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Effect of bond loss of tension reinforcement on the flexural behaviour of reinforced concrete beams

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KEYWORDS

Beams;
Reinforced concrete;
Bond loss;
Flexure;
Ultimate load;
Deflection

Abstract An experimental programme has been conducted in order to investigate the flexural behaviour of concrete beams with variable un-bonded length of tension reinforcement. A test series of six simple beams containing different nominal length without bond close to the support had been conducted in this investigation. The tested beams are of 2250 mm total span loaded at the middle third with two equal concentrated loads. The bond loss had been introduced with plastic tubes surrounding the longitudinal tension reinforcement leaving short bonded lengths over supports and at positions of stirrups crossing the longitudinal reinforcement. The effect of reinforcement bond loss on the response, cracking load, crack propagation, deflection, ultimate capacity, reinforcement strain at mid span and mode of failure of beams is examined in this paper. The cracking load, number of cracks in the flexural zone, and the crack width are affected significantly with increasing the area of bond loss. On the other hand, the reduction in the ultimate load capacity is surprisingly low even with 73% loss of bond. This refers to the creation of high bond forces at the small bonding areas at the crossing stirrups which compensates the high bonding loss in the longitudinal bars between stirrups.

Introduction

The bond between the reinforcing steel and surrounding concrete depends primarily on the contact area, the surface texture of reinforcing bars, bar diameter and concrete cover. Therefore, it is expected that the shape, location, length, width and propagation of cracks as well as the load carrying capacity be affected by the un-bonded length of tensile reinforcement. This un-bonded length may be caused by construction errors. Honeycombed concrete resulting from bad compaction and the use of dry and rough formwork could remove the concrete cover. Washout also affects the bond properties of reinforcing steel bars embedded in underwater concrete [1]. Over and above, bond-loss is closely related to deterioration of structure. Corrosion of reinforcement, internal frost damage, and alkali-silica reaction are three deterioration mechanisms that have a negative influence on bond between concrete and reinforcement. Investigations had been conducted to explain the flexural strength, shear strength, and bond as function of corrosion

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intensity [2–8]. Different studies had been performed by researchers to evaluate the effect of different degrees of reinforcement corrosion on the bond degradation using the pull-out test [6,9]. Review of literature showed that limited work on un-bonded length of reinforced concrete beams has been carried out. Nevertheless there are many studies on un-bonded post tension tendons prestressed beams [10–15].

The purpose of this research is to study the effect of the unbounded length of tensile reinforcement on the behaviour and reduction of flexural capacity of concrete beams. The loss of bond had been artificially introduced in the longitudinal reinforcement close to the supports and with varied length. The objective of this paper was to provide better understanding of the influence of loss of bond along the longitudinal tension reinforcement on the flexural behaviour of beams.

Experimental programme

A test series of six beams had been designed in order to investigate the influence of bond loss along the longitudinal reinforcement close to the support, on the behaviour of this series under flexural static loading. The unbounded length was accurately created using a plastic tube with inner diameter slightly larger than the longitudinal reinforcement surrounded by these tubes. The ends of the plastic tubes were sealed with silicon and also surrounded with plastic tape. This method was chosen to simulate the unbounded length due to corrosion. One reference beam (B_0) was reinforced with two full bonded longitudinal bars at the bottom and without stirrups in order to examine the failure mode when compared with another reference beam with stirrups (B_1). The dimensions of the tested beams were 2250 mm length × 200 mm height × 120 mm width. The six tested beams were simply supported and loaded with two equal point loads at the middle third of the span. The bottom longitudinal reinforcement was 2Φ16 and the upper was 2Φ10 with 15Ø6/2100 stirrups as shown in Fig. 1a. For beams with stirrups the unbounded length varied from two spaces between stirrups close to each support, as in beam B_2 to six spaces, beam B_4. The bond is available at all intersections between stirrups and longitudinal reinforcement (~20 mm), Fig. 1b. The bottom reinforcement in all beams studied was straight except in beam B_5 where it had 90° hook at the end in order to develop better anchorage of the longitudinal bars as shown in Fig. 2.

