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Title no. 93-S29

Bond Strength of Noncontact Tension Lap Splices

by Bilal S. Hamad and Mohamad Y. Mansour

The subject of transverse spacing between two reinforcing bars lapped in a noncontact or spaced tension splice is addressed in the ACI Building Code (ACI 318-89). The code provisions are based on monotonic tests performed before 1957 of pullout specimens, beam-end specimens, and small-scale beam specimens, where the clear splice-bar spacing was small (less than 3 d_b or 50 mm). Tests reported in 1991 of full-scale flat plate specimens subjected to monotonic and repeated inelastic loading in direct tension did not check splice-bar spacings beyond the ACI Code limit of one-fifth of the required lap length. The study reported in this paper provides data on 17 full-scale slab specimens, each reinforced with three lap splices, loaded in flexure, and designed to fail in a splitting mode. Splice-bar spacings below and above the ACI limit were checked. The objective was to check the validity of the ACI provisions based on the results of this study and other studies of noncontact lap splices.

Keywords: bond (concrete to reinforcement); development length; reinforced concrete; splice length; structural detailing; tests.

INTRODUCTION

A tension lap splice is a common and necessary detail in reinforced concrete construction. A noncontact lap splice (also called a spaced splice) is a structural detail in reinforced concrete that provides continuity to the reinforcement by overlapping the ends of the steel bars without the bars touching each other. The subject of bar spacing in a noncontact lap splice is addressed in the ACI 318-89 Building Code.[1] Section 12.14.2.3 states that "bars spliced by noncontact lap splices in flexural members shall not be spaced transversely farther apart than one-fifth the required lap splice length, nor 6 in." This provision was first incorporated into the 1971 ACI Building Code (ACI 318-71)[2] and was based on research studies previously performed. The commentary argues that if individual bars in noncontact lap splices are too widely spaced, an unreinforced section is created, forcing a potential crack to follow a zigzag line (5 to 1 slope). The commentary points out that the 6 in. (152 mm) maximum spacing is added because most research available on the lap splicing of deformed bars was conducted with reinforcement within this spacing.

In 1947, the ACI Building Code ACI 318-47[3] specified that the minimum clear spacing between spliced bars was not to be less than 1 1/2 times the bar diameter for round bars or 1 1/3 times the maximum size of aggregate, and, in any case, at least 1 in. The 1951 Code (ACI 318-51)[4] retained the previous stipulations except that the 1 1/2 times the bar diameter was changed to 1 bar diameter. Engineering practices before 1950 usually required that an allowance be made for a reduction in bonded area for tied lap splices; this was accomplished by lengthening the splice. It was only in 1963 that the ACI Building Code (ACI 318-63)[5] allowed both spaced or contact lap splices based on reported experimental work on spaced lap splices.[6-9]

Inherent in the analysis of a reinforced concrete section is the assumption that the strain in the concrete and the steel is equal at the location of the steel. This implies perfect bond between the concrete and the steel. In a lap splice, the force in one bar is transferred to the concrete, which, in turn, transfers it to the adjacent bar. This transfer of forces from one bar to another in a splice can be seen from the crack pattern, as shown in Fig. 1 (MacGregor[10]).

Previous bond research reported in the literature involving pullout tests, beam-end tests, and flat plate tests of spaced and contact tension lap splices indicated that the spacing between lapped bars did not affect the ultimate bond strength significantly.

In research done before 1957,[6-9] the tests were mostly pullout specimens or small-scale beam specimens. The range of clear spacing between lapped bars was very limited (less than 3 d_b or 50 mm) to set up a trend or design criteria.

On the other hand, tests reported in 1991[11] were full-scale flat plate specimens reinforced with noncontact lap splices and subjected to monotonic and repeated inelastic loading in direct tension. The tension capacity of monotonically loaded splices was independent of the spacing of the spliced bars up to the ACI 318-89 code-specified spacing limit of 6 in. (152 mm), or one-fifth of the required lap length, which corresponded to 6 d_b in the tests. One disadvantage is that no

ACI Structural Journal, V. 93, No. 3, May-June 1996.

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tests were done where the spacing exceeded the ACI Code limit. Also, the method of loading did not simulate flexure as in a real structure.

RESEARCH SIGNIFICANCE

The research program reported in this paper was conducted at the American University of Beirut to give a more complete understanding of the effect of bar spacing in a tension lap splice on the bond strength of splices failing in a splitting mode of failure. Seventeen slab specimens, each reinforced with three lap splices, were loaded in flexure and were designed to fail in bond splitting. The significance of the study is that the clear transverse spacing between lap spliced bars in eight out of the 17 tested slab specimens was greater than the 20 percent of the splice length specified by ACI. The objective was to check the validity of the ACI specification and to determine a design phenomenon based on the test results.

REVIEW OF PREVIOUS RESEARCH

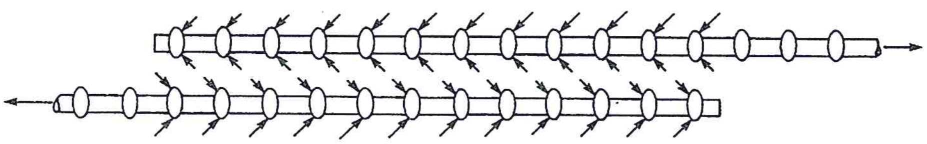
In 1950, Walker[6] conducted a series of pullout and beam tests to compare the performance of spaced and tied lap splices. Two levels of concrete strength and three types of deformed reinforcing bars were studied. In all tests where the spliced bars were spaced, the clear spacing was 1$^1/_2$ bar diameters. Beam tests showed no significant difference between the two splicing methods (zero spacing and 1.5 d_b spacing), but at high loads close to ultimate, there was some indication that spaced spliced bars might be slightly preferable showing less center deflection and end slip at a given load level. In the pullout tests, there was no weakening of bond at the tied splice. On the average, the performance of the tied bar arrangement was even better than that of the spaced bar arrangement.

Considering the entire data (some tests showed a high superiority in performance of spaced bars and others showed a slight superiority of tied bars), Walker concluded that within the scope of his study there was no important loss of bond when deformed bars were tied together at the splice.

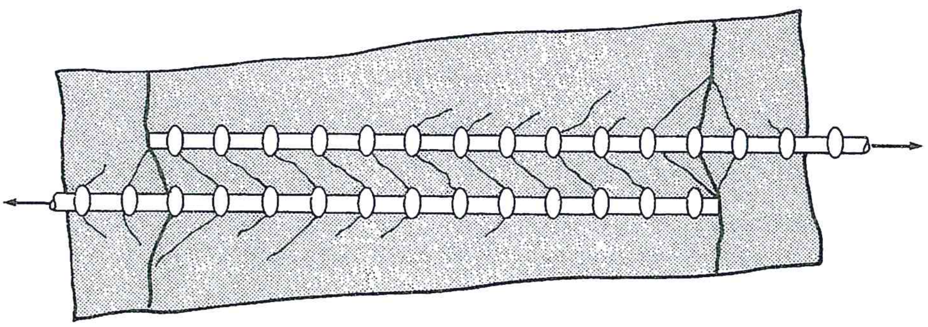
In 1952, Chamberlin[7] investigated the effect of spacing of spliced bars in tension pullout specimens. The tests were designed to provide data on the effect of spacing of lapped bars on bond and also on the effect of length of overlap in relation to effectiveness of stress transfer from one bar to another at a splice. Each specimen was reinforced with a spiral of wire to prevent splitting.

Based on test results, Chamberlin concluded that the bond strength of the plain bars was not affected significantly by the bar spacing at the splice. Although deformed bars developed better average bond stress in adjacent tied splices (zero spacing) than spaced splices, the differences in bond for clear spacings of one-bar diameter and three-bar diameters were not significant.

