Shear strength of reinforced high strength concrete beams with and without end anchorage: experimental study

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This paper presents results from an extensive experimental study including the fabrication, instrumentation, and testing to failure thirty-two simply supported reinforced concrete beams. Eight beams were made from normal-strength concrete whereas twenty-four beams were made from high-strength concrete. The main objective of the study was to investigate the behavior and shear strength of reinforced concrete beams provided or not provided with end anchorage. The effect of other significant parameters were also considered such as: concrete strength, shear span-to-depth ratio, the presence of vertical stirrups; and the presence of short columns at beam ends. Beam deflections were measured at three locations. Longitudinal steel strain and vertical stirrups strain were measured and recorded. The initiation and propagation of cracks was recorded and cracking patterns and failure modes were observed. Test results revealed that the behavior of tested beams was seriously affected by the presence of end anchorage. Also, the effects of concrete strength, shear span-to-depth ratio, and the presence of vertical stirrups significantly affected the behavior and shear strength of tested beams. Finally, the experimental results for the ultimate shear failure loads of tested beams were compared to the theoretical ones from some international codes of practice and other available equations found in the literature. The examined codes were: the Egyptian code; the ACI code; the British Standards; the Japanese code; and the Canadian code. The comparisons revealed that some of these equations such as those presented by the Egyptian code are reliable in predicting the ultimate shear strength for normal-strength and high-strength reinforced concrete beams.

يقدم هذا البحث نتائج من دراسة معملية مكثفة تضمنت صب وتجهيز وإختبار إثنين وثلاثين كمرة خرسانية مسلحة بسيطة الإرتكاز. تم صب ثمانية كمرات بإستخدام خرسانة عادية المقاومة فى حين أنه تم صب أربعة وعشرون كمرة بإستخدام خرسانة عالية المقاومة. كان الهدف الرئيسى من هذه الدراسة هو التعرف على سلوك وإجهاد القص للكمرات الخرسانية المسلحة المزودة أو الغيرمزودة برباط طرفى. تم دراسة تأثير عوامل هامة أخرى مثل: إجهاد الخرسانة، نسبة بحر القص إلى العمق، وجود كانات رأسيه، و وجود أعمده قصيره عند أطراف الكمره. تم قياس سهم الإنحناء الرأسى للكمرات المختبره عند ثلاث أماكن و كذلك تم قياس الإنفعال فى صلب التسليح الطولى وكذلك الكانات الرأسية. تم ملاحظة بداية ظهور الشروخ فى الكمرات وتم تتبع تطورها، كذلك تم ملاحظة شكل الشروخ وشكل الإنهيار لجميع الكمرات المختبرة. أوضحت النتائج المعملية أن سلوك الكمرات المختبرة قد تأثر تأثراً كبيراً بوجود رباط طرفى، كذلك كان تأثير باقى العوامل التي شملها البحث كبيراً مثل: إجهاد الخرسانة، نسبة بحر القص إلى العمق، وجود كانات رأسية، ووجود أعمدة قصيرة عند أطراف الكمرات. أخيراً تم مقارنة النتائج المعملية لحمل القص الأقصى للكمرات المختبرة للنتائج النظرية من المعادلات الموجودة فى بعض الأكواد وكذلك بعض المعادلات الموجودة فى المراجع. تم فحص المعادلات الموجوده في ألاكواد التاليه: الكود المصري، الكود الأمريكي، الكود البريطاني، الكود الياباني، و الكود الكندي. أوضحت المقارنة أن بعض هذه المعادلات مثل تلك الموجوده في الكود المصري تعطى نتائج مقبولة لاجهاد القص للكمرات ذات الخرسانة عادية المقاومة أو الخرسانة عالية المقاومة.

Keywords: Beams, Codes of practice, End anchorage, High-strength, Shear, Reinforced concrete

1. Introduction

In recent years, there has been rapid growth in the use of high-strength concrete. Furthermore, the strength level of commercially available high-strength concrete is being increased. Since the mechanical properties of concrete changes as the compressive strength of concrete increases, therefore additional information is necessary to understand the structural behavior of high-strength concrete members such as beams. Several experimental investigations studied the behavior and shear strength of high-strength concrete beams [1 to 15]. Some of the observations drawn from these studies are: (i) the ACI code

[16] equation is seriously un-conservative for high-strength concrete beams without stirrups but is conservative for high-strength concrete beams with stirrups; (ii) the redistribution of forces at diagonal tension cracking in high-strength concrete beams can result in substantial reductions in the reserve and excess shear strength; (iii) stirrups rupture would stop any further redistribution of forces and could result in a diminished reserve capacity; (iv) the ACI code [16] minimum requirement for web reinforcement should be increased in the case of high-strength concrete beams; and (v) the British Standards [17] equations for shear strength well predicts the capacity of high-strength concrete beams.

1.1. Reinforced concrete beams without stirrups

In RC beams without shear reinforcement under two point loads or one point load, the critical crack typically involves two branches [18]. The first branch is a slightly inclined shear crack, the height of which is approximately that of the flexural crack. The second branch initiates from the tip of the first branch and propagates towards the load point crossing the compression zone, with its line meeting the support point. Failure occurs by formation of this second branch. The second branch of the critical diagonal crack is caused due to a type of splitting of concrete in the compressive zone, according to which the stress distribution along the line of splitting is not similar to the one occurring in the common split cylinder test.

1.2. Reinforced concrete beams with stirrups

The pattern of cracking of RC beams with stirrups is similar to that of RC beams without stirrups [18]. The critical crack, in both cases of beams, typically involves two branches, which are formed in the same region of beams. It is rational to consider that the cause of formation of the second branch of the critical diagonal crack as well as the corresponding cracking load is identical in both cases. Up to the formation of the second branch of the critical crack, the effect of stirrups can be considered negligible.

The normal stresses along the line of the second branch compose a group of forces in self-equilibrium that is forces not balancing any external load. This implies that, by cracking of the second branch, the concrete shear force in the compression zone above the beginning of the second branch is equal to that at the end of the second branch. The same also occurs for the concrete compression force. The normal force and the shear force of the longitudinal steel bars are also depicted. These two forces of the main reinforcement (together with the force of stirrups are the only forces acting on the faces of the first branch of the critical crack, as the opening of this branch is orthogonal (perpendicular to its direction). By the cracking of the second branch of the critical crack the stirrups are brought into action. The gradual opening of the second branch, from the tip of the first branch towards the load point, requires a gradual increase of the concrete shear force at the beginning of the second branch to balance the developed force of stirrups. The concrete shear force at the end of the second branch remains unchanged.

1.3. End anchorage of tension reinforcement in reinforced high strength concrete beams

Although the end anchorage of tension reinforcement seriously affects the structural behavior of reinforced concrete beams, however no research efforts were directed towards the study of such anchorage in reinforced high-strength concrete beams. It is important to provide reserve strength in the end anchorage length in order to maintain beam ductility since failure in end anchorage is brittle. It is also important to study the end anchorage at the beam end supports since at this region the bending moment is equal to zero whereas the shearing force is high.

1.4. The current research

In this paper the shear strength and behavior of reinforced high-strength concrete beams are studied. An experimental program was conducted including the fabrication, instrumentation, and testing of thirty-two simply supported RC beams under the effect of one concentrated load. The parameters studied included: the shear span-to-depth ratio, the concrete compressive strength, the presence of vertical stirrups, the presence of short columns at beam ends and the presence of end anchorage. Also, the experimental results for shear strength of tested simply supported beams were compared to the theoretical results from the equations found in some international codes of practice regarding the estimation of shear strength of reinforced concrete beams.

2. Experimental program

The objective of the current experimental work was to study the behavior of reinforced high-strength concrete beams with and without end anchorage and subjected to one concentrated load. The experimental program included casting, instrumentation, and testing thirty-two simply supported beams. Twenty-four beams were made with high-strength concrete. All tested beams had rectangular cross-section. The span length was kept the same for all tested beams. For comparison, eight reinforced normal-strength concrete beams, were also tested. Such beams had the same dimensions as tested high-strength concrete beams. The structural behavior of tested beams were observed through observing deflections, concrete cracking, strains in longitudinal steel reinforcement and vertical stirrups, mode of failure and the ultimate failure loads of such beams.

2.1. Details of tested beams

The experimental study involved testing twenty-four simply supported reinforced high strength concrete beams and eight reinforced normal-strength concrete beams. The beams were subjected to monotonic concentrated load applied at the top surface of each beam. All beams had a rectangular cross-sections with dimensions of 120 mm width and 260 mm height. The beams were simply supported with span length of 2600 mm. All beams had the same longitudinal reinforcement ratio of 0.82%. The main parameters studied in the experimental program were: (i) concrete strength; (ii)shear span-to-depth ratio (a/d); (iii) the presence of vertical stirrups; (iv) the presence of end anchorage; and (v) the presence of short columns at the beam ends. Therefore, the test program consisted of five groups of RC beams as follows:

Group (N) consisted of eight beams; namely S1 to S8. The aim of this group was to study the effect of the presence of end anchorage and shear span-to-depth ratio (a/d) on the behavior of reinforced normal-strength concrete beams. It should be noted that all beams included in this group were provided with vertical stirrups and short columns at the beam ends.

Group (H1) consisted of eight beams, namely SH1 to SH8. The aim of this group was to study the effect of the presence of end anchorage and shear span-to-depth ratio (a/d) on the behavior of reinforced high-strength concrete beams without vertical stirrups. It should be noted that all tested beams included in this group were provided with short columns at beam ends.

Group (H2) consisted of eight beams, namely SH9 to SH16. The aim of this group was to study the effect of the presence of end anchorage and shear span-to-depth ratio on the behavior of reinforced high-strength concrete beams provided with vertical stirrups. It should be noted that all beams in this group were provided with short columns at beam ends. It should be also noted that comparing the results of testing high-strength concrete beams in group (H2) to those of testing normal-strength concrete beams in group (N) shall reveal the effect of concrete strength in the behavior of simply supported reinforced concrete beams. Also, comparing the results of testing high-strength concrete beams in group (H2) having vertical stirrups to those of testing high-strength concrete beams in group (H1) without vertical stirrups shall reveal the effect of the presence of vertical stirrups on the behavior of reinforced high-strength concrete beams.

Group (H3) consisted of four beams, namely SH17 to SH20. The aim of this group was to study the effect of the presence of end anchorage and shear span-to-depth ratio on the behavior of reinforced high-strength concrete beams without vertical stirrups and without short columns at beam ends. It should be noted that comparing the results of testing high-strength concrete beams in group (H3) without short columns at beam ends to those of testing high- strength concrete beams in group (H1) having short columns at beam ends shall reveal the effect of the presence of short columns at beam ends on the behavior of reinforced high- strength concrete beams without vertical stirrups.

Group (H4) consisted of four beams, namely SH21 to SH24. The aim of this group was to study the effect of the presence of end anchorage and shear span-to-depth ratio on the behavior of reinforced high-strength concrete beams provided with vertical stirrups but without short column at beam ends. It should be noted that comparing the results of testing high- strength concrete beams in group (H4) without short columns at beam ends to those of testing high-strength concrete beams in group (H2) having short columns at beam ends shall reveal the effect of the presence of short columns at beam ends on the behavior of reinforced high- strength concrete beams provided with vertical stirrups. The dimensions and reinforcement details for all tested beams are shown in table 1 and figs.1 and 2.

