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Bond strength of reinforcement in splices in beams

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Abstract. The primary aim of this study was to investigate the bond strength between reinforcement and concrete. Large sized nine beams, which were produced from concrete with approximately $f_c' = 30$ MPa, were tested. Each beam was designed to include two bars in tension, spliced at the center of the span. The splice length was selected so that bars would fail in bond, splitting the concrete cover in the splice region, before reaching the yield point. In all experiments, the variable used was the reinforcing bar diameter. In the experiments, beam specimens were loaded in positive bending with the splice in a constant moment region. In consequence, as the bar diameter increased, bond strength and ductility reduced but, however, the stiffnesses of the beams (resistance to deflection) increased. Morever, a empirical equation was obtained to calculate the bond strength of reinforcement and this equation was compared with Orangun *et al.* (1977) and Esfahani and Rangan (1998). There was a good agreement between the values computed from the predictive equation and those computed from equations of Orangun *et al.* (1977) and Esfahani and Rangan (1998).

Key words: beams; bond of reinforcing bar-concrete; deformed bar; bending; splice length.

1. Introduction

Transfer of load or stress in reinforced concrete is based on bond between the reinforcing steel and the surrounding concrete. This transfer is provided by the resistance to relative motion or slippage between the concrete and the rib face of the embedded steel bar. The resistance to slippage is defined as bond or bond stress. In base, bond between a reinforcing steel bar and the surrounding concrete depends on three reasons: (1) chemical adhesion; (2) friction; (3) mechanical interaction between the ribs of the bar and the surrounding concrete (Fig. 1).

Lap splice, because of its simplicity, is a common method of splicing a re-bar in reinforced concrete beams. Many researchers have investigated the behaviour of splices and several test results (Sagan *et al.* 1991) and theoretical predictions on splice strength (Orangun *et al*. 1977) are reported in the literature. These tests show that splice behaviour is strongly influenced by splitting cracks

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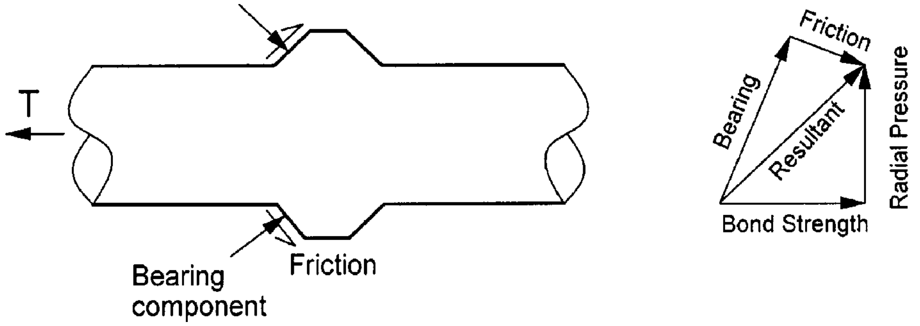

Fig. 1 Free body diagram of portion of reinforcing embedded in concrete and bond strength components (Hamad 1995)

which develop along the bars (Tepfers 1973) and by flexural cracks which mainly develop at the splice ends.

Both flexural and splitting cracks are governed by bond between steel re-bar and surrounding concrete. In particular, flexural cracks are strictly related to the maximum re-bar slip which depends on the local micro- crushing the porous concrete layer in front of the rib (Gambarova and Giuriani 1985). Splitting cracks are caused by rib-wedging action and govern the bond strength and stiffness (Tepfers 1979).

Larrad *et al.* (1993), performed bond tests on beams, consisting of two rectangular blocks joined at midspan by a steel ball on the compression side and by the reinforcement on the tension side of the neutral axis, to study the effect of bar diameter on bond strength. They reported that an increase in bond strength in high strength concrete elements, compared with the normal strength ones, is around %80 when the reinforcing bar size is 10 mm, and that it drops to %30 when the size is 25 mm.

Because of complexity of the phenomena involved, the study of cracking effects on splice behaviour requries basic tests to be performed in order to obtain detailed information on flexural and splitting cracks along the overlapped bars. Since large-sized beam specimen, which can loaded in positive bending or combined bending, is most suitable type to obtain the bond strength of the reinforced concrete elements, in this study, large-sized beams, which have overlapped tension bars, were used.