In 1955, Chin, Ferguson, and Thompson[8] reported a research program conducted at the University of Texas to investigate the effect of many variables on the bond capacity of spliced reinforcement, including beam width, concrete cover over steel bars, length of splice, clear spacing between spliced bars, bar size, stirrups in splice zone, splice position (top or bottom), number of splices in a beam, and concrete strength. The clear spacing between the spliced bars was either zero (contact splice), 0.75, 1.00, 1.25, or 1.88 in. (20,



(a) Forces on bars at splice.



(b) Internal cracks at splice.

Fig. 1—Schematic of bar forces and internal cracks in noncontact tension lap splice (MacGregor[10])

Table 1—Test parameters of slab specimens

Slab no.	Specimen notation	Bar diameter, mm	Splice length, mm	Clear transverse spacing between lapped bars		
				mm	l_s, percent	Multiple of d_b
1	S1-14-300-0	14	300	0	0	0.0
2	S2-14-300-30	14	300	30	10	2.1
3	S3-14-300-60	14	300	60	20	4.3
4	S4-14-300-90	14	300	90	30	6.4
5	S5-14-300-120	14	300	120	40	8.6
6	S6-14-300-150	14	300	150	50	10.7
7	S7-16-300-0	16	300	0	0	0.0
8	S8-16-300-30	16	300	30	10	1.9
9	S9-16-300-60	16	300	60	20	3.8
10	S10-16-300-90	16	300	90	30	5.6
11	S11-16-300-120	16	300	120	40	7.5
12	S12-16-300-150	16	300	150	50	9.4
13	S13-20-350-0	20	350	0	0	0.0
14	S14-20-350-35	20	350	35	10	1.8
15	S15-20-350-70	20	350	70	20	3.5
16	S16-20-350-105	20	350	105	30	5.3
17	S17-20-350-140	20	350	140	40	7.0

Note: 1 in. = 25.4 mm.

25, 32, or 48 mm). Forty beam specimens were tested. Each beam contained either one or two splices placed in a constant moment region at the center of the beam. Most of the tested beams contained a single splice with the bars in contact at the splice. In all beams the final failure was rather sudden and violent, with the final large splitting cracks sometimes deviating from the smaller cracks that had been progressing. Test results related to the effect of clear spacing at the splice indicated no substantial difference in the crack pattern or bond strength that could be attributed to the splice bar spacing.

Chin et al. concluded that within the scope of their study, their tests confirmed earlier tests reported by Walker[6] and Chamberlin,[7] which showed little difference in strength between contact and spaced lap splices.

In 1957, Chamberlin[9] reported the second phase of his research program designed to determine the effect of spacing of lapped bars on bond and the effect of length of lap on the load-carrying capacity of small beams. Twenty-one beams were tested with no restraint against splitting. All beams were 6 x 6 in. (152 x 152 mm) in cross section and 36 in. (915 mm) in length, simply supported under symmetrical two-point loading. The clear spacing between lapped bars was either 1/2 or 1 in. (12.5 or 25.4 mm). Based on the test results, Chamberlin concluded that there was little difference in strength between adjacent and spaced splices. This was in agreement with the results obtained with tension pullout specimens reported previously by Chamberlin.[7]

In 1989, Sagan, Gergely, and White[11] conducted a study to understand the behavior of noncontact lap splices subjected to monotonic and repeated inelastic loading. Forty-seven full-scale flat plate specimens were tested. Each specimen was reinforced with two splices. Variables included splice-bar spacing, concrete compressive strength, splice-bar size, the amount and distribution of transverse reinforcement, and lap length. Specimens were loaded slowly in direct tension. If a specimen survived the first loading to yield, it was unloaded slowly and then reloaded to yield; this process was repeated until failure. The procedure was selected to simulate loading representative of high earthquake risk levels.

Based on their experimental results, Sagan et al. made the following observations.

1. Noncontact lap splice behavior was observed and modeled as a plane truss. Load is transferred between the two splice bars through the concrete by compressive struts. The tension elements are provided by the transverse reinforcement and surrounding concrete.

2. The failure mode for the spaced bar splices was an in-plane splitting crack forming between the bars of the splice. The crack was induced by the bond-induced bursting and the Poisson strains generated by the compression stress field. The observed cracking along a lap splice changed with bar spacing. Diagonal surface cracking of the concrete between the splice bars became more prominent as the splice-bar spacing increased. Even the large cracks that formed at the ends of the splice were diagonal.

3. The splice strength of the monotonically loaded specimens increased when transverse reinforcement was provided. Also, the number of inelastic load cycles sustained by a tension splice was dependent on the amount of confinement provided by transverse reinforcement.

4. The ultimate load carried by a splice was independent of the splice-bar spacing up to at least six times the bar diameter for monotonic loading. Under repeated loading up to the yield strength of the splice bars, the ultimate load (equal to the yield load) was also independent of the splice-bar spacing up to eight times the bar diameter for both #6 and #8 bars.

EXPERIMENTAL PROGRAM

Seventeen slabs were tested in positive bending. The loading system was designed to produce a constant moment region in the middle of the slab specimen. Reinforcement on the tension side consisted of three reinforcing bars spliced at the center of the span. No transverse reinforcement was provided in the splice region, allowing for random formation of cracks.

Variables used in the investigation were the size of the reinforcing bar: 14, 16, or 20 mm (0.55, 0.63, or 0.79 in.) and the clear transverse spacing between the spliced bars. Test specimens are identified in Table 1. A four-part notation system was used to indicate the variables of each slab. The first part of the notation indicates the number of the slab in the sequence it was tested (from S1 to S17). The second part is the bar size in mm (14, 16, or 20). The third part is the length of the lap splice l_s, and the fourth part is the clear spacing between the lapped bars, both given in mm. The clear spacing between lapped bars varied between 0 and 50 percent of the splice length for slabs reinforced with bars 14 and 16 mm in diameter, and between 0 and 40 percent of the splice length for the 20-mm bar specimens. As an example of the notation system, S2-14-300-30 indicates that the second slab tested included three splices of bars 14 mm in diameter, with a splice length of 300 mm, and a clear spacing between the lapped bars of 30 mm (10 percent of l_s).

The splice length of the deformed bars was selected to develop a steel stress less than yield to insure a splitting mode of failure in all slab specimens. A yielding mode of failure provides little or no information regarding bond strength of a reinforcing bar, and the objective was to compare relative bond behavior of noncontact lap splices and not ductilities of the splices. The splice length was set at 300 mm (11.8 in.) for slabs reinforced with bars 14 and 16 mm in diameter, and 350 mm (13.8 in.) for the 20-mm bar specimens.

A 20-mm (0.79-in.) concrete cover to the reinforcing bars in the splice region was chosen as a typical side and bottom cover. This is very close to the minimum concrete cover for slab structures (0.75 in.) as specified in the ACI Code. All slab specimens had a width of 600 mm (23.6 in.) and a depth of 200 mm (7.9 in.); 600 mm was the maximum width that the testing machine would allow. The length of the slab was chosen to be 2000 mm (78.7 in.), with a distance of 1900 mm (74.8 in.) between the supports. The distance between the two applied concentrated loads was 600 mm (23.6 in.) for slabs reinforced with the 14- and 16-mm bars, and 700 mm (27.6 in.) for slabs reinforced with the 20-mm bars. This design provided a constant moment region long enough to allow random distribution of cracks outside the splice region. Longitudinal and cross-sectional details of the slab specimens are shown in Fig. 2 and 3. Slabs reinforced with bars 20 mm in diameter required transverse reinforcement in the shear spans to avoid shear failure.

Bars of each size were from the same heat of steel and had the same deformation pattern. The bars met ASTM specifications and were Grade 60. Two coupons of each bar size were tested to confirm the mill test report obtained from the supplier. The average yield stresses were 469 MPa (68 ksi) for the 14-mm bars, 476 MPa (69 ksi) for the 16-mm bars, and 474 MPa (68.7 ksi) for the 20-mm bars. A non-air-entrained concrete mix was designed to provide a minimum 28-day compressive strength of 21 MPa (3000 psi). Mixing was performed at the laboratory. The maximum size aggregate was 20 mm (0.79 in.). The slump varied between 50 and 100 mm (2 and 4 in.).

