Reinforced high strength concrete deep beams with web openings: experimental study

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This paper presents results from an experimental study on the behavior and shear strength of simply supported reinforced high strength concrete deep beams, subjected to two concentrated loads applied on the top of the beams. The experimental study included the fabrication and testing of ten deep beams. The effects of many important parameters on the shear strength of deep beams were studied through the experimental program. In order to investigate the structural behavior of tested deep beams deflection was measured. Also crack patterns, cracking loads, failure loads, and failure modes were monitored. Test results revealed the significant effect of the location and size of web openings on the shear strength of deep beams.. Also, the web reinforcement pattern and the height to effective span ratio significantly affected the behavior and the shear strength of deep beams. The shear strength test results of tested deep beams were compared to the theoretical predictions from current codes of practice in order to check the validity of the empirical equations presented by such codes which were originally developed and calibrated using test results from testing reinforced normal strength concrete deep beams. The comparison revealed that such presented equations are extremely conservative in predicting the concrete contribution to shear strength in the case of high strength concrete deep beams.

يقدم هذا البحث نتائج دراسة معملية أجريت على سلوك الكمرات العميقة المسلحة بسيطة الارتكاز ذات الخرسانة عالية المقاومة المعرضة لحملين مركزين موضوعين أعلى الكمرات. وقد شملت الدراسة المعملية صب واختبار عشرة كمرات عميقة. وقد تم دراسة تأثير العوامل الهامة على مقاومة الكمرات في القص. وقد تم قياس سهم الإنحاء عند منتصف البحر لجميع الكمرات المختبرة ومن ثم ايجاد العلاقة بين الحمل وسهم الإنحاء.أيضاً تم ملاحظة حمل التشريخ وحمل الانهيار وشكل الانهيار ومن ثم مناقشة السلوك الإنشائي. وقد أظهرت النتائج المعملية التأثير الفعال لمكان ومقاس الفتحات على مقاومة الكمرات العميقة في القص. أيضا شكل تسليح الجذعى ونسبة العمق للبحر الفعال تؤثر تأثيراً كبيراً على سلوك الكمرات العميقة ومقاومتها في القص. أخيراً تم مقارنة النتائج مع معادلات بعض المواصفات للتحقيق من صلاحية هذه المعادلات التي تم استنتاجها ومعايرتها باستخدام نتائج معملية من اختبار كمرات عميقة مسلحة ذات خرسانة عادية المقاومة. وقد أظهرت المقارنة أن المعادلات الخاصة بتقدير مساهمة الخرسانة في مقاومة الكمرات العميقة في القص تعطى نتائج أقل بكثير من النتائج المعملية في حالة الكمرات العميقة ذات الخرسانة عالية المقاومة.

Keywords: Codes of practice, deep beams, high strength concrete, shear strength, web openings.

1. Introduction

Reinforced concrete deep beams may exist in many structural applications such as offshore structures, transfer girders, pile caps, tall buildings, and water tanks. The depth of a deep beam is much greater than normal in relation to their span. Since the beam is short in this case, shear deformations become more important. Therefore, it is important to apply special design methods rather than normal beam theory [1]. Simply supported deep beams are defined in the Egyptian Code of Practice (ECP) [2], as those beams whose height to effective span ratio greater than 0.8. Reinforcement ratios in normal strength concrete deep beams are low and provided that the design is not limited by serviceability requirements, there is a trend to increase the performance of such beams by increasing reinforcement ratio in the case of high strength concrete deep beams [3]. Deep beams are members with special features. In such beams, plane sections do not remain plane after bending, with significant warping of the cross-sections because of high shear stresses. The resulting strain distribution is no longer linear and flexural stresses are not linearly distributed even in the elastic range, hence they are classified as disturbed regions [1].

Numerous experimental and theoretical investigations were conducted throughout the years to study the behavior and shear strength of reinforced normal strength concrete deep beams. Mau and Hsu [4] investigated theoretically the shear behavior of deep beams. They used the softened truss model theory. They concluded that by adding an effective transverse compression stress to the web shear element of a deep beam, the softened truss model is shown to predict accurately the shear strength of beams with transverse web reinforcement. Mansur and Ong [5] investigated analytically and experimentally the behavior of reinforced fiber concrete deep beams in shear. They modified the softened truss model theory for non-fibrous concrete using new stress-strain relationships for fiber concrete . They concluded that the addition of discrete steel fiber in concrete mix provides better crack control and enhances the strength and deformation characteristics of deep beams. Wang et al. [6], using the effective strength concept, concluded that the contributions of the shear strength of the deep beam by horizontal and vertical web reinforcements are a function of their ratio and the reinforcement degree. They proposed formulas to predict the ultimate shear strength of reinforced concrete deep beams. Fafitis and Won [7] proposed a finite element model for reinforced concrete deep beams. They used a quadrilateral quadratic nine-node element. The reinforcement is assumed perfectly bonded to the corresponding nodes of the concrete element. Kong et al. [8] experimentally concluded that the progressive reduction of end anchorage of the tension reinforcement rarely had any serious harmful effects to ultimate loads, maximum crack widths, or deflections due to the presence of normal pressure. Ashour and Morley [9] presented an upper-bound analysis of reinforced concrete continuous deep beams assuming the concrete as a rigid perfectly plastic material obeying the modified coulomb failure criteria. They concluded that the effect of the horizontal and vertical web reinforcement on the load capacity is mainly influenced by the type of web reinforcement and the vertical web reinforcement had more influence on the shear capacity than the horizontal web reinforcement.