Material and concrete proportions

Portland cement (CEM I 42,5N) was used in preparing the concrete mix of this programme. The fine aggregate used was natural siliceous sand with a fineness modulus of 2.6, specific gravity 2.63 and unit weight of 1750 kg/m^3, and the coarse aggregate was gravel of two sizes 10 mm and 20 mm. The grading of aggregates satisfied the requirements of the Egyptian specifications [16]. The superplasticizer used was the sulphated naphthalene formaldehyde condensate type. The used silica fume (SF) contains silica (SiO_2) of 95% and was of 20% of cement weight. The concrete mix chosen for casting the test beams was designed to be high strength concrete and its proportions are presented in Table 1. The compressive strength (f_{cu}) was tested for 150 mm cubes, the tensile strength (f_{sp}) was determined from splitting tension tests of 150 mm × 300 mm cylinders and the bond strength (f_b) was calculated from pull out tests on cylinders of 150 mm × 300 mm size with central ribbed bars of 16 mm diameter. In all cases at least six specimens were used. The following mean values were obtained: $f_{cu} = 67.32$ MPa, $f_{sp} = 4.53$ MPa, and $f_b = 8.97$ MPa, Table 1.

For the reinforcement, three specimens were tested for every bar diameter. The longitudinal reinforcement in tension consisted of two ribbed bars with diameter 16 mm at the bottom of the beam, with an average yield strength $f_y = 498$ MPa. The longitudinal compression reinforcement at the top of the beam consisted of two ribbed bars of 10 mm diameter, with an average yield strength of 427 MPa. Plain round bars of 6 mm diameter were used as stirrups with spacing 150 mm and with average yield strength of 300 MPa.

Specimen preparation and test procedure

Six steel moulds were used for casting the specimens; they were stiff enough to prevent any significant movement during

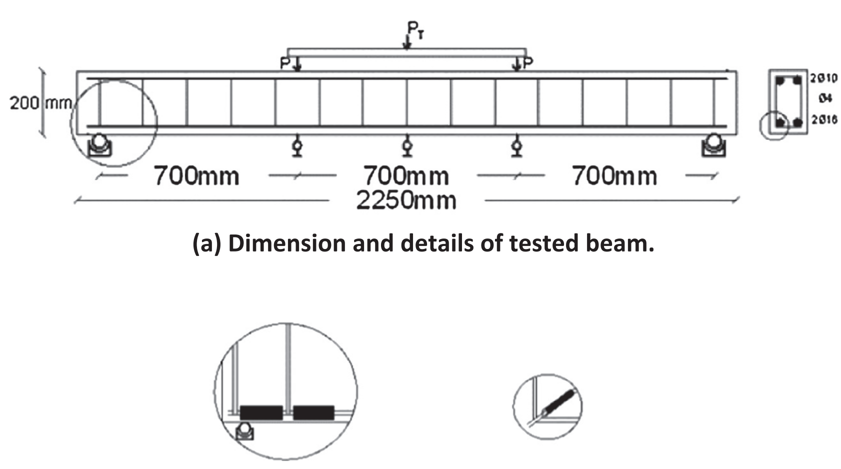

Fig. 1 Concrete dimensions and details of tested beam and un-bonded zone.

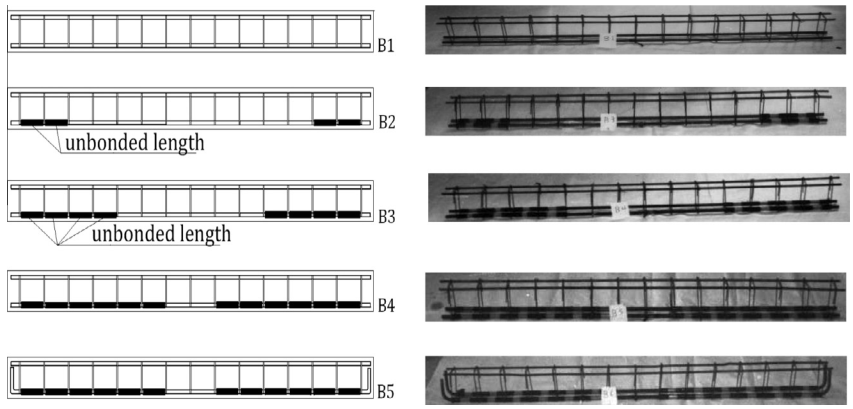

Fig. 2 Pictures showing the details of the un-bonded zones for different beams.

Table 1 Concrete mix proportion and its properties.

