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Ultimate bond strength of plain round bars embedded in concrete subjected to uniform lateral tension

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HIGHLIGHTS

- The analytical solution of bond strength for plain round bars subjected to uniform lateral tension.
- The experimental study on bond behavior of plain round bars under equi-biaxial lateral tension.
- The sensitivity analysis for evaluating the effects of main factors on the ultimate bond strength of plain round bars.

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ABSTRACT

The bond strength of plain round bars, which is important for the assessment of historical buildings, is greatly influenced by the lateral stress state. To predict the bond strength of plain round bars subjected to lateral tension, a few empirical models were presented based on test results. However, these models are probably restricted for application since the test parameters adopted in the experiment are limited. Therefore, an analytical study, which is independent of test parameters, is made in this paper to investigate the bond behavior of plain round bars embedded in concrete subjected to uniform lateral tension. Based on the theory of elasticity, an analytical solution for the ultimate bond strength is derived. When the shrinkage of concrete and the geometric and mechanical parameters of bars and concrete are provided, the analytical solution can be used to evaluate the ultimate bond strength of plain round bars subjected to uniform lateral tension. 72 pull-out specimens are made and tested to verify the analytical solution. The results show that, the analytical predictions are in good agreement with the experimental results. Finally, a sensitivity analysis is made to evaluate the effects of main factors on the ultimate bond strength of plain round bars, and a simplified model is provided for practical applications.

1. Introduction

Recently, rehabilitation of historical buildings reinforced with plain round bars has become more and more highlighted [1]. One of the main purposes of the assessment or seismic checking of these old buildings is to examine whether the anchorage between concrete and plain round bars is reliable or not. Thus, the bond strength of plain round bars needs to be estimated.

Many efforts have been made to investigate the bond strength of plain bars. Abrams [2] first investigated the bond behavior between plain bars and concrete with pull-out tests. The experimental results showed that the bond resistance between plain bars and concrete is mainly composed of two components: chemical adhesion force and frictional force, and that the bond strength of plain bars is closely related to the square root of the compressive strength of concrete. Based on experimental results, Feldman and Bartlett [3,4] derived a regressive formula for the bond strength of plain bars by considering the strength of concrete and the surface conditions of bars. Verderame et al. [5,6] studied the bond strength of plain bars under monotonous and cyclic pull-out loads. Recently, MacLean and Feldman [7] evaluated the effects of casting position and bar shape on the bond behavior of plain bars.

Besides experimental studies, theoretical analyses have also been made to estimate the resistance of the pull-out system.

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Nomenclature

D	diameter of plain round steel bar	α	ratio of E_s to E_c
E_c	elastic modulus of concrete	β	ratio of R_s to R_c
E_s	elastic modulus of plain round steel bar	ε_0	shrinkage strain of concrete
f_{cu}	compressive strength of concrete	σ_N	normal stress applied to plain round bar
f_t	tensile strength of concrete	$\sigma_{\varepsilon 0}$	normal stress due to shrinkage of concrete
f_y	yield strength of plain round steel bar	σ_{pm}	normal stress due to uniform lateral tension
l_d	embedment length	σ_s	normal stress due to the radial contraction of steel bar caused by tensile stress
P	pull-out load	μ	coefficient of friction
P_u	ultimate pull-out load	τ	bond stress
p_m	uniform lateral tension	τ_a	chemical adhesion
p_{mcr}	critical uniform lateral tension	τ_u	ultimate bond strength
R_s	radius of plain round bar	τ_{uf}	bond strength due to frictional effect
R_c	radius of concrete element	υ_s	Poisson's ratio of plain round steel bar
s	average slip of bar	υ_c	Poisson's ratio of concrete
s_0	slip at peak bond stress		

Takaku and Arridge [8] analyzed the pull-out process of a fiber from a cement matrix and gave an analytical solution of the pull-out load. Laldji and Young [9] adopted a similar method to deduce a theoretical expression for the pull-out load of steel strands. By taking the thickness of adhesive into account, Wu et al. [10,11] studied an anchor-mortar-concrete anchorage system and derived an analytical solution of the pull-out load for different failure modes. They also investigated the pull-out response of fiber reinforced polymer rods embedded in steel tubes filled with cement grout [12]. It should be pointed out that, in these theoretical analyses, only the frictional mechanism is considered and the contribution of chemical adhesion to the pull-out resistance is neglected. As a result, when these solutions are applied to plain round bars embedded in concrete, the pull-out load or bond strength is highly dependent on the lateral stress applied on the bar/concrete interface [8,9].