Specimens were tested using the MTS (Materials Testing System) closed-loop servo-hydraulic testing machine with a 1000-KN capacity dynamic actuator. A 600 x 100 x 15-mm (23.6 x 3.9 x 0.6-in.) steel plate was placed under each point load to distribute the load evenly over the 600-mm width of the slab. Load was applied incrementally until failure occurred. At each load stage, deflection readings were taken at the center of the slab using a dial gage and flexural cracks were marked. The side and bottom (tension face) cracking patterns were recorded for each slab specimen for comparison purposes.

GENERAL BEHAVIOR AND MODE OF FAILURE

The first flexural cracks in all slabs occurred randomly in the constant moment region on the tension side of the slab outside the splice length. Load P_{cr}, where cracking started, was approximately 15.5 KN (3.5 kips) in the 14-mm bar specimens, 20 KN (4.5 kips) in the 16-mm bar specimens, and 25 KN (5.5 kips) in the 20-mm bar specimens.

As loading continued, cracks formed along the entire length of the constant moment region, including the splice region. Before failure, and as loading continued, the width of flexural cracks in the splice region and their propagation along the height of the slab were noticeably less than the width and propagation of cracks outside the splice region. The reason is that at load levels below failure, the bond stress

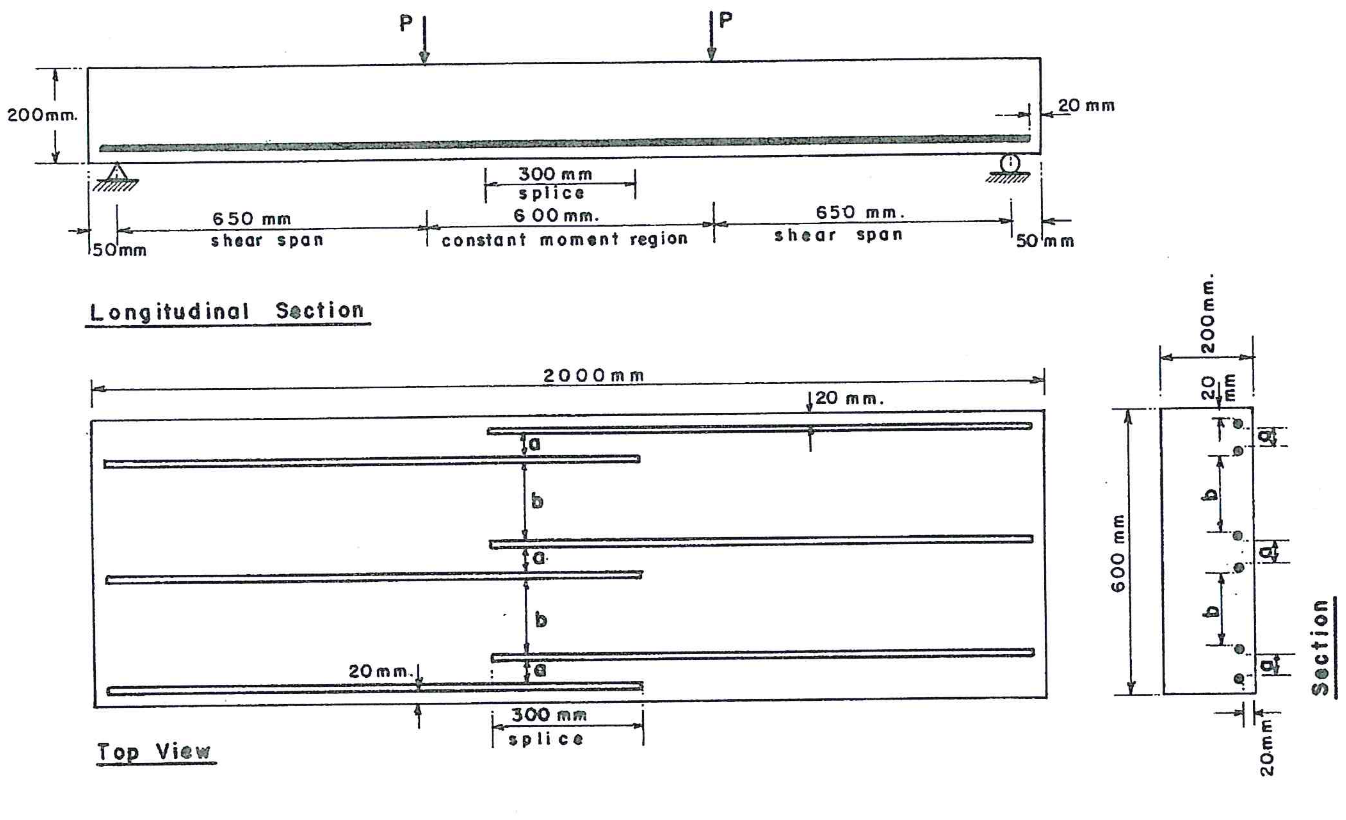


Fig. 2—Details and test setup of slabs reinforced with bars 14 and 16 mm in diameter (1 in. = 25.4 mm)

in the splice is below capacity and there is effectively twice as much steel as outside the splice. Failure of the slabs occurred just after longitudinal splitting cracks formed in the bottom cover at the tension face directly below the splices and in the side cover adjacent to the bars. The final mode of failure was by sudden face-and-side splitting. After failure, the slabs carried virtually no load. Additional deflections were imposed to increase the severity of the splitting in the splice region while the load continued to drop.

The observed cracking patterns on the bottom tension face and on the side of the slab specimen changed with splice-bar spacing for each tested bar size, but were similar for different bar sizes. Typical cracking patterns after failure of slabs with small and large splice-bar spacings are shown in Fig. 4 and 5, respectively.

As the clear spacing between lapped bars increased, flexural cracks that formed at the side edges of the slab in the splice region were inclined at a larger angle from the horizontal and propagated higher. With small spacing (less than 10 percent of the splice length), the final cracking pattern on the slab side was more or less confined to the level of the reinforcement. As for the bottom tension face cracking, longitudinal splitting cracks developed along the splices for small splice-bar spacings, whereas diagonal surface cracking of the concrete between the spliced bars became more prominent as the splice-bar spacing increased (see Fig. 4 and 5).

TEST RESULTS

To allow direct comparison of all slab specimens, the corresponding load-deflection data, steel stresses, and bond strengths were normalized at a common concrete strength of 21 MPa (3000 psi). The adjustment was made by multiplying the load at each defection by $(21/f'_c)^{1/2}$, where f'_c is the concrete strength in MPa of the slab specimen under consideration at the day of testing. The maximum stress that developed in the steel bars in each slab specimen was determined by analyzing the section based on cracked elastic behavior. The analysis ignored the tensile stresses in the concrete below the neutral axis and assumed linear stress-strain behavior. The measured ultimate steel stresses ranged from 70 to 90 percent of the yield stresses of the reinforcing bars. The splitting mode of failure of all slab specimens indicates that the splices reached their maximum capacity. Therefore, bond strength could be determined directly from the stress developed in the steel bars. To evaluate the average bond stress u, the total force developed in the bar $A_b f_s$ was divided by the surface area of the bar over the splice length $\pi d_b l_s$

$$u = (A_b f_s)/(\pi d_b l_s)$$

$$u = (f_s d_b)/4l_s$$

Results of the 17 slab specimens tested in the research program are presented in Table 2. The listed data includes the concrete strength at the day of testing and the ultimate load P_{max} and the corresponding maximum steel stress f_{su}, deflection at the center of the slab, average bond stress u_t, and bond ratio. The bond ratio is the bond stress of the slab with noncontact lap splices divided by the bond stress of the slab with