2.2. Materials

Two concrete mixes were used throughout the experimental study. The first concrete mix consisted of Ordinary Portland Cement, sand, and crushed stone with 19 mm maximum nominal size. The mix proportions by weight were 2.8: 1.6: 1.0 and the water cement ratio (w/c) was 0.4. Such concrete mix was used for casting normal-strength concrete beams. The second concrete mix consisted of Ordinary Portland Cement, locally available natural desert sand, and crushed stone with 10 mm maximum nominal size. The mix proportions by weight were 2.2: 1.6: 1.0 and the water cement ratio (w/c) was 0.25. Silica fume was added to replace 10% of cement weight in order to increase concrete strength. A commercially available super-plastisizer (water-reducing agent) was used to increase workability. Such concrete mix was used for casting high-strength concrete beams. For each two beams, standard control specimens consisted of three 150 mm cubes and three 150 x 300 mm cylinders were cast. The concrete was mixed and compacted mechanically. The steel used for bottom main longitudinal reinforcement was high tensile steel bars. The average yield stress was 400 N/mm^2 and the average ultimate stress was 600 N/mm^2. The steel used for the upper longitudinal reinforcement and the vertical stirrups was ordinary mild steel bars with an average yield stress of 240 N/mm^2 and an average ultimate stress of 350 N/mm^2.

2.3. Instrumentation and test procedure

The assigned concentrated load was applied to the beams by means of a 200 kN capacity hydraulic jack. The load was monitored through a calibrated load cell. The load was applied to the beam through rolled bar with diameter 20 mm. A steel rig was designed conveniently to be used for testing the beams. The supports of the beams were designed such that they can rotate freely on the bearings. One of the two supports was hinged and the other was a roller support. Electrical strain gauges, of gauge length 10 mm and resistance 120 ohms, were used to measure strains of the main bottom longitudinal reinforcement at the point of applied concentrated load and electrical strain gauges, of gauge length 6 mm and resistance 120 ohms, were used to measure strains of the vertical stirrups within the shear span. An electrical strain indicator, type Bruel-Kajeir-1526 provided with multi- point selector type 1545 was used to record all the strain readings. The deflections of the beams were measured using mechanical dial gauges, having sensitivity of 0.01 mm. The dial gauges were placed at three locations under each beam to measure the vertical deflections. The first dial was placed under load point, the second dial was placed at the mid-span of the beam, and the third dial was placed at the mid of the shear span.

Each beam was placed and leveled on the test rig. Then, the loading bar was placed on the top surface of the beam. The electric strain gauges and load cell were wired and connected to the strain indicator. During testing of each beam and at each load increment, the

Fig. 1. Dimensions and reinforcement details of tested beams in groups N, H1, and H2.

Fig. 2. Dimensions and reinforcement details of tested beams in groups H3, and H4.

Table 1
Details of tested beams

Group	Beam	Type of concrete	Shear span (mm)	Shear span to depth ratio (a/d)	Vertical stirrups	Presence of end anchorage	Presence of short columns at beam ends
Group "N"	S1	Normal	345	1.5	2br6mm@200mm	With end anchorage	With columns
	S2	Normal	345	1.5	2br6mm@200mm	Without end anchorage	With columns
	S3	Normal	460	2.0	2br6mm@200mm	With end anchorage	With columns
	S4	Normal	460	2.0	2br6mm@200mm	Without end anchorage	With columns
	S5	Normal	690	3.0	2br6mm@200mm	With end anchorage	With columns
	S6	Normal	690	3.0	2br6mm@200mm	Without end anchorage	With columns
	S7	Normal	920	4.0	2br6mm@200mm	With end anchorage	With columns
	S8	Normal	920	4.0	2br6mm@200mm	Without end anchorage	With columns
Group "H1"	SH1	High	345	1.5	No vertical stirrups	With end anchorage	With columns
	SH2	High	345	1.5	No vertical stirrups	Without end anchorage	With columns
	SH3	High	460	2.0	No vertical stirrups	With end anchorage	With columns
	SH4	High	460	2.0	No vertical stirrups	Without end anchorage	With columns
	SH5	High	690	3.0	No vertical stirrups	With end anchorage	With columns
	SH6	High	690	3.0	No vertical stirrups	Without end anchorage	With columns
	SH7	High	920	4.0	No vertical stirrups	With end anchorage	With columns
	SH8	High	920	4.0	No vertical stirrups	Without end anchorage	With columns
Group "H2"	SH9	High	345	1.5	2br6mm@200mm	With end anchorage	With columns
	SH10	High	345	1.5	2br6mm@200mm	Without end anchorage	With columns
	SH11	High	460	2.0	2br6mm@200mm	With end anchorage	With columns
	SH12	High	460	2.0	2br6mm@200mm	Without end anchorage	With columns
	SH13	High	690	3.0	2br6mm@200mm	With end anchorage	With columns
	SH14	High	690	3.0	2br6mm@200mm	Without end anchorage	With columns
	SH15	High	920	4.0	2br6mm@200mm	With end anchorage	With columns
	SH16	High	920	4.0	2br6mm@200mm	Without end anchorage	With columns
Group "H3"	SH17	High	345	1.5	No vertical stirrups	With end anchorage	Without columns
	SH18	High	345	1.5	No vertical stirrups	Without end anchorage	Without columns
	SH19	High	460	2.0	No vertical stirrups	With end anchorage	Without columns
	SH20	High	460	2.0	No vertical stirrups	Without end anchorage	Without columns
Group "H4"	SH21	High	345	1.5	2br6mm@200mm	With end anchorage	Without columns
	SH22	High	345	1.5	2br6mm@200mm	Without end anchorage	Without columns
	SH23	High	460	2.0	2br6mm@200mm	With end anchorage	Without columns
	SH24	High	460	2.0	2br6mm@200mm	Without end anchorage	Without columns

following was observed and recorded: (i) strains in the main bottom longitudinal reinforcement and vertical stirrups; (ii) vertical deflections at different locations; (iii) cracks initiation and propagation; and (iv) failure loads and failure modes.

3. Experimental results and discussions

The main objective of the current experimental study was to investigate the behavior and shear strength of reinforced high-strength concrete beams. Thirty two simply supported beams were tested to failure under the effect of single concentrated load. The structural behavior was observed for all tested beams through measuring deflections, and steel strains. Also, cracking loads, failure loads, and modes of failure were determined for all tested beams. The effect of the following significant parameters on the behavior and shear strength of reinforced concrete beams shall be investigated in the following sections: (i) concrete strength; (ii) the presence of vertical stirrups; (iii) shear span-to-depth ratio (a/d); (iv) the presence of end anchorage; and (v) the presence of short columns at beam ends.

The experimental test results are summarized in tables 2 and 3. The results include: (i) deflection under the applied load point in the elastic range of loading δ_e at a load = 10 kN; (ii) deflection under the applied load point at cracking loads, δ_{cr}; (iii) deflection under the applied load point at failure loads, δ_f; (iv) bottom longitudinal steel strain in the elastic range, ξ_e at a load = 10 kN; (v) bottom longitudinal steel strain at cracking loads, ξ_{cr}; (vi) bottom longitudinal steel strain at failure loads, ξ_f; (vii) bottom longitudinal steel yield

Table 2
Deflections and steel strains for tested beams

Group	Beam	Deflection***, mm			Bottom longitudinal steel strain*** (micro strain)		
		δ_e	δ_{cr}	δ_f	ξ_e	ξ_{cr}	ξ_f
Group “N”	S1	0.62	1.10	12.00	50	170	3300
	S2	0.78	1.68	8.85	50	580	2420
	S3	0.75	1.52	12.61	70	190	2500
	S4	0.80	2.56	12.81	70	820	2240
	S5	1.02	2.90	12.58	120	730	2150
	S6	1.12	3.10	13.52	120	870	1880
	S7	1.19	2.30	14.43	180	780	2120
	S8	1.22	2.32	17.89	180	920	2180
Group “H1”	SH1	0.41	1.25	7.54	90	550	2460
	SH2	0.47	0.98	7.65	90	550	4260
	SH3	0.63	1.29	9.56	110	700	3300
	SH4	0.65	1.82	10.23	110	950	3100
	SH5	0.73	2.86	10.85	N.A	N.A.	N.A.
	SH6	0.79	2.01	12.20	120	1130	>2370
	SH7	0.82	1.93	12.02	170	1100	4250
	SH8	0.85	3.95	12.47	180	1350	4470
Group “H2”	SH9	0.42	0.90	8.90	50	310	3880
	SH10	0.46	0.99	10.27	50	540	8600
	SH11	0.61	0.93	9.8	70	500	4750
	SH12	0.65	1.03	11.52	70	600	4480
	SH13	0.75	1.14	11.72	120	800	5220
	SH14	0.78	2.20	12.87	120	820	2820
	SH15	0.82	2.34	14.36	180	810	10830
	SH16	0.85	3.11	17.37	180	850	14090
Group H3	SH17	0.63	1.54	7.70	90	700	2150
	SH18	0.73	1.79	8.30	90	730	2100
	SH19	0.67	1.42	9.93	100	750	9000
	SH20	0.78	1.66	10.51	100	780	2230
Group “H4”	SH21	0.62	1.34	8.33	50	340	2480
	SH22	0.79	1.35	8.65	50	600	3250
	SH23	0.73	1.49	10.49	60	520	3350
	SH24	0.88	1.69	11.72	60	720	6450

***

δ_e = Deflection under the applied load point in the elastic range at a load = 10 kN.
δ_{cr} = Deflection under the applied load point at cracking load.
δ_f = Deflection under the applied load point at failure load.
ξ_e = Bottom longitudinal steel strain in the elastic range at a load = 10 kN.
ξ_{cr} = Bottom longitudinal steel strain at cracking load.
ξ_f = Bottom longitudinal steel strain at failure load.

load; (viii) flexural cracking loads; (ix) shear cracking loads; (x) ultimate failure loads; (xi) modes of failure. Figs. 3- 6 present load-deflection relationships for tested beams in groups “N”, “H1”, “H2”, and “H3 and H4”, respectively. Figs. 7- 10 present load-steel strain relationships for tested beams in groups “N”, “H1”, “H2”, and “H3 and H4”, respectively. Figs. 11- 15 present cracking patterns after failure for tested beams in groups “N”, “H1”, “H2”, “H3”, and “H4”, respectively.

3.1. Effect of concrete strength

A comparison between the results of testing reinforced normal strength concrete beams in group “N” to those of testing reinforced high strength concrete beams in group “H2” shall reveal the effect of concrete strength on the behavior and shear strength of beams. Generally the increase in the concrete strength resulted in significant decrease in the deflection in the elastic range, at cracking loads, and also at failure loads. The following can be observed: (i) the decrease in the deflection in the elastic range ranged between 19% and 41% depending on the shear span to depth ratio and the presence of end anchorage; (ii) such decrease in the deflection in the elastic range was more significant in the case of beams not provided with end anchorage; (iii) the decrease in the deflection

Table 3
Cracking loads, failure loads, and modes of failure for tested beams

Group	Beam	Bottom longitudinal steel yield load (kN)	Flexural cracking load (kN)	Shear cracking load (kN)	Ultimate failure load (kN)	Mode of failure
Group “N”	S1	65.0	20.0	35.0	75.0	Shear
	S2	55.0	25.0	35.0	65.0	Shear
	S3	60.0	20.0	45.0	65.0	Shear
	S4	60.0	30.0	45.0	65.0	Shear
	S5	40.0	20.0	------	45.0	Flexural
	S6	35.0	20.0	30.0	40.0	Flexural
	S7	30.0	15.0	------	32.5	Flexural
	S8	25.0	15.0	------	32.5	Flexural
Group “H1”	SH1	65.0	30.0	55.0	75.0	Shear
	SH2	60.0	25.0	70.0	70.0	Shear
	SH3	50.0	25.0	50.0	65.0	Shear
	SH4	50.0	30.0	50.0	65.0	Shear
	SH5	N.A.	25.0	-------	52.5	Flexural
	SH6	35.0	20.0	52.5	52.5	Shear
	SH7	35.0	20.0	-------	42.5	Flexural
	SH8	35.0	25.0	-------	42.5	Flexural
Group “H2”	SH9	65.0	25.0	50.0	80.0	Shear
	SH10	55.0	25.0	60.0	80.0	Shear
	SH11	50.0	20.0	45.0	65.0	Shear
	SH12	50.0	20.0	55.0	65.0	Flexural
	SH13	40.0	15.0	-------	50.0	Flexural
	SH14	40.0	20.0	-------	50.0	Flexural
	SH15	30.0	20.0	-------	45.0	Flexural
	SH16	30.0	20.0	-------	42.5	Flexural
Group “H3”	SH17	55.0	25.0	-------	75.0	Flexural
	SH18	55.0	25.0	60.0	70.0	Shear
	SH19	45.0	20.0	-----	60.0	Flexural
	SH20	45.0	20.0	40.0	55.0	Shear
Group “H4”	SH21	60.0	25.0	45.0	75.0	Flexural
	SH22	50.0	20.0	50.0	70.0	Shear
	SH23	45.0	20.0	50.0	62.5	Flexural
	SH24	50.0	20.0	50.0	62.5	Shear