1.1. Reinforced high strength concrete deep beams

Recently, high strength concrete, defined by the code of the American concrete Institute ACI 318 [10] as concrete with cylinder compressive strength greater than 40 Mpa, is being widely used in the construction industry. The effort to increase the strength-to-dead weight ratio of reinforced concrete structures has long been the topic of researchers [11]. High strength concrete may be used in achieving the economic use of space and durable structures. However, very limited research effort was directed towards the study of the behavior and shear strength of reinforced high strength concrete deep beams. Fang *et al.* [11] concluded experimentally that high strength concrete moderately deep beams were able to resist the cyclic loads to a displacement ductility factor of 3 to 4. The beams exhibited less severe spalling in the plastic-hinge zone, which led to slower strength degradation and a better energy-dissipation capability than normal strength concrete beams. Tan et al. [12] concluded that the shear span to depth ratio has a significant influence on the ultimate shear strength but only a marginal influence on the diagonal cracking strength. Tan *et al.* [13] concluded that web reinforcement can play an important role for high strength concrete deep beams. Foster and Gilbert [3] concluded that the crack patterns and failure mechanisms observed in the case of high strength concrete deep beams were similar to those observed in beams fabricated using normal strength concrete. Tan et al. [14] concluded that the ACI code predictions give the most conservative estimates of shear strength of deep beams. Darwish [1] concluded that web reinforcement increases the ultimate shear strength of reinforced high strength concrete deep beams.

In all the above-presented investigations, the chosen dimensions for the deep beams do not satisfy the definition of deep beams presented in the Egyptian Code for practice ECP [2] (height to effective span ratio greater than 0.8).

1. 2. Reinforced concrete deep beams with web openings

Sometimes, web openings have to be provided in deep beams for the purpose of access or for services. The presence of such openings may affect the behavior and the shear strength of deep beams. However, very limited investigations were found in the literature on reinforced concrete deep beams with web openings. Hassanien and Shukry [15] tested four simply supported reinforced concrete deep beams under the effect of uniform load. The considered beams have one opening along the beam span. They concluded that the presence of an opening at the mid span of the deep beam had a slight effect on its behavior and ultimate strength whereas an opening close to the deep beam support decreased the shear strength of the beam by about 30%. Siao [16] concluded that the strut and tie approach can be used for the analysis of shear strength of deep beams punctuated with web openings.

1.3. The required research

It can be seen from the available literature, that the behavior of high strength concrete deep beams is different than that of deep beams made of normal strength concrete. Reinforcement ratios in normal strength concrete deep beams are generally low since such non-flexural members are limited by the strength of concrete. There is capacity to increase the concrete strength in conjunction with increasing the reinforcement area to achieve members with higher capacities or alternatively smaller section sizes [3]. Therefore, there is a need for additional experimental data on the behavior of high strength concrete deep beams especially those having height to effective span ratio ranging between 0.4 and 0.8. Also, since the existing design methods and the empirical equations presented by different codes of practice were originally developed and calibrated using normal strength concrete deep beams test results, therefore their applicability to high strength concrete deep beams is questionable. This is not well covered in the literature especially for deep beams having a height to effective span ratio ranging between 0.4 and 0.8.

The Egyptian Code of Practice (ECP) [2] presents empirical equations for the design of reinforced concrete deep beams defined by the code as those beams having a height to effective span ratio greater than 0.8. However, all experimental investigations found in the literature were on beams having dimensions not satisfying this definition. Therefore, there is a need for experimental data on high strength concrete deep beams having dimensions compatible with such definition.

The presence of web openings in deep beams for the purpose of access or for services may affect the behavior and shear strength of deep beams. These effects are questionable and not fully understood in the literature.

