Amirkabir University of Technology
(Tehran Polytechnic)
Vol. 45, No. 2, Winter 2013, pp. 25-28

Amirkabir Journal of Science & Research (Civil & Environmental Engineering)
(AJSR - CEE)

A Modification to ACI 440.1R-06 Equation for Determining the Bond Strength of GFRP Bars Using Reliability Analysis

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(Received 19 Oct 2011; Accepted 30 Jan 2013)

ABSTRACT

ACI 440.1R-06 Code overestimates the bond strength of lap-spliced FRP reinforced concrete beams. In this code, the effect of transverse reinforcement along the splice length on bond strength is not taken into account. In this paper, ACI 440.1R-06 equation was modified for calculating the bond strength of spliced bars in specimens without transverse reinforcement along the splice length using reliability analysis and experimental results. Then, 13 beam specimens were manufactured and tested for evaluating the effect of transverse reinforcement on bond strength. Experimental results show that the influence of transverse reinforcement depends on surface geometries of FRP bars. In this study, the bond strength produced by transverse reinforcement is formulated as a function of surface geometries of bars. This equation is obtained by means of experimental results and Monte Carlo simulation. The bond strength calculated by the proposed equations correlates well with the experimental results in comparison with the values predicted by the code provisions.

KEYWORDS

FRP Bars, Transverse Reinforcement, Reliability Analysis, Monte Carlo Method, Bond Strength

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1- BRIEF INTRODUCTION

The bond strength of GFRP bars is lower than that of steel bars. This depends on several parameters such as: concrete cover, bar diameter, embedment length, surface geometries of GFRP bars, amount of transverse reinforcement along splice zone and modulus of elasticity of reinforcing bars. There are uncertainties in the parameters that should be considered in the bond strength. Wambeke and Shield [1] utilized an approach similar to one used to create the development length equation for steel reinforcing bars and proposed an equation for calculating the average bond strength of GFRP bars. This equation is used for bond strength calculation in the ACI 440.1R-06 [2] guideline. Harajli and Abouniaj [3] compared ACI 440.1R-06 equation with the experimental results of FRP-reinforced spliced beam specimens and concluded that ACI 440.1R-06 equation overestimates the bond strength of these types of specimens. In this paper, ACI 440.1R-06 equation is modified and the effect of transverse reinforcement is taken into account in the modified equation.

2- MODIFICATION FACTOR FOR SPECIMENS WITHOUT TRANSVERSE REINFORCEMENT

A comparison has been made between available test results and ACI 440.1R-06 equation. It is observed that this equation overestimates the bond strength of specimens with no transverse reinforcement. In other words, the bond failure is highly probable if ACI 440.1R-06 equation is used for design of GFRP spliced concrete beams. In order to reduce the probability of bond failure of ACI 440.1R-06 equation, the bond strength of this equation should be multiplied by a strength reduction factor φb as follows:

$$\frac{u}{0.083\sqrt{f'_c}} = \varphi_b \frac{1}{\alpha}(4.0 + 0.3\frac{C}{d_b} + 100\frac{d_b}{L_d})$$

In Eq. (1), u is the bond strength between the GFRP bar and concrete in MPa, f 'c is the compressive strength of concrete in MPa, C is the distance from the bottom cover to the center of the bars or half the distance between the centers of spliced bars in mm, whichever is smaller, db is the diameter of the bar in mm, Ld is the embedment length of the reinforcement inside the concrete in mm, α is the factor of top bars effect. The results of test specimens with no transverse reinforcement form literature [3], [4] and [5] were used to determine the value of φb so that the probability of a test to predicted ratio less than 1.0 was 0.22. Using the Monte Carlo method, a total of 1000 simulated specimens were produced for each of the test specimens. Using the results of these simulations the value of φb was calculated to be 0.59.

3- EXPERIMENTAL SPECIMENS

In the experimental part of the study, thirteen lap-spliced beam specimens with the dimensions of 150×200×2300 mm were manufactured and tested. The parameters of concrete compressive strength, amount of transverse reinforcement over the splice length, the diameter of longitudinal bars, and the surface properties of GFRP bars were selected as the variables for the specimens. The main parameter investigated in the test program was the amount of transverse reinforcement along the splice length in the different cases. The structural details of test specimens are shown in Table 1. The specimens were designed so that the bond failure mode governs.

Test	Surface geometry	f'_c (MPa)	d_b (mm)	L (mm)	S (mm)	E_{frp} (GPa)
B-1	Ribbed	40	16	400	-	60
B-2					150	60
B-3					100	60
B-4					50	60
B-5		40	12	400	150	60
B-6					100	60
B-7					50	60
B-8		70	12	400	150	60
B-9					100	60
B-10					50	60
B-11	Sand coated	40	10	180	-	37
B-12					80	37
B-13					22	37

Table 1-Details of test specimens

Fig.1 shows that in the specimen without transverse reinforcement and with lower amount of transverse reinforcement such as Specimen B-8, splitting failure occurred at the bottom and sides of the specimen (Fig.1a). In addition, with a decrease in the spacing of transverse reinforcement along the splice zone, splitting cracks appeared only at the bottom of the beam (Fig.1b). The sand coated GFRP-reinforced specimens which have transverse reinforcement along splice length failed by pullout mode of bond failure (Fig.1c).