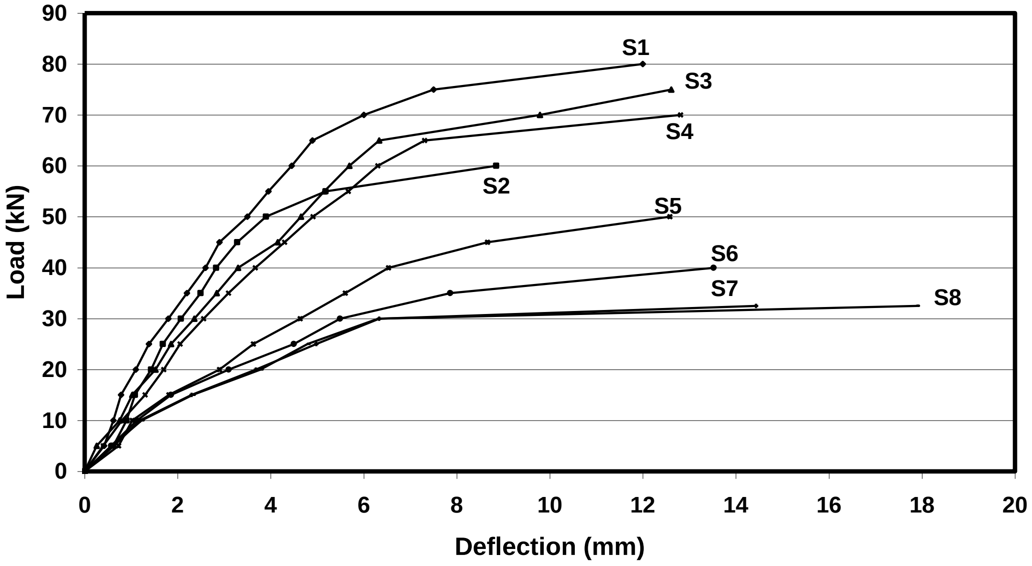

Fig. 3. Load-deflection relationships for tested beams in group “N”.

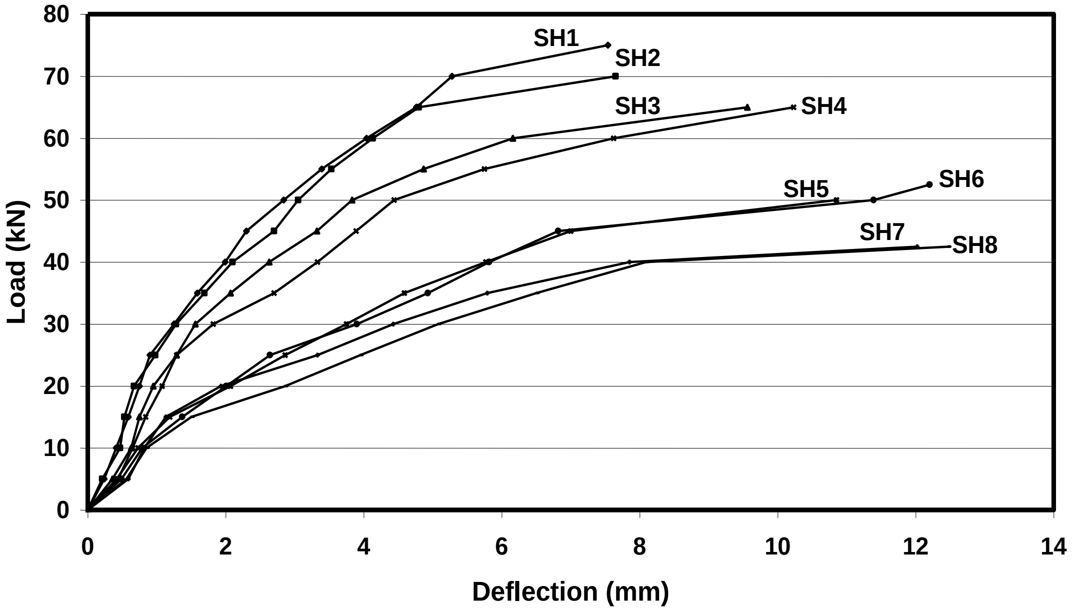

Fig. 4. Load-deflection relationships for tested beams in group "H1".

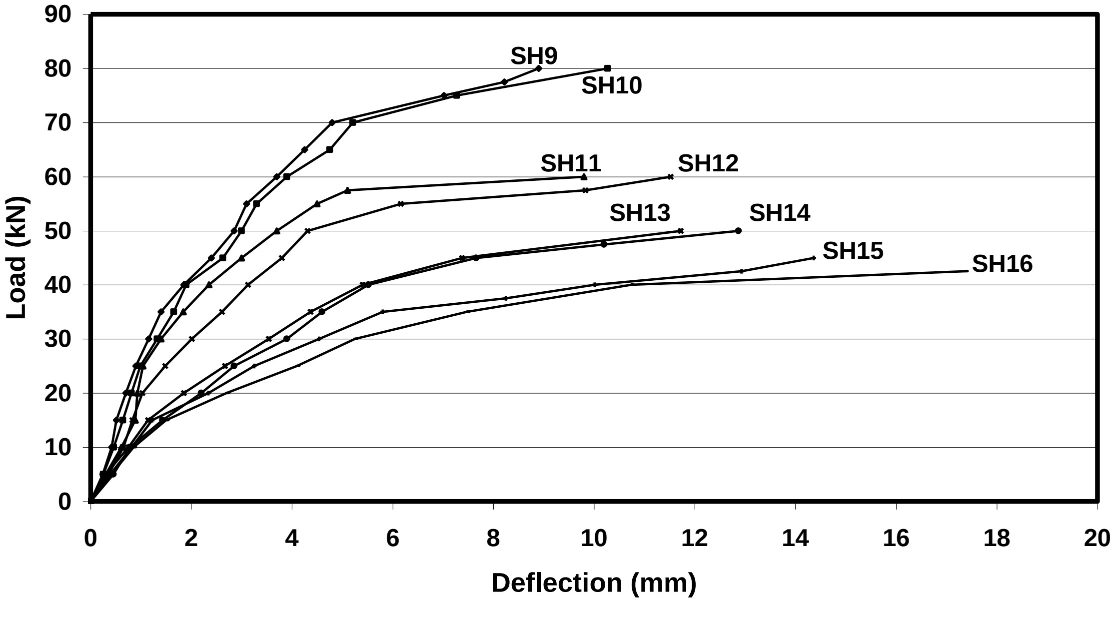

Fig. 5. Load-deflection relationships for tested beams in group "H2".

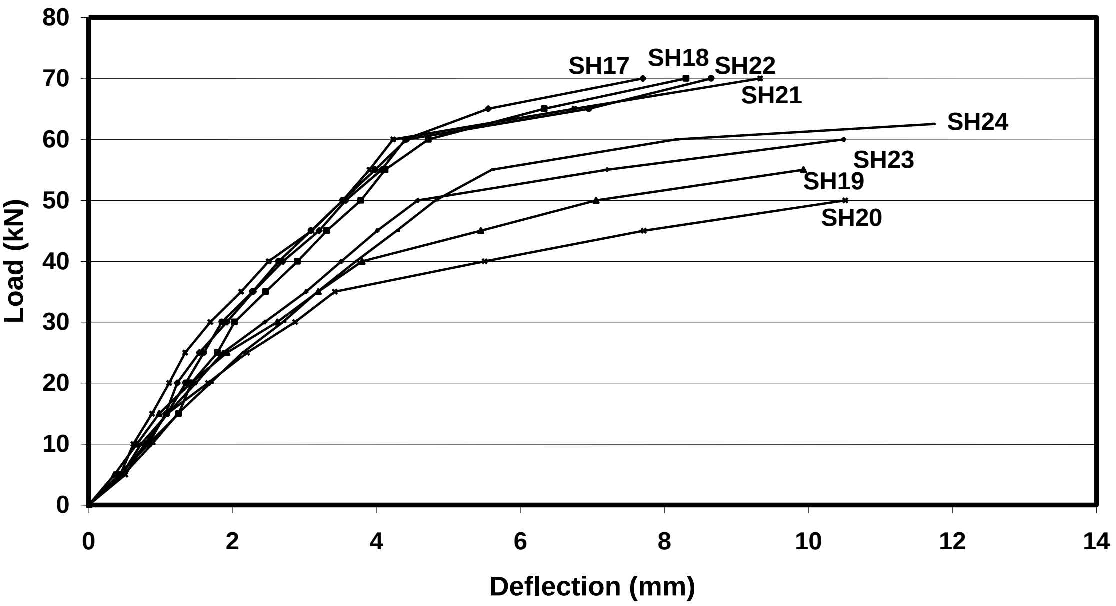

Fig. 6. Load-deflection relationships for tested beams in groups "H3 and H4".

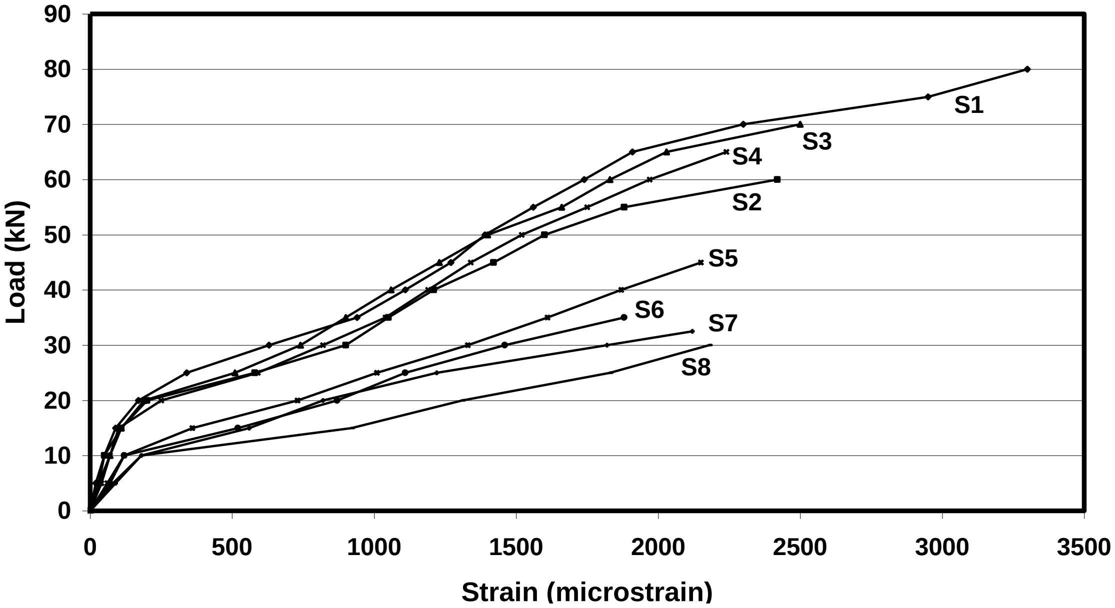

Fig. 7. Load-strain relationships for tested beams in group "N".