1. 4. The current research

In this paper, the effect of using high strength concrete as well as the effect of the presence of web openings on the behavior and shear strength of simply supported reinforced concrete deep beams are studied. This is done through an experimental investigation including 10 deep beams. The dimensions of eight beams are chosen to satisfy the definition of deep beams presented by the ECP [2] whereas two beams have dimensions not compatible with such definition. This is done for the sake of comparison. The effect of other parameters are also studied such as: (i) web reinforcement pattern; (ii) beam height; (iii) shear span to depth ratio; and, (iv) size and location of web openings. For the tested beams, the mid span deflections were measured and hence load-deflection relationships were determined. Also, the crack pattern, failure loads, and failure modes were observed and recorded. Finally, the validity of the empirical equations presented in the Egyptian Code of practice (ECP [2]) and other building codes such as ACI 318 [10] and the Canadian Standard Association (CSA [17]) for the estimation of the shear strength of deep beams are assessed in the case of high strength concrete deep beams.

2. Experimental study

The main objective of the experimental study is to investigate the effect of using high strength concrete as well as the effect of the presence of web openings on the behavior, shear strength, and failure mode of simply supported reinforced concrete deep beams subjected to two concentrated loads applied on the top of the beam, Fig. 1. In addition, the effects of other important parameters are also studied such as: (i) web reinforcement pattern, (ii) beam height, (iii) shear span to depth ratio, (iv) height to effective span ratio; and, (v) size and location of web openings. In order to achieve these objectives, tests were carried out on 10 simply supported reinforced high strength concrete deep beams, all having a width of 120 mm and an effective span length of 1000 mm. The dimensions of eight of the tested beams were chosen to satisfy the definition of deep beams presented by the ECP 98 whereas two beams had dimensions not compatible with such definition for the sake of comparison. The tested deep beams were divided into three groups. Group (I) contains four deep beams, namely DB1, DB2, DB3, and DB4. Group (I) was directed to study the effect of using different web reinforcement patterns on the behavior and shear strength of high strength concrete deep beams. All deep beams in this group have a height of 800 mm, and a shear span 300 mm, yielding a shear span to depth ratio $a/d = 0.417$ and a height to effective span ratio $h/l_e = 0.8$. The main tension reinforcement was the same for all deep beams in this group. Such reinforcement consists of 6 bars of diameter 16 mm high tensile deformed bars yielding a tension reinforcement ratio $\rho = 1.38\%$.

Deep beam DB1 was not provided with any web reinforcement. Deep beam DB2 was provided with vertical web reinforcement only. Such reinforcement consisted of 2 bars of diameter 10 mm high tensile deformed bars placed at a horizontal spacing of 100 mm yielding a vertical web reinforcement ratio $\rho_v = 1.32\%$. Deep beam DB3 was provided with horizontal web reinforcement only. Such reinforcement consisted of 2 bars of 10 mm diameter high tensile deformed bars placed at a vertical spacing of 100 mm yielding a horizontal web reinforcement ratio $\rho_h = 1.32\%$. Deep beam DB4 was provided with both vertical and horizontal web reinforcement having the same ratio as in beams DB2 and DB3. Fig. 2 shows reinforcement details for tested deep beams group (I).

Group (II) contains three deep beams, namely DB4, DB5, and DB6. Group (II) was directed to study the effect of changing the beam height and hence changing both the shear span to depth ratio (a/d) and the height to effective span ratio (h/l_e). Deep beam DB4 had a height of 800 mm and therefore $a/d = 0.417$ and $h/l_e = 0.8$. The height was decreased for beam DB5 to 600 mm and hence a/d changed to 0.577 and h/l_e was reduced to 0.6. Again, the height was decreased for beam DB6 to 400 mm and the ratio a/d changed to 0.938 and the h/l_e ratio was reduced to 0.4.

All deep beams in group (III) contained two web openings symmetrically placed within the two shear spans in order to study their effect on the behavior and shear strength of high strength concrete deep beams. Deep beam DBO1 had two web openings 200 x 200 mm placed within the two shear spans at the mid height of the beam. The size of the openings was increased for deep beam DBO2 to 250 x 250 mm. Deep beam DBO3 had two web openings 200 x 200 mm placed within the two shear spans at a distance 250 mm from the beam top to the opening center. Deep beam DBO4 had two web openings 200 x 200 mm within the two shear spans at a distance 250 mm from the beam bottom to the opening center. The dimensions of beams in group (III) are shown in Fig. 3. The details of all tested deep beams are summarized in Table 1.

