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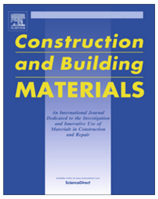

Bond behaviour of reinforcing steel bars in early age concrete

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HIGHLIGHTS

- We tested the bond behaviour of early age concrete and steel bars.
- We considered small concrete cover to bar diameter ratios.
- We determined the bond strength, critical slip and shape parameters.
- We established time-dependent model of bond slip behaviour of early age concrete.
- Good agreement between model predictions and data in literature was achieved.

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ABSTRACT

Concentric pull-out tests on early age concrete were conducted to quantify the bond–slip relationship. Different concrete strengths and cover-thickness-to-steel-bar-diameter ratios (c/d) were considered. It was found that the bond strength was proportional to the concrete compressive strength and c/d (up to a limit value of 1.39), while the slip corresponded to the peak stress and the shape parameters had weak correlations with the concrete compressive strength and c/d. A complete bond–slip model was established and verified based on test results in the literature, and good agreement was achieved.

1. Introduction

Bond behaviour is of fundamental importance for the monolithic action in bonded concrete and reinforcing steel bars and the structural responses of reinforced concrete (RC) members. The strength of early age concrete increases with the development of the cement hydration process, as does the bond behaviour between the reinforcing steel bars and the surrounding concrete; however, this process is also affected by other factors, such as steel bar diameter and concrete cover thickness.

It has been reported that the failure mode of an RC member may be different in early age than in later age, due to the bond–slip behaviour of early age concrete [1]. Shah et al. tested RC beams at various ages (from 1 to 28 days) and found that the failure mode varied from brittle shear-type failure to flexural ductile failure [2]. Wilson reported that, under concentrated loading, a beam loaded at early age and then loaded to failure after 3 months was subjected to more diagonal cracks than a similar but not preloaded beam failing at the same age [3].

Cooper, although disagreeing on the influence of early age loading on the ultimate load-carrying capacity of mature concrete members, did conclude that early loading may cause excessive deflection and concrete cracking [4]. Hughes and Videla also claimed that early age bond may affect the strength and ductility of anchorage at both ultimate and serviceability limits [5].

A good understanding of the bond behaviour of early age concrete and steel bars is, therefore, pertinent to proper design and maintenance of reinforced concrete members. The bond behaviours of mature concrete (concrete age equal to or greater than 28 days) and steel bars have been studied in detail, including the failure mechanism, influential factors, testing methods, numerical modelling techniques, bond strength and constitutive law of bond stress and slip. Only a limited number of studies have reported on early age concrete until recently.

There is growing interest in the life-cycle analysis of concrete structures, especially for cracking analysis and construction management of RC structures during the construction period [6–10]. Most of these studies, however, focused on the development of

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bond strength τ_1. There is a general consensus that τ_1 is closely related to the compressive strength of concrete, i.e., the cubic compressive strength f_{cu}. Many mathematical models, taking the form of power functions, have been proposed for this relationship with a rather wide range of power coefficients (0.5–0.8) [1,5]. However, a linear function is a desirable alternative, since it can achieve a comparable fitting effect, as shown in Fig. 1 using Hughes and Videla's data [5] as examples.

The correlation between τ_1 and the ratio of the concrete cover thickness c to the steel bar diameter d (c/d) also needs to be investigated. It is generally believed that the bond strength corresponding to splitting failure increases with increased c/d and that the bond strength corresponding to pull-out failure is independent of c/d. For example, Harajli et al. derived a power relationship between the normalized bond strength from splitting failure results ($\tau_1/f_c'^{0.5}$, where f_c' is the cylinder compressive strength of concrete) and small c/d values (between 0.5 and 2.1) [11]. Xu and Shen found that this correlation ceased to exist for c/d values larger than 4.5, due to the change in failure mode from splitting to pull out [12].

Hughes and Videla's results for early age concrete, however, indicated that a linear relationship existed between the normalized bond strength and c/d (3.5–12) for both splitting and pull-out failure modes, as shown in Fig. 2. (The relationship is even more prominent if the bond strength is normalized by $f_{\text{cu}}^{0.5}$.) This implies that there may be a mutual effect between the two failure modes and the overall bond strengths for a certain range of c/d values in early age concrete. Therefore, the bond strength related to splitting failure (based on observation) may be independent of c/d.

The complete bond–slip relationship is indispensable in the analysis of crack width and member stiffness if bond failure is of concern. Many studies have been done on bond–slip models of mature plain concrete of high or normal strength and fibre concrete (e.g., [11,13]). Such information is, however, rare for early age concrete. Research work on this aspect will be of special significance to construction safety analysis, where thermal and shrinkage induced concrete cracking and early loading of concrete members are frequently encountered.