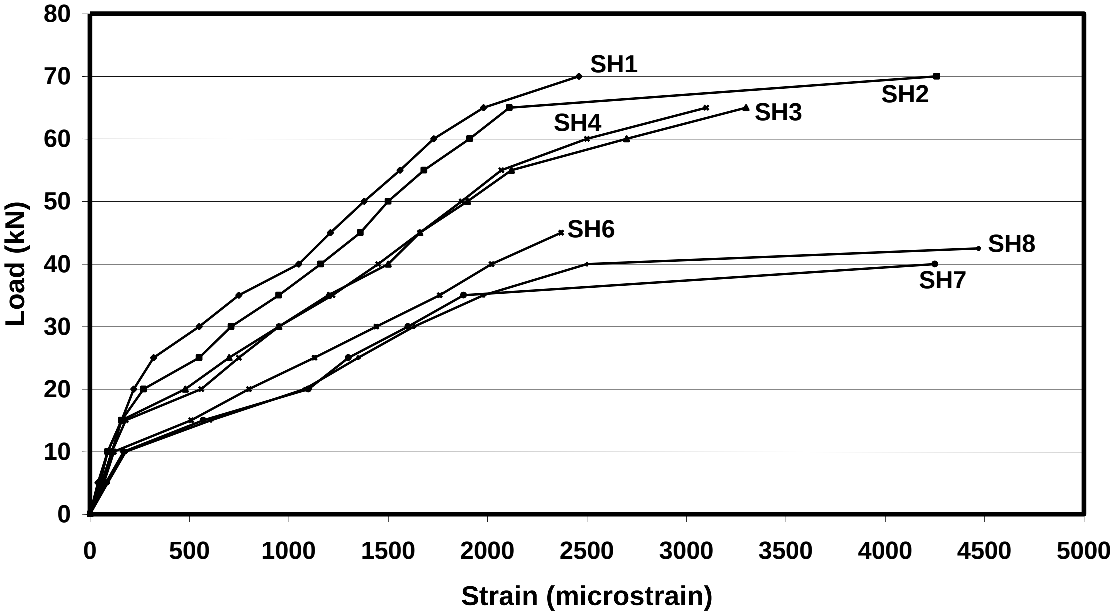

Fig. 8. Load-strain relationships for tested beams in group "H1".

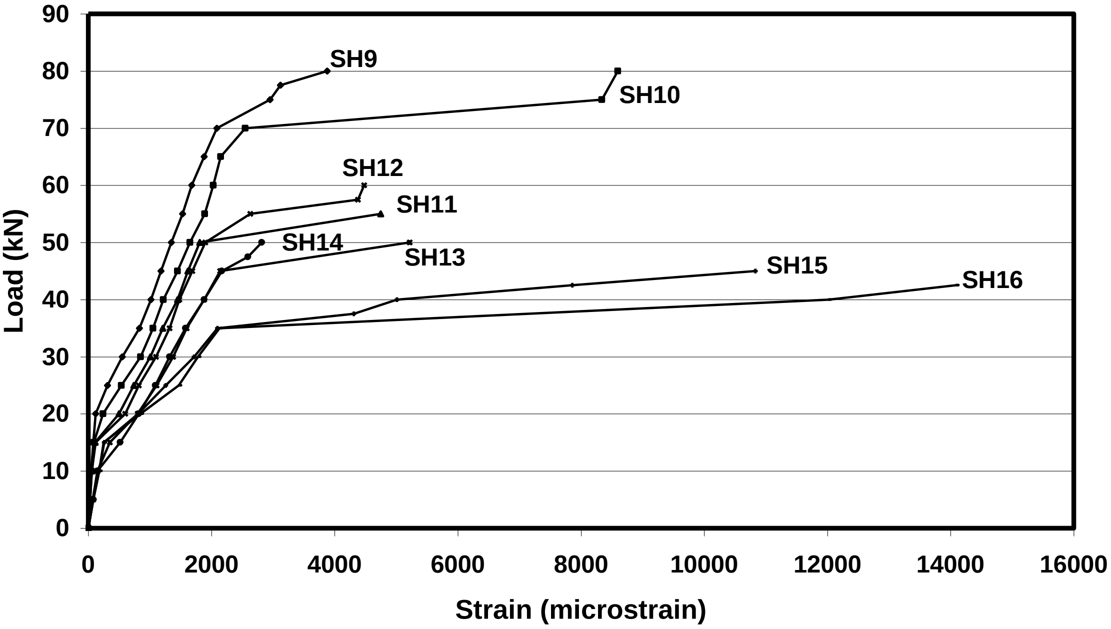

Fig. 9. Load-strain relationships for tested beams in group "H2".

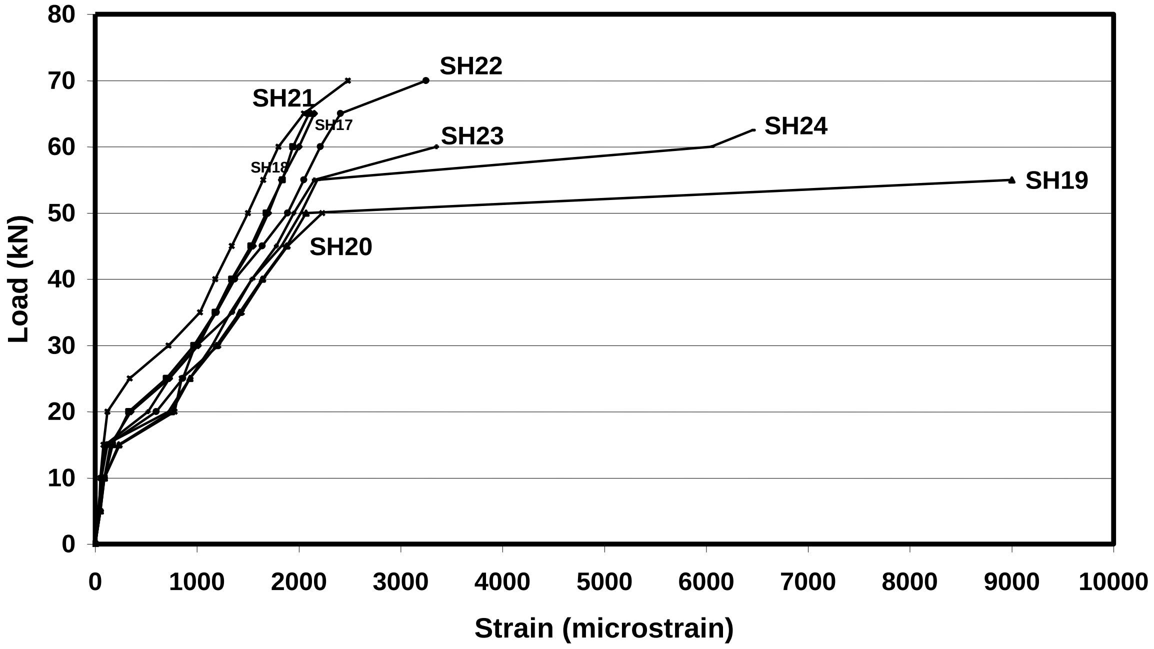

Fig. 10. Load-strain relationships for tested beams in groups "H3 and H4".

at cracking loads ranged between 0% and 60% depending on the shear span to depth ratio and the presence of end anchorage; and (iv) the decrease in the deflection at failure loads ranged between 0.5% and 26% depending on the shear span to depth ratio and the presence of end anchorage.

It was also found that the bottom longitudinal steel strain in the elastic range was not affected by the concrete strength. However, different observations were found for the effect of concrete strength on the bottom longitudinal steel strain at cracking loads and failure loads. Such observations may be summarized as follows: (i) as a result of increasing the concrete strength, the steel strain at cracking loads increased for beams provided with end anchorage by about 4% and 163% depending on the shear span to depth ratio; (ii) however, such increase in the concrete strength resulted in a significant decrease in the steel strain at cracking loads for beams not provided with end anchorage ranging between 6% and 27% depending on the shear span to depth ratio; and (iii) the increase in the concrete strength resulted in a significant increase in the steel strain at failure loads for all cases of shear span to depth ratios and end anchorage.

Furthermore, the increase in the concrete strength resulted in a significant increase in both shear cracking loads and failure loads of tested beams. Such increase in the shear cracking load ranged between 0% and 71%. Also, the increase in the ultimate failure load ranged between 0% and 38% depending on the shear span to depth ratio and the presence of end anchorage.

Generally, failure of high strength concrete beams was much more catastrophic and explosive than that in the case of normal strength concrete beams. In the case of high strength concrete beams failure was associated with louder noise. However, as shown in table 2, the mode of failure of beams was not affected by the concrete strength except for beams having shear span to depth ratio (a/d) of 2.0 and not provided with end anchorage. In this case the mode of failure changed from shear mode of failure in the case of normal strength concrete beams to flexural mode of failure in the case of high strength concrete beam.

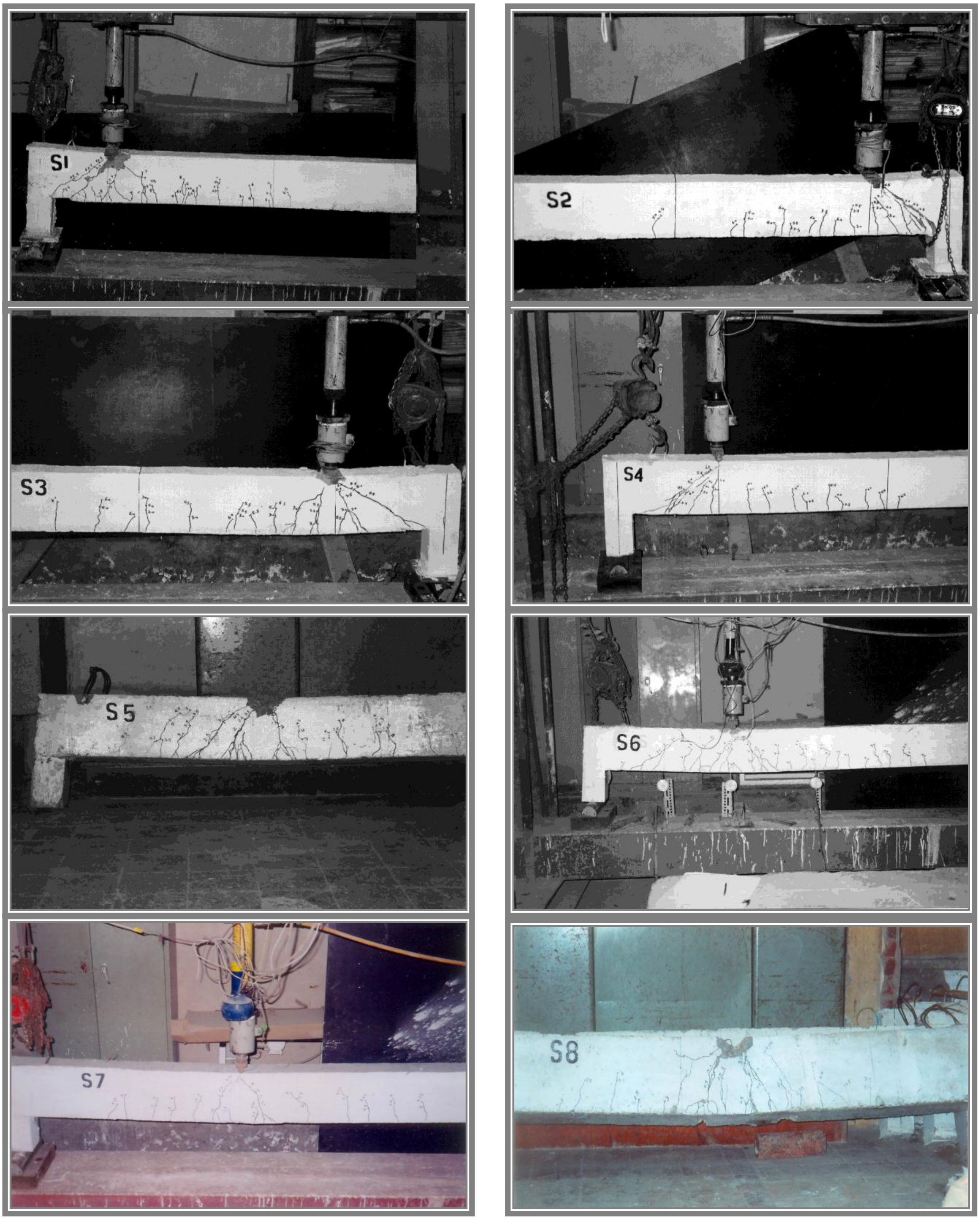

Fig. 11. Cracking patterns after failure for tested normal strength concrete beams with stirrups in group “N”.