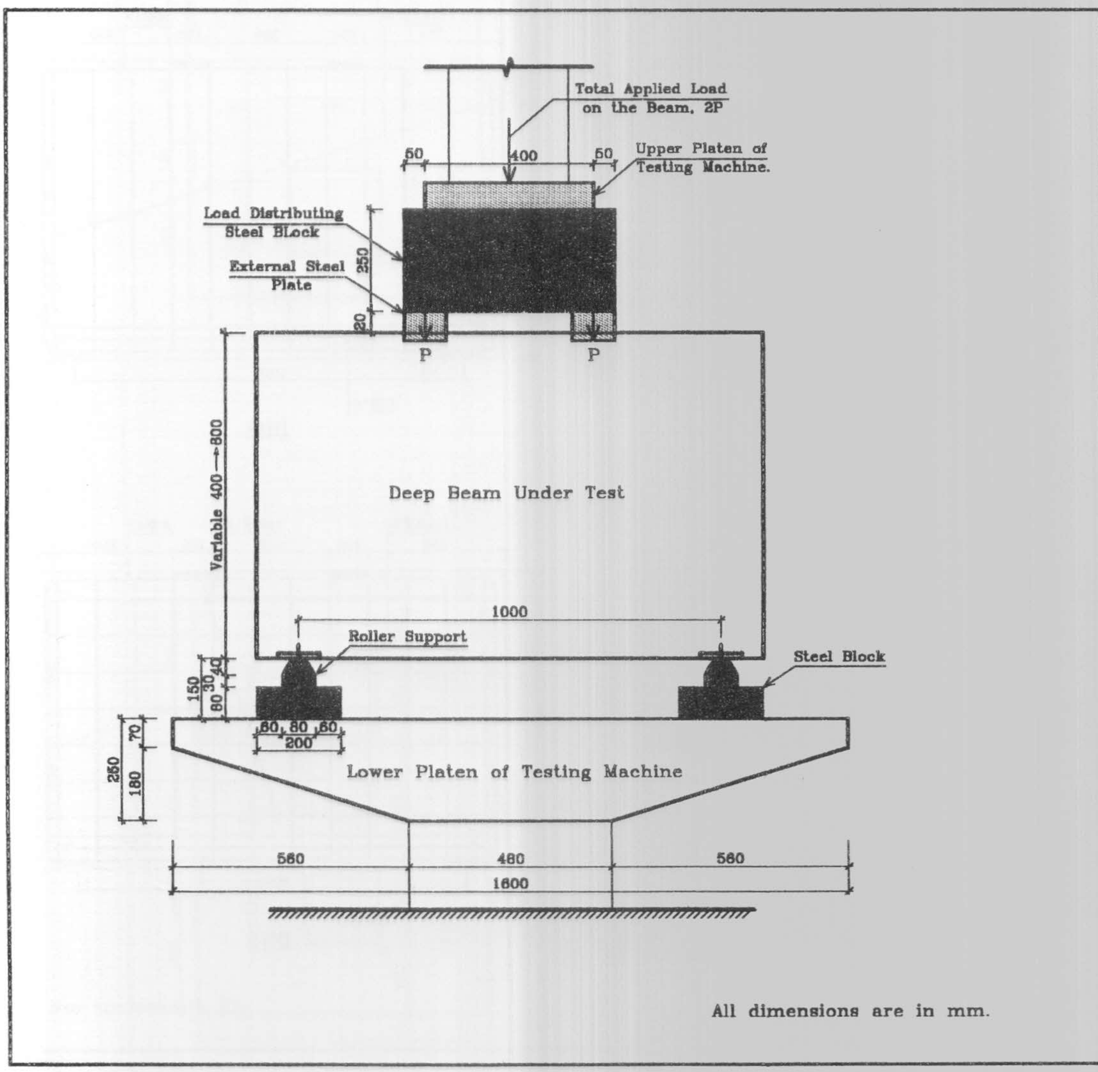

Fig. 1. Loading setup for tested deep beams.