Mix proportion (kg/m^3)						
Cement content	Sand content	Gravel content		Water content (water/binder)	Silica fume	Superplasticizer (SP%)
		Size 5:10 mm	Size 10:20 mm			
500	604	374	748	132(0.22)	100	15 (2.5%)

Mix properties			
Slump (mm)	Comp. strength f_{cu} (MPa)	Split. tens. strength. f_{sp} (MPa)	Bond strength f_b (MPa)
110	67.32	4.53	8.97

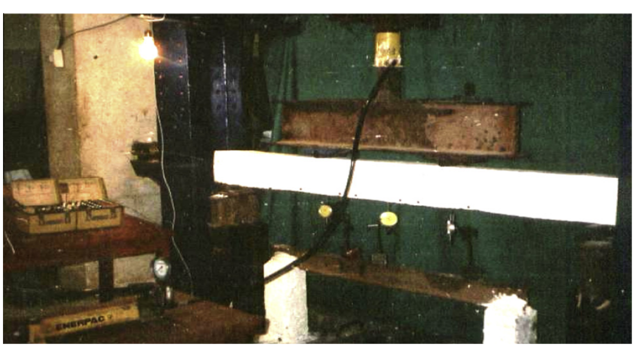

Fig. 3 Test set-up.

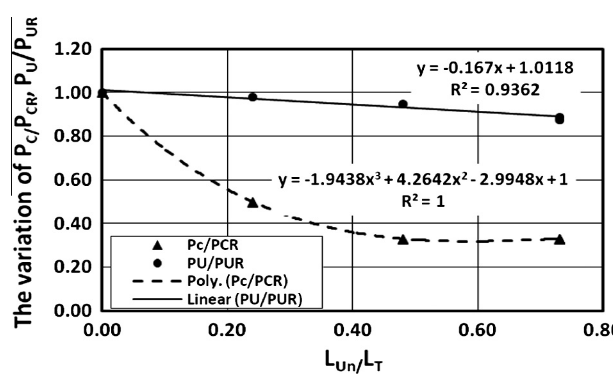

Fig. 4 The variation of P_C/P_{CR}, P_U/P_{UR} ver. L_{Un}/L_T.

Table 2 Comparison of ultimate load (P_u) to cracking load (P_C).

Beam No.	P_U (kN)	P_C (kN)	P_U/P_{UR}	P_C/P_{CR}	[a]L_{UN}/[b]L_T
B_0	55.0	10.5	0.920	0.70	0.00
B_1 (Ref.)	60.0	15.0	1.000	1.00	0.00
B_2	57.5	7.5	0.960	0.50	0.24
B_3	57.0	5.0	0.950	0.33	0.48
B_4	52.5	5.0	0.875	0.33	0.73
B_5	53.5	5.0	0.892	0.33	0.73

[a] L_{UN} = Un-bonded length.
[b] L_T = Total length of steel bar between the supports.

placing the concrete. The internal dimensions of the moulds were 120 mm × 200 mm × 2500 mm. Before casting the specimens, electrical resistance strain gages (with 120 Ohm resistance) were installed to measure the strain at the middle of the two longitudinal tension bars. The strain gages were fixed on the steel bars using special glue and then covered with a water proofing material for protection. Concrete mix was cast in the moulds then compacted using a vibrating table. The cast specimens were exposed to identical curing conditions: they were stored in the laboratory, then de-moulded after 24 h and covered with wet burlap at room temperature for 28 days.

The six beams were tested under static load applied at the two-third points of the beams. A hydraulic jack was used to apply the static load with an increment of 10 kN. The load

