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Improving the behavior of reinforced concrete beams with lap splice reinforcement

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ABSTRACT: The main objective of this paper is to study the behavior of lap splice of steel reinforcement in tension zones in reinforced concrete beams. An experimental program is conducted on twelve simply supported concrete beams. The main studied variables are: cut-off ratio, lap splices length, the type, spacing and shape of transverse reinforcement in the splice zone. It is concluded that for the same value of the lap splice length as that recommended by Egyptian Code, without the use of transverse reinforcement at the spliced zone, the change of the cut off ratio from 25% to 100% resulted in a reduction in ductility. On the other hand, there is a drastic increase in ductility of beams when transverse reinforcement was used.

1 INTRODUCTION

When reinforcement is spliced together within a concrete beam, it is necessary to overlap the bars long enough for tensile stresses in one bar to be fully transferred to other bars without inducing a pullout failure in the concrete. Most design codes allow the use of bars with lap splice and specify minimum length of the lap as well as the required transverse reinforcement.

The Egyptian Code 203-2007 requires the lap splice length; Lo, for flexural members to be taken as the development length; Ld, when the area of steel in the section; As applied, is greater or equal to the required steel area; As required, and the percentage of lapped steel is less than 25% of the total steel area at that section. Otherwise, the lap splice length is taken as 1.3 Ld. For flexural bar terminated in a tension zone, excess stirrups are provided over a distance along each terminated bar from the point of cut off to 0.75 the depth of the element. It should be mentioned that all the previous versions of the Egyptian Code prohibited splicing more than one quarter of the total number of tension bars at the same section.

According to ACI 318-05, the minimum length of lap for tension lap splices for Class A = 1.0 Ld and =1.3 Ld for class B. Stirrup area in excess of that required for shear and torsion is provided along each terminated bar or wire over a distance from the termination point equal to three-fourths the effective depth of member. Most of design codes do not specify a specific shape of transverse reinforcement required for spliced bars.

Ferguson and Breen (1965) studied thirty-five beams, focusing on bar diameter, stirrups, and concrete strength. From these tests, they concluded that stirrups increased splice strength, minimum stirrups as much as 20%, and heavy stirrups up to 50%. The splitting prior to failure gradually developed over the full splice lengths seemed almost to stabilize with a substantial center length remaining un-split until a final catastrophic failure occurred.

Jeanty et al. (1988) tested thirteen specimens to study the effect of transverse reinforcement on the bond performance among other variables. The main conclusions of this research were that for beams with and without transverse reinforcement crossing the plane of splitting, the top bar factor was found to be 1.22, which means that the required lap splice length must be increased by 22% for spliced top tension bars. The presence of transverse reinforcement across the plane of potential splitting reduced significantly the required development length for both bottom-cast and top-cast bars.

Hamad et al. (2006) investigated eighteen full-scale beam specimens. In this study, the amount of transverse reinforcement, bar size, and the bar type (black or galvanized) were considered. They concluded that in beams without transverse reinforcement in the splice region, surfaces of black and galvanized bars were relatively clean with limited signs of concrete crushing in the vicinity of very few bar lugs. In beams with transverse reinforcement in the splice region, however, there were relatively more signs of concrete crushing adjacent to the bar lugs indicating the positive role of confinement by transverse reinforcement in mobilizing more bar lugs in the stress transfer mechanism between the steel bars and the surrounding concrete.

2 OBJECTIVES

The main objectives of this study were:

1. To study the behavior of reinforced concrete simply-supported beams with lap splice of tension steel reinforcement zones with different lap splice lengths and arrangements.
2. To obtain a spliced beam that can achieve at least the same strength and ductility of the same beam without any splices using transverse reinforcement with different shapes.
3. To investigate the old condition of the Egyptian code, which was removed from the last version of the code (2007), not to splice more than one quarter of tension steel at the same section.