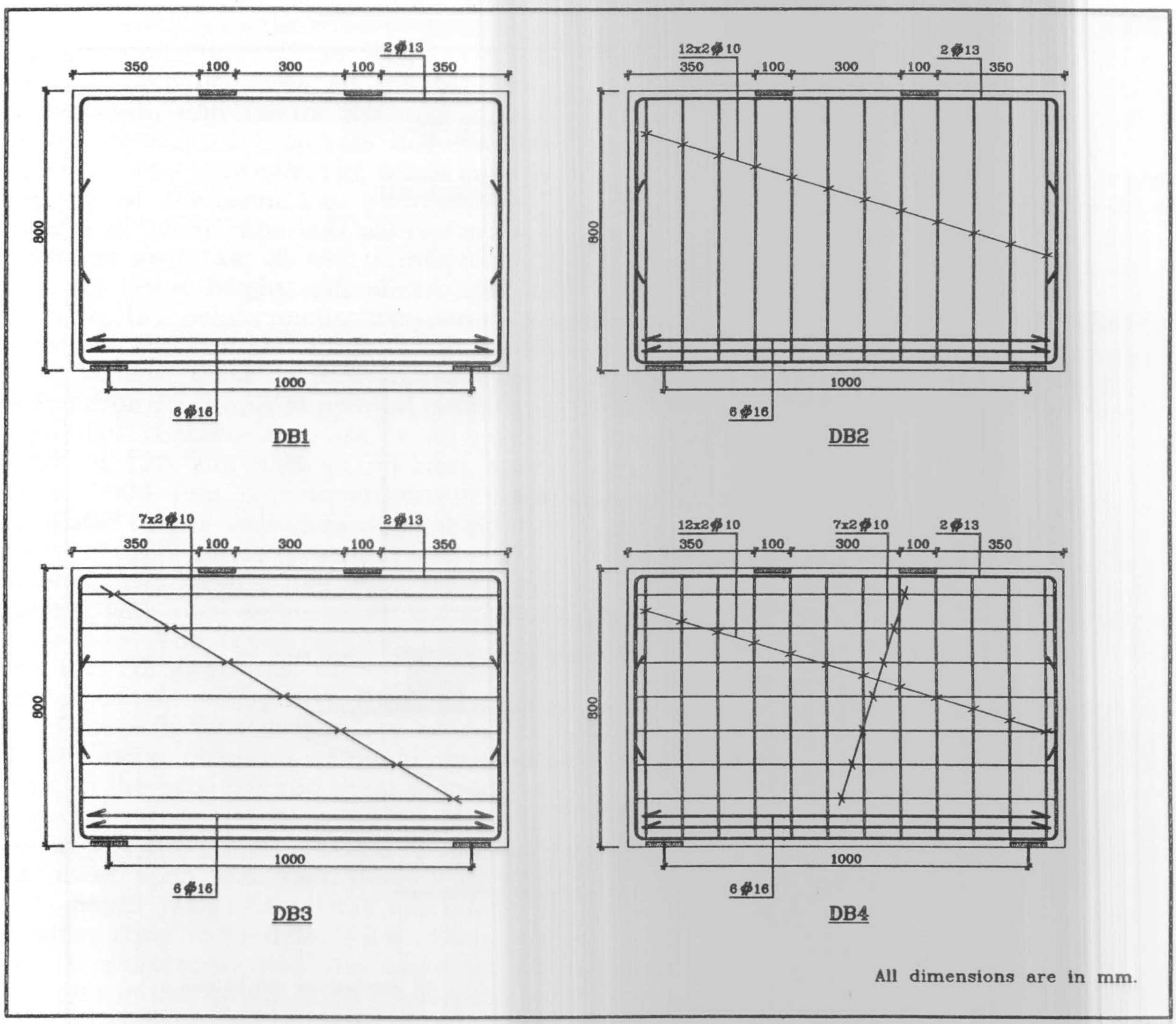

Fig. 2. Reinforcement details for tested deep beams group (I).