Fig. 12. Cracking patterns after failure for tested high strength concrete beams without stirrups in group “H1”.

Fig. 13. Cracking patterns after failure for tested high strength concrete beams with stirrups in group "H2".

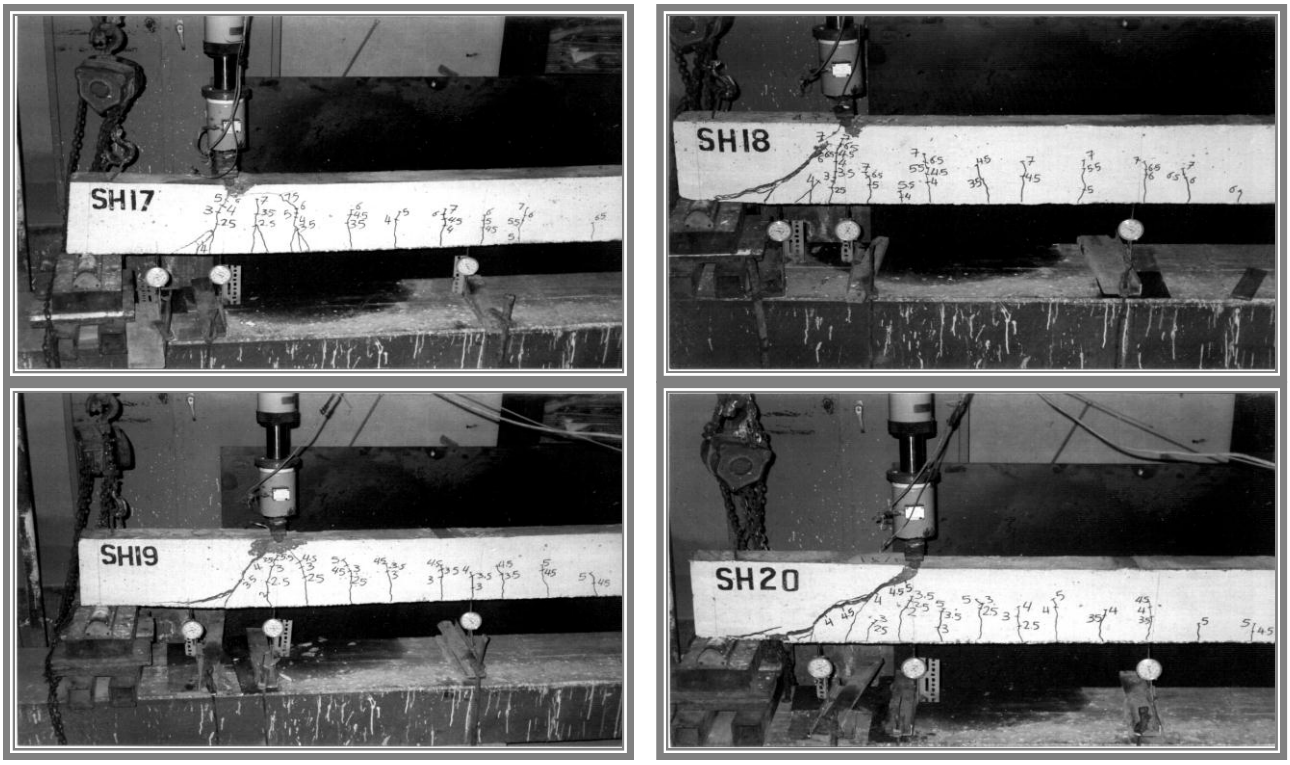

Fig. 14. Cracking patterns after failure for tested high strength concrete beams without stirrups in group “H3”.

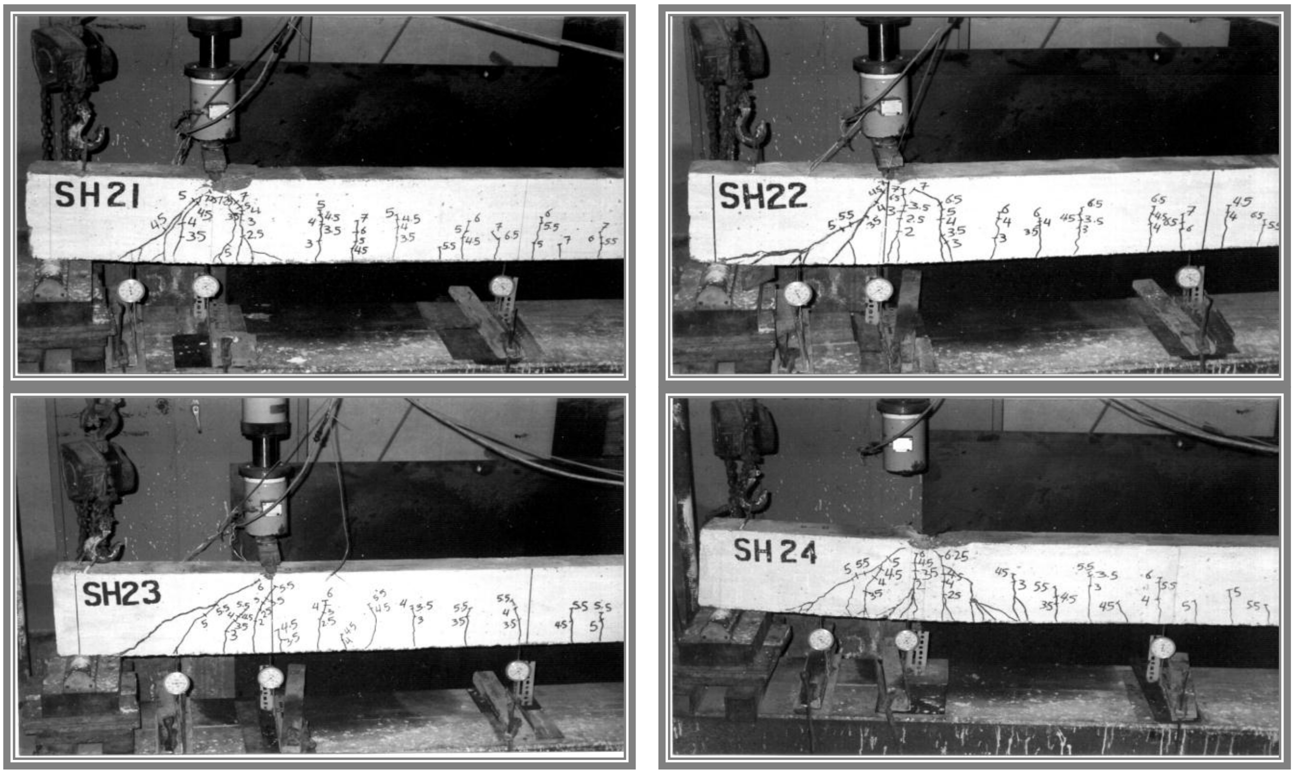

Fig. 15. Cracking patterns after failure for tested high strength concrete beams with stirrups in group “H4”.

3.2. Effect of the presence of vertical stirrups

The Effect of the presence of vertical stirrups on the behavior and shear strength of reinforced high strength concrete beams provided with short columns at beams ends can be detected when comparing the results of testing beams in group “H1” without stirrups to those of testing beams in group “H2” which were provided with stirrups. Also, such effect can be detected for beams not provided with short columns at beams ends through a comparison between the results of testing beams in group “H3” without stirrups to those of testing beams in group “H4” which were provided with stirrups.

It can be observed that the deflection under the applied load point in the elastic range was marginally affected by the presence of vertical stirrups. However, different observations were found for the effect of the presence of vertical stirrups on the deflection at cracking and failure loads. These observations may be summarized as follows: (i) the deflection at cracking loads for beams provided with short columns at beams ends decreased significantly as a result of the presence of vertical stirrups by up to 60% depending on the shear span to depth ratio and the presence of end anchorage; (ii) such decrease in the deflection at cracking loads ranged between 13% and 25% in the case of beams having (a/d) ratio of 1.50 and not provided with short columns at beams ends; (iii) however, the deflection at cracking loads increased by about 2% to 5% as a result of the presence of vertical stirrups for beams having (a/d) ratio of 2.0 and not provided with short columns at beams ends; and (iv) the deflection at failure load increased significantly as a result of the presence of vertical stirrups. Such increase in the deflection ranged between 2% and 39% for beams provided with short columns at beams ends depending on the shear span-to-depth ratio and the presence of end anchorage. Also, such increase in the deflection ranged between 4% and 11% in the case of beams not provided with short columns at beams ends.

The bottom longitudinal steel strain was also affected by the presence of vertical stirrups. The following can be observed: (i) the steel strain in the elastic range decreased significantly as a result of the presence of vertical stirrups; (ii) such decrease in the steel strain becomes much less significant as the shear span to depth ratio increases; (iii) the steel strain at cracking loads also decreased significantly as a result of the presence of vertical stirrups; and (iv) however, the steel strain at failure loads increased significantly as a result of the presence of vertical stirrups.

The presence of vertical stirrups affects the ultimate failure loads of the beams when the mode of failure is a shear mode. For example, the ultimate failure load increased from 75.0 and 70.0 kN for beams SH1 and SH2, without vertical stirrups, to 80.0 kN for beams SH9 and SH10 provided with vertical stirrups. All these beams had a shear span-to-depth ratio (a/d) of 1.5 and failed in a shear mode of failure. However the ultimate failure load decreased from 52.5 kN for beams SH5 and SH6, without vertical stirrups to 50.0 kN for beams SH13 and SH14 provided with vertical stirrups. These beams had a shear span-to-depth ratio (a/d) of 2.0 and failed in a flexural mode. It was also clearly observed that failure of beams provided with vertical stirrups was much more ductile compared to that of beams without vertical stirrups. There is a definite increase in the area under load-deflection and load-strain curves as a result of the presence of vertical stirrups which reflects an enhancement in the beam ductility.

3.3. Effect of shear span-to-depth ratio (a/d)

The shear span-to-depth ratio (a/d) is one of the most important parameters affecting the behavior and shear strength of reinforced concrete beams. Such effect can be detected for tested beams when comparing the test results of beams having different shear span-to-depth ratios within each group. Generally the increase in the shear span-to-depth ratio resulted in a significant increase in the deflection within the elastic range as expected. However, the following observations were found: (i) the deflection in the elastic range increased by about 21%, 65% and 92% as a result of increasing (a/d) ratio from 1.5 to 2.0, 3.0, and 4.0 respectively for normal-strength concrete beams with end anchorage; (ii) such increase in the deflection in the elastic range was about 3% , 44% and 56%, respectively for normal-strength concrete beams without end anchorage; (iii) such increase in the elastic deflection was about 45%, 79% and 95% for high-strength concrete beams provided with vertical stirrups and end anchorage ; and (iv) the increase in the deflection in the elastic range was about 41%, 70% and 85% for high-strength concrete beams provided with vertical stirrups but not provided with end anchorage.

