The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Bond behavior of hooked bar and headed bar

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ABSTRACT

The development length of hooked and headed reinforcing bars is affected by the both bond stress distribution, and hook and head anchorage. Unlike existing empirical models, the present study develops the development length of the reinforcing bars theoretically considering various design conditions. The proposed method is applied to existing test specimens, to estimate the development length or the average bond stress of the reinforcing bars.

1. INTRODUCTION

In general, hooked or headed bars are used to reduce the development length. Current design codes specify the development lengths of hooked or headed bars on the basis of existing test results. To evaluate the bond strength of hooked or headed bars, a beam-end test or a beam-column joint test is typically used (see Fig. 1). However, due to the limited number of studies, current design codes limit the application range of the design equations, considering the allowable material properties, minimum concrete cover, and details of transverse reinforcement and hooks. To use newly developed materials, a large number of test results are required to verify the effects of the new design parameters. Thus, a theoretical model needs to be considered to develop a rational design method.

Recently, Hwang et al. (2017) developed a non-uniform bond stress distribution model for the development length of straight reinforcing bars, considering the variation in bar bond strength along the development length. The present study focuses on the non-uniform bond stress distribution of reinforcing bars, on the basis of Hwang et al. (2017) model. The proposed models should better predict the development length of hooked and headed bars.

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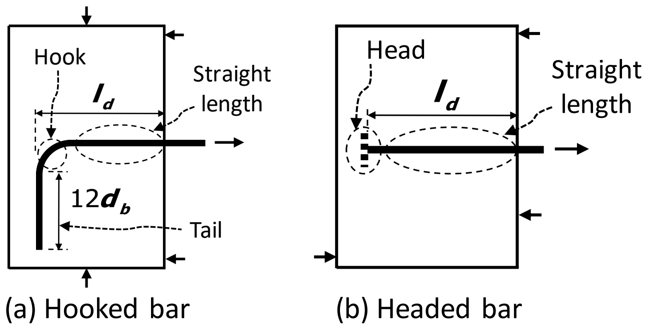


Fig. 1 Anchorage of hooked and headed bars

2. PROPOSED METHOD FOR BAR DEVELOPMENT LENGTH

2.1 Equivalent straight bar model

Fig. 2 shows an equivalent straight bar model with a spring (i.e. hook bearing or head bearing) which is used to describe the pull-out resistance of a hooked bar or a headed bar. The equivalent development length l of a hooked bar is defined as the sum of the straight length l_s and the length of the hook. In a hooked bar, the tension force is resisted by the damaged and undamaged bond stresses and the bearing force of the hook. In a headed bar, the tension force is resisted by the damaged and undamaged bond stresses and the bearing force of the head. In order to consider the bearing force and deformation of the hook or head, a spring model with bearing strength F_h and stiffness K_h is used. In the present study, the following assumptions were used for hooked or headed bars: 1) The contribution of the hook tail to the development length is not significant; 2) The effect of the hook can be separated into two contributions: bond effect and bearing effect; 3) The diagonal strut formed by the bearing force of the head has an angle of cotθ = 2.0 according to the bearing pressure distribution; 4) The head diameter is $d_h \approx$ 2.0 to 2.5 d_b; and 5) The bond strength increase due to the bearing force in the wedge zone is not considered.