3 EXPERIMENTAL PROGRAM

Twelve simply supported reinforced concrete beams of dimensions 150 mm × 260 mm × 2600 mm were tested in the reinforced concrete lab, Alexandria University (2008). All the specimens had the same concrete strength, and the same longitudinal reinforcement. Four 10 mm-diameter 400/600 high strength steel were used as tension reinforcement. Plain bars of 6 and 8 mm diameter agree with grade 280/450 were used for stirrups outside the splice zone and top reinforcement respectively. The test setup of the studied beams is shown in figure 1. The studied parameters are given in Table 1 and are discussed in the following sections. Additionally, the required lap splice length as well as transverse reinforcement required by several design codes were obtained in Table 2. Figure 2 shows reinforcement details of some of the test beams.

3.1 *Test groups*

The tested beams are divided into four groups. The main studied parameters were:

1. Cut off ratio; Group 1
   Cut off ratio is ratio of the spliced area to the total area of tension bars of the beams. Three values of cut-off ratio were investigated: 0% (Beam D1), 25% (Beam D2), and 100% (Beam D3). No transverse reinforcement was used in the lap splice zone.
2. Length of lap splice; Group 2
   Three values of lap splice length were investigated: 54 db (Beam D3), 27 db (Beam D4), and 75 db

Figure 1. Test setup.

Table 1. Details of tested beam specimens.

Beam	Average cube strength (N/mm^2)	Splice length	Cutoff ratio	Transverse reinforcement shape in the splice zone
D1	36.4	no splice	0.00%	None
D2	36.3	54 db*	25%	None
D3	37.3	54 db	100%	None
D4	38.8	27 db	100%	None
D5	38.4	27 db	100%	Stirrups with additional legs
D6	35.4	27 db	100%	Separate stirrups
D7	36.4	27 db	100%	Rectangular stirrups around spliced bars two interlocking
D8	34.7	27 db	100%	Spirals
D9	38.7	27 db	100%	Continuous rectangular stirrups.
D10	37.6	75 db	100%	None
D11	36.6	27 db	100%	Separate stirrups
D12	38.0	27 db	100%	Separate stirrups

*d_b: Bar diameter.

Table 2. Calculated lap splice length by several codes.

Code	Required lap splice	Calculated transverse reinforcement
Egyptian Code 203-2007	540 mm	φ6 mm @ 30 mm
ACI 318-05	300 mm	φ6 mm @ 30 mm
Eurocode 2-1996	455 m	φ6 mm @ 35 mm

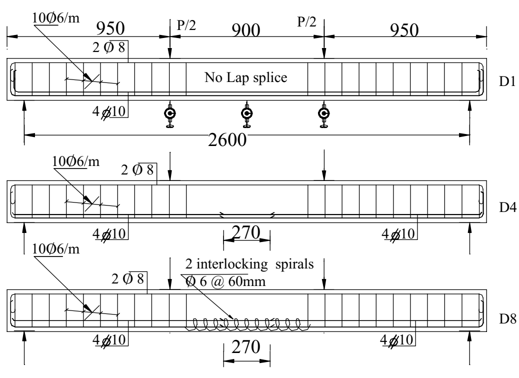

Figure 2. Details of some tested specimens.

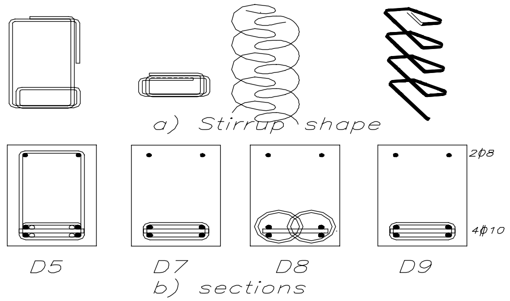

Figure 3. Details of transverse reinforcement.

(Beam D10). The cut off ratio for beams in Group 2 was 100% with no transverse reinforcement in the lap splice zone.

3. Types of transverse reinforcement; Group 3
   Beam D6 included vertical stirrups in the lap splice zone, while vertical stirrups with additional legs in the splice zone were used in Beam D5. Rectangular hoops around the spliced bars were used in Beam D7. Two interlocking spirals were provided in the splice zone in Beam D8. Continuous rectangular stirrups in the lap splice zone were used in beam D9. Beam D4 had no stirrups in the splice zone. All beams of this group had the same lap splice length (27 db) and 100% cut off ratio. The diameter and spacing of transverse reinforcement were 6 mm and 60 mm respectively. The shapes of the used stirrups are demonstrated in figure 3.

