were considered in this phase.

In the second phase (II) the previous crushed dolomite, natural siliceous sand of 2.6 specific gravity and 2.4 fineness modulus, Silica fume and type F high range water reducing were used. The used dosage of the admixtures was determined by trial to achieve a constant slump of 100 ± 20 mm. Table 2 shows the concrete mixtures of phase II. Portland cement type I according to ASTM C150 was used in this study. In phase I, one deformed steel bar with diameter of 16 mm was used while two different deformed bars of 16 mm, and 18 mm diameter were used in phase II. The properties of the used steel bars are shown in Table 3.

2.2. Test specimen

In the first phase two different configuration test specimens were used. The first was a cube specimen of 150 × 150 × 150 mm with a steel bar of ∅16 mm in the middle as shown in Fig. 1, where the concrete in this specimen was subjected to compressive stress. The second one was prismatic specimens of 150 × 150 × 320 mm in dimension containing two bars of ∅16 mm which were put exactly in the same level and in the opposite direction with 2 cm space between each other, each bar was fixed to a steel chair of ∅8 mm, and the detail of this specimen is shown in Fig. 2. The cross section of specimen was reinforced with four bars of 12 mm and two stirrups were put at the end of the specimen. During the test, the two opposite bars were subjected to a tensile force that which is transferred to the concrete as tensile stresses throughout the bond stresses between the concrete and the steel. The used cover and embedded length of this specimen were 67 mm and 160 mm, respectively. Each result for different tests represents the average of two specimens.

In the second phase, prismatic specimens of 100 × 100 × 325 mm, 150 × 150 × 325 mm, and 150 × 150 × 365 mm were used as shown in Fig. 2. The specimens in phases I and II were cured in water for 28 days until test date. In phase II, the bar slip was recorded for each applied load until failure.

The bond strength was computed using the following equation:

$$\tau = P/(\pi L_m d_b) \quad (1)$$

where τ is the bond strength, P is the ultimate load, L_m is the embedded length, and d_b is the bar diameter.

Please cite this article in press as: A.M. Diab et al., Bond behavior and assessment of design ultimate bond stress of normal and high strength concrete, Alexandria Eng. J. (2014), http://dx.doi.org/10.1016/j.aej.2014.03.012