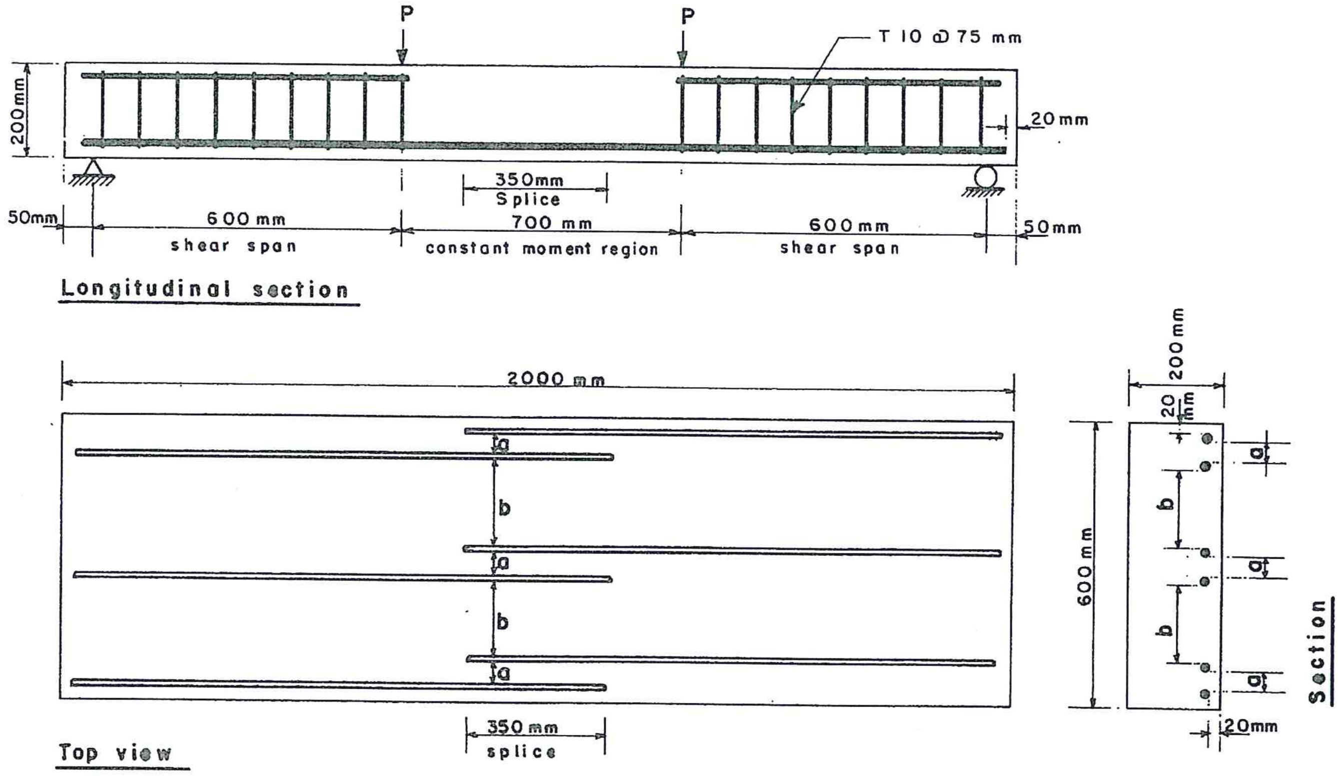


Fig. 3—Details and test setup of slabs reinforced with bars 20 mm in diameter (1 in. = 25.4 mm)

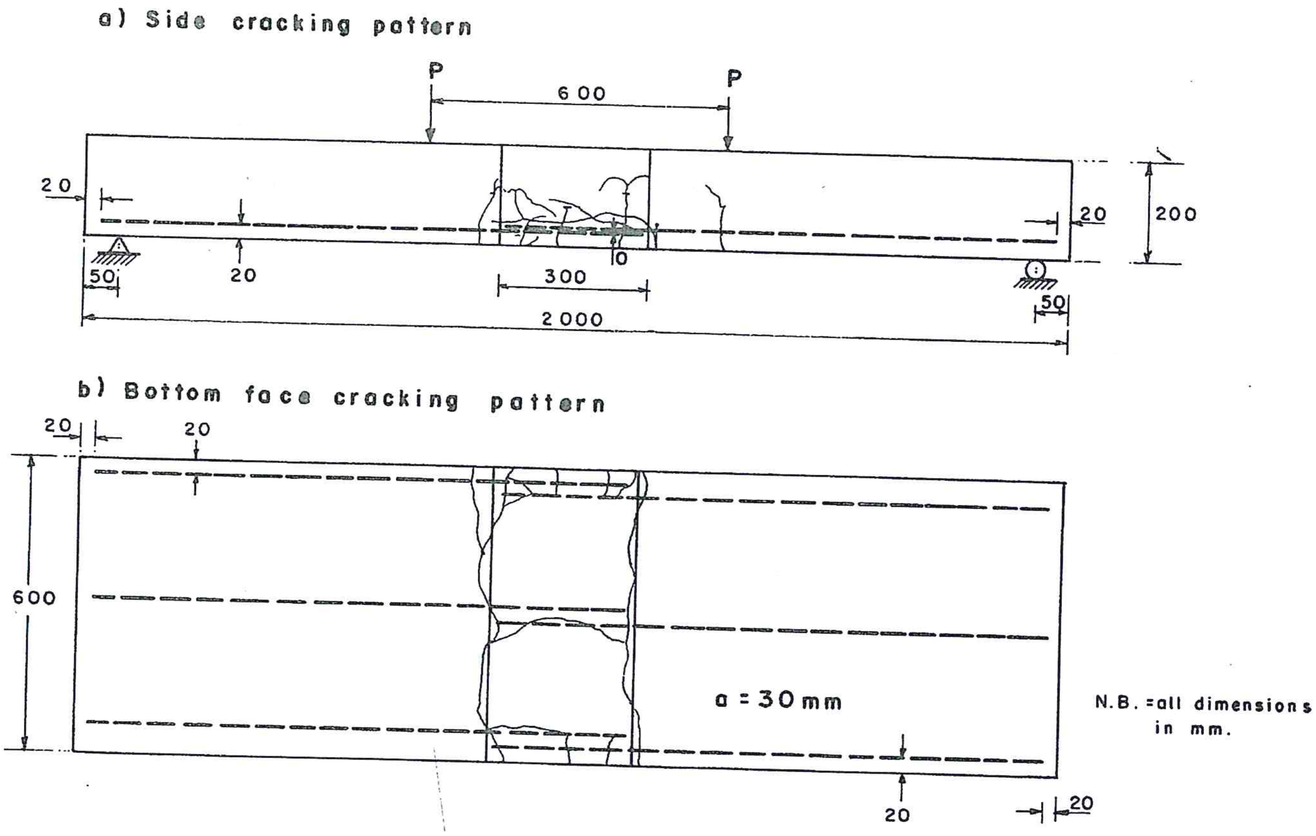


Fig. 4—Typical cracking pattern of slabs with small splice-bar spacing [Slab S2-14-300-30 (1 in. = 25.4 mm)]