4 Stirrups spacing; Group 4
   Three different spacing values of vertical separate stirrups were studied: S = 60 mm (Beam D6), S = 90 mm (Beam D12), and S = 120 mm (Beam D11). Beam D4 had no stirrups.

3.2 *Test procedure and instrumentation*

Figure 1 shows the details of the test rig. The load was applied using a calibrated hydraulic jack of 200 kN capacity. A strong spreader beam was used to transfer the vertical load to the tested beam through two concentrated loads 900 mm apart. Three dial gauges of 0.01 mm accuracy were used to record deflection at the center of the beams as well as under positions of the two loads. For each beam, at least two electrical strain gauges of 5 mm length and were used to measure steel strain. The load is applied in increments equal to 2.5 kN.

4 TEST RESULTS AND DISCUSSIONS

The main obtained results are given in Table 3. The longitudinal steel in all the beams reached the yield strain except for beam D4 where a sudden bond failure occurred. The ratio between the steel strain at the middle to that at the start of the lap splice was almost 0.50. This means that the lap splice worked efficiently along its all length. Figures 4–6 show the crack patterns of some of the tested beams.

Table 3. Main test results.

Beam	Average cube strength; f_{cu} (N/mm^2)	Ultimate load P_u,KN	Deflection at yield load Δ_y,mm	Deflection at ultimate load Δ_u,mm
D1	36.4	80.0	11.42	16.40
D2	36.3	77.5	10.00	18.74
D3	37.3	84.3	14.00	18.00
D4	38.8	52.5	*NY	7.20
D5	38.4	82.5	12.58	17.75
D6	35.4	87.5	9.42	34.00
D7	36.4	85.0	26.00	36.00
D8	34.7	88.0	11.61	47.50
D9	38.7	87.5	11.08	43.00
D10	37.6	87.5	9.32	27.00
D11	36.6	80.0	12.00	20.00
D12	38.0	83.0	11.80	21.00

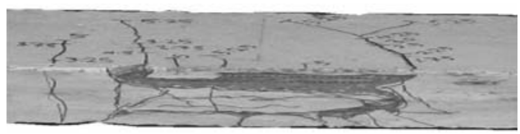

Figure 4. Crack pattern of beam D4 at failure.

Figure 5. Crack pattern at the bottom of beam D5 at failure.

Figure 6. Cracks at bottom and side of beam D8 at failure.

All beams in Group 1 had no stirrups in the lap zone. For beam D2, with 25% cut off ratio, longitudinal splitting cracks under the longitudinal lap spliced bar only began to form between flexural cracks at the bottom of the beam. These cracks became wide with the increase of load until a splitting of the concrete cover from bars occurred at a load of 77.5 kN accompanied by crushing of concrete in compression. For beam D3, with 100% cut off ratio, longitudinal splitting cracks began to form rapidly at the bottom of the beam between flexural cracks. Just after yield of longitudinal spliced bars, splitting cracks became wider, and failure occurred by splitting and loss of bond between spliced bars and concrete at a load of 84.3 kN.

In Group 2, all beams had no stirrups in the lap zone. For beam D4 with a splice length = 27 db, flexural cracks propagated upward to the compression zone. At a load of 50 kN, a horizontal splitting crack along the splice length appeared. and a sudden bond failure occurred at a load of 52.5 kN. For beam D10, with lap splice length = 75 db, the extension of the flexural cracks at lap splice zone in beam D10 was about 0.6 the height of the beam. After the load reached 80 kN, the flexural and flexural shear cracks began to extend upwards with a slow rate. Just before failure, very narrow longitudinal splitting cracks occurred under the two ends of the splice, without a splitting failure. A ductile flexural failure occurred by crushing of concrete in compression nearby the concentrated load at a load of 87.5 kN.

