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Bond of reinforcing bars to steel fiber reinforced concrete

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HIGHLIGHTS

- Bond of rebars to SFRC was analyzed through Pull Out Tests.
- Semi-empirical equations for bond strength and toughness were obtained.
- The effect of fiber content on bond strength is limited.
- Toughness of bond failure is clearly improved by steel fibers.

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ABSTRACT

Steel fiber reinforced concrete (SFRC) has been increasingly used during recent years. Regarding bond of rebars to concrete, fibers provide passive confinement and improve bond capacity in terms of bond strength and, more importantly, toughness. An extensive experimental programme has been carried out, and SFRC specimens with embedded rebars have been subjected to the Pull Out Test to obtain the bond stress–slip curves, retaining the bond strength and the area under the curve as measures of the bond capacity of concrete. The following parameters were considered: concrete compressive strength (30–50 MPa), rebar diameter (8–20 mm), concrete cover (between 30 mm and 5 times rebar diameter), fiber content (up to 70 kg/m^3), and the slenderness and length of the steel fibers used. Predictive equations have been obtained to relate the experimental results to the factors considered, and the trends observed have been analyzed and discussed.

1. Introduction

Bond of reinforcement to concrete has been studied for different types of concrete and different experimental setups and structural situations. On the other hand, steel fiber reinforced concrete (SFRC) has been increasingly used. This introduction aims at contextualizing this study and justifying its objectives, which are detailed after that.

1.1. Bond between reinforcement and concrete

Bond between reinforcement and concrete is measured as a shear stress, or bond stress, at the interface between the two materials, distributed over the surface of the rebar along the embedded length. Following this definition, bond stress is the ratio between the rate of change in axial force along the rebar and the area of rebar surface over which this change takes place [1]. In addition to this shear stress there are other aspects involved, especially in the case of deformed, ribbed rebars [1–3]. This is illustrated in Fig. 1: the tensile load pulling the rebar out of concrete causes reaction forces applied onto the surrounding concrete. As a result of the ribbed geometry, these reactions are oblique and therefore consist of two components: (a) a shear component, parallel to the rebar axis, and (b) a radial component which affects the surrounding concrete. Therefore, bond implies not only bond stresses but radial stresses as well.

Concrete between ribs is subjected to a multiaxial stress state caused by the shear component of bond stresses. This wedging action increases with the axial load pulling the rebar out, which eventually results in concrete crushing between ribs. Radial stresses increase as well, until concrete tensile strength is reached in the concrete surrounding the rebar. As a result, transverse microcracking occurs, with the consequent loss of strain compatibility between rebar and concrete: the rebar progressively slips out of concrete with the development of these microcracks. The initiation and progress of the slippage results in the activation of bond. As

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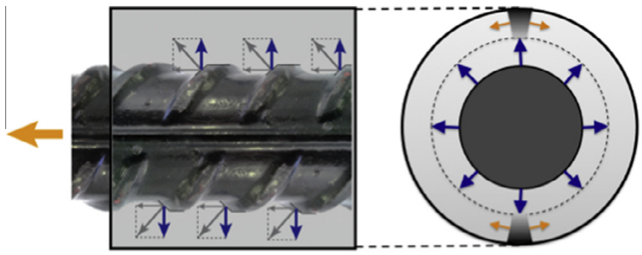

Fig. 1. Bond stresses and radial stresses generated at the rebar–concrete interface.

long as confinement is sufficient and the cracks do not imply the total failure of concrete surrounding the rebar, bond stresses keep increasing until the ultimate value, known as bond strength, is reached. After this peak, bond stress–slip curves exhibit a softening behavior.

Depending on the confinement conditions, bond failure can occur in two different major modes: pullout failure (when the rebar is pulled out after the shear failure of the rebar–concrete interface), or splitting failure (when the concrete surrounding the rebar undergoes total splitting as a result of the radial stresses). The confining effect of concrete cover is most usually typified by rebar diameter: concrete cover/diameter ratio is the reference parameter. According to the Model Code [4], concrete is considered well confined when this ratio is not less than five, and it must be higher than 2.5 to prevent splitting failures [5,6], although this threshold varies depending on different factors. A detailed analysis of these factors determining the mode of bond failure and the effect that fibers have on the risk of concrete splitting has already been published [7].

Confinement affects bond performance in terms of bond strength and bond failure ductility [4] in addition to the mode of bond failure [8,9]. In terms of ductility, increasing the concrete cover has been shown to improve the ductility of bond failure, as bond stress–slip curves become steeper when concrete cover increases [10].

1.2. Effect of steel fibers on bond between reinforcement and concrete

Steel fibers have been increasingly introduced in concrete production in recent years [11,12]. They improve bond between reinforcement and concrete even when they are dosed at low contents [13] as a result of their confining effect and their broadening the range of crack width values within which passive confinement remains active [13–15].

The positive effect of fibers on bond capacity is acknowledged in codes and recommendations for structural concrete but is not always considered in expressions to determine development lengths. Their effect on bond performance is especially noticeable in terms of toughness of bond failure and the ductility of the material [10,16]. However, accounting for the enhanced bond capacity of SFRC in order to reduce required anchorage length values is not a straightforward issue. In this sense, several studies have been performed attempting to model the bond phenomenon and anchorage behavior in general [17–24].

2. Objectives

As it has been highlighted in the introduction, a number of variables are involved in terms of bond of reinforcing bars to SFRC, and there was a need to study all of them together in order to quantify their importance, detect potential synergies between them and non-linear trends. This research aimed at studying bond capacity of SFRC from a multivariate perspective. The main objectives were:

- To study different parameters characterizing the toughness of bond failure under the conditions of the Pull Out Test (POT), and their relation with bond strength.
- To study the effect that steel fiber content, fiber length and slenderness, concrete compressive strength, rebar diameter and concrete cover have on bond capacity of SFRC and on the toughness of bond failure.
- To obtain analytical expressions that can be used to estimate bond strength and bond toughness in relation to the factors considered.

3. Experimental investigation

3.1. Definition of variables and experimental programme

The following factors were considered: concrete compressive strength (f_c), rebar diameter (D), concrete cover (C), steel fiber content (C_f), fiber slenderness (λ_f) and fiber length (l_f). The values considered for each of these factors are summarized in Table 1.

Three different groups of concrete mixes were considered, providing compressive strength values between 30 and 50 MPa. They are referred to throughout this paper as Type I, II, and III, and they are based on the reference mix designs given in Table 2. The mixes within each group vary in fiber content. The dosages of superplasticizer and limestone filler were slightly adjusted in all cases to maintain a similar workability throughout all mixes (slump values between 10 and 15 cm).

A highly fractioned factorial plan [25] was followed to define the experimental program. It was organized in three blocks, corresponding to Type I, Type II, and Type III mixes, resulting in the

Table 1
Factors and levels considered.

Factor	Type I mixes	Type II mixes	Type III mixes
Rebar diameter, mm	8 16 20	8 12 16	8 12 16
Concrete cover	C1 = 30 mm C2 = (C1 + C3)/2 C3 = 5.0 D	C1 = 2.5 D C2 = 3.5 D C3 = 5.0 D	C1 = 2.5 D C2 = 3.5 D C3 = 5.0 D
Fiber geometry (slenderness/length, mm/mm)	65/60 80/50	45/50 80/50 80/35	45/50 80/50 80/35
Fiber content, kg/m^3	0 40 70	0 40 60	0 40 60