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Model for Side-Face Blowout Strength of Large-Diameter Headed Bars in Beam-Column Joint

*Sungchul Chun[1] and Min-Seo Bae[2]

[1], [2] Div. of Arch. & Urban design, Incheon National University, Incheon, 22012, Korea
[1] scchun@inu.ac.kr

ABSTRACT

The provisions of ACI 318 on headed bars have several limitations on the bar diameter and yield strength, cover thickness, and effects of transverse reinforcement. The anchorage strengths significantly depend on failure modes and geometric conditions where headed bars are anchored. The main variables affecting the anchorage strengths were found to be a compressive strength of concrete, a side cover thickness, an embedment length, and a transvers reinforcement index. From regression analyses of 52 sets of data, a model is proposed for predicting the anchorage strength of headed bars terminated within exterior beam-column joints. The mean and COV values of the ratios of tests to predictions are 1.0 and 9.5%, respectively.

1. INTRODUCTION

According to ACI 318-14 (2014), the development length of headed bars is equal to 80 percent of that used for hooks, provided that headed bars meet the requirements of Class HA heads in ASTM A970-15 (2015). In addition, the following conditions must be satisfied: the net bearing area of the head is at least four times the cross-sectional area of the bar; the smaller of the concrete cover to the surface of the bar and half the clear bar spacing is at least twice the bar diameter; the diameter of headed bars does not exceed 36 mm; the maximum yield strength f_y used to design l_{dt} is limited to 420 MPa; and f_c' is limited to a maximum of 40 MPa. The minimum limits on head size, clear cover, and clear spacing, and the restrictions on the upper limit of bar diameter, bar yield strength, and compressive strength of concrete are based on the available data from tests (Thompson et al. 2005, 2006a, and 2006b). Commentary R25.4.4.2 of ACI 318-14 states that because transverse reinforcement has been shown to be largely ineffective in improving the anchorage of headed deformed bars (Thompson et al. 2005, 2006a, and 2006b), additional reductions in development length are not used for headed bars.

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[1] Associate Professor
[2] Graduate Student

The application of headed bars of the diameter of 43 or 57 mm is not permitted. The savings of material and fabrication labor, one of the major benefits of headed bars, increase as the bar diameter increases, as shown in Fig. 1. For large-diameter headed bars of 43 and 57 mm, the minimum side cover of $2d_b$ is larger than the minimum cover of 40 mm. Moreover, transverse reinforcement is believed to be effective for the anchorage of headed bars because the confinement by transverse reinforcement limits the progression of splitting cracks, and thus increases the bursting force required to cause failure (Chun et al. 201X). To extend beyond these limitation of the ACI 318 provisions for headed bars, an experimental study on 43 and 57 mm headed bars of Gr. 550 was conducted by Chun et al. (201X). In this paper, statistical analyses were conducted and, a model is proposed for predicting the anchorage strength of headed bars terminated within exterior beam-column joints.

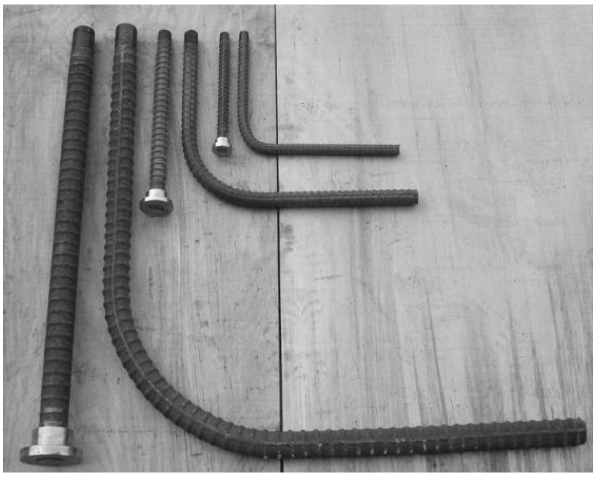

Fig. 1 Headed and hooked bars

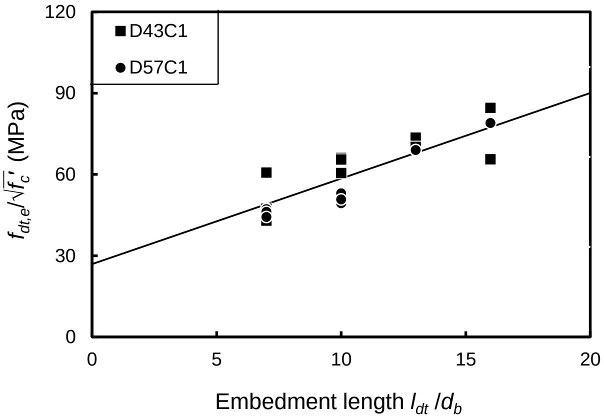

Fig. 2 Effect of splice length on developed bar stresses normalized by $\sqrt{f_c'}$.