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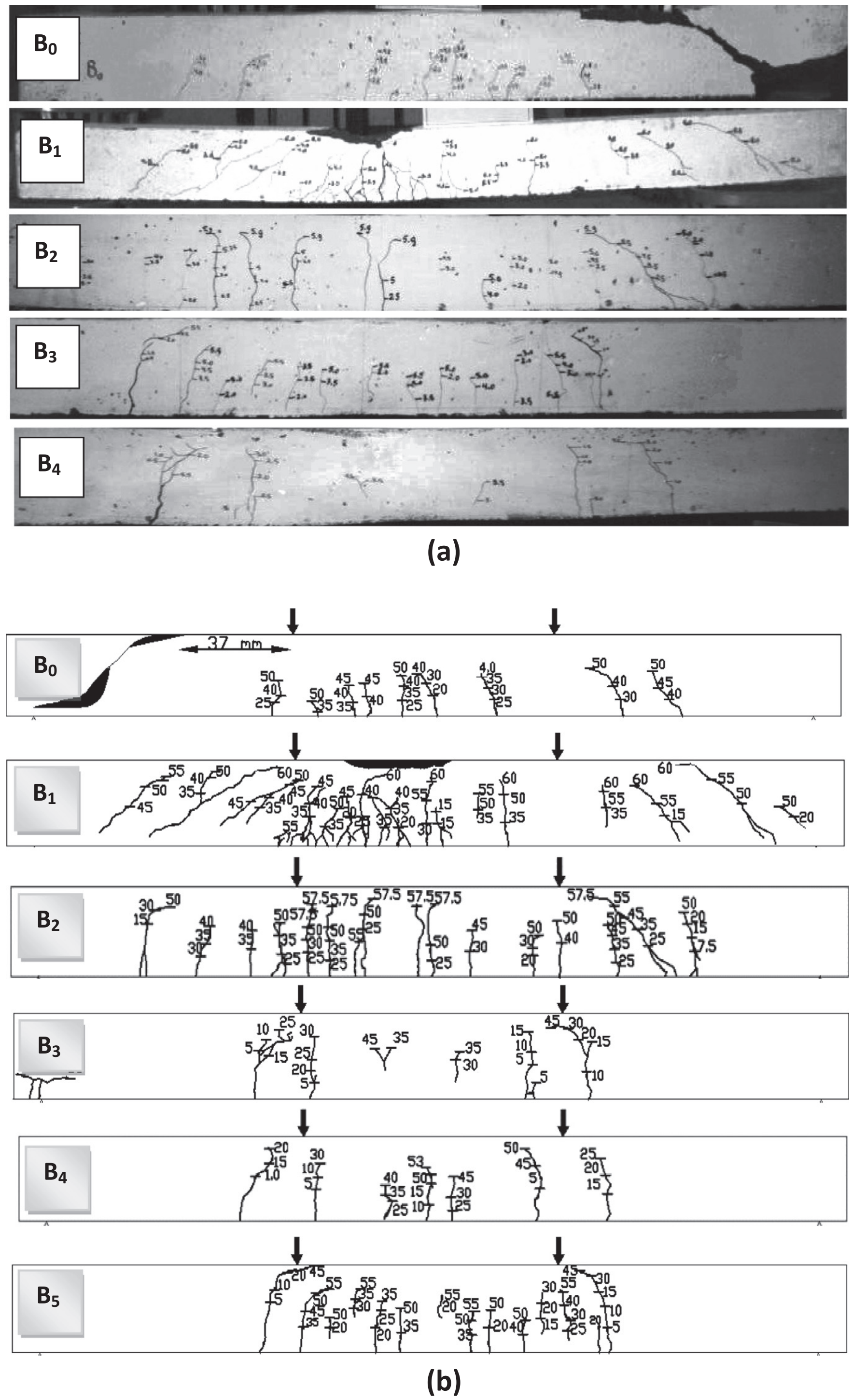

Fig. 5 The crack pattern of different beams.

was kept constant for about fifteen minutes during each increment while the readings were being recorded. The test was terminated when the compression zone in concrete was damaged or when the load falls to zero. Fig. 3 shows the general arrangement of the test set-up for all beams.

The deflection at the middle and one-third of the span of the beams was measured using three dial gages with 0.01 mm accuracy. The width of the most obvious crack was recorded, and measured using a crack-width comparator.

Test results and discussion

Cracking and failure load

The cracking load was affected sharply in the beams with bond loss compared to the reference beam. The cracking load (P_C) reduced by about 50% in the beam with 24% bond loss of its length and the reduction increased up to 67% in the beam

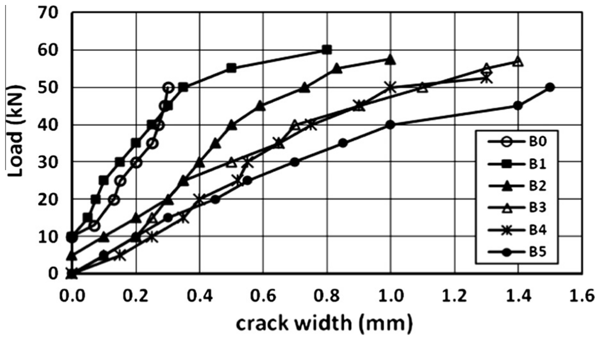

Fig. 6 Load-crack width relationship.

with about 73% bond loss compared to the cracking load of the reference beam (P_{CR}) as given in Table 2. On the other hand, the reduction in the load carrying capacity was surprisingly much less [12], approximately 13%, considering that almost 73% of the available bond length is removed, Table 2. The presence of anchor at the end of the tension reinforcement, with 73% bond loss (B_5), did not improve the cracking load (67% reduction), but the failure load improved slightly (2% increase) compared with the similar beam without anchor (B_4).