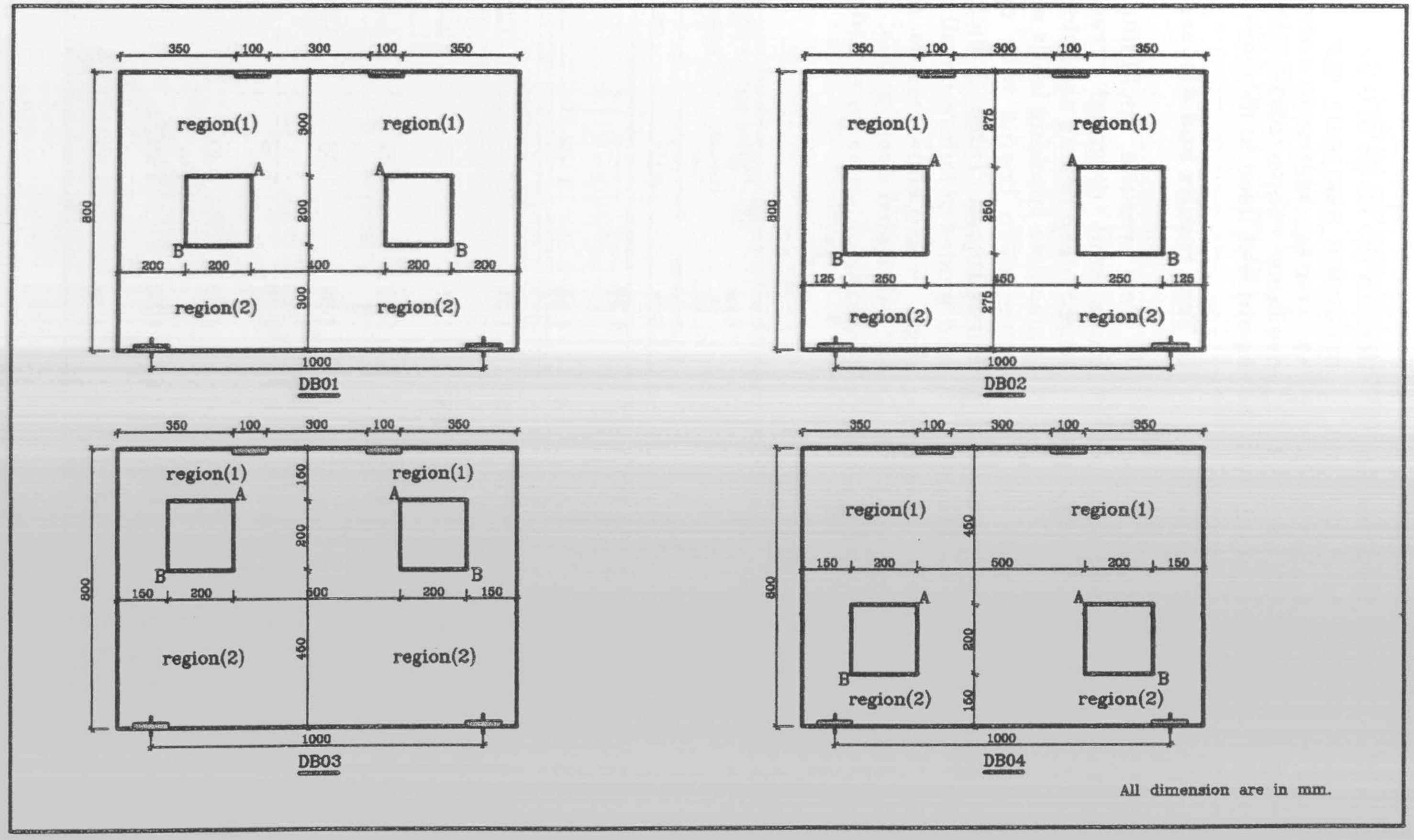

Fig. 3. Dimensions of tested deep beams with openings (group III).

For all deep beams tested, reinforcement cages were provided at the support and loading positions to prevent premature crushing or bearing failure. All the deep beams considered in the experimental study were tested under two symmetric concentrated loads, 2P, using a 3000 kN testing machine. Dial gauges were installed in order to measure the mid span deflection. The load was applied in increments of 25 kN, up to beam failure. Deflections, cracking, failure loads, and failure modes were observed and recorded.

High strength concrete was used for all deep beams tested. The cement used was locally produced commercially available ordinary Portland cement, type I. Locally available natural desert sand was used as fine aggregate. The water cement ratio, w/c was kept in the range of 0.28, pink lime stone with maximum aggregate size of 13 mm was used as coarse aggregate, and a commercially available super-plasticizer (water reducing agent) was used to increase workability.

3. Test results and discussions

Test results including flexural cracking loads and diagonal cracking loads for all tested deep beams are listed in Table 2. Table 2 also lists cracking loads around openings for tested deep beams with openings (group III). Furthermore, Table 2 includes failure loads and modes of failure for all deep beams tested. Figs. 4 to 6 show load vs. mid-span deflection for all tested deep beams. Figs. 7 and 8 show cracking patterns for tested deep beams.

Table 1 Details of tested deep beams.

Beam	Effective Span (l_e) mm	Width (b_w) mm	Height (h) mm	Shear Span (a) mm	$\frac{a}{d}$	$\frac{h}{l_e}$	Ratio Of Tension Reinforcement (ρ)%	Ratio of Vertical Web Reinforcement (ρ_v) %	Ratio of Horizontal Web Reinforcement (ρ_h) %	Concrete Cube Compressive Strength N/mm^2
DB1	1000	120	800	300	0.417	0.8	1.38	-----	-----	66
DB2	1000	120	800	300	0.417	0.8	1.38	1.32	-----	66
DB3	1000	120	800	300	0.417	0.8	1.38	-----	1.32	66
DB4	1000	120	800	300	0.417	0.8	1.38	1.32	1.32	66
DB5	1000	120	600	300	0.577	0.6	1.29	1.32	1.32	70
DB6	1000	120	400	300	0.938	0.4	1.39	1.32	1.32	70
DBO1	1000	120	800	300	0.417	0.8	1.38	1.32	1.32	67
DBO2	1000	120	800	300	0.417	0.8	1.38	1.32	1.32	67
DBO3	1000	120	800	300	0.417	0.8	1.38	1.32	1.32	67
DBO4	1000	120	800	300	0.417	0.8	1.38	1.32	1.32	67

Table 2 Experimental cracking and failure loads for tested deep beams.

