Construction and Building Materials 94 (2015) 826–836

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of loading rate on the bond behavior of plain round bars in concrete under lateral pressure

Xinxin Li [a], Zhimin Wu [a,*], Jianjun Zheng [b], Wei Dong [a]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, PR China
[b] School of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou 310014, PR China

HIGHLIGHTS

- The influence of loading rate on the bond behavior of plain bar is depended upon the magnitude of lateral pressure.
- Effect of loading rate and lateral pressure on the bond parameters of plain bar was investigated.
- A bond stress–slip relationship considering the loading rate and lateral pressure is proposed.

ARTICLE INFO

Article history:
Received 13 December 2014
Received in revised form 18 June 2015
Accepted 13 July 2015
Available online 21 July 2015

Keywords:
Plain round bar
Concrete
Loading rate
Lateral pressure
Bond stress–slip relationship

ABSTRACT

The bond behavior of steel bars in concrete subjected to complex lateral stresses has received wide attention over the last two decades and various bond strength models and bond stress–slip relationships have been proposed. However, the knowledge of how the loading rate affects the bond behavior of steel bars remains limited. In this paper, a total of 237 pull-out specimens were tested to investigate the effect of the loading rate on the bond behavior between plain round bars and concrete under different lateral pressures. The experimental results showed that, when a lateral pressure is applied, the bond performance is greatly affected by the loading rate. For a given lateral pressure, the ultimate and residual bond strengths increase but the slip at the peak bond stress decreases with the increase of the loading rate. The larger the lateral pressure is, the more pronounced the loading rate effect is. Finally, an empirical bond stress–slip relationship considering lateral pressure, the loading rate, the strength of concrete, and the bar diameter is proposed and verified with experimental results.

1. Introduction

The bond between concrete and reinforcement plays a crucial role in stress transfer and is of primary importance to the overall performance and serviceability of concrete structures. During the past few decades, plain round bars have been widely adopted in reinforced concrete structures, and considerable efforts have been made on their bond mechanism under monotonic static loading [1,2]. It was shown that the bond resistance of plain round bars is rely mainly on the chemical adhesion and friction [3]. The distribution of bond stress along the bond length is non-uniform [4,5]. After adhesion fails, the relative slip between concrete and bar takes place and the bond strength is depended upon friction [6]. Mu [7] investigated the bond performance of plain bars subjected to repeated loading and examined the effect of cyclic loads on the ultimate and residual bond strengths. The results showed that the decrease of the residual bond strength is more pronounced compared with the peak bond strength. Pul [8] analyzed the bond behavior of steel bars in lightweight and ordinary concrete under repeated loading. He found that the deterioration of bond performance of lightweight concrete is more significant compared with ordinary concrete, and the larger the bar diameter is, the more obviously the bond strength decreases. Verderame et al. [9,10] studied the effect of reversed loading on the bond performance of plain bars with pull-out tests and evaluated the effects of the number and amplitude of cycles. Based on the test results, a constitutive hysteretic bond stress–slip relationship was established. In addition, many factors that affect the bond strength of plain round bars have been investigated, including the type and strength of concrete [11,12], bar diameter [2,13], loading rate [14–16], and lateral stress [17–19].

In beam-column joints or simply supported structures, the concrete around steel bars will be subjected to lateral compressive

* Corresponding author.
E-mail address: wuzhimin@dlut.edu.cn (Z. Wu).

http://dx.doi.org/10.1016/j.conbuildmat.2015.07.085
0950-0618/

Nomenclature

D	nominal diameter of steel bar	s_f	slip at unloaded end of bar
E_c	elastic modulus of concrete	s_0	slip at peak bond strength
E_s	elastic modulus of steel bar	τ_u	ultimate bond strength
f_{cu}	compressive strength of concrete	τ_r	residual bond strength
f_y	yield strength of steel bar	k_r	ratio of residual to ultimate bond strength
υ_c	Poisson's ratio of concrete	p_1, p_2	lateral pressures
υ_s	Poisson's ratio of steel bar	p_m	average lateral pressure
l_b	embedment length	α, β	parameters used to describe the ascending and descending branches of bond stress–slip curve
P	pull-out load	v	loading rate
s	average slip of bar	v_0	quasi-static loading rate
s_l	slip at peak bond stress		

stresses, which exert great influence on the bond parameters and bond stress–slip relationship [17–19]. Based on pull-out tests, Robins and Standish [17,18] observed that the bond strength of plain bars significantly increases with an increase in uniaxial lateral pressure. Xu et al. [19] conducted a detailed study on the bond behavior of plain bars under complex lateral pressures and concluded that, as lateral pressure increases, the ultimate and residual bond strengths increase but the slip at the peak bond stress first drops dramatically and then increases. A bond stress–slip constitutive relationship was then established.