2. Experimental program

A total of nine beam specimens, which each series was involved three beams, was made and tested to investigate the bond strength of deformed bars. The details of test beams are given in Table 1 and Fig. 2. In all the experiments, the variable used was the reinforcing bar diameter. The reinforcing bars, which were used as tension bar, had 12, 16 and 22 mm diameter.

The specimens were tested with lap-spliced bar centered on the midspan in a region of constant positive bending, as shown in Fig. 2. The splice length (l_s, Table 1) was selected so that the bars would fail in bond, splitting the concrete cover in the splice region, before reaching the yield point. As an example of the notation system, B12.M indicates that beam specimen had 12 mm bar diameter and was loaded with bending moment.

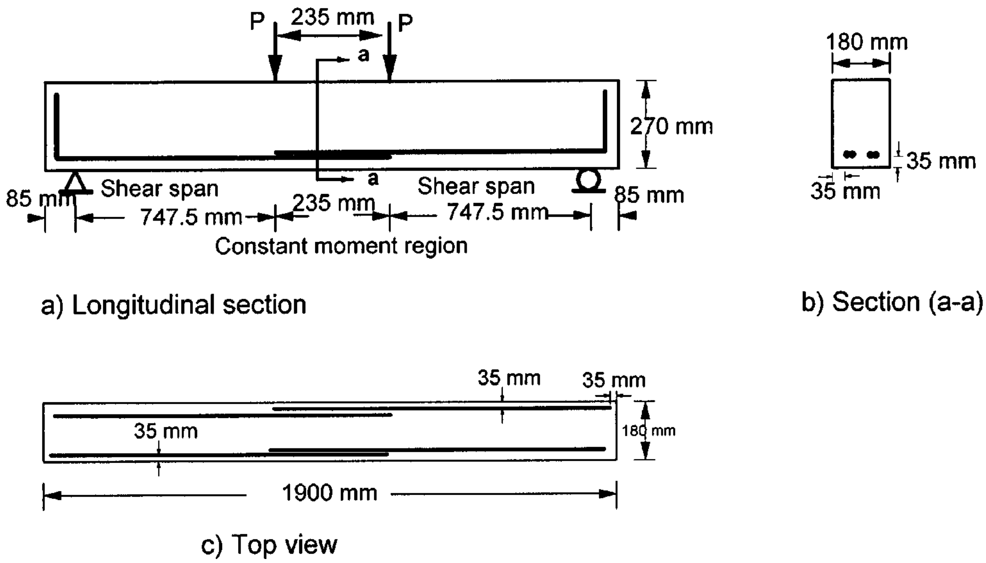

Fig. 2 Longitudinal and cross section details of beam specimens

Table 1 Details of test specimens

Specimen notation	Specimen Number	f'_c (MPa)	d_b (mm)	l_s (mm)	b (mm)	h (mm)	ρ
B12. M	1	29.3	12	235	180	270	0.0054
	2	30.8					
	3	31.1					
B16. M	1	29.5	16	235	180	270	0.0095
	2	29.7					
	3	30.8					
B22. M	1	29	22	235	180	270	0.0180
	2	29.7					
	3	32.5					

Table 2 Concrete mix design

Cement (R425)	Water	Sand	Gravel	Plasticizer	Units
350	115.50	1320	566	7	kg/m^3

Water-cement ratio was selected approximately 0.33 for the concrete mixes; mix propotions are presented in Table 2. Attaining the higher strengths depended only on minimizing the water-cement ratio with the aided of superplasticizer. No pozzolanic admixture, such as silica fume or fly ash, was added. The compressive strengths were obtained from test conducted on $\phi 150 * 330$ mm cylinders.

Table 3 Properties of reinforcing bars

Type of steel	d_b (mm)	A_b (mm^2)	f_y (MPa)	f_{su} (MPa)	Elongation percent
BÇ III (S420)	12	113.10	476.48	719.97	17.23
	16	201.06	454.63	671.63	19.44
	22	380.13	446.13	663.18	20.97

All reinforcement of a given size came from the same heat of Grade 60 steel. The mechanical properties of the reinforcing bars are reported in Table 3.

Test beams were cast in a horizontal position with the lap-spliced bars placed in the bottom of the steel forms. The lab-batching concrete was vibrated mechanically by spud vibrators and hand troweled. Immediately following casting, the beams were cured and covered with wet burplap and plastic for two weeks. Cylinders were cast in steel molds and cured in the same manner as the test beams.