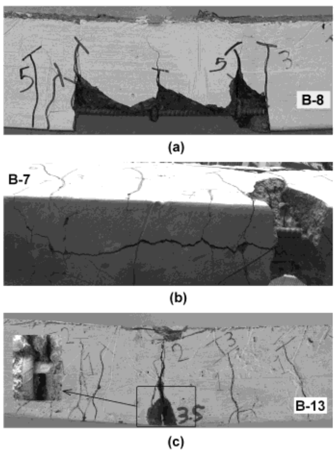

Fig. 1- bond failure states of specimens.

4- THE EFFECT OF TRANSVERSE REINFORCEMENT

The load versus mid-span displacement relationships for all specimens are presented in Fig.2. Specimens demonstrated in Fig.2a are reinforced with ribbed GFRP bars with a diameter of 16 mm and concrete with strength of 40 MPa. The only variable in these specimens is the spacing of the transverse reinforcement. While the Specimen B-1 has not transverse reinforcement, the spacing of transverse bars in the other specimens range from 50 mm to 150 mm. Considering Fig.2a, it can be conducted that the ultimate force and the bond strength increase as the transverse reinforcement is increases. This fact can be concluded by figs. 2b and 2c.

The effect of transverse reinforcement on spliced sand-coated bars can be evaluated by comparing the load versus displacement relationships of specimens shown in Fig.2d. It is observed that in specimens reinforced with sand-coated bars, transverse reinforcement has no considerable effect on the ultimate force and bond strength of the spliced beam specimen. Considering the discussions on the influence of transverse reinforcement on the bond strength of GFRP bars, it can be concluded that the surface properties of the reinforcing bars should be taken into account in bond strength equations. The bond strength of GFRP-reinforced spliced beam specimens with transverse reinforcement in the splice zone can be given by:

$$u = u_c + u_{tr} \qquad (2)$$

where uc is the bond strength of spliced bars without transverse reinforcement and utr is the portion of the bond strength contributed by transverse reinforcement. The parameter representing the effect of transverse reinforcement is a function of the transverse bar's cross section (Atr), the transverse bar's yield stress (fyt), the spacing between the transverse reinforcements (S) and the diameter of the tensile reinforcement (db) as follows:

$$u = \frac{1}{\alpha}\left[0.083\sqrt{f_c'}\ (2.36 + 0.177\frac{C}{d_b} + 59\frac{d_b}{L_d} + \beta\frac{A_{tr}\ f_{yt}}{S\ d_b})\right] \qquad (3)$$

Similar to the previous section, the Monte Carlo method was used to obtain the coefficient β. Using reliability analysis , the value of β was calculated to be 0.08 for the specimens tested by Harajli and Abouniaj [3], 0.17 for those tested by Aly [5] and 0.21 for the specimens tested in this study. The average value and the standard deviation of the utest/uEq.3 ratio are equal to 1.10 and 0.12, respectively. In addition, the results of the proposed equation (Eq. 3) are compared to those of available design codes. The comparison indicates that Eq. (3) provides a reasonable and conservative estimate for the bond strength of spliced GFRP reinforcing bars.

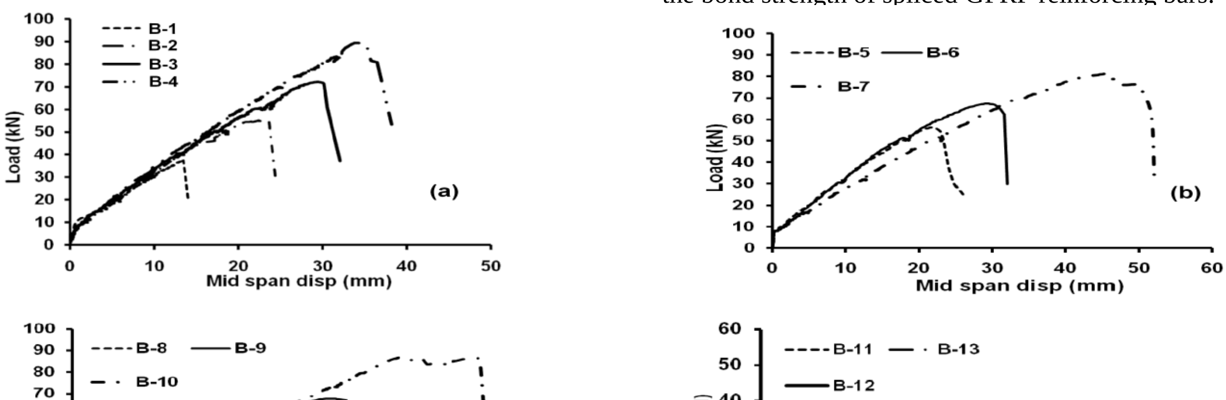

Fig. 2- Load-displacement relationships of test Specimens

5- CONCLUSION

The objective of this research was to investigate the bond strength and of concrete beams reinforced with lap-spliced GFRP bars. Thirteen beam specimens were manufactured and tested. Also, the results of other beam specimens tested by past researchers were used in the study. A comparison of the test results with the ACI 440.1R-06 code provisions was carried out. Based on the study, the following conclusions are drawn:

1. The effect of transverse reinforcement on the bond strength of spliced GFRP bars in beams depends on the surface properties of the reinforcing bars. In the case of ribbed GFRP bars, transverse reinforcement increases the bond strength of spliced bars. However, it does not have considerable effect on the bond strength of spliced sand-coated GFRP bars.

3. Transverse reinforcement is an important factor affecting the bond strength of spliced bars in beams. Using the Monte Carlo simulation, an equation was proposed for the bond strength of the spliced GFRP reinforcing bars in concrete beams. It was shown that this equation presents better results in comparison with the available design code provisions.

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