To model the actual stresses in beam-column joints or simply supported structures, Robins and Standish [13,14] studied the effect of uniaxial lateral pressure on the bond behavior of plain round bars with pull-out tests. Based on experimental results, an analytical relationship between the bond strength and lateral pressure was established. Xu et al. [15,16] made a systematic study on the bond behavior of plain round bars under uniaxial lateral pressure, and derived both empirical and analytical expressions for the bond strength by considering the effects of the strength of concrete, the bar diameter, and the lateral pressure. It was shown that the bond strength of plain bars increases with an increase in lateral pressure. In slabs or bridge decks with orthogonal reinforcement, besides the pressure caused by gravity loads, steel bars at the bottom are also subjected to lateral tension. Contrary to lateral pressure, lateral tension is negative to the structural safety by weakening the bond anchorage [17]. Through pull-out tests, Zhang et al. [18] and Wu et al. [19] studied the bond behavior of plain round bars under lateral tension and tensile-compressive stresses, respectively. The experimental results indicated that increasing lateral tension decreases the bond strength significantly.

Owing to its significant influence, the lateral stress state should be considered when the bond strength of plain bars is evaluated. Aforementioned literatures [15,16,18,19] explicitly revealed the positive and negative effects of lateral pressure and tension on the bond behavior of plain bars, and gave the empirical equations of the bond strength under complex lateral stresses. However, it should be noted that application of these empirical models is limited according to the test parameters adopted in the experiment, such as the strength of concrete and the bar diameter. To overcome this deficiency, it is necessary to develop an analytical model independent of test parameters to reveal the bond mechanism of plain round bars, and further to estimate the ultimate bond strength of plain bars under lateral tension. In practice, the lateral stress state around the steel bar is complicated, while the uniform lateral tension is the most unfavorable condition for the bond strength of plain round bars [18]. When any component of lateral stresses around the steel bar is tensile stress, it is safe to calculate the bond strength with the effect of uniform lateral tension, and the conservative results can be used for design. Therefore, it is essential to further study the effect of uniform lateral tension on the bond behavior of plain round bars and to evaluate the ultimate bond strength in an analytical manner.

This paper presents a study on the ultimate bond strength of plain round bars embedded in concrete subjected to uniform lateral tension. With the help of the theory of elasticity [8,9,13,16], an analytical solution of the ultimate bond strength is derived and verified with experimental results of 72 pull-out specimens. Based on the analytical solution, the effects of main factors on the ultimate bond strength are evaluated in a quantitative manner.

2. Analytical derivation of ultimate bond strength

When a plain round bar is pulled from a concrete matrix, the chemical adhesion and frictional action between the bar and concrete prevent the bar from sliding. During the first stage, the bond resistance is attributed mainly to the chemical adhesion [20,21]. When a relative slip between the bar and concrete occurs, the frictional action becomes a primary factor [2]. When a lateral tension is applied, however, it exerts a negative effect on the bond behavior by weakening the compaction of the bar/concrete bond interface. With the increase of the lateral tension, the bar/concrete bond interface is gradually looser and becomes instable. Once the lateral tension exceeds a certain value, the bar and concrete separate from each other and the anchorage fails completely. Therefore, the key to analyzing the bond strength of plain bars subjected to lateral tension is the contact conditions between the bar and concrete.

According to the theory of elasticity [22], when concrete is subjected to a shrinkage strain ε_0 as shown in Fig. 1, the radial displacement of concrete at the bar/concrete bond interface, u_{rc1}, can be expressed as

$$u_{rc1} = \frac{1}{E'_c}\left[-(1+v'_c)\frac{A_1}{R_s} + 2C_1(1-v'_c)R_s\right] \tag{1}$$