3. Test setup and procedures

The test beams were simply supported over a span of 1730 mm. The test setup and loading arrangement for each test are shown schematically in Fig. 3. A 5000 kN capacity test machine applied load. The load from the test machine was transferred through a stiff steel girder onto the test beam in the form of two equally concentrated loads. Also, load was applied incrementally until failure occurred. Testing was done at least 28 days after casting.

At each load stage, deflection readings were taken at the center of the beam using a dial gage, and flexural cracks were marked. The side and bottom (tension face) cracking patterns were recorded for each beam specimen for comparison purposes. The duration of each test was about 4 min. All specimens failed in bond due to splitting of concrete cover over the splice length in a brittle manner.

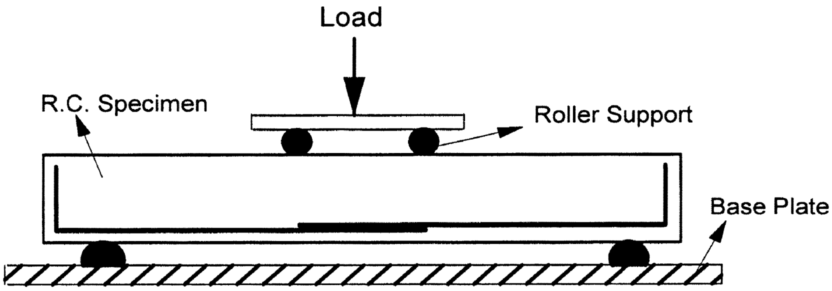

Fig. 3 Schematic of test setup

4. Mode of failure

The first flexural cracks in all beams occured randomly in the constant moment region on the tension side of the beams outside the splice. As loading continued, cracks formed along the entire length of the constant moment region including the splice. In all test specimens, failure occured just after longitudinal splitting cracks started to form along the splices. The longitudinal cracks formed in the bottom cover adjacent to the bars. The final mode of failure was a sudden face-and-side split failure with the load almost dropping completely after reaching ultimate.

Typical cracking patterns of a beam specimen are shown in Fig. 4. The observed cracking patterns on the bottom tension face and on the side of all beam specimens were similiar. In the beam specimens, which had bars with small diameter, far too many cracks developed in both the bottom tension face and on the side. Morever, in these beam specimens crack widths were very small.

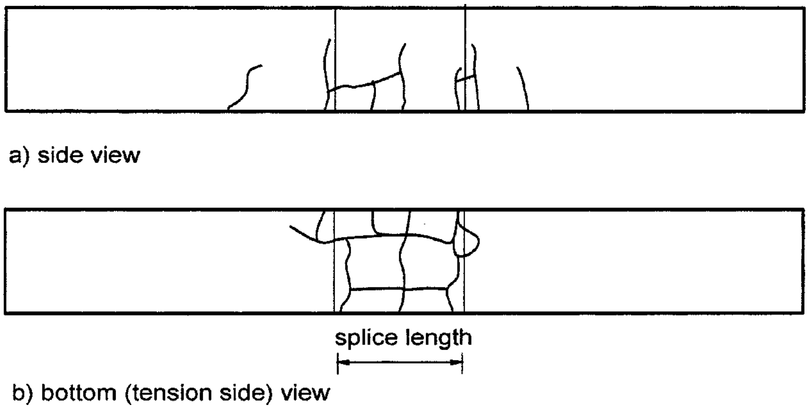

Fig. 4 Crack patterns for beam B12. M: (a) side view; and (b) bottom (tension side) view

5. Test results

The mode of failure in all beam specimens was a face-and-side split failure. The splitting mode of failure indicated that the splice reached its maximum capacity. Therefore, bond strength could be determined directly from the stress developed in the steel. The stress in the steel f_s was calculated based on elastic cracked section analysis and was determined from the maximum load obtained for each beam specimen. In this analysis the modulus of elasticity of steel E_s was taken as 203.000 MPa and the modulus of elasticity of concrete E_c was given by $E_c = 4730\sqrt{f_c'}$ MPa (ACI 318-89). The analysis ignored the tensile stress in the concrete below the neutral axis and assumed linear stress-strain behaviour. To evaluate the average bond stress u_t, the total force developed in the bar $A_b f_s$ (A_b is the cross-sectional area of the bar) was divided by the surface area of the bar over the splice length $\pi d_b l_s$

$$u_t = \frac{(A_b f_s)}{\pi d_b l_s} \; ; \; u_t = \frac{f_s d_b}{4 l_s} \tag{1}$$

where f_s is the calculated bar stress, d_b is the bar diameter, and l_s is the splice length. Values of u_t are shown in Table 4; all splitting failures were attained before the bar yielded.