2. MODEL FOR SIDE-FACE BLOWOUT STRENGTH

The embedment length, side cover, transverse reinforcement, and concrete compressive strength largely affect the bar stresses. A new model for predicting the anchorage strength of headed bars in beam-column joints with sufficient transverse reinforcement was developed, on the basis of statistical analyses of the main variables. Generally, the strength of headed bars is provided by bond and head bearing components (Chun et al. 2007, Thompson et al. 2006, Chun 2015) but, in this study, a simplified model is proposed by merging the two components for practical purposes.

First, the effects of concrete compressive strength are assessed. Considering that the side-face blowout capacity of anchors (ACI 318 2014, Furche and Eligehausen 1991, Eligehausen et al. 2006) relies on the tensile strength of concrete which has been thought to be proportional to $\sqrt{f_c'}$, for the sake of simplicity, the bar stresses can be assumed to be proportional to $\sqrt{f_c'}$.

Among the test variables, the embedment length was the most effective parameter. Figure 2 shows the bar stresses with varying embedment lengths for the unconfined headed bars with the side cover of 1d_b, where the stresses were normalized with $\sqrt{f_c'}$. The normalized bar stresses are almost linearly proportional to the embedment lengths. A regression analysis is carried out for all unconfined 28 data with a 1d_b side cover and an equation is provided for predicting the mean strengths of the headed bars as follows.

$$f_{dt,p1,uncon} = \left(3.16\frac{l_{dt}}{d_b} + 26.9\right)\sqrt{f_c'} \tag{1}$$

where $f_{dt,p1,uncon}$ is a predicted anchorage strength of an unconfined headed bar with 1d_b side cover.

The side cover is one of the key parameters in the design of the development lengths of hooked bars and straight bars. This test revealed that the anchorage strength of headed bars is also affected by the side cover. The ratios of measured bar stresses to predictions by Eq. (1) are shown in Fig. 3 with varying c_{so}/d_b values. Because the failure mode of all specimens is the side-face blowout, providing a thicker side cover delayed the blowout failure. Equation (1) can be modified by including a confinement factor for the side cover as follows.

$$f_{dt,p,uncon} = \left(3.16\frac{l_{dt}}{d_b} + 26.9\right)\left(0.74 + 0.26\frac{c_{so}}{d_b}\right)\sqrt{f_c'} \tag{2}$$

where $f_{dt,p,uncon}$ is the predicted anchorage strength of an unconfined headed bar and c_{so}/d_b cannot be less than 1.0 or greater than 2.0.

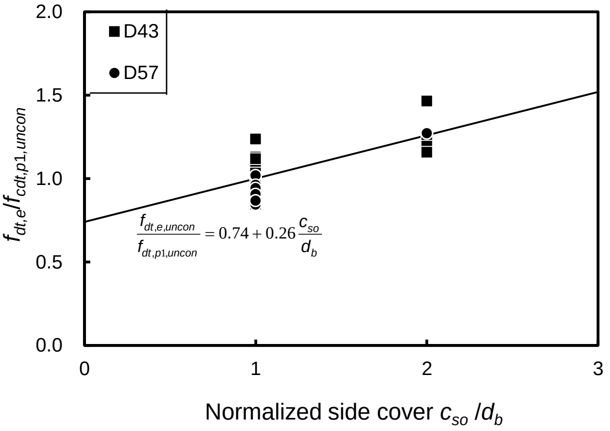

Fig. 3 Increase in bar stresses with varying c_{so}/d_b values.