Beam	Flexural Cracking Load, P_{Fcr} kN	Diagonal Cracking Load, P_{Dcr} kN	Cracking Around Openings Load, P_{Ocr} kN	Failure Load (P_{ult})* kN	Mode Of Failure
DB1	-------	225	-------	630	Crushing of Strut
DB2	-------	300	-------	790	Crushing of Strut
DB3	-------	275	-------	720	Crushing of Strut
DB4	-------	315	-------	910	Shear Compression
DB5	150	225	-------	710	Crushing of Strut
DB6	75	100	-------	395	Crushing of Strut
DBO1	-------	300	175	740	Crushing of Strut
DBO2	-------	275	150	485	Crushing of Strut
DBO3	-------	288	200	640	Crushing of Strut
DBO4	-------	275	200	475	Crushing of Strut

* Total load applied on the beam = 2P

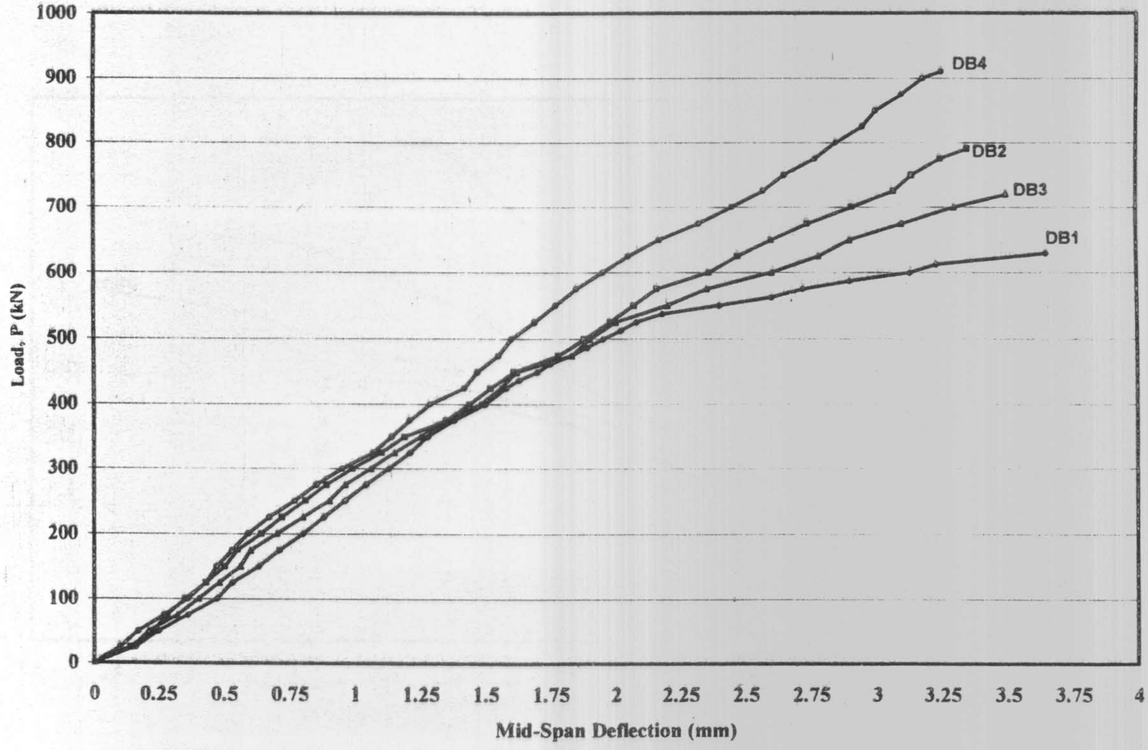

Fig. 4. Load vs. mid span dflection for tested deep beams group (I)

