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Study on straight development length of tensile threaded bars in high-strength reinforced concrete members

Kai-Ning Chi [a], Chien-Kuo Chiu [b,]*, Ker-Chun Lin [a]

[a] National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Rd. Xinhai, Taipei, Taiwan
[b] Dept. of Civil and Constr. Eng., National Taiwan University of Science and Technology, No. 43, Sec. 4, Rd. Keelung, Taipei, Taiwan

HIGHLIGHTS

- Ratio of rib height to rib spacing (R_r) of rebars is a critical factor for bond of RCs.
- Based on ACI 318-14 code, threaded bars can also provide the expected bond performance.
- The correlation between R_r and bond performance is approximately linear.
- Tensile threaded bars with enough R_r can be used in high-strength concrete.

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ABSTRACT

The main purpose of this study is to investigate fundamental bonding behavior of high-strength reinforced concrete adopting tensile threaded bars and to verify the applicability of the formula of the straight development length as recommended in ACI 318-14 on tensile threaded bars embedded in the high-strength reinforced concrete. Additionally, appropriate surface geometric properties of threaded bars shall be defined for ensuring enough bond strength. This study conducts 42 sets of bonding tests, of which 2 sets adopt plain bars as the control group, and the remaining sets adopt threaded bars. The primary study parameters include the concrete compressive strength, the relative rib area of threaded bars involving the rib height and rib spacing, and splitting index. The test results show that when the concrete strength is limited to 70 MPa by ACI 318-14 recommendations, all sets of threaded bars can provide the expected bond strengths. However, when the concrete strength is not limited to 70 MPa, only the threaded bars with relative rib area exceeding 0.17 can provide the expected bond strengths. In addition, the correlation between relative rib area R_r and the effectiveness of the bonding performance is approximately perfect.

1. Introduction

The range of uses of high-strength concrete (HSC) has been gradually expanding for more than six decades, as mentioned by the American Concrete Institute (ACI). HSC commonly refers to concrete whose compressive strength equals to or exceeds 60 MPa and less than 130 MPa. The range of applications of HSC has been continuously expanding, because of its highly desirable characteristics, such as high early age strength, low deflections as results of its high modulus elasticity, and high load resistance per unit weight (including shear and moment). Therefore, HSC is highly effective in constructing skyscrapers and long-span suspension bridges.

The use of high-strength reinforcement in construction is increasing around the world. In 2010 in Taiwan, the National Center for Research on Earthquake Engineering (NCREE) launched a project called "The Taiwan New RC Project" to develop high-strength reinforced-concrete structural systems. High-strength reinforced-concrete (HSRC) included HSC with a specified compressive strength $\geq$70 MPa and high-strength reinforcement with a specified yield strength $\geq$685 MPa (SD 685 for main bars and SD 785 for the transverse reinforcement). Meanwhile, the most common specification for concrete engineering design in Taiwan, ACI 318-14 (2014), sets an upper bound of 420 MPa on the yield strength of reinforcing steel bars for the design usage of the flexure and axial force in special seismic systems. Since the strength of concrete and reinforcing steel is increasing, the mechanical behaviors of HSRC structural members differ from those of normal-strength RC members. Additionally, current design formulas and

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* Corresponding author.
E-mail address: ckchiu@mail.ntust.edu.tw (C.-K. Chiu).

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mechanical models are based on normal-strength RC members. Therefore, the applicability of these formulas and models to HSRC members must be verified or new ones must be proposed.

The bond behavior between concrete and reinforcement is the most fundamental and important concept in relation to the mechanical aspects of RC. The reinforcement and the concrete can form composite structures that can be loaded by the bonding force between two of them. The bond strength between the reinforcement and concrete arises from the interlocking behavior between the frictional resistance and binding force of the two materials. When a specified strength is provided by the reinforcement on a certain section of an RC member, the reinforcement must be configured with the straight extension, hooked, or mechanical anchorage. When the bond strength between the reinforcement and concrete is insufficient, concrete-bar slippage occurs, causing the thin protective layers of the concrete around the bar to split along the reinforcement. Generally, the bond strength is related to the rib geometric dimensions of the bar surface, concrete strength, characteristics of the aggregate, the size of being bonded bar, the confinement conditions of the transverse reinforcement and other factors.

In general, the straight development length of a reinforcing bar can be used to be the anchorage for developing its specified strength in concrete. When the straight development length of reinforcement cannot be applied owing to the limited size of the member, hooked or mechanical anchorage can be used to obtain the required development length of the bar. Since the high-strength reinforcement contains large amounts of carbon, neither standard hooked nor welded connections can be used for the anchorage. Therefore, reinforcing bars with threaded surfaces replace deformed surfaces to generate convenient mechanical anchorages and splices with the uses of the threaded end-anchorage grout-filled device and threaded splice grout-filled sleeves (Fig. 1).