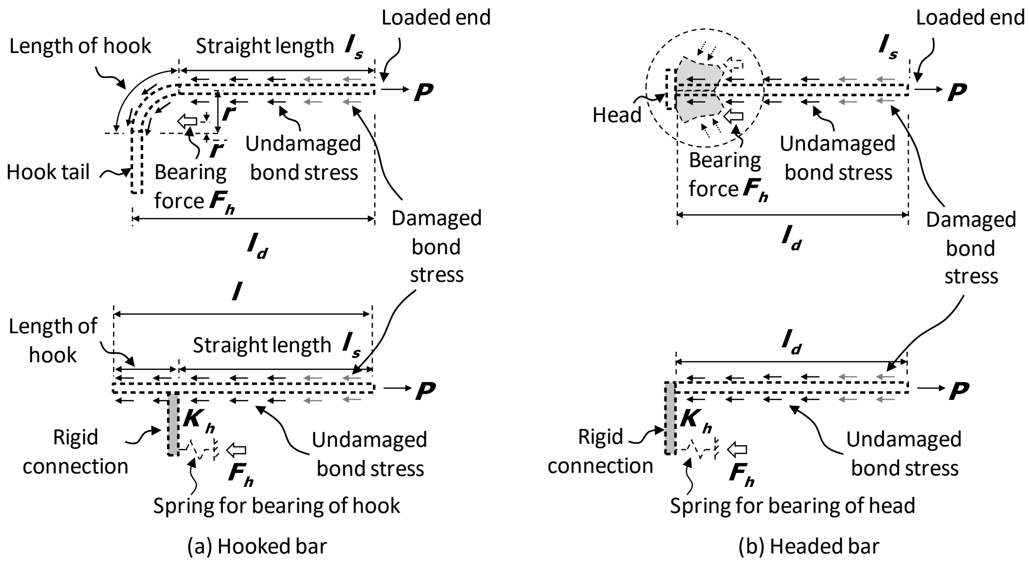
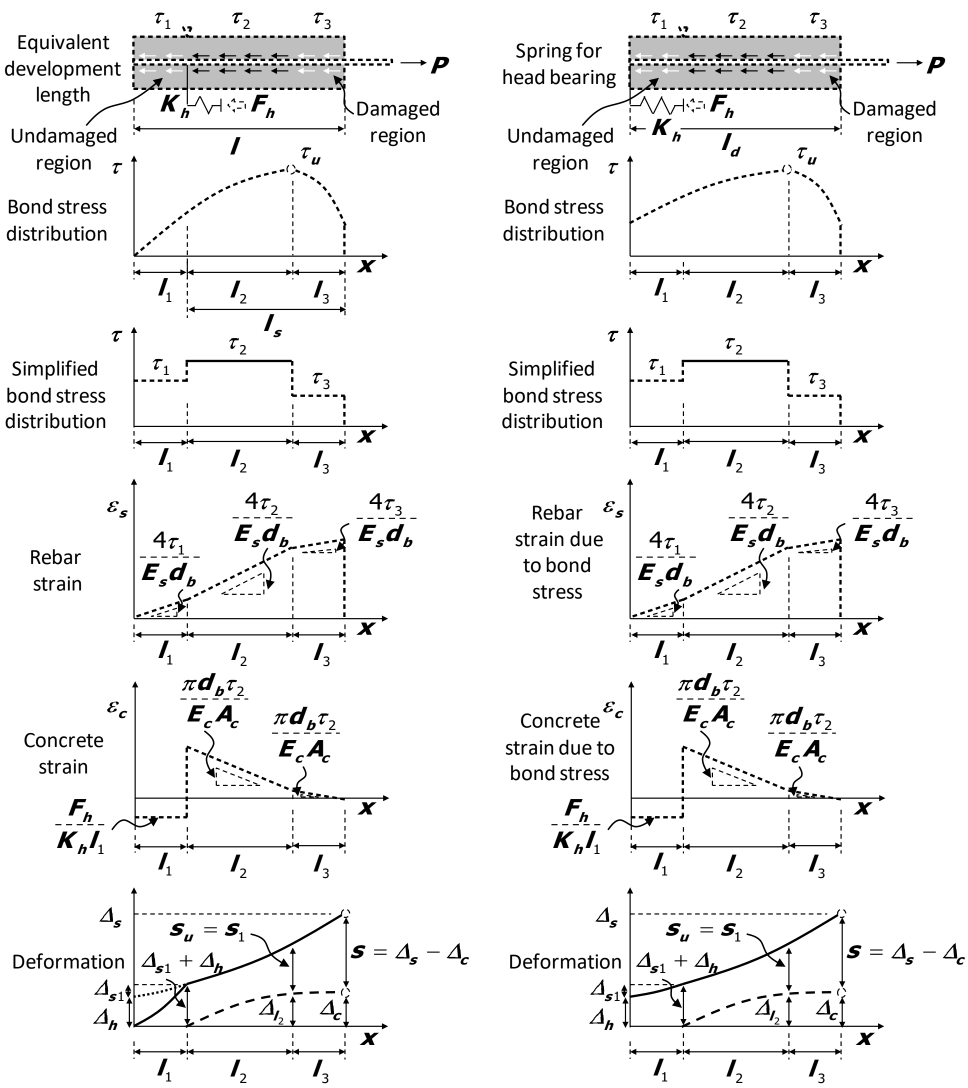


Fig. 2 Equivalent straight bar model

2.2 Non-uniform bond stress distribution model

Fig. 3 shows the non-uniform bond stress distribution of the equivalent straight bar model for a hooked bar and headed bar. The relative deformation between the rebar and concrete increases along the length from the unloaded end to the loaded end of the rebar. In the unloaded region of the hooked and headed bars, the bond stress increases as the relative deformation increases. On the other hand, the bond stress at the loaded end of the hooked and headed bars decreases due to the local bond damage, because the relative deformation exceeds the deformation corresponding to the peak bond strength. To describe the variation of the bond stresses in the undamaged region and damaged region, the bond stress distribution was simplified with three uniform stresses: undamaged bond stress τ_1 at the hook length or bearing region l_1, undamaged bond stress τ_2 at the straight length l_2, and damaged bond stress τ_3 at the straight length l_3.