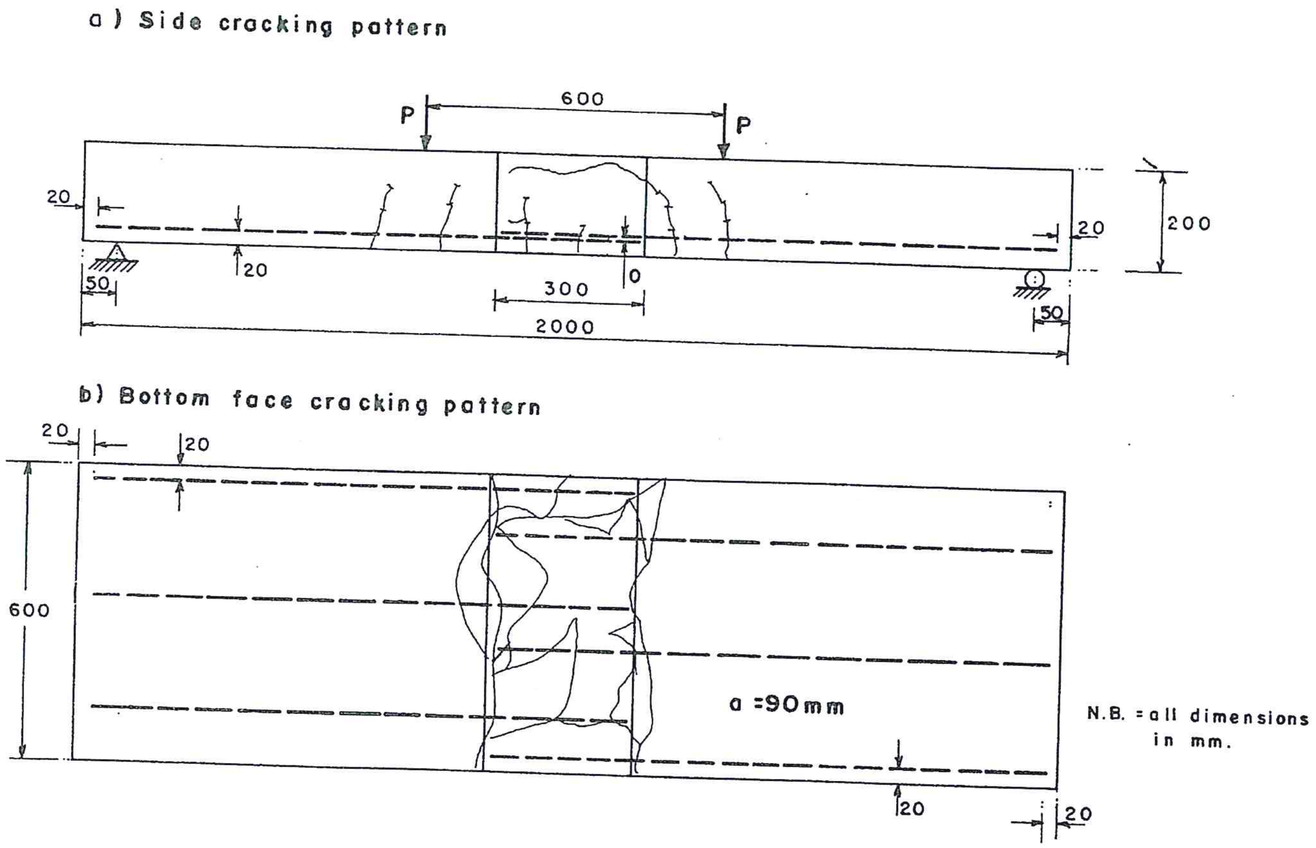


Fig. 5—Typical cracking pattern of slabs with large splice-bar spacing [Slab S4-14-300-90 (1 in. = 25.4 mm)]

adjacent or contact splices in the same series (for the same bar size).

ANALYSIS OF TEST RESULTS

Slab stiffness

Slab Specimens S1 to S6 were each reinforced with three splices of bars 14 mm in diameter. The splice length was 300 mm. The clear spacing between lapped bars varied from 0 (contact splices) in Slab S1 to 150 mm (10.7 d_b or 50 percent l_s) in Slab S6. Load-deflection curves of the six slab specimens are shown in Fig. 6. Except for Slab S6, other slabs showed almost identical load-deflection histories at low levels of loading and up to the cracking load. At loads higher than the cracking load, Slabs S2, S3, and S4, with clear spacings of 10, 20, and 30 percent of splice length, had greater stiffness (greater load for a given deflection) than Slab S1 with contact splices. However, the stiffness of Slabs S5 and S6, with clear spacings of 40 and 50 percent of splice length, was lower than that of Slab S1. Slab S3, with a clear spacing between lapped bars of 60 mm (4.3 d_b or 20 percent l_s), developed the highest stiffness beyond the cracking load and had the smallest midspan deflection at ultimate load.

As the clear spacing between lapped bars increased from 0 (contact splices) to 90 mm (30 percent l_s), the ultimate steel stress was greater than in the contact splice specimen. Slabs S3 and S4, with clear spacings of 60 and 90 mm (20 and 30 percent l_s), respectively, developed a similar ultimate steel stress that was greater than all other specimens. The improving trend was reversed with Specimens S5 and S6 with spacings of 120 and 150 mm (40 and 50 percent l_s), respectively. Slab Specimens S7 to S12 were each reinforced with three splices 16 mm in diameter. Load-deflection curves shown in Fig. 7 indicate similar stiffnesses of Slabs S7 to S11 before cracking. The stiffness of Slab S12, with clear spacing of 150 mm (50 percent l_s), was lower than all slabs in this series. After cracking, stiffness, as measured from the load-deflection curves, increased as the splice-bar spacing increased from 0 to 90 mm (30 percent l_s). Beyond the 90-mm spacing, stiffness dropped even below that of Slab S7 with contact splic-

Table 2—Test results

Slab no.	Bar diameter, mm	f'_c at day of testing, MPa	At ultimate* P_{max}, kN	f_{su}, MPa	Deflection, mm	Measured bond stress: Bond stress, MPa	Bond ratio†
1	14	23.1	40.8	379	3.81	4.42	1.00
2	14	22.4	42.3	393	3.51	4.58	1.04
3	14	22.8	43.8	406	3.21	4.74	1.07
4	14	21.4	43.3	402	3.86	4.69	1.06
5	14	20.8	39.8	371	3.94	4.32	0.98
6	14	22.1	39.0	363	4.83	4.23	0.96
7	16	21.8	45.9	331	4.50	4.41	1.00
8	16	20.6	47.0	338	4.34	4.51	1.02
9	16	22.1	48.6	350	4.40	4.66	1.06
10	16	23.2	49.9	363	4.12	4.79	1.09
11	16	22.4	45.9	331	5.46	4.41	1.00
12	16	23.4	44.5	321	5.59	4.28	0.97
13	20	20.0	79.3	340	5.59	4.85	1.00
14	20	19.4	85.1	363	5.33	5.19	1.07
15	20	21.4	86.7	370	5.21	5.28	1.09
16	20	24.1	87.7	374	4.94	5.34	1.10
17	20	21.9	81.2	347	6.25	4.95	1.02

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.9 MPa.
*P_{max}, f_{su}, and average bond stress normalized at common f'_c of 21 MPa (3 ksi).
†Bond ratio = bond stress (noncontact splice)/bond stress (contact splice).