Table 4 Average values of test results

Specimen notation	f_c' (MPa)	P_{max} (kN)	δ (mm)	x (mm)	f_s (MPa)	u_t (MPa)
B12.M	30.4	50.30	1.97	58.68	394.38	5.03
B16.M	30	60.80	1.74	74.85	273.95	4.66
B22.M	30.4	71.50	1.51	95.69	175.75	4.11

Average values of test results obtained from the beam specimens are given in Table 4. The listed data include the concrete strength at the day of testing, the ultimate load (P_{max}), the deflection at the center of the beam (δ), neutral axial width (x), steel stress (f_s) and average bond stress (u_t).

6. Analysis of test results

Table 4 summarizes the test results indicating the effect of reinforcing bar diameter on bond strength. For all test specimens, variables were kept constant except reinforcing bar diameter. The results shown in Table 4 indicate that bond strength (u_t) decreases as reinforcing bar diameter increases. For the test results, ($u_t/\sqrt{f_c'}$) was plotted against $1/d_b$ in Fig. 5. The best fit for the test results plotted in Fig. 5 is given by

$$\frac{u_t}{\sqrt{f_c'}} = 0.571 + \frac{4.175}{d_b} \tag{2}$$

The stiffnesses of the various beams were compared by plotting the load versus midspan deflection curve for each beam. The stiffnesses of the beams resulted in a reduction (resistance to deflection) above cracking load level. It was observed that the stiffnesses of beams increased but the ductility of beams reduced as diameter of the tension bars used in the beam specimens increased (see Figs. 6, 7 and 8).

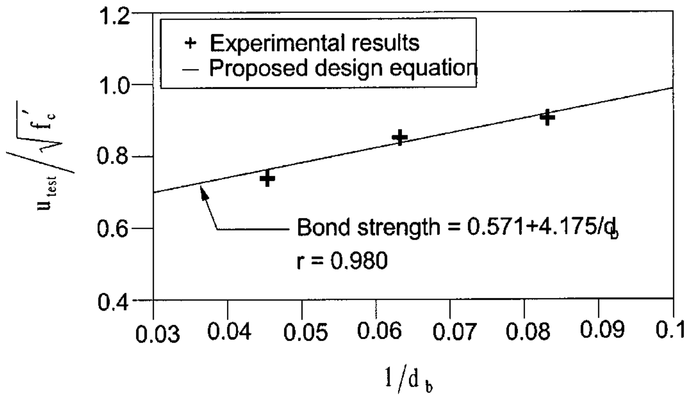

Fig. 5 Proposed equation for bond strength

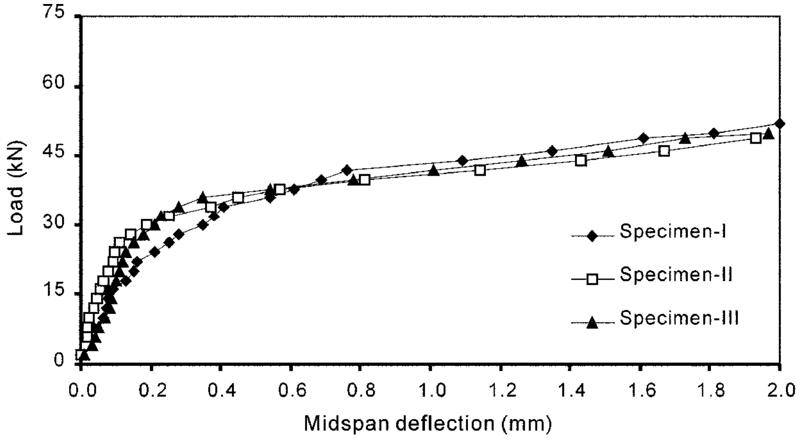

Fig. 6 Load-deflection curves for d_b=12 mm beam specimens (B12. M)