Reinforced concrete structures may be subjected to high loading rates. For deformed bars, the loading rate influences the bond behavior in a positive way [20–23]. Eligehausen and Popoc [20] chose a pull-out loading rate of 2.83 mm/s to simulate seismic conditions. Compared with quasi-static loading rates, the ultimate and residual bond strengths increase with increasing the loading rate and are proportional linearly to the logarithm of the loading rate. Yan and Chen [21] obtained similar conclusions and found that the overall shape of the bond stress–slip curve almost keeps unchanged. In most previous studies [14,15,22,23], the minimum loading time to failure ranges from 0.2 to 10 ms. It was shown that the loading rate increases the strength of concrete around the bond region. The larger the loading rate is, the more obviously the bond resistance increases. But the increase in bond strength becomes less significant with increasing the strength of concrete. For plain bars, Hjorth [14] studied the effect of the high loading rate on the bond resistance of plain bars. However, the results showed that the bond strength of plain bars is insensitive to the loading rate. Vos [15] reported similar results and suggested that the bond stress–slip relationship under static loading could be used for the case of dynamic loading. Mo [16] found that, as the loading rate increases, the bond strength is seldom affected but the slip at the peak bond stress increases significantly. During the service life of historical reinforced concrete structures, they may be suffered from severe earthquakes or cyclic loads with high loading rates. To accurately evaluate and rehabilitate these historical concrete structures under severe seismic loading, the knowledge of the bond behavior between concrete and reinforcing bars with lateral pressure and loading rate effects are important. However, such knowledge is now extremely limited. Therefore, it is highly essential to investigate the effect of the loading rate on the bond behavior of plain round bars under lateral pressure.

The objective of this paper is to present an experimental investigation into the bond behavior of plain round bars subjected to lateral pressure and monotonic dynamic loading. The effects of the bar diameter, the strength of concrete, the loading rate, and different ratios and levels of transverse pressure on the bond strength are evaluated. Finally, a bond stress–slip relationship is proposed.

2. Experimental procedure

Pull-out specimens with dimensions of 150 × 150 × 150 mm were adopted in the test. As shown in Fig. 1, a plain reinforcing bar was embedded in the center of the specimen with a bond length l_b five times the nominal diameter of the bar, which is reasonable for defining the constitutive relationship of bond stress–slip [20]. Polyvinyl chloride tubes were used to separate the unbonded parts of the steel bar from concrete. In the unbonded parts, a layer of sponge was introduced between the PVC tube and the steel bar to prevent the cement paste from penetrating into the unbonded part. All the specimens were cast in a horizontal position with special

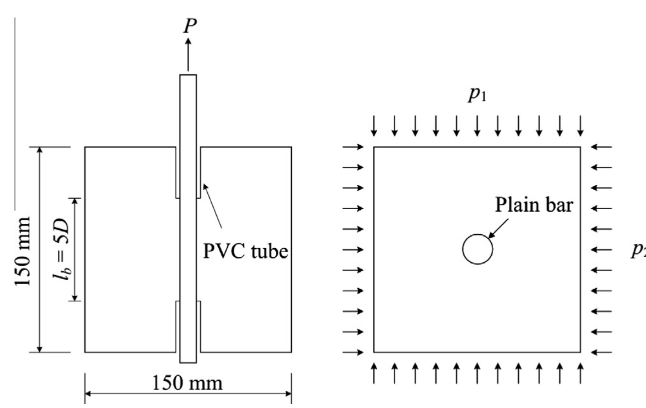

Fig. 1. Schematic of pull-out specimen.

Table 1
Diameters and mechanical parameters of plain round steel bars.

Type	P12	P16	P20
Nominal diameter D (mm)	12	16	20
Yield strength f_y (MPa)	270	310	300
Elastic modulus E_s (GPa)	210	210	210
Poisson's ratio υ_s	0.3	0.3	0.3

Table 2
Mix proportions and mechanical properties of concrete.

Type	C30	C40
Target compressive strength f_{cu} (MPa)	30	40
Cement:water:sand:coarse aggregate	1:0.62:1.81:4.20	1:0.47:1.30:3.02
Elastic modulus E_c (GPa)	31.7	34.9
Poisson's ratio υ_c	0.22	0.23