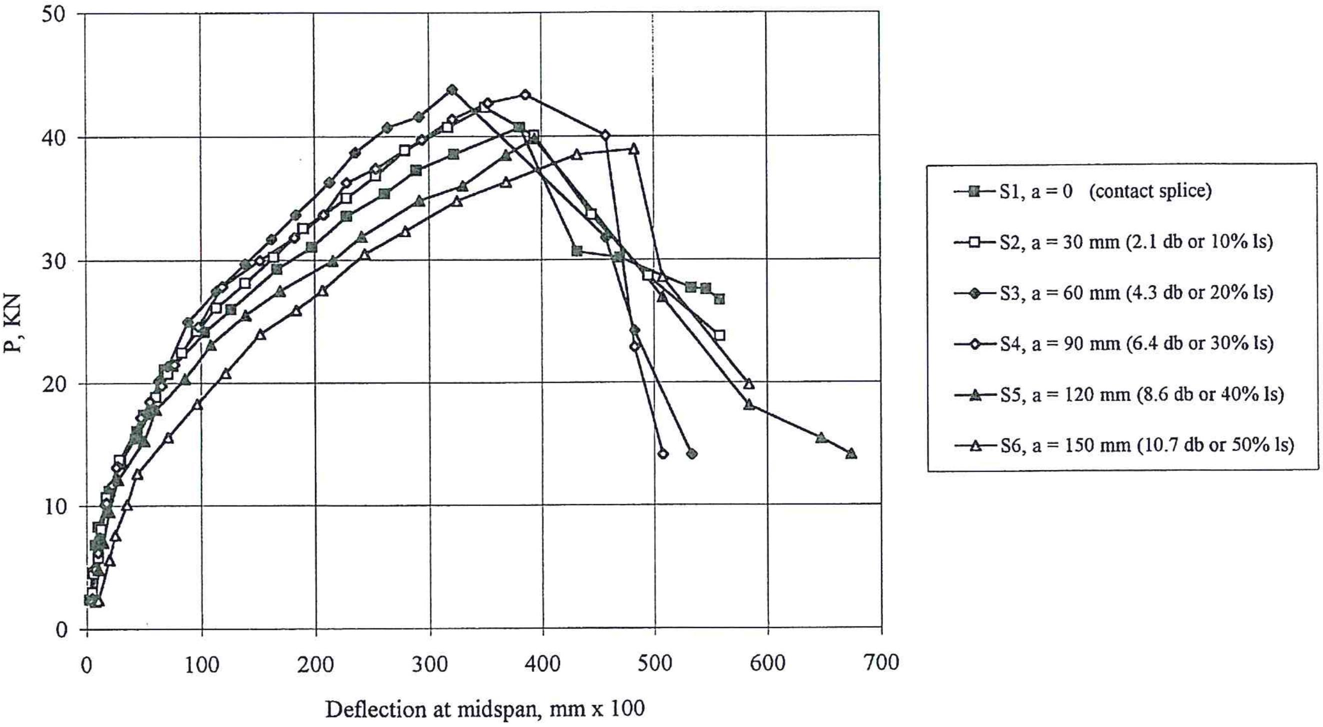


Fig. 6—Load-deflection curves of slabs reinforced with bars 14 mm in diameter (1 in. = 25.4 mm; 1 kip = 4.45 KN)

es. Slab S10, with a splice-bar spacing of 90 mm (5.6 d_b or 30 percent l_s), developed the highest ultimate steel stress, and had the smallest midspan deflection at ultimate. Slabs S11 and S12, with clear spacings of 120 and 150 mm, corresponding to 40 and 50 percent of splice length, developed lower ultimate steel stresses than all other specimens in the second series.

The third series of Slab Specimens S13 to S17 were each reinforced with three splices of bars 20 mm in diameter. Slab S16, with a clear spacing of 105 mm (5.3 d_b or 30 percent l_s), had the highest ultimate steel stress and load-deflection stiffness (see Fig. 8). Deflection at midspan was smaller for Slab S16 than for all other slabs in this series.

Bond ratios

Bond ratios are plotted versus the splice-bar spacing in Fig. 9 and 10. Splice-bar spacing is expressed as the percent of splice length in Fig. 9 and as a multiple of the bar diameter in Fig. 10. For the three bar sizes studied, bond strength of the noncontact or spaced splices increased relative to the contact splices, up to a splice-bar spacing of around 30 percent of splice length. The improving trend was not sustained for spacings of 40 and 50 percent of splice length. The spacing of 30 percent of splice length corresponded to 90 mm (3.5 in.) for the 14- and 16-mm bar splices and to 105 mm (4.1 in.) for the 20-mm bar splices. It should be noted that at the optimum clear spacing of 30 percent of splice length, the bond ratios (spaced to contact splices) were 1.06 for the 14-mm bars, 1.09 for the 16-mm bars, and 1.10 for the 20-mm bars. Also, at the clear spacing of 50 percent of splice length, the bond ratios were 0.96 for the 14-mm bars and 0.97 for the 16-mm bars. In other words, although a trend was determined, the increase and decrease in bond strength, as compared with the contact splice, were within 10 percent, regardless of bar size.

The ACI Building Code (ACI 318-89)[1] limits the transverse spacing of noncontact lap splices to 20 percent of splice length or 6 in. (152 mm), whichever is smaller. Based on the test results, the limit of 20 percent of splice length is conservative. No tests were made with a clear spacing greater than 6 in. (152 mm). Such a spacing would have required a wider slab specimen (more than 600 mm), which the testing machine would not allow. It would be more appropriate from a designer point of view to limit the clear splice-bar spacing to a multiple of the bar diameter. With reference to Fig. 10, it could be concluded that regardless of bar size, spaced lap splices developed greater bond strength than contact lap splices up to an optimum transverse clear spacing between lapped bars of around 5 times the bar diameter.

COMPARISON WITH ORANGUN AND ACI 318-89

The measured splice bond strength of each slab was compared with the theoretical value computed using the empirical equation developed by Orangun, Jirsa, and Breen[12]

$$u = [1.2 + 3\,(c/d_b) + 50\,(d_b/l_s) + k_{tr}]\,(f'_c)^{1/2}$$

where

$$k_{tr} = (a_{tr} f_{yt}) / (500\, s\, d_b),\ (c/d_b) \le 2.5,\ k_{tr} \le 3.0 \quad (1)$$

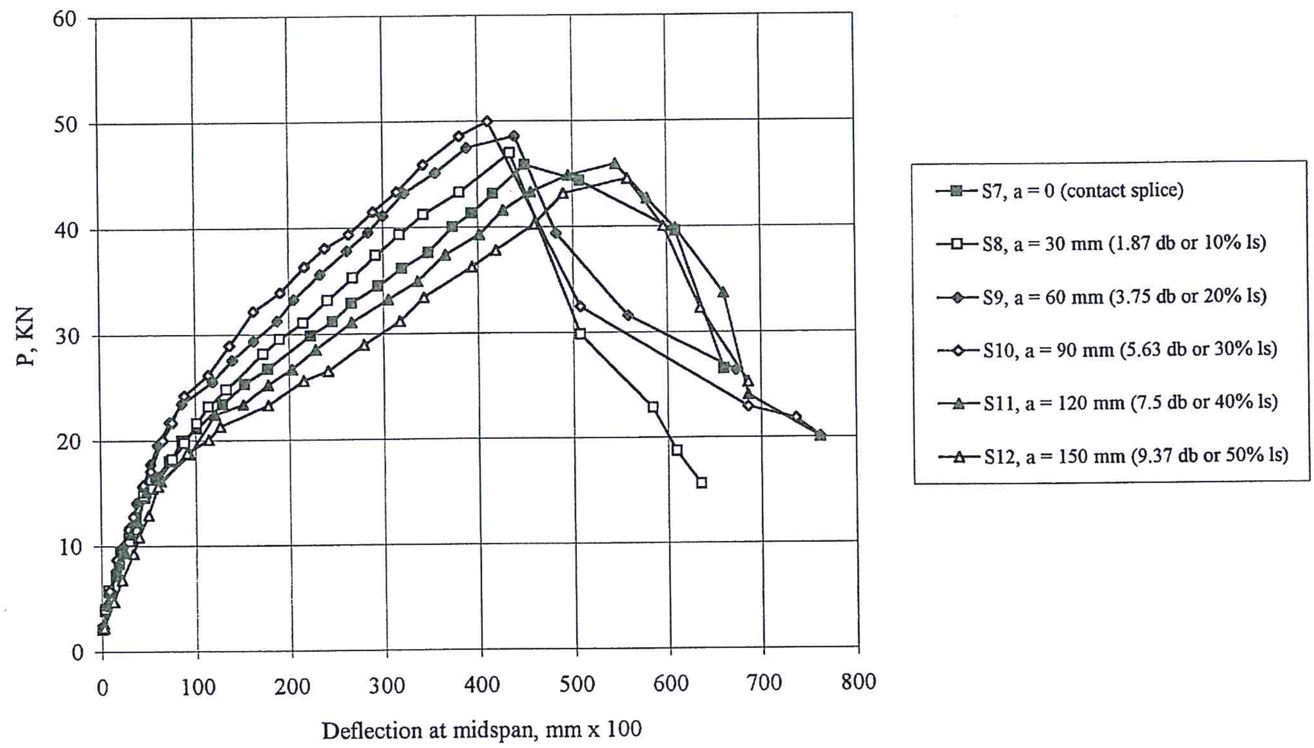


Fig. 7—Load-deflection curves of slabs reinforced with bars 16 mm in diameter (1 in. = 25.4 mm; 1 kip = 4.45 KN)