Fig. 4 shows the relation between the beam cracking load to the reference cracking load (P_C/P_{CR}) and the beam ultimate load to the reference ultimate load (P_U/P_{UR}) relative to un-bonded length to the total length of steel bar (L_{UN}/L_T), respectively. Regarding the effect of transverse stirrups, it can be noticed by comparing the results of beam B_0 without stirrups to that of beam B_1 with stirrups; the cracking and the ultimate load of B_0 represents about 70% and 92%, respectively, to that of B_1.

Crack propagation

The crack patterns of all studied beams are shown in Fig. 5. Beam B_0 failed in shear as expected since it was reinforced with flexural reinforcement only. The main shear crack initiated at about 370 mm far from the load and ran inclined towards the support of the beam. Thus, the failure mode of beam B_0 was very brittle failure (shear failure), while the other beams did not exhibit brittle failure even those with high loss of bond (B_4, B_5). The reference beam B_1, experienced around eighteen

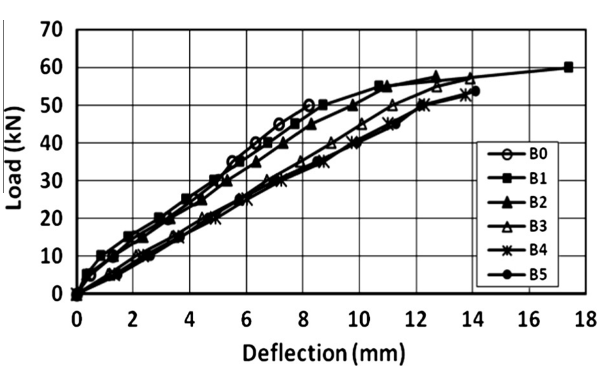

Fig. 7 Load and mid-span deflection relationship.

flexural cracks accompanied with concrete crushing in the compression zone as shown in Fig. 5. Regarding the loss of bond of beams, it was observed that the cracks reduced in number as the length of un-bond increased. The cracks started close to the ends of bond loss and spread along the bond length of reinforcement. The reason for this behaviour may be attributed to the concentration of stress where the concrete starts to transfer strains to the reinforcement in bonded zone. Only six cracks (main and secondary) appeared in the beam with 73% bond loss (B_4).

From the relation between crack width and load for all beams shown in Fig. 6, it is obvious that, the crack width increased as the un-bonded length of tension reinforcement increased. In the bonded zone, the behaviour indicates that the cracking is expected to occur when the induced tensile stress in concrete reached its ultimate tensile strength. At the cracking stage, due to the loss of the tensile stresses in the concrete at the crack position, the concrete tensile stresses are transmitted to the reinforcement through the bond developed between the concrete and the reinforcement. Thereafter at the crack location, the reinforcement is carrying additional tensile forces released by the cracked concrete. Therefore, a sudden increase in the reinforcement elongation takes place and consequently leads to high width cracking formation. At service load level (which is considered approximately 50% of ultimate load of the reference beam $P_S \sim 30$ kN) the crack width increased by 5.5 times for beam with un-bonded length 73% (B_4) compared to the crack width of the reference beam.

Load–deflection relation

Fig. 7 shows the load deflection relation of all beams including the reference beam. From the figure, it is obvious that the loss of bond by about 24% (B_2) relatively does not change the behaviour at the beginning but afterwards the stiffness is slightly reduced (slope of the load deflection curve). At ultimate load, the deflection decreased to reach about 73% of the reference beam. The beams with bond loss 48–73% (B_3–B_5) exhibited almost linear relation of load–deflection with a much reduction of stiffness in comparison with the reference beam with full bond, Table 3. At the service load (~30 kN), the deflection increased with increasing the bond loss length and recorded 50% increase in the beam with 73% bond loss (B_4) and 45% increase in the beam with 73% bond loss and hooked at the ends of the tension reinforcement (B_5) compared to the reference beam, while, the ultimate deflection of these beams was markedly reduced compared to the reference beam, about 79% and 81% for B_4 and B_5, respectively, reflecting a reduction in the beams ductility.