In Group 3, all beams had 100% cut off ratio and length of lap splice = 27db. For beam D5, yield of longitudinal steel occurred at a load of 80 kN. Compared with beam D1, and D4 (without transverse reinforcement), splitting cracks did not appear. After yielding of tension steel, the crack extended upwards, cracks became wider. Failure occurred at a load of 82.5 kN due to crushing of concrete in compression. In beam D6, with vertical stirrups, with load increase, flexural cracks propagated toward the compression zone. Yield of longitudinal steel occurred at a load of 70 kN. At a load of 87.5 kN, a ductile flexural failure took place due to crushing of concrete in compression with no splitting cracks. In beam D7, with rectangular stirrups in the tension splice zone, yield of longitudinal steel occurred at a load of 82.5 kN. Before failure, all cracks extended to be very close to the top surface of the beam and were concentrated around the applied load positions. At a load of 85.0 kN, a ductile failure took place without the occurrence of any longitudinal splitting cracks parallel to the bars. In beam D8, with two interlocking spirals in the splice zone, yield of longitudinal steel occurred at a load of 72.5 kN. Away from the splice zone, almost all the cracks extended to be very close to the top surface of the beam, and the vertical extension of the cracks was slow. No splitting cracks were observed. At a load of 88.0 kN, a ductile failure took place. For beam D9, with rectangular continuous stirrups in the splice zone, yield of longitudinal steel occurred at a load of 72.5 kN. No splitting cracks at the splice zone took place. A ductile flexural failure took place. It is clear that the use of transverse reinforcement eliminated the occurrence of splitting cracks at the splice zone, and changed the mode of failure from bond failure to ductile flexural failure.

In Group 4, the effect of the spacing of the vertical stirrups was studied. For beam D11, with 120 mm stirrups spacing, yield of longitudinal steel occurred at a load of 70.0 kN. Then splitting cracks appeared just prior to failure and after yield. After yielding, cracks extended and became wider, then, a ductile failure took place at a load of 80.0 kN. In beam D12, with 90 mm stirrups spacing, yielding of longitudinal steel occurred at a load of 77.5 kN. Prior to failure, the splitting cracks became wider, and the flexural crack at the start of the splice severely opened just before failure. At a load of 83 kN, the beam failed due to crushing of concrete in compression at the start of the lap splice. The splitting cracks were sufficiently wide but the use of stirrups prevented the occurrence of splitting failure. For beam D6 with 60 mm stirrups spacing, yield of longitudinal steel occurred at a load of 70 kN. At a load of 87.5 kN, a ductile failure took place. Splitting cracks did not appear at all.

4.1 *Effect of cut off ratio (Group 1)*

Figure 7 shows the relationship between load and mid-span deflection for beams D1, D2, and D3. The figure shows that at any level of loading the mid-span deflection of beam D3 (100% cut off ratio) was less than that of beam D1. This may due to the doubling of reinforcement at mid-span section of beam D3. However, the deflection at mid-span of beam D2 (25% cut off ratio) was higher than that of beam D1at any level of load. Beam D2 achieved deflection at ultimate load; Δu, of 114% of that of beam D1, and for beam D3 this ratio was 110%.

The area under the load-deflection curve was calculated to obtain the strain energy achieved by tested beams and was 0.886, 1.003, and 1.062 kN.m for beams D1, D2, and D3 respectively.

4.2 *Effect of lap splice length (Group 2)*

Figure 8 shows the relationship between load and mid-span deflection for the tested beams in this group.

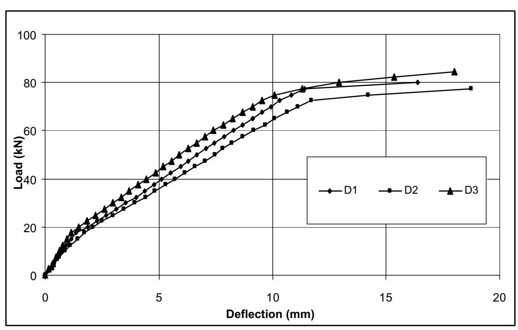

Figure 7. Load deflection curve for Group 1.