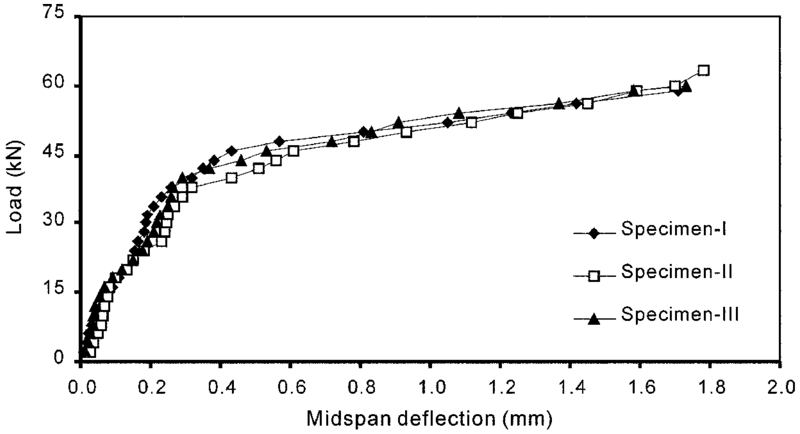

Fig. 7 Load-deflection curves for d_b=16 mm beam specimens (B16. M)

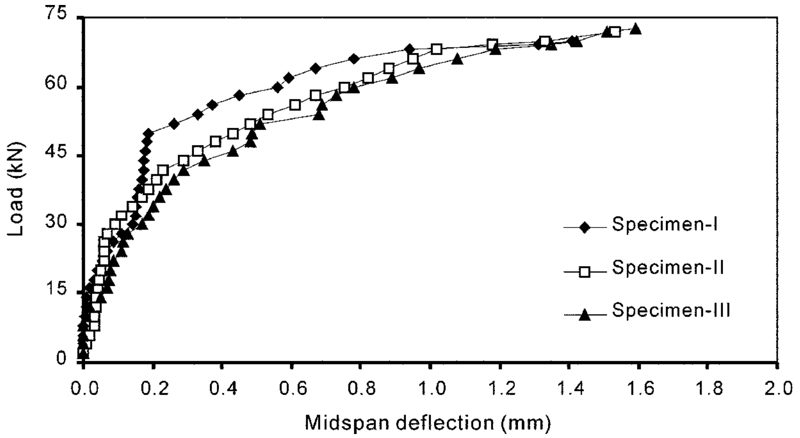

Fig. 8 Load-deflection curves for d_b=22 mm beam specimens (B22. M)

7. Comparison with Orangun and Esfahani

The values computed from Eq. (2) were compared with those computed from Eq. (3) of Orangun *et al.* (1977).

$$u = [1.2 + 3(c/d_b) + 50(d_b/l_s) + K_{tr}]\sqrt{f_c'} \tag{3}$$

Where

$$K_{tr} = \frac{A_{tr} f_{yt}}{500 s d_b} \tag{3a}$$

Moreover, the values computed from Eq. (2) were also compared with those computed from Eq. (4) of Esfahani and Rangan (1998).

$$U = u_c \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{c_{med}}{c_m}\right) \tag{4}$$

Where

$$u_c = 4.9\frac{c_m/d_b + 0.5}{c_m/d_b + 3.6} f_{ct} \quad \text{for} \quad f_c' < 50 \text{ MPa} \tag{4a}$$

$$u_c = 8.6\frac{c_m/d_b + 0.5}{c_m/d_b + 5.5} f_{ct} \quad \text{for} \quad f_c' \geq 50 \text{ MPa} \tag{4b}$$

$$M = \cosh\left(0.0022 L_d \sqrt{R\frac{f_c'}{d_b}}\right) \tag{4c}$$

in which U and f_c' are in MPa; $f_{ct} = 0.55\sqrt{f_c'}$; c_m is the smallest value and c_{med} is the second larger value of side cover, bottom cover or 1/2 of center-to-center spacing of bars; R varies between 3 and 4.25, which depends on type of reinforcing bar.