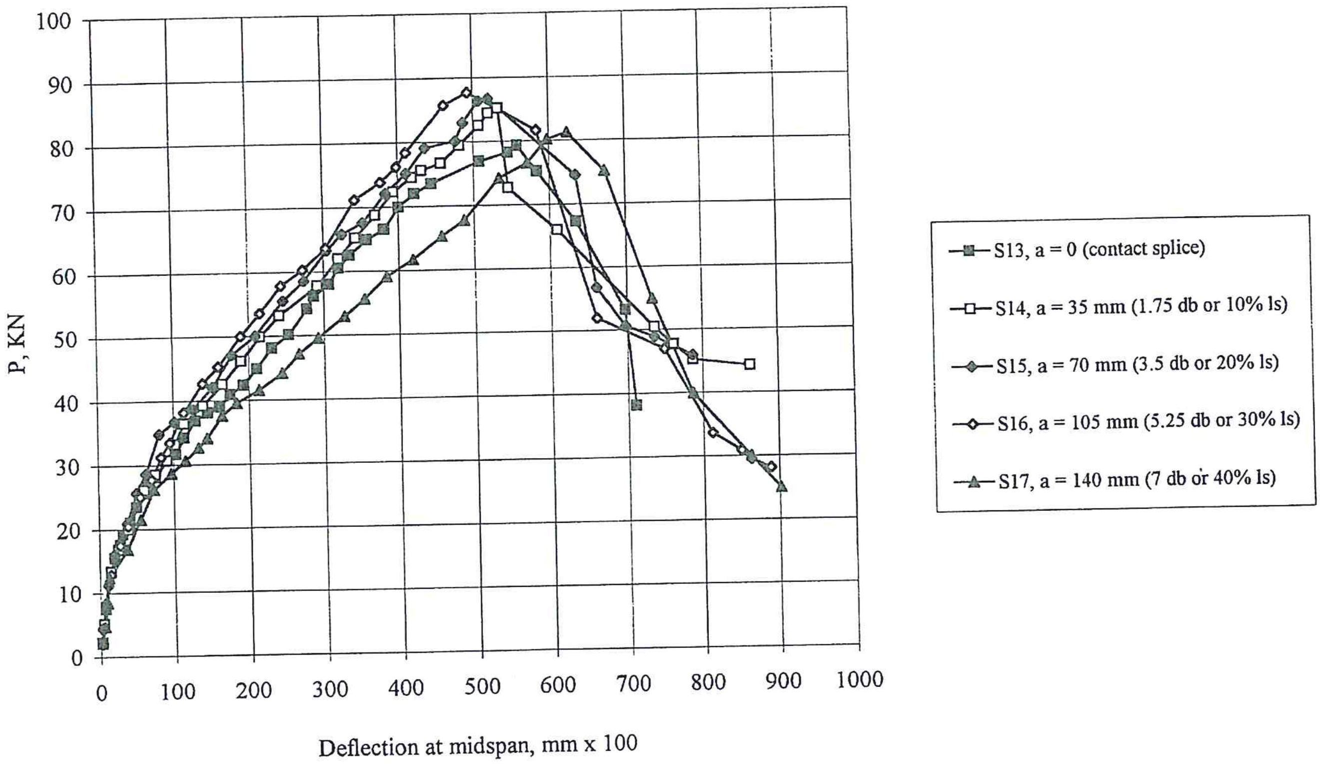


Fig. 8—Load-deflection curves of slabs reinforced with bars 20 mm in diameter (1 in. = 25.4 mm; 1 kip = 4.45 KN)

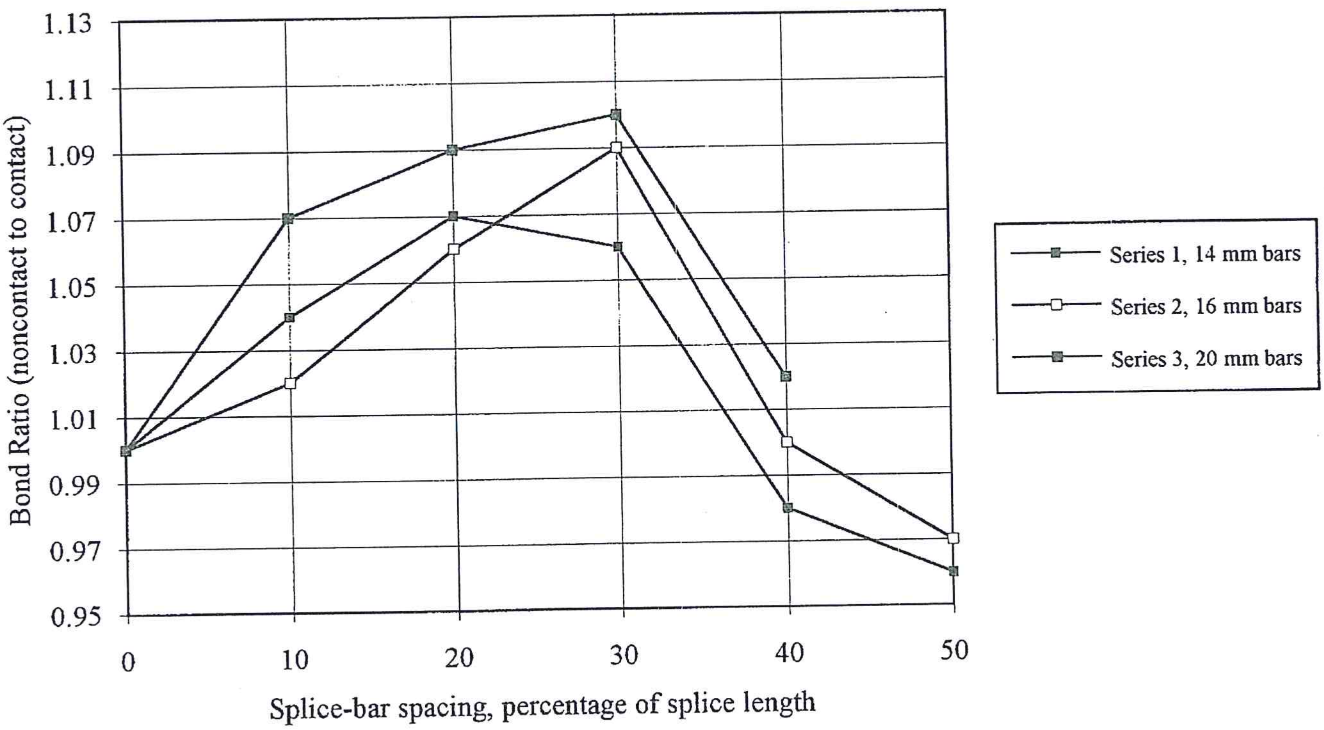


Fig. 9—Variation of bond ratio with splice-bar spacing expressed as percentage of splice length

A comparison was also made with the current ACI Code (ACI 318-89)[1] bond specifications using $l_s = 1.3\ l_{db}$ according to Section 12.15 of the Code

$$l_s = 1.3\, l_{db},\ l_{db} = (0.04\, A_b f_y) / (f'_c)^{1/2} \geq 0.03\, (d_b f_y) / (f'_c)^{1/2}$$

Combining the previous equations with $u\pi d_b l_s = A_b f_y$, then

$$u = \left[6.12\,(f'_c)^{1/2}\right] / d_b \leq 6.41\,(f'_c)^{1/2} \qquad (2)$$

Since all bars in the study were bottom-cast, no top bar factor was applied to Eq. (1) and (2). Concrete strength f'_c was taken as 21 MPa (3 ksi) in both equations. The factor for transverse reinforcement in Eq. (1) k_{tr} was zero since no stirrups were placed in the splice region in any of the tested slab specimens. Also, a modification factor for spacing between splices and for concrete cover was applied to Eq. (2). This factor was either 1.0 or 2.0, since the 1.4 factor was not applicable. The predicted bond stresses computed using Eq. (1) and (2) are listed in Table 3. The measured bond stress for each specimen was divided by the predicted values to obtain the bond efficiencies listed in Table 3. These bond efficiencies indicate a big discrepancy between measured bond stresses and the predicted values. The current ACI Code (ACI 318-89)[1] bond specifications are overly conservative and should be modified to provide a better and more reasonable estimate of the bond strength of bar splices in slab specimens.