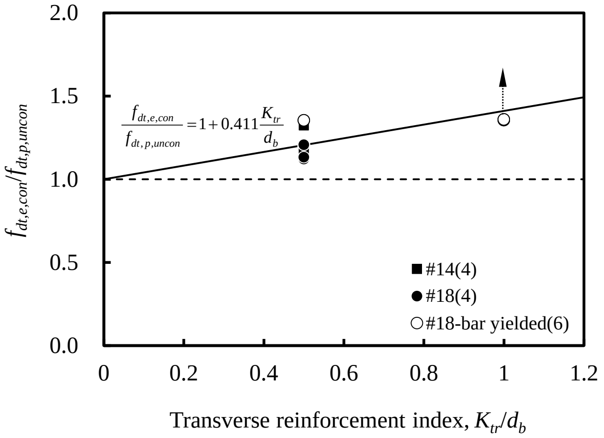

Fig. 4 Increase in bar stresses with varying K_{tr}/d_b values.

By placing a hairpin-type transverse reinforcement of K_{tr} = 0.5d_b or 1.0d_b, the anchorage strengths of headed bars increased by up to 44% compared with the unconfined headed bars with the same conditions. As is well-known, the hairpins limited the splitting cracks arising from the bond stresses along the development length and therefore reduced the bearing stress in front of the head, which resulted in delaying the blowout failure. In addition, the hairpins close to the heads obviously increased the bearing capacity of the heads.

The increases in the strength of the confined headed bars compared with Eq. (2) are shown in Fig. 4 with varying K_{tr}/d_b values. Among seven confined specimens, three specimens did not fail and their actual strengths were not measured because, for safety, the tests were stopped after the headed bars yielded. If higher-strength headed bars were used and their actual strengths were recorded, the slope of the trend line might be steeper. Therefore, the confinement factor ($1+0.411K_{tr}/d_b$) by the transverse reinforcement will give a conservative result for confined headed bars. Incorporated with the confinement factor, an equation for predicting the mean strengths of the bar stresses is given as follows.

$$f_{dt,p1}=\left(3.16\frac{l_{dt}}{d_b}+26.9\right)\left(0.74+0.26\frac{c_{so}}{d_b}+0.411\frac{K_{tr}}{d_b}\right)\sqrt{f_c'} \quad (3)$$

where $f_{dt,p1}$ is the predicted anchorage strength of a headed bar and K_{tr}/d_b cannot be greater than 1.0.

The average and COV values of the ratios of tests to predictions by Eq. (3) are 1.0 and 9.5% for 52 data sets. The anchorage strengths predicted using Eq. (3) are compared with the test values for 52 data sets in Fig. 5.

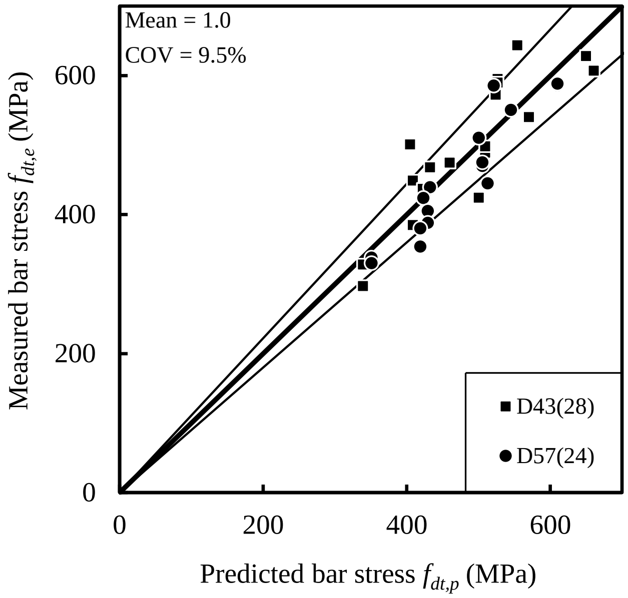

Fig. 5 Comparison of test results and predicted values.
(Values in parentheses are the number of data.)

3. CONCLUSIONS

The provisions of ACI 3181 on headed bars have several limitations on the bar yield strength, concrete compressive strength, bar spacing, cover, and consideration of the confinement effects of transverse reinforcement due to the lack of experimental verifications beyond the limitations. In addition, the anchorage strengths of the headed bars significantly depend on the failure mode and geometric conditions where the headed bars are anchored. From regression analyses for 52 data, a model for predicting the anchorage strength of headed bars terminated within exterior beam-column joints is proposed, which includes the effects of transverse reinforcement and side cover. The mean and COV values of the ratios of tests to predictions are 1.0 and 9.5%, respectively.

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