Based on the observations regarding the effect of (a/d) ratio on the deflection in the elastic range it can be concluded that such effect is much more significant for beams provided with end anchorage than that in the case of beams without end anchorage. Also, it was found that the effect of increasing (a/d) ratio on increasing the deflection in the elastic range is much more significant in the case of high-strength concrete beams than that in the case of normal- strength concrete beams. Furthermore, the effect of (a/d) ratio on the deflection in the elastic range becomes much less significant for beams without short columns at its ends.

A significant effect of the (a/d) ratio was also found on the deflection at cracking loads and failure loads. For example, the deflection at cracking loads increased by about 38%, 164% and 109% as a result of increasing (a/d) ratio from 1.5 to 2.0, 3.0, and 4.0, respectively for normal-strength concrete beams provided with end anchorage. Also, such increase in the deflection at cracking loads was 52%, 85% and 38%, respectively for normal-strength concrete beams without end anchorage. Furthermore, such increase in the deflection at cracking loads was about 3%, 27%, and 160%, respectively for high-strength concrete beams provided with end anchorage and was about 4%, 122%, and 214% for high-strength concrete beams without end anchorage, for beams in group “H2” provided with vertical stirrups. However, different observations were found for beams without short columns at its ends. In this case, the deflection at cracking loads decreased as a result of increasing the shear span-to-depth ratio (a/d).

The effects of increasing the shear span to depth ratio (a/d) on the bottom longitudinal steel strain can be summarized as follows: (i) significant increase in the steel strain in the elastic range; (ii) significant increase in the steel strain at cracking loads; (iii) significant decrease in the steel strain at failure loads for normal strength concrete beams; and (iv) significant increase the steel strain at failure loads for high strength concrete beams. It was also found that the increase in (a/d) ratio resulted in a significant decrease in the load at which the bottom longitudinal steel yields for all cases of normal strength and high strength concrete beams.

The increase in the shear span to depth ratio (a/d) also resulted in a significant decrease in the ultimate failure loads of beams and also resulted in a change in the failure modes. The following can be observed: (i) the decrease in the ultimate failure load was about 13%, 40%, and 57% as a result of increasing (a/d) ratio from 1.5 to 2.0, 3.0, and 4.0, respectively for normal strength concrete beams with end anchorage; (ii) such decrease in the ultimate failure load was about 0%, 38%, and 50%, respectively for normal strength concrete beams without end anchorage; (iii) the decrease in the ultimate failure load was about 19%, 38%, and 44% for high strength concrete beams with end anchorage and vertical stirrups; and (iv) such decrease in the ultimate failure load was about 19%, 38%, and 47% for high strength concrete beams without end anchorage but provided with vertical stirrups.

It was generally found that the effect of increasing (a/d) ratio on decreasing the ultimate failure loads was much more significant for beams provided with end anchorage than that for beams not provided with end anchorage. Also, such effect was much more significant in the case of normal strength concrete beams than that in the case of high strength concrete beams. Furthermore, such effect was less significant in the case of beams not provided with short columns at beams ends.

Moreover, the effect of the shear span to depth ratio on the failure modes of the beams can be summarized as follows: (i) the failure mode was shear in the case of (a/d) ratios of 1.5 and 2.0; (ii) the failure mode changed to a flexural mode as the (a/d) ratio was increased to 3.0 and 4.0 ; and (iii) however, the failure mode was flexural mode in the case of high strength concrete beams having (a/d) ratio of 1.5 and 2.0 in the case of beams not provided with short columns at beams ends but provided with end anchorage.

3.4. Effect of the presence of end anchorage

The main objective of the current experimental study was to investigate the effect of the presence of end anchorage on the behavior and shear strength of reinforced normal and high strength concrete beams. The sixteen tested beams having odd numbers were provided with end anchorage whereas the other sixteen beams having even numbers were not provided with end anchorage. Therefore, comparisons between the results of testing beams having odd numbers to those having even numbers shall reveal the effects of the presence of end anchorage. Such effects shall be investigated in the following sections.

The deflection in the elastic range of loading significantly decreased as a result of the presence of end anchorage. Such decrease in the deflection in the elastic range ranged between 2% and 21% in the case of normal strength concrete beams in group “N”, depending on the shear span to depth ratio (a/d). Also, such decrease in the elastic deflection ranged between 3% and 13% for high strength concrete beams without vertical stirrups in group “H1”. Furthermore, the decrease in the deflection in the elastic range was between 4% and 9% for high strength concrete beams with vertical stirrups in group “H2”. The decrease in elastic deflection was 14% for high strength concrete beams in group “H3” and ranged between 17% and 22% for high strength concrete beams in group “H4”. Therefore, the following may be concluded: (i) the decrease in the deflection in the elastic range as a result of the presence of end anchorage was much more significant for normal strength concrete beams than that in the case of high strength concrete beams; (ii) such decrease in the deflection in the elastic range was more significant in the case of high strength concrete beams without vertical stirrups than that in the case of high strength concrete beams with vertical stirrups; and (iii) the decrease in the deflection in the elastic range was much more significant in the case of beams not provided with short columns at beam ends than that in the case of beams having short columns at beam ends.

Much more significant reductions were observed for the deflection at cracking loads as a result of the presence of end anchorage. The following may be observed: (i) the decrease in the deflection at cracking loads as a result of the presence of end anchorage was much more significant in the case of normal strength concrete beams having (a/d) ratio of 1.5 and 2.0 than that for the corresponding high strength concrete beams; (ii) however, such decrease in the deflection at cracking loads was much more significant in the case of high strength concrete beams having (a/d) ratio of 3.0 and 4.0 than that for the corresponding normal strength concrete beams; and (iii) the decrease in the deflection at cracking loads as a result of the presence of end anchorage was much less significant in the case of beams having short columns at beam ends than that in the case of beams without short columns at beam ends.

Similar observations were found for the effect of the presence of end anchorage on the deflection at failure loads. It was also found that the bottom longitudinal steel strain in the elastic range was not affected by the presence of end anchorage in all cases of normal strength concrete beams, high strength concrete beams with or without vertical stirrups, and for all values of (a/d) ratio. However, the bottom longitudinal steel strain at cracking loads decreased significantly as a result of the presence of end anchorage. Such decrease in the steel strain at cracking loads ranged between 15% and 77% in the case of normal strength concrete beams. Also, the decrease in the steel strain at cracking loads ranged between 0% and 26% and between 2% and 43% in the case of high strength concrete beams without and with vertical stirrups, respectively. Furthermore, such decrease in the steel strain at cracking loads was 4% and ranged between 28% and 43% for high strength concrete beams without short columns at beam ends, without and with vertical stirrups, respectively.

It was also found that the load at which the bottom longitudinal steel strain yielded increased in most cases as a result of the presence of end anchorage. Furthermore, the ultimate failure loads of the beams were marginally affected by the presence of end anchorage. The failure modes also were not affected by the presence of end anchorage except for some cases which may be summarized as follows: (i) in the case of high strength concrete beams without vertical stirrups having (a/d) ratio of 3.0, the failure mode changed from a shear mode to a flexural mode as a result of the presence of end anchorage; and (ii) in all cases of high strength concrete beams not provided with short columns at beam ends, the failure mode changed from a shear mode to a flexural one as a result of the presence of end anchorage.

3.5. Effect of the presence of short columns at beam ends

The effects of the presence of short columns at beam ends may be detected when comparing the results of testing high strength concrete beams in group “H3” without short columns at beam ends to those of the corresponding beams in group “H1” having short columns at beam ends, for the case of beams not provided with vertical stirrups. The same can be detected for high strength concrete beams with vertical stirrups through a comparison between the results of testing beams in group “H4” to those of the corresponding beams in group “H2”.

Generally, the presence of short columns at beam ends leads to the following effects: (i) significant decrease in the deflection in the elastic range, the deflection at cracking loads, and the deflection at failure loads; (ii) marginal effect was found for the presence of short columns at beam ends on the bottom longitudinal steel strain in the elastic range; (iii) significant decrease in the bottom longitudinal steel strain at cracking loads; (iv) increase in the load at which the bottom longitudinal steel yielded; (v) increase in the flexural cracking loads; (vi) increase in the shear cracking loads; and (vii) increase in the ultimate failure loads.

Furthermore, the failure modes of the beams were clearly affected by the presence of short columns at beam ends. The failure mode changed from a shear mode to a flexural one as a result of the presence of short columns at beam ends for high strength concrete beams provided with end anchorage.

4. Codes of practice predictions

Although there are significant efforts to rationalize the ultimate shear strength of reinforced concrete beams, however the equations presented in some international codes of practice are based on empirical formulas. Such formulas were originally developed using experimental data from testing normal-strength concrete beams. Furthermore, some of the equations presented by these codes ignore the effect of some significant parameters such as: the ratio of bottom longitudinal reinforcement and the effect of the shear span-to-depth ratio (a/d). The validity of the equations presented by these codes for the calculation of the ultimate shear strength of reinforced concrete beams shall be examined in this section using the current experimental results. The equations given by the following codes of practice shall be examined: (i) The Egyptian code of practice (ECP-2001) [19]; (ii) The American Concrete Institute code (ACI 318-05) [16]; (iii) The British Standards (BS 8110) [17]; (iv) The Japanese code (JSCE) [20]; and (v) The Canadian code [21]. Furthermore, the equation presented by Zsutty [22 and 23] shall be examined.

4.1. The Egyptian Code of Practice (ECP-2001) [19]

The ultimate shear strength v_u is given by:

$$v_u = v_s + 0.5\ v_c\ , \tag{1}$$

$$v_c = 0.75\sqrt{f_{cu}}\ , \tag{2}$$

$$v_s = \frac{A_v\ f_{yv}}{S}\ , \tag{3}$$

where: v_s = the shear strength provided by the shear reinforcement; v_c = the shear strength provided by the concrete; S = spacing between vertical stirrups; A_v = area of vertical stirrups; f_{yv} = yield strength of vertical stirrups; and f_{cu} = concrete cube compressive strength.

The equation presented by the Egyptian code ignores the effects of the bottom longitudinal steel reinforcement and the shear span to depth ratio (a/d). The equations presented above are based on empirical formulas.

4.2. The American Concrete Institute code (ACI 318-05) [16]

The American Concrete Institute code (ACI 318-05) [16] adopts a 45 degrees truss model. The ultimate shear load is given by:

$$V_u = V_c + V_s \, , \tag{4}$$

where: V_c = the concrete contribution to the ultimate shear load; and V_s = the stirrups contribution to the ultimate shear load.

$$V_c = \left[\sqrt{f'_c} + 120\,\rho_{sl}\,\frac{V_u\,d}{M_u}\right]\frac{b_w\,d}{7} \le 0.3\sqrt{f'_c}\,b_w\,d \, , \tag{5}$$

where: f_c' = concrete cylinder compressive strength; ρ_{sl} = ratio of longitudinal steel reinforcement; V_u and M_u = the applied shear force and bending moment at the critical section; d = effective depth; and b_w = width of the beam.

The ACI code also allows the use of the following simplified equation:

$$V_c = 0.17\sqrt{f'_c}\,b_w\,d \, . \tag{6}$$

$$V_s = \frac{A_{sv}\,f_{syv}\,d}{S} \, , \tag{7}$$

where: A_{sv} = area of vertical stirrups; f_{syv} = yield strength of vertical stirrups; d = effective depth; and S = spacing of vertical stirrups.