This paper presents the results of early age concrete bond tests with deformed steel bars. The specimens were designed with commonly used steel bar diameters and concrete cover thicknesses, which resulted in small c/d values (1.07–2.5), in an effort to target our research on practical RC members, where concrete covers tend to be thin to maximize the material utilization efficiency, especially for flexural members. The test results were used to quantify key parameters of the bond behaviour: bond strength τ_1, corresponding slip s_1, and shape parameters α and k of the ascending and post-peak branches of the bond–slip curves, respectively. The sensitivities of the parameters to the concrete strength and c/d value were also investigated. The proposed formulas for the parameters and the complete time-dependent bond–slip model were verified.

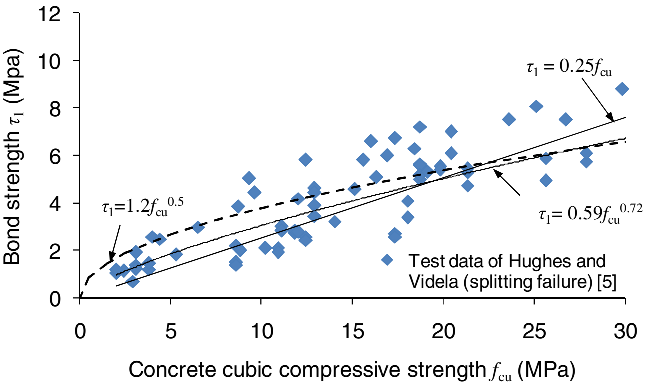

Fig. 1. Relationship between bond strength τ_1 and concrete cubic compressive strength f_{cu} characterized by power and linear functions.

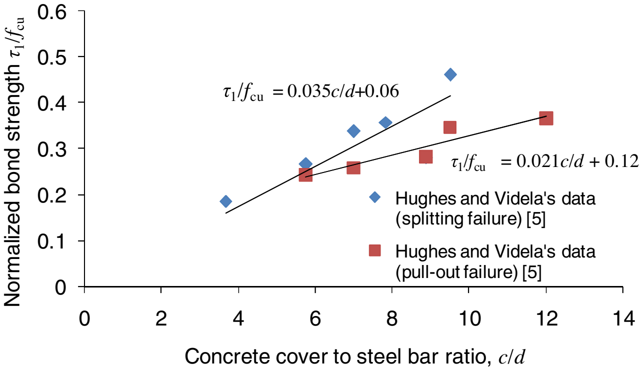

Fig. 2. Relationship between normalized bond strength τ_1/f_{cu} and c/d ratio for specimens failed in splitting and pull-out modes.

2. Experimental programs

2.1. Test specimens and variables

Many testing methods have been proposed for the study of bond–slip behaviour, including the concentric pull-out test, the modified pull-out test, the beam end test, and the beam test. The beam and beam end test methods are generally favoured, especially for mature concrete testing, due to the more realistic tensile stress state of concrete. However, the testing setup is complicated [14], and concrete flexural cracking may add greater uncertainty into the test results, considering the low mechanical properties of early age concrete.

The modified pull-out test utilizes two steel bars pulling at the opposite ends of a concrete block, in order to have the concrete in tension [1,5]. However, the inevitable misalignment of the two steel bars may cause flexural stresses in the concrete, thereby requiring particular attention to specimen preparation. In the concentric pull-out test, the disadvantage of concrete being in compression can be alleviated by limiting the embedment length, which is believed to have no effect on the bond–slip behaviour under particular conditions [1,5].

In this study, a modified pull-out testing method was employed with a short embedment length in the middle section of the concrete blocks. The concrete cover thickness was adjusted by offsetting the steel bars to one side of the concrete blocks, as shown in Fig. 3.

A total of 154 bond specimens were tested. The specimens were prepared according to the requirements of China's standard for test method of concrete structures (GB/T 50152-2012) [15]. The concrete blocks were 150 × 150 × 150 mm. The steel bars were bonded at a length of 70 mm inside the concrete blocks (i.e., embedment length l_e = 70 mm) and had bond-free lengths of 50 and 30 mm, respectively, at the loading and free ends. The steel bars were extended roughly 150 and 50 mm outside the concrete blocks for slip measurements. The bond-free length was secured by placing the steel bars inside PVC tubes, which were properly sealed to prevent concrete intrusion during casting. The specimens were cast using wood

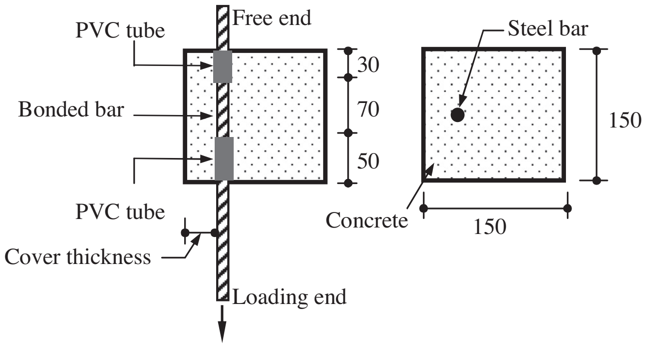

Fig. 3. Bond slip test specimen configuration.