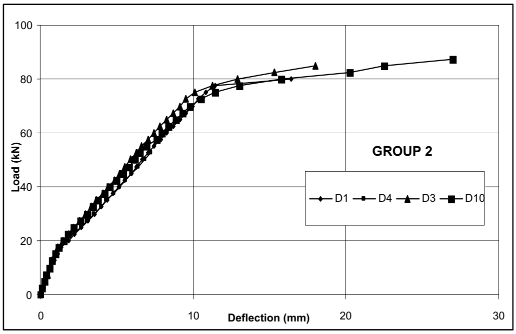

Figure 8. Load deflection curve for Group 2.

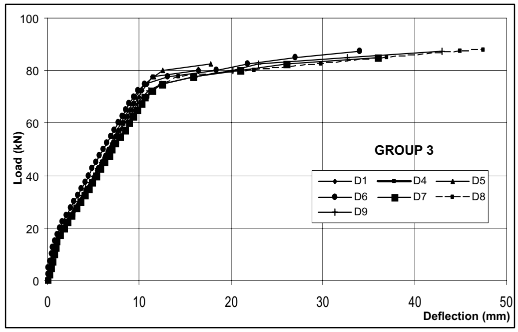

Figure 9. Load deflection curve for Group 3.

Beams D4, D3, and D10 achieved an ultimate load of 66%, 105%, and 109% respectively of that of the reference beam D1. It is clear that beam D4, with a lap splice length of 27 db, did not reach the expected ultimate load. Figure 8 shows that after cracking, beams D1 and D4 showed almost the same behavior up to the sudden failure of beam D4, while beams D3 and D10 showed lower deformation than that of beam D1 at the same loads. After yielding, excessive deformations took place. Beam D1, D4, D3, and D10 achieved maximum deflection at ultimate load of 16.4, 7.2, 18, and 27 mm respectively. These results indicate that the use of lap splice length equals to that recommended by the Egyptian code (54 db), or greater (75 db) increased the maximum deflection at ultimate load. The calculated strain energy for beams D1, D4, D3, and D10 was 0.886, 0.218, 1.062 and 1.796 kN · m respectively. The ratio between the maximum deflection at ultimate load and the deflection at yield load; $\Delta u/\Delta y$, was 1.44, 1.29, and 2.90 for beams D1, D3, and D10 respectively. It is clear that beam D10 was the most ductile beam.

4.3 *Effect of transverse reinforcement (Group 3)*

All beams in this group had transverse reinforcement except beam D4. Figure 9 shows the relationship between ultimate load and mid-span deflection for this group. The ultimate load of beams D4, D5, D6, D7, D8, and D9 was 52.5, 82.5, 87.5, 85, 88, and 87.5 kN respectively. It is clear that spliced beams with transverse reinforcement showed higher ultimate loads comparing with both un-spliced (beam D1), and spliced beam without confinement (beam D4). Beams D5, D6, D7, D8, and D9 achieved 103.1%, 109.4%, 106.3%, 110%, and 109.4% of the ultimate load of the un-spliced beam D1 respectively. This increase in the ultimate load values is mainly due to the use of transverse reinforcement, which eliminated the formation of splitting cracks at the tension splice zone and minimized the width of crack. The use of vertical stirrups (beam D6) or vertical stirrups with additional leg (beam D5) in the splice zone, resulted in small values of mid-span deflections. Beams D7, D8, D9 with special transverse reinforcement in splice zone showed deformation higher than that of the reference beam D1 as well as that of the beams with separate stirrups. Beam D4 suddenly failed at 52.5 kN due to loss of bond strength.

The calculated strain energy for the tested beams of D1, D4, D5, D6, D7, D8, and D9 was 0.886, 0.218, 1.017, 2.393, 2.506, 3.338, and 3.154 kN · m respectively. Spliced beams with transverse reinforcement D5, D6, D7, D8, and D9 achieved 115%, 270%, 283%, 377%, and 356% respectively of that of un-spliced beam D1. From the previous results, it is clear that the use of transverse reinforcement increases the energy absorbed by the beams up to failure. The ratio between the maximum deflection at ultimate load and the deflection at yield load; Δ_u/Δ_y was 1.44, 1.41, 3.61, 1.38, 4.09, and 3.88 for beams D1, D5, D6, D7, D8, and D9 respectively. It is clear that beam D8 had the highest ratio, which indicates that beam D8 was the most ductile beam compared with other tested beams in this group.