(a) Hooked bar (b) Headed bar

Fig. 3 Bond stress distribution

For simple calculation, these three bond stresses were assumed to be uniformly distributed. Thus, the maximum tensile strength f_s of the reinforcing bar can be defined as a function of τ_1, τ_2, τ_2, l_1, l_2, l_3, and F_h.

$$f_s = \frac{4}{d_b}\left[\tau_1 l_1 + \tau_2 l_2 + \tau_3 l_3\right] + F_h \tag{1}$$

In Eq. (1), the ratio of the undamaged length $l_1 + l_2$ to the development length l_d is required to calculate the maximum stress f_s. In the present study, $l_1 + l_2$ was simplified as $0.75l_d$ on the basis of a parametric study and the results of previous studies (Hwang et al. 2017) for the non-uniform bond stress distribution of straight bars. On the basis of stress and strain distribution, the maximum stress f_s can be defined as follows (Table 1).

Table 1 Proposed method

Hooked bar	Headed bar
$f_s = \frac{1}{d_b}\left[2\tau_1 \pi r + (3\tau_2 + \tau_3) l_s\right] + \frac{d_b f_y}{4.6r + 1.7d_b} \le f_y$	$f_s = \frac{l_d}{d_b}\left[(\tau_1 - \tau_2)\frac{4d_h}{l_d} + 3\tau_2 + \tau_3\right] + F_h \le f_y$
$\tau_1 = \frac{\tau_u}{1.4}\left(\frac{s_{l1}}{s_1}\right)^{0.4}$	$\tau_1 = \tau_u\left(\frac{s_{l1}}{s_1}\right)^{0.4}$
$\tau_2 = \frac{\tau_u}{1.4}\left[\frac{1-(s_{l1}/s_1)^{1.4}}{1-(s_{l1}/s_1)}\right] \le \tau_u$	$\tau_2 = \frac{\tau_u}{1.4}\left[\frac{1-(s_{l1}/s_1)^{1.4}}{1-(s_{l1}/s_1)}\right] \le \tau_u$
$\tau_3 = \left[\frac{4 - C_1\{4\pi r \tau_1 + 6 l_s \tau_2\}}{4 + C_1 l_s \tau_u}\right]\tau_u \ge \frac{\tau_u}{2}$	$\tau_3 = \left\{\frac{4 - C_1\left[8d_h(\tau_1 - \tau_2) + 6 l_d \tau_2\right]}{4 + C_1 l_d \tau_u}\right\}\tau_u \ge \frac{\tau_u}{2}$
$\tau_u = \frac{0.91\alpha_d\sqrt{f'_c}}{\alpha_{m1}\alpha_{m2}\alpha_{m3}}$ $\alpha_{m1} =$ 0.85 for $c_b > d_b$, otherwise 1.0 $\alpha_{m2} = 0.7 \le 1 - 0.1(c_d/d_b - 1) \le 1.0$ $\alpha_{m3} = 0.7 \le 1 - 0.3\left(\sum A_{tr} - 0.25A_s\right)/A_s \le 1.0$	For lap splice, $\tau_u = 0.91\alpha_d\sqrt{f'_c}\left[\frac{(c_0 w + K_{atr})/d_b}{2.5}\right]$ For CCT node and beam-column joint, $\tau_u = \frac{0.91\alpha_d\sqrt{f'_c}}{\alpha_{m1}\alpha_{m2}\alpha_{m3}}$
$\frac{s_{l1}}{s_1} = \frac{F_h}{s_1 127\sqrt{f'_c}d_b^{-2/3}} = \frac{F_h d_b^{2/3}}{6.96 f'_c} \le 1$	$\frac{s_{l1}}{s_1} = \frac{F_h}{s_1}\frac{d_h}{E_c}\left(\frac{1}{A_{nh}/A_b}\right) = \frac{F_h d_h}{257 f'_c}\left(\frac{1}{A_{nh}/A_b}\right) \le 1$
$F_h = \frac{3\pi^2 d_b^3 f_y}{32(3\pi r - 4r_i)A_s} = \frac{d_b f_y}{4.6r + 1.7d_b}$	$F_h = \psi\frac{A_{Nc}\sqrt{f'_c}}{0.72nA_b\sqrt{l_d}}\left(0.7 + \frac{c}{5l_d}\right)$