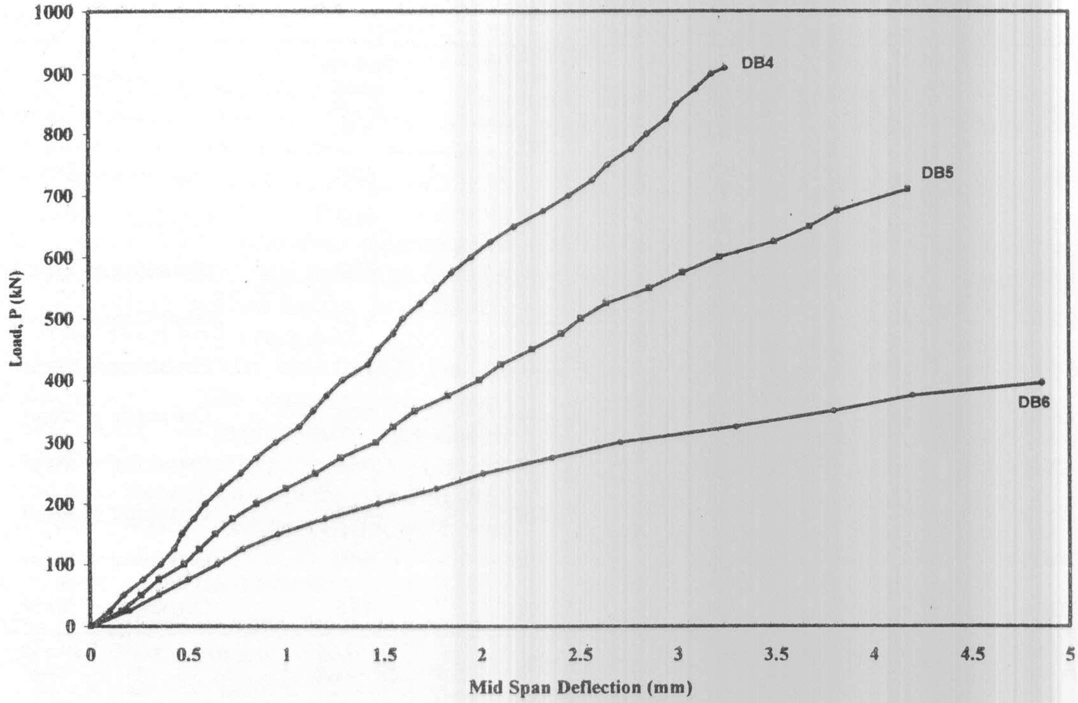

Fig. 5. Load vs. mid span deflection for tested deep beams group (II)

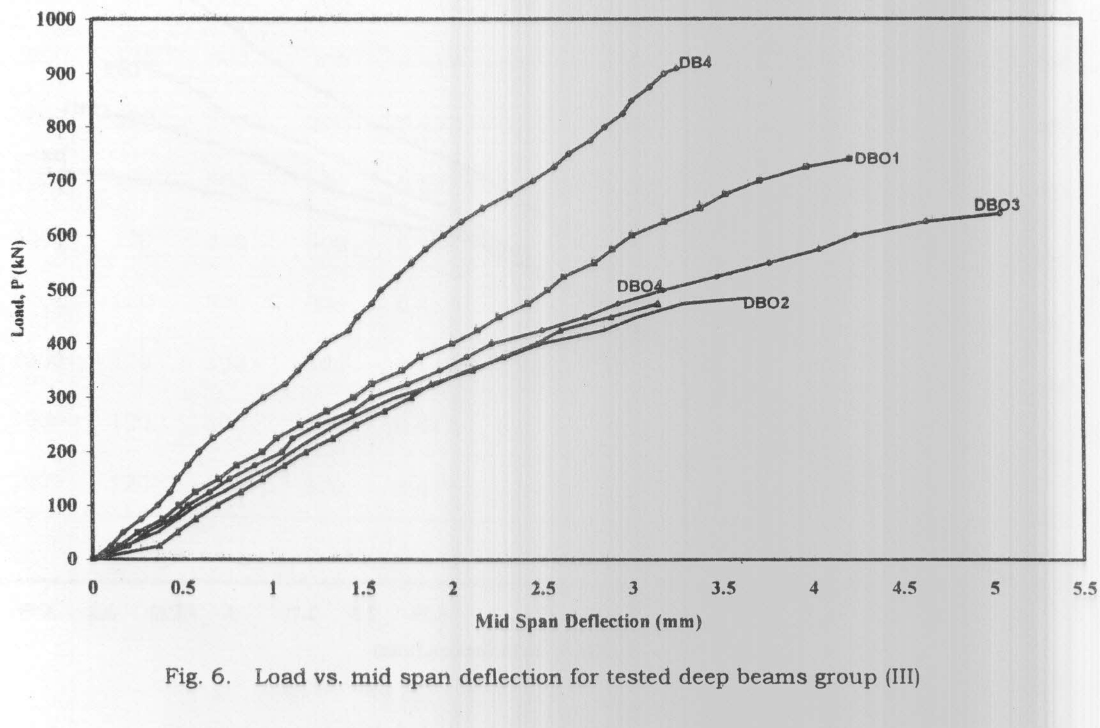

Fig. 6. Load vs. mid span deflection for tested deep beams group (III)