The equations presented by the ACI 318-05 take into account the beneficial effect of bottom longitudinal reinforcement. However, it ignores the effect of the shear span to depth ratio (a/d).

4.3. The British Standards (BS 8110) [17]

Similar to the American Concrete Institute code [16], the British Standards (BS 8110) [17] adopts a 45 degrees truss model. The ultimate shear load is given by:

$$V_d = V_{cd} + V_{sd} \le 0.8\sqrt{f_{cu}}\,b_w\,d \le 5.0\,b_w\,d \, . \tag{8}$$

$$V_{cd} = 0.925\left(100\,\rho_l\right)^{\frac{1}{3}}\left(\frac{f_{cu}}{40}\right)^{\frac{1}{3}}\left(\frac{400}{d}\right)^{\frac{1}{3}} b_w\,d \, . \tag{9}$$

$$V_{sd} = \frac{A_{sv}\,f_{syv}\,d}{S} \, , \tag{10}$$

where: V_{cd} = the concrete contribution to the ultimate shear load; V_{sd} = the vertical stirrups contribution to the ultimate shear load; f_{cu} = concrete cube compressive strength; b_w = beam width; d = effective depth; ρ_l = ratio of longitudinal steel reinforcement; f_{syv} = yield strength of vertical stirrups; A_{sv} = area of vertical stirrups; and S = spacing of vertical stirrups.

The equations presented by the British Standards (BS 8110) [17] take into account the beneficial effect of the bottom flexural reinforcement but it ignore the effect of the shear span to depth ratio (a/d).

4.4. The Japanese code (JSCE) [20]

The ultimate shear load is given by:

$$V_d = V_{cd} + V_{sd} \, . \tag{11}$$

$$V_{cd} = \beta_d\,\beta_p\,\beta_n\,f_{vcd}\,b_w\,d \, , \tag{12}$$

$$f_{vcd} = 0.2\left(f'_{cd}\right)^{\frac{1}{3}} . \tag{13}$$

$$\beta_d = \left(\frac{100}{d}\right)^{\frac{1}{4}} \le 1.5 \, . \tag{14}$$

$$\beta_p = \left(\frac{100}{\rho_{sl}}\right)^{\frac{1}{3}} \le 1.5 . \tag{15}$$

$$\beta_n = 1 + \frac{M_o}{M_d} \quad for \ N_d \ \ge 0 . \tag{16}$$

$$\beta_n = 1 + \frac{2\,M_o}{M_d} \quad for \ N_d \ < 0 . \tag{17}$$

$$V_{sd} = \left[A_{sv}\, f_{syv} \, \frac{(\sin a_s + \cos a_s)}{S} \right] j_d \, , \tag{18}$$

where: V_{cd} = the concrete contribution to the ultimate shear load; V_{sd} = the steel contribution to the ultimate shear load; f_{cd}' = compressive strength of concrete; b_w = beam width; d = effective depth; ρ_{sl} = ratio of longitudinal steel reinforcement; N_d = axial compressive force; M_d = the design bending moment; M_o = the decompression moment; a_s = angle between shear reinforcement and member axis; j_d = shear depth = $d/1.15$; A_{sv} = area of shear reinforcement; f_{syv} = yield strength of shear reinforcement; and S = spacing of shear reinforcement.

4.5. The Canadian code [21]

The ultimate shear load is given by:

$$V_d = V_c + V_s \, , \tag{19}$$

where: V_c = the concrete contribution to the ultimate shear load; and V_s = the stirrups contribution to the ultimate shear load.

$$V_c = 0.2\,\lambda \sqrt{f'_c}\; b_w \;\; d \quad d > 300\,mm . \tag{20}$$

$$V_c = \frac{260}{1000 + d}\,\lambda \sqrt{f'_c}\, b_w\, d \ge \sqrt{f'_c}\, b_w d \, d > 300\,mm \, , \tag{21}$$

where: λ = 1.0 for normal density concrete; f_c' = concrete cylinder compressive strength; b_w = beam width; and d = effective depth.

$$V_s = \frac{A_{sv}\; f_{syv}\; d}{S} \le 0.8\,\lambda \sqrt{f'_c}\; b_w \;\; d \, , \tag{22}$$

where: A_{sv} = area of vertical stirrups; f_{syv} = yield strength of vertical stirrups; d = effective depth; and S = spacing of vertical stirrups.

4.6. Zsutty's eq. [22 and 23]

The ultimate shear load is given by:

$$V_u = 0.85 \left[60 \left(\frac{f'_c \;\; \rho\, d}{a} \right)^{\frac{1}{3}} (b_w\; d) + \frac{A_{sv}\; f_{syv}\; d}{S} \right] , \tag{23}$$

where: f_c' = concrete compressive strength; ρ = ratio of longitudinal reinforcement; d = effective depth; a = shear span; b_w = beam width; A_{sv} = area of vertical stirrups; f_{syv} = yield strength of vertical stirrups; and S = spacing of vertical stirrups.

The equation presented above by Zsutty [22 and 23] takes into account the beneficial effect of the bottom flexural reinforcement. Moreover, the equation takes into account the effect of the shear span to depth ratio (a/d) on the ultimate shear load.

4.7. Comparison of the experimental results to codes predictions

The equations presented above for the calculation of the ultimate shear load take into account the beneficial effects of the flexural reinforcement on enhancing the ultimate shear loads of reinforced concrete beams, except those presented by the Egyptian code of practice (ECP-2001) [19] and the Canadian code [21]. However, the equations presented by the five codes of practice considered in the comparison ignore the effect of the shear span-to-depth ratio (a/d) on the ultimate shear loads of reinforced concrete beams whereas the equation presented by Zsutty [22 and 23] considered its effect. Furthermore, the equations presented by these codes of practice are based on empirical formulas which were originally developed using experimental data from testing normal-strength concrete beams. The variation of the ultimate shear load with the concrete compressive strength differs significantly from a code to another. In the Egyptian code of practice (ECP-2001) [19], the ACI code (ACI 318-05) [16], and the Canadian code [21], the ultimate shear load is expressed as proportional to the square root of the concrete compressive strength. However, in the British Standards (BS 8110) [17], the Japanese code (JSCE) [20], and Zsutty's eq. [22 and 23], the ultimate shear load is expressed as proportional to the cubic root of the concrete compressive strength.

The equations presented above from five different codes of practice in addition to Zsutty's equation were used to calculate the ultimate shear loads of the tested beams. Only beams that failed in shear were considered. The experimental results were compared to the theoretical ones as shown in table 4. And Figs. 16- 19. It can be observed that the equations presented by the Egyptian code of practice (ECP-2001) [19] and Zsutty [22 and 23] well predict the ultimate shear loads of tested beams. The ECP equation reasonably predicts the ultimate shear loads for normal-strength concrete beams and high-strength concrete beams without vertical stirrups. However, in the case of high-strength concrete beams provided with stirrups, the equation overestimates the ultimate shear load by 37% in the case of a/d = 2.0, for beams provided with short columns at its ends and by 43% for beams without short columns at its ends. The same observations may be applied in the case of Zsutty's equation. It was also found that the equation presented by the Canadian code [21] is conservative in estimating the ultimate shear loads of tested beams with a difference not exceeding 29% in the case of normal-strength concrete beams and up to 32% in the case of high-strength concrete beams. However, it can be observed that the equations presented by the ACI code [16] and the British Standards [17] are extremely conservative in estimating the ultimate shear loads of tested beams, especially in the case of high-strength concrete beams without vertical stirrups.

5. Summary and conclusions

Detailed literature review was conducted including all available previous experimental and theoretical investigations on the behavior and shear strength of reinforced high-strength concrete beams. The strength level of commercially available high-strength concrete is being increased. The mechanical properties of concrete changes as the compressive strength of concrete increases, therefore additional information is necessary to understand the structural behavior of high-strength concrete members such as beams. Although the end anchorage of tension reinforcement seriously affects the structural behavior of reinforced concrete beams, however no research efforts found in the literature were directed towards the study of such anchorage in reinforced high-strength concrete beams. It is important to provide reserve strength in the end anchorage length in order to maintain beam ductility since failure in end anchorage is brittle. It is also important to study the end anchorage at the beam end supports since at this region the bending moment is equal to zero whereas the shearing force is high. Although there are significant efforts to rationalize the ultimate shear strength of reinforced concrete beams, however the equations presented in some international codes of practice are based on empirical formulas. Such formulas were originally developed using experimental data from testing normal strength concrete beams. Furthermore, some of these equations ignore the effect of some significant parameters such as: the ratio of bottom longitudinal reinforcement and the effect of the shear span-to-depth ratio (a/d). This paper presents results from an extensive experimental study including the fabrication, instrumentation, and testing to failure thirty-two simply supported reinforced concrete beams. Eight beams were made from normal-strength concrete whereas twenty-four beams were made from high-strength concrete. The main objective of the study was to investigate the

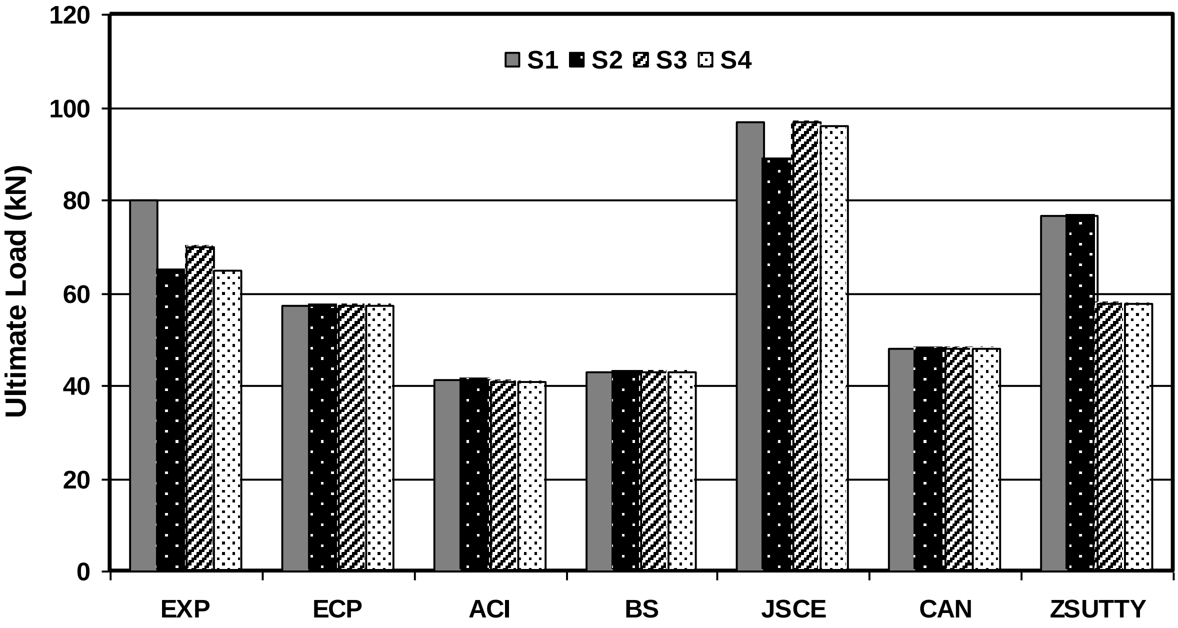

Fig. 16. Experimental ultimate shear loads versus code predictions for tested beams in group “N”.