The predicted bond stresses computed using equations of Orangun *et al.* (1977) and Esfahani and Rangan (1998) are listed in Table 5. For each specimen, the bond efficiencies listed in Table 5 were determined by dividing the obtained bond stress by the predicted bond stress. The bond efficiency for all bar splices using Eq. (3) of Orangun is 0.88 with a standard deviation of 0.02. Morever, the mean bond efficiency using Eq. (4) of Esfahani is 0.99 with a standard deviation of 0.05.

Table 5 Bond stress and bond efficiency of the beam specimens

Specimen notation	Ultimate Load (kN)	f_c' MPa	Bond stress obtained from Eq. (2) (MPa)	Predicted bond stress (MPa)		Bond efficiency	
				Orangun, Jirsa and Breen (1975, 1977) Eq. (3)	Esfahani and Rangan (1998) Eq. (4)	$\frac{u_{Obtained}}{u_{Orangun}}$	$\frac{u_{Obtained}}{u_{Esfahani}}$
B12. M	50.30	30.4	5.07	5.75	4.86	0.88	1.04
B16. M	60.80	30	4.56	5.09	4.62	0.90	0.99
B22. M	71.50	30.4	4.20	4.88	4.41	0.86	0.95

The results refer that for the splices tested in the study, Eq. (4) of Esfahani and Rangan (1998) provides on the average a better estimate of bond strength than Eq. (3) of Orangun *et al.* (1977).

8. Conclusions

Nine beam specimens containing an overlapping splice of two bars 12, 16 and 22 mm in diameters, under constant bending moment, were experimentally studied. Based on the analysis and comparison of modes of failure, ultimate loads, load-deflection behaviour and bond stresses of the beam specimens with spliced bars in the constant moment region tested in this study, the following conclusions were made:

1. The experimental ultimate moment is lower than the theoretical one calculated using the classical approach. This indicates that specimen failure occured due to the collapse of the overlapping splice which was provoked by concrete splitting. In fact, at the ultimate moment, a sudden increase of the splitting crack width occured over the whole splice.
2. It was shown that the reinforcing bar diameter had very important effect on the bond strength, i.e. the bond strength increased with reducing the diameter of the steel reinforcement.
3. The stiffnesses of the beams (resistance to deflection) increased but the ductilities of the beams reduced as the diameter of tension splice bars increased.
4. An empirical equation was derived from regression analysis of test results that is applicable to tension lap splices. When this equation was compared with Eq. (3) of Orangun *et al.* (1977) and Eq. (4) of Esfahani and Rangan (1998), it was found that there was better agreement with Esfahani and Rangan than with Orangun *et al.* (1977).

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Notation

ρ	: reinforcing bar ratio ($\rho = A_b/bd$)
δ	: deflection at the center of the beam
x	: neutral axial width
W/C	: water-cement ratio
A_b	: area of one reinforcing bar being spliced
A_{tr}	: area of transverse reinforcement crossing plane of splitting adjacent to single anchored reinforcing bar
b	: width of beam
$c_{\max}$	: maximum of c_x, c_y ve $(c_s + \phi)/2$
c_{med}	: median of c_x, c_y ve $(c_s + \phi)/2$ ($c < c_{med} < c_{\max}$)
c_m	: minimum of c_x, c_y ve $(c_s + \phi)/2$
c_s	: spacing between the spliced bars
c_y	: bottom cover
c_x	: side cover
d	: useful heigth
d_b	: bar diameter
E_c	: modulus of elasticity of concrete
E_s	: modulus of elasticity of steel
f_c'	: concrete compressive strength of the standard cylinder specimen
f_{ct}	: tensile strength of concrete
f_s	: tensile stress in the reinforcing bar
f_{su}	: ultimate stress in reinforcing bar
f_{yt}	: yield strength of transverse reinforcement
f_y	: yield stress of reinforcing bar
h	: height of beam
K	: modulus of displacement
K_{tr}	: index of transverse reinforcement provided along anchored bar
L_d	: development length
l_s	: length of lap splice
M	: bond strength parameter given by Eq. (4c)
P	: applied load
$P_{\max}$	: maximum applied load
R	: K/f_c', taken as 3 when ρ is close to 0.07
r	: correlation coefficient
s	: spacing of transverse reinforcement
T	: tension force
u	: average bond stress
u_c	: bond stress when the concrete cover cracks
u_t	: average bond stress corresponding to maximum applied load
u_{test}	: bond stress calculated from experimental testing