where $C_1 = l_s\Big/\left[4\left(1 - \sqrt{0.003f'_c}\right)E_s d_b\right]$; r = radius of the hook (= $3.5d_b$ for $d_b \le 25.4$ mm, otherwise $4.5d_b$); ψ = 2.5 for beam-column joint, and 5 for CCT node and lap splice.

3. COMPARISON BETWEEN TEST RESULTS AND PREDICTIONS

To verify the validity of the proposed methods, it was applied to existing test specimens for hooked bars and headed bars. For the 493 specimens of the hooked bars, the ranges of the parameters are the development length l_d = 50.8 - 860 mm, hooked bar diameter d_b = 12.7 - 43.0 mm, concrete strength f_c' = 16.6 - 113.9 MPa, and yield strength of the rebar f_y = 410 - 897 MPa (Marques et al. 1975, Pinc et al. 1977, Johnson et al. 1981, Hamad et al. 1993, Ramirez et al. 2008, Lee et al. 2010, Peckover et al. 2013, Sperry et al. 2015). For the 361 specimens of the headed bars, the ranges of the parameters are the development length l_d = 89 - 917 mm, headed bar diameter d_b = 15.9 - 57.3 mm, net head area-to-reinforcing bar area A_{nh} / A_b = 1.1 to 14.9, concrete strength f_c' = 20.3 - 226.0 MPa, and yield strength of the rebar f_y = 433 - 959 MPa (Bashandy 1996, Choi et al. 2002, Thompson et al. 2006a, Thompson et al. 2006b, Chun 2015, Shao et al. 2016, Sim et al. 2016, Chun et al. 2017). For direct comparison with the test results, safety factors were not considered. Fig. 4 compares the predictions and test results for all specimens. The prediction of the proposed methods showed an average ratio = 1.17 and 1.06, and COV. = 0.196 and 0.207 for the hooked bars and headed bars, respectively.

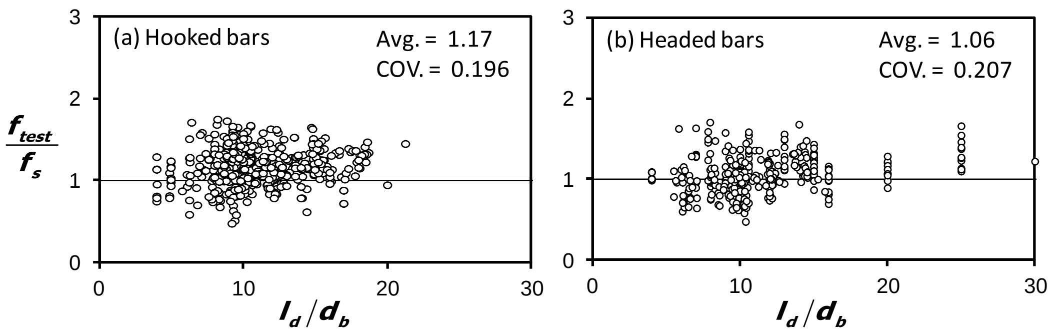


Fig. 4 Comparison of test results and predictions

4. CONCLUSIONS

In reinforced concrete structures, inaccurate prediction of development length of reinforcing bars may increase the structural vulnerability or deteriorate the cost-effectiveness. In the present study, a non-uniform bond stress distribution based model was developed to more accurately predict the development length of a hooked bar and a headed bar. The tension force of the hooked or headed bars was proposed on the basis of the three mechanisms: hook or head bearing force, damaged bond stress, and undamaged bond stress. The proposed methods predict well the existing test results. In the proposed model, the effects of unit bond strength, bond stress distribution, and bearing resistance were separately modeled. Such component models can be used in future experimental and theoretical studies.

ACKNOWLEDGEMENT

This research was financially supported by National Key Research Program of China (2016YFC0701400) and National Natural Science Foundation of China (Grant No. 51650110500). The authors are grateful to the authorities for their support.

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