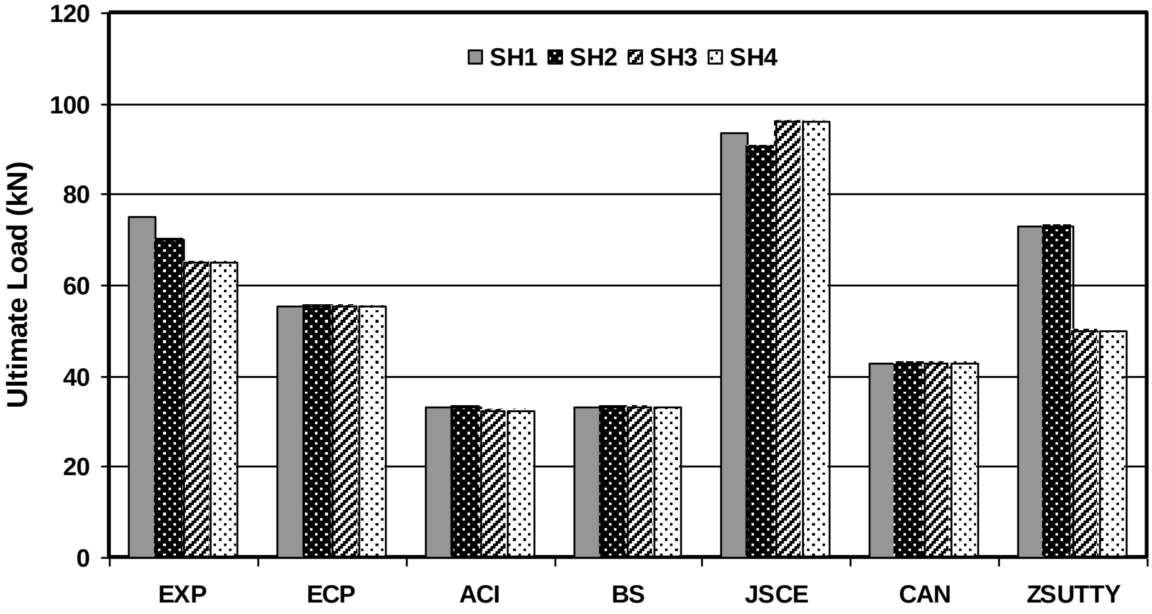

Fig. 17. Experimental ultimate shear loads versus code predictions for tested beams in group “H1”.

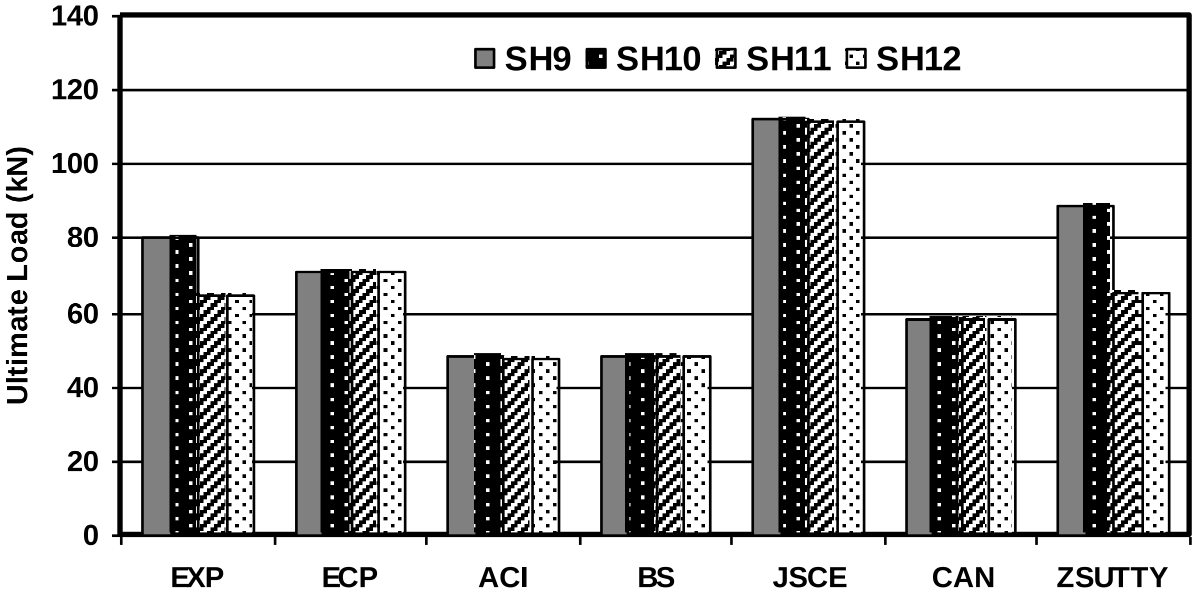

Fig. 18. Experimental ultimate shear loads versus code predictions for tested beams in group "H2".

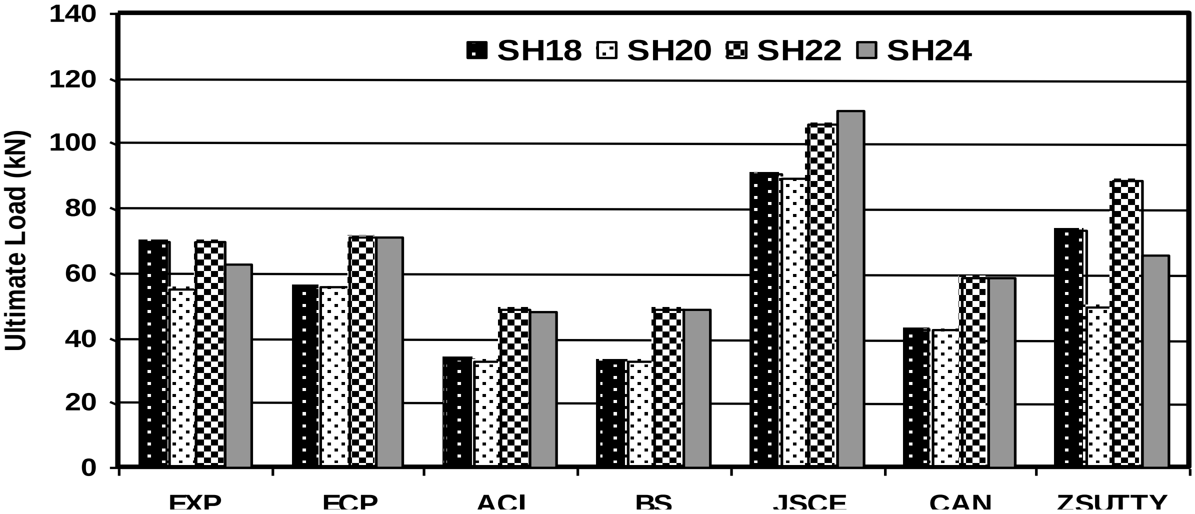

Fig. 19. Experimental ultimate shear loads versus code predictions for tested beams in groups "H3 and H4".

behavior and shear strength of reinforced concrete beams with or without end anchorage. The effect of other significant parameters were also considered such as: concrete strength, shear span-to-depth ratio, the presence of vertical stirrups; and the presence of short columns at beam ends. Finally, the experimental results for the ultimate shear failure loads of tested beams were compared to the results obtained from some international codes of practice and other equations found in literature. The codes examined were: the Egyptian code; the ACI code; the British Standards; the Japanese code; and the Canadian code. Based on this study the following conclusions may be drawn:

1. The increase in the concrete strength resulted in a significant decrease in the deflection in the elastic range, at cracking loads, and also at failure loads. The bottom longitudinal steel strain in the elastic range

was not affected by the concrete strength. However, the increase in the concrete strength resulted in a significant increase in the steel strain at failure loads for all cases of shear span-to-depth ratios and end anchorage.

2. The increase in the concrete strength resulted in a significant increase in both shear cracking loads and failure loads of tested beams. Also, failure of high-strength concrete beams was much more catastrophic and explosive than that in the case of normal strength concrete beams. In the case of high-strength concrete beams failure was associated with louder noise. However, the mode of failure of beams was not affected by the concrete strength in most cases.

3. The bottom longitudinal steel strain was affected by the presence of vertical stirrups as follows: (i) the steel strain in the elastic range decreased significantly as a result of the presence of vertical stirrups; (ii) such decrease in the steel strain becomes much less significant as the shear span-to-depth ratio increases; (iii) the steel strain at cracking loads also decreased significantly as a result of the presence of vertical stirrups; and (iv) however, the steel strain at failure loads increased significantly as a result of the presence of vertical stirrups.

4. The presence of vertical stirrups affects the ultimate failure loads of the beams when the mode of failure is a shear mode. It was also clearly observed that failure of beams provided with vertical stirrups was much more ductile compared to that of beams without vertical stirrups. There is a definite increase in the area under load-deflection and load-strain curves as a result of the presence of vertical stirrups which reflects an enhancement in the beam ductility.

5. The increase in the shear span to depth ratio (a/d) results in a significant increase in the deflection in the elastic range. Such effect is much more significant for beams provided with end anchorage than that in the case of beams not provided with end anchorage. Also, the effect of increasing (a/d) ratio on increasing the deflection in the elastic range is much more significant in the case of high strength concrete beams than that in the case of normal strength concrete beams. Furthermore, the effect of (a/d) ratio on the deflection in the elastic range becomes much less significant for beams not provided with short columns at beams ends.

6. The effects of increasing the shear span to depth ratio (a/d) on the bottom longitudinal steel strain can be summarized as follows: (i) significant increase in the steel strain in the elastic range; (ii) significant increase in the steel strain at cracking loads; (iii) significant decrease in the steel strain at failure loads for normal strength concrete beams; and (iv) significant increase the steel strain at failure loads for high strength concrete beams.

7. The increase in the shear span to depth ratio (a/d) also resulted in a significant decrease in the ultimate failure loads of beams and also resulted in a change in the failure modes. It was generally found that the effect of increasing (a/d) ratio on decreasing the ultimate failure loads was much more significant for beams provided with end anchorage than that for beams not provided with end anchorage. Also, such effect was much more significant in the case of normal strength concrete beams than that in the case of high strength concrete beams. Furthermore, such effect was less significant in the case of beams not provided with short columns at beams ends.

8. The decrease in the deflection in the elastic range as a result of the presence of end anchorage was much more significant for normal strength concrete beams than that in the case of high strength concrete beams. Such decrease in the deflection in the elastic range was more significant in the case of high strength concrete beams without vertical stirrups than that in the case of high strength concrete beams with vertical stirrups. Also, the decrease in the deflection in the elastic range was much more significant in the case of beams not provided with short columns at beam ends than that in the case of beams having short columns at beam ends.

9. Much more significant reductions were observed for the deflection at cracking loads and failure loads as a result of the presence of end anchorage. Also, it was also found that the bottom longitudinal steel strain in the elastic range was not affected by the presence of end anchorage in all case of normal strength concrete beams, high strength

concrete beams with or without vertical stirrups, and for all values of (a/d) ratio. However, the bottom longitudinal steel strain at cracking loads decreased significantly as a result of the presence of end anchorage.

10. The ultimate failure loads of the beams were marginally affected by the presence of end anchorage. The failure modes also were not affected by the presence of end anchorage except for all cases of high strength concrete beams not provided with short columns at beam ends. In these cases the failure mode changed from a shear mode to a flexural one as a result of the presence of end anchorage.
11. The Egyptian code of practice (ECP) equation reasonably predicts the ultimate shear loads for normal strength concrete beams and high strength concrete beams without vertical stirrups. However, in the case of high strength concrete beams provided with stirrups, the equation overestimates the ultimate shear load by 37% in the case of a/d = 2.0, for beams provided with short columns at beam ends and by 43% for beams not provided with short columns at beam ends. The same observations may be applied in the case of Zsutty's equation.
12. The equation presented by the Canadian code is conservative in estimating the ultimate shear loads of tested beams with a difference not exceeding 29% in the case of normal strength concrete beams and up to 32% in the case of high strength concrete beams. However, it can be observed that the equations presented by the ACI code and the British Standards are extremely conservative in estimating the ultimate shear loads of tested beams, especially in the case of high strength concrete beams without vertical stirrups.

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