On the other hand, the deflection at service load of B_5 was reduced with 3.2% only compared to beam B_4 with straight ends while the deflection increased with about 2.5% at ultimate load showing a limited increase in ductility. Generally, the minor increase in the stiffness and in ductility of B_5 can be attributed to the presence of hooks. In spite of relatively similar stiffness of beams B_0 and B_1 (Table 3), the deflection of B_1 with respect to B_0 was about 2.12 times at ultimate load. This observation reflects a higher ductility of B_1 due to the contribution of transverse stirrup in increasing the bond strength. The variations of the deflection corresponding to service load for all studied beams and the stiffness (initial slope of load–deflection curve) in comparison with the reference

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Table 3 Variation of different measurements relative to the reference beam.

Beam No.	Deflection (D)[a]		Strain of steel bar (ε_S)[a]		Crack width (C_W)[a]		Stiffness ratio
	D_S (mm)	(D_S/D_{SR})	$\varepsilon_S \times 10^3$	$(\varepsilon_S/\varepsilon_{SR})$	C_W (mm)	(C_W/C_{WR})	(S/S_R)
B_0	4.99	1.03	1.270	0.82	0.20	2.0	0.98
B_1(Ref.)	4.83	1.00	1.545	1.00	0.10	0.0	1.00
B_2	5.31	1.10	1.265	0.82	0.40	4.0	0.96
B_3	6.71	1.39	1.356	0.88	0.50	5.0	0.84
B_4	7.23	1.50	1.230	0.80	0.55	5.5	0.78
B_5	7.00	1.45	1.835	1.19	0.70	7.0	0.79

R: refer to the reference beam.
[a] The value at service load.

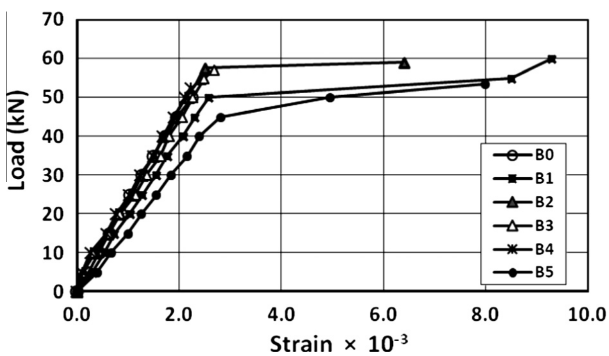

Fig. 8 Load-tension reinforcement strain relationship.

beam are listed in Table 3. The maximum reduction in stiffness was about 22% for the beam with 73% loss in bond (B_4).

Steel strain of the main steel

The tension steel of B_3 and B_4 did not reach the yield strain while in B_1, B_2, and B_5 the main bars yielded sufficiently, more than twice the yield strain. At service load the strain of the beam with un-bonded length of 73% (B_4) was reduced by about 20% relative to that of the reference beam (B_1), Table 3. On the other hand, in the beam with 73% un-bonded length and anchor at main steel ends (B_5), the strain increased by about 50% compared to the beam without anchor at the ends (B_4) and arrived to about 86% of the reference beam at ultimate load.

Fig. 8 illustrates the relationship between the applied load and the corresponding strain in the main steel of the tested beams at the mid-span. Increasing the un-bonded length of the main reinforcement, leads to a reduction in the flexural capacity of the beam which consequently causes a redistribution of internal stresses; hence, the recorded strain at mid-span of steel is reduced.

Conclusions

An experimental investigation was conducted in order to study the behaviour of reinforced concrete beams with different degrees of bond loss in the longitudinal tension reinforcement. The results were compared with their reference beam with full bond along the tension steel. From the results presented and discussed in this paper, the following conclusions can be drawn.