According to the ACI 408-03 specifications [5], the surface geometric property of a deformed bar is one of the most important factors that affect the bond behavior of RCs. Furthermore, the researches on the bond behavior between the high-strength threaded bars and high-strength concrete are very limited. Therefore, this study mainly investigates the bond behavior between the threaded bars with the specified yield strength of 685 MPa and concrete with the specified compressive strength of greater than 70 MPa. It focuses especially on the effect of the relative rib area R_r which is defined as the ratio of the rib height to the spacing between the ribs on the surface of threaded bars. A total of 42 sets of straight bonding tests were carried out in this study. The main study parameters are the R_r value of the threaded bar and the compressive strength of concrete. The key objective of this paper is to investigate the applicability of the straight development length formula in ACI 318-14 for tensile threaded bars in the high-strength (compressive strength >70 MPa) reinforced concrete.

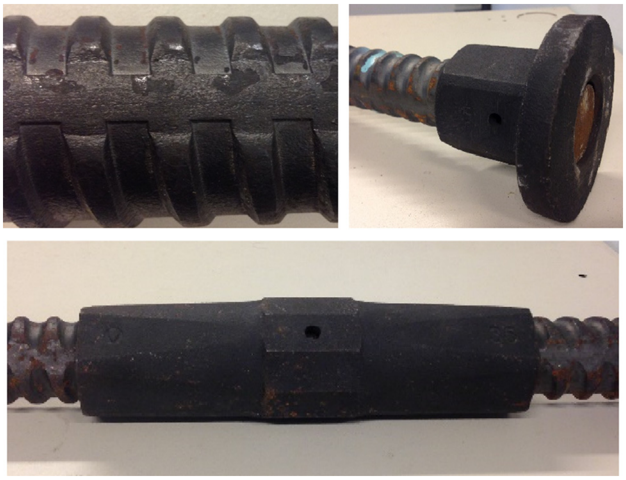

Fig. 1. Details of threaded bar and grout-filled end-anchorage device and splice sleeve.

2. Literature review

Based on the assumed uniformity of the distribution of bond stress, the straight bonding design of a reinforcing bar is suggested: the development length L_d equals the bonding force ($A_b \times f_s$) divided by the bond strength and the perimeter of a reinforcing bar (Eq. (1)).

$$L_d = \frac{A_b \times f_s}{\pi \times d_b \times u} \tag{1}$$

where L_d is the development length of a reinforcing bar (mm); A_b is the sectional area of a bonded reinforcing bar (mm^2); f_s is the specified developing stress of a reinforcing bar (MPa); d_b is the nominal diameter of a reinforcing bar (mm); and u is the bond strength between the concrete and reinforcement (MPa), which is an average value.

According to [2], the bond strength between the concrete and reinforcement could be estimated using Eq. (2). Based on Eqs. (1) and (2), ACI 318-71 (1971) includes Eq. (3) as a proposed design formula for the straight development length L_d. This formula includes an additional reduction factor of 1.2 for bond strength.

$$u = \frac{20\sqrt{f'_c}}{d_b} \leqslant 5.52\ \text{MPa} \tag{2}$$

$$L_d = 0.019\frac{f_y A_b}{\sqrt{f'_c}} \tag{3}$$

where f_y is the specified yield stress of a reinforcing bar (MPa); f_c' is the specified compressive strength of concrete (MPa). However, the design formula of development length in this version of ACI 318 excluded confining the effect resulted from the transverse reinforcement.

Orangun, Jirsa and Breen [16,17] developed a well-known model of the bonding behavior between the reinforcement and concrete, called the OJB Model herein, to determine the required straight development length of the reinforcement. This model was able to estimate the bond strength of a reinforcing bar with or without the confinement effect of the transverse reinforcement. According to these two papers, Eq. (4), for the required straight development length of the reinforcement, was built based on the average bond stress at failure, as determined by the regression analysis. An upper bound on the splitting effect, including the cover and amount of the transverse reinforcement was set to $2.5d_b$, as follows.

$$L_d = \frac{\frac{1}{\phi}\left(\frac{f_y}{\sqrt{f'_c}} - 16.6\right)}{\frac{1}{d_b}\left(c_{\min} + 0.4d_b + \frac{A_{tr}f_{yt}}{10.34sn}\right)}d_b, \quad \frac{1}{d_b}\left(c_{\min} + 0.4d_b + \frac{A_{tr}f_{yt}}{10.34sn}\right) \leqslant 2.5 \tag{4}$$

where the strength reduction factor ϕ of 0.8 proposed by [17]; c_{min} is smaller of minimum clear cover of the bar and 1/2 of clear spacing between bars (mm); f_{yt} is the specified yield stress of the transverse reinforcement (MPa); A_{tr} is total sectional area of all transverse reinforcement within spacing s that crosses the potential plane of splitting through the reinforcement being developed or developed along the plane of splitting (mm^2); s is center-to-center