4.4 *Group 4: Effect of spacing of stirrups (Group 4)*

Figure 10 shows the relation between load and mid-span deflection for beams D1, D4, D11, D12, and D6. The ultimate load of there beams was 80.0, 52.5, 80.0, 83.0, and 87.5 kN, respectively. The use of stirrups controlled the splitting cracks width at the tension splice zone in beams D11, and D12, and prevented the splitting cracks at the tension splice zone in beam D6. Beam D6 with 60 mm spacing showed the lowest deformation, before cracking. After cracking and before yield, figure 10 emphasizes that the decrease of stirrups spacing decreased the deflection at the working loads. After yielding, the presence of stirrups resulted in an increase in the mid-span deformation at

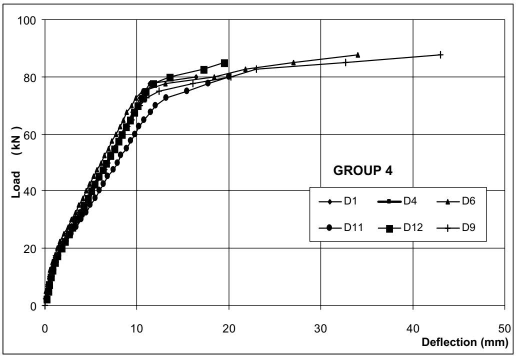

Figure 10. Load deflection curve for Group 4.

the ultimate load. Beams D11, D12, and D6 showed maximum mid-span deflections of 20 mm, 21 mm, and 34 mm, respectively, while beam D1 reached 16.4 mm ultimate deflection. The use of 120 mm, 90 mm, and 60 mm stirrups spacing resulted in an increase in the maximum deflection by 21%, 28%, and 107% of that of the un-spliced beam D1 respectively.

The strain energy achieved by tested beams D1, D4, D11, D12, and D6 was 0.886, 0.218, 1.02, 2.39, 2.51 kN · m, respectively. One can conclude that the use of stirrups enhances the energy observed by the beams up to failure, because the use of stirrups controls the formation of splitting crack in the splice zone. The ratio of the maximum deflection at ultimate load to the deflection at yield load; $\Delta u/\Delta y$, was 1.44, 1.67, 1.78, and 3.61 for beams D1, D11, D12, and D6 respectively. As mentioned before, beam D4 did not reach the yield strength. It is clear that beam D6 with the lowest stirrups spacing had the highest ratio, and consequently the highest ductility. This means that the decrease of stirrups spacing, increases the ability of the beam to absorb energy, and to sustain excessive deformations after yielding.

5 SUMMARY AND CONCLUSIONS

Twelve concrete beams were tested to study the effect of lap splice of tension reinforcement with different splice lengths, cut off ratio, shape of the stirrups and its spacing on the behavior of these beams. From the results of the studied beams, the following conclusions were obtained:

1. The behavior of a beam without any splice can be achieved in a spliced beam with 100% cut off ratio when: $L_o = 27$ db using transverse reinforcement with spacing ≤ 120 mm, or if the lap length ≥ 54 db without transverse reinforcement.
2. The use of a lap splice with 100% cut off ratio, with length of 27 db and without transverse reinforcement resulted in a brittle bond failure.
3. Using transverse reinforcement with lap splice length $= 27$ db, and 100% cut off ratio showed a better behavior than that of the un-spliced beam. Higher ultimate loads and an increase in the ductility were achieved comparing with the un-spliced beam.
4. Although the spacing of stirrups in the splice zone was twice, three times, and four times that recommended by several building codes, an increase in the ultimate strength and ductility were observed.
5. All beams with transverse reinforcement showed large values of deflection at ultimate load. These values ranged from two to three times that of the un-spliced beam.

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