1. The cracking load was significantly reduced with about 50% in the beam with 24% un-bonded length in comparison with the reference beam. This reduction increased to 67% when the un-bonded length increased to 73%.
2. A moderate reduction in the load carrying capacity was observed even in beams with significant bond loss; the reduction was only about 13% in the beam with 73% bond loss of length. This observation may be attributed to the presence of small areas of bond of the crossing stirrups which compensates for the loss of bond and creates high bond forces.
3. The predominant mode of failure of tested beams is flexural failure except in the beam without stirrups, which exhibited shear failure. The cracks, to a large extent, appeared only in the bonded zone of the tension reinforcement.
4. Generally, increasing the un-bonded length along the tensile steel reinforcement reduces the number of cracks and at the same time increases the width of cracks.
5. The deflection of beams with loss of bond is in general higher than that of the reference beam with full bond at the same load reflecting lower stiffness. With increasing the degree of bond loss, the deflection of beams increased; the loss of bond by about 73% increased the deflection by 50% at service load compared to the reference beam. All the beams with bond-loss showed lower ductility than the reference beam (the ultimate deflection decreased).
6. The mid-span strain of the main steel decreased for the beams with un-bonded length compared to the beam with full bond. The exception was in the beam with anchor at its ends which showed significant strain increase in comparison with the beam without anchor (2.3 times) and was about 93% of the reference beam with full bond.
7. The comparison of the findings of the beam B_0 (without stirrups) and B_1 (with stirrups) produces the important role of the transverse stirrups in achieving flexural and ductile failure of B_1 instead of shear failure of B_0. The significant increase in cracking load, ultimate load, ultimate deflection, and tension steel strain, besides smaller crack width of B_1 relative to B_0 is due to the increase in bond strength due to the attribution of the stirrups.

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References

[1] J.A. Joseph, A.I. Camille, Effect of washout Loss on bond behaviour of steel embedded in underwater concrete, ACI Struct. J. 110 (3) (2013) 511–519.

[2] P.S. Mangat, M.S. Elgarf, Flexural strength of concrete beams with corroding reinforcement, ACI Struct. J. 96 (1999) 149–158.

[3] Y. Haken, E. Oygur, S. Serhan, An experimental study on the bond strength between reinforcement bars and concrete cover, strength and corrosion levels, Cem. Concr. Res. 34 (11) (2012) 2159–2167.

[4] C. Fang, K. Lundgren, L. Chen, C. Zhu, Corrosion influence on bond in reinforced concrete, Cem. Concr. Res. 34 (11) (2004) 2159–2167.

[5] L. Chung, J.-H.j. Kim, S.-T. Yi, Bond strength predication for reinforced concrete members with highly corroded reinforcement bars, Cem. Concr. Compos. 30 (7) (2008) 606–611.

[6] C. Fang, K. Lundgren, M. Plos, K. Gylltoft, Bond behaviour of corroded reinforcing steel bars in concrete, Cem. Concr. Rese. 36 (10) (2006) 1931–1938.

[7] A.A. Almusallan, A.S. Al-Gahtani, A.R. Aziz, Rasheeduzzafar. Effect of reinforcement corrosion on bond strength, Constr. Build. Mater. 10 (2) (1996) 123–129.

[8] L. Amleh, S. Mirya, Corrosion influence on bond between steel and concrete, ACI Struct. J. 96 (3) (1999) 415–423.

[9] F. Li, Y. Yuan, Effects of corrosion on bond behaviour between steel strand and concrete, Constr. Build. Mater. 38 (2013) 413–422.

[10] D. Coronelli, Corrosion cracking and bond strength modelling for corroded bars in reinforced concrete, ACI Struc. J. 99 (3) (2002) 267–276.

[11] H.S. Lee, T. Noguchi, F. Tomosawa, Evaluation of the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion, Cem. Concr. Res. 32 (2002) 1313–1318.

[12] J. Joakim, T. Sven, Behaviour of reinforced concrete beams with loss of bond at longitudinal reinforcement, ASCE Struct. J. 129 (10) (2003) 1376–1383.

[13] J. Yamazaki, B.T. Kattula, A.H. Mahock, Comparative study of prestressed concrete beams, with and without bond, ACI. Proc. 68 (1971) 116–125.

[14] P.R. Chakrabati, T.P. Whang, W. Brown, K.M. Arsad, E. Amezeua, Unbonded post-tensioning tendons and partially prestressed beams, ACI Struct. J. 91 (5) (1994) 616–625.

[15] I.M. Zaki, H.R. Sami, R.Z. Ezz–Eldin, Transfer and development lengths of carbon fibre reinforced polymers presstressing reinforcement, ACI J. 96 (4) (1999) 594–602.

[16] E.S.S. 1109/2008, 2008, Egyptian Standard Specification for Aggregates, Egypt.

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