CONCLUSIONS

Based on the analysis and comparison of ultimate steel stresses, load-deflection curves, and bond strengths, the following conclusions were made:

1. For slabs with contact lap splices or small clear splice-bar spacing (10 percent l_s), the final cracking pattern on the

Table 3—Bond stresses and bond efficiencies of slab specimens

Slab no.	Bar diameter, mm	Measured bond stress u_t, MPa	Predicted bond stress, MPa: Orangun Eq. (1)	Predicted bond stress, MPa: ACI 318-89 Eq. (2)	Bond efficiency: u_t/u (Orangun)	Bond efficiency: u_t/u (ACI)
1	14	4.42	2.95	2.42	1.50	1.83
2	14	4.58	2.95	2.42	1.55	1.89
3	14	4.74	2.95	2.42	1.61	1.96
4	14	4.69	2.95	2.42	1.59	1.94
5	14	4.32	2.95	2.42	1.46	1.79
6	14	4.23	1.86	1.21	2.32	3.49
7	16	4.41	2.88	2.42	1.53	1.82
8	16	4.51	2.88	2.42	1.57	1.86
9	16	4.66	2.88	2.42	1.62	1.93
10	16	4.79	2.88	2.42	1.66	1.98
11	16	4.41	2.88	2.42	1.53	1.82
12	16	4.28	1.71	1.21	2.50	3.54
13	20	4.85	2.67	1.21	1.82	4.01
14	20	5.19	2.67	1.21	1.94	4.29
15	20	5.28	2.67	1.21	1.98	4.36
16	20	5.34	2.67	1.21	2.00	4.41
17	20	4.95	1.82	1.21	2.72	4.10

Note: 1 in. = 25.4 mm; 1 ksi = 6.9 MPa.

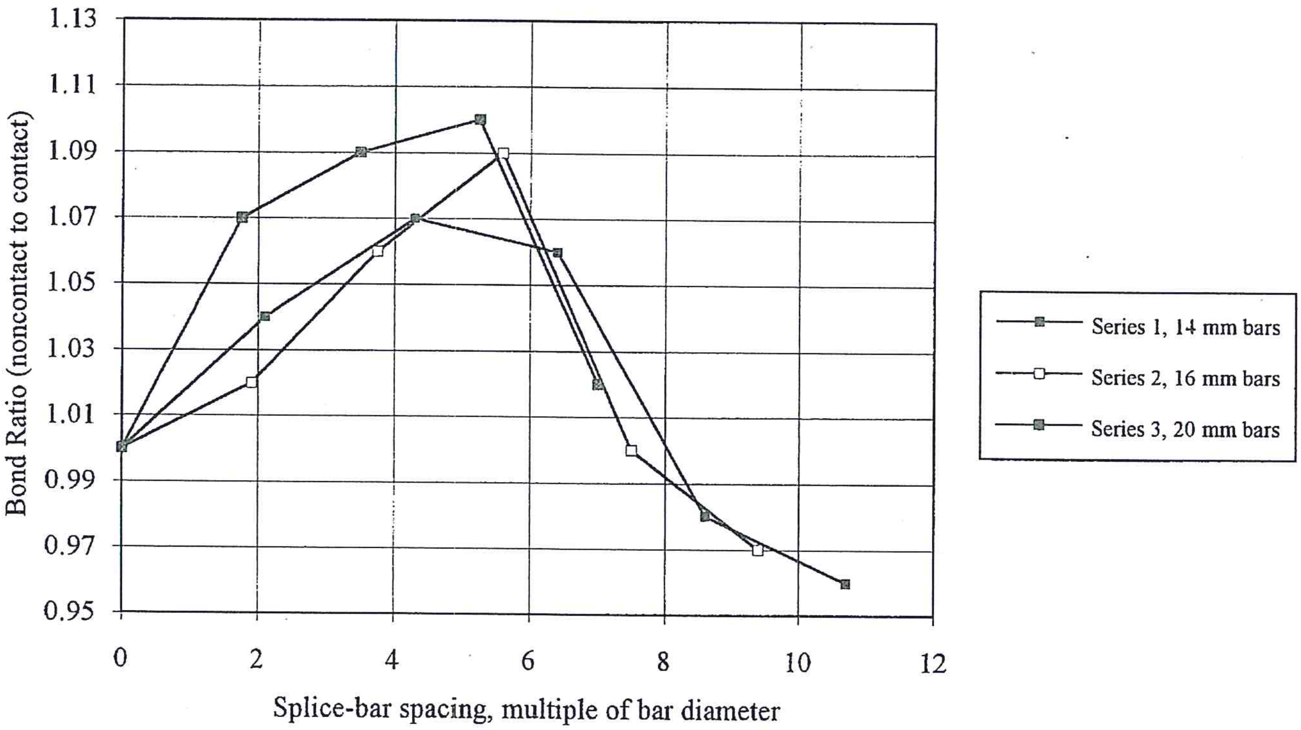


Fig. 10—Variation of bond ratio with splice-bar spacing expressed as multiple of bar diameter

side faces of the splice region was more or less confined to the level of the reinforcement. Also, longitudinal splitting cracks on the bottom tension face developed along the splices. As the splice-bar spacing increased, flexural cracks on the side faces of the splice region were inclined at a larger angle from the horizontal and had higher propagation along the slab height. Also, diagonal surface cracking of concrete between the splice bars became more prominent.

2. At load levels above the cracking load, slabs with noncontact splices developed greater flexural (load-deflection) stiffness than slabs with contact splices. The improvement was valid up to a clear splice-bar spacing of 30 percent of the lap length (around 5 d_b).

3. The ultimate load resisted by the slab specimens varied with spacing between lapped bars. The optimum clear splice-bar spacing was 4.3 d_b (20 percent l_s) for slabs reinforced with bars 14 mm in diameter, 5.6 d_b (30 percent l_s) for the 16-mm bar specimens, and 5.3 d_b (30 percent l_s) for the 20-mm bar specimens.

4. For the three bar sizes studied, bond strength of noncontact splices increased relative to the contact splices up to an optimum clear splice-bar spacing of 30 percent of the splice length. At this spacing, bond ratios (noncontact to contact splices) were 1.06 for the 14-mm bars, 1.09 for the 16-mm bars, and 1.10 for the 20-mm bars.

5. When the measured bond stresses of splices in the current study were compared with the theoretical values computed using the 1989 ACI Building Code (ACI 318-89)[1] bond provisions, it was found that the ACI 318-89 bond specifications are overly conservative and should be modified to provide a better and more reasonable estimate of the bond strength of bar splices in slab specimens.

Based on this study, it can be concluded that the ACI limit concerning the transverse spacing of noncontact tensile lap splices of 20 percent of the lap length is conservative. A limit of 30 percent of splice length is recommended. It would be even more appropriate from a designer point of view to set the limit in terms of bar diameter. Within the scope of this study, spaced-bar splices developed greater bond strength than contact-bar splices up to an optimum clear spacing of around five times the bar diameter (5 d_b).

NOTATION

a	= clear transverse spacing between spliced bars
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
c	= smaller of c_b or c_s
c_b	= clear (bottom or side) concrete cover to main reinforcement
c_s	= half clear spacing between anchored bars or splices or half available concrete width per bar or splice resisting splitting in failure plane
d_b	= diameter of reinforcing bar
f_c	= compressive strength of concrete
f_s	= stress in reinforcing bar
f_{su}	= ultimate stress in reinforcing bar
f_{yt}	= yield strength of transverse reinforcement
k_{tr}	= index of transverse reinforcement provided along anchored bar
l_{db}	= basic development length
l_s	= length of lap splice
P_{cr}	= load at which flexural cracking started
P_{max}	= maximum applied load
u	= average bond stress
u_t	= average bond stress corresponding to maximum applied load

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the University Research Board at the American University of Beirut. Also, the assistance of Mr. Hilmi Khatib, Supervisor of the Materials Testing Laboratory at AUB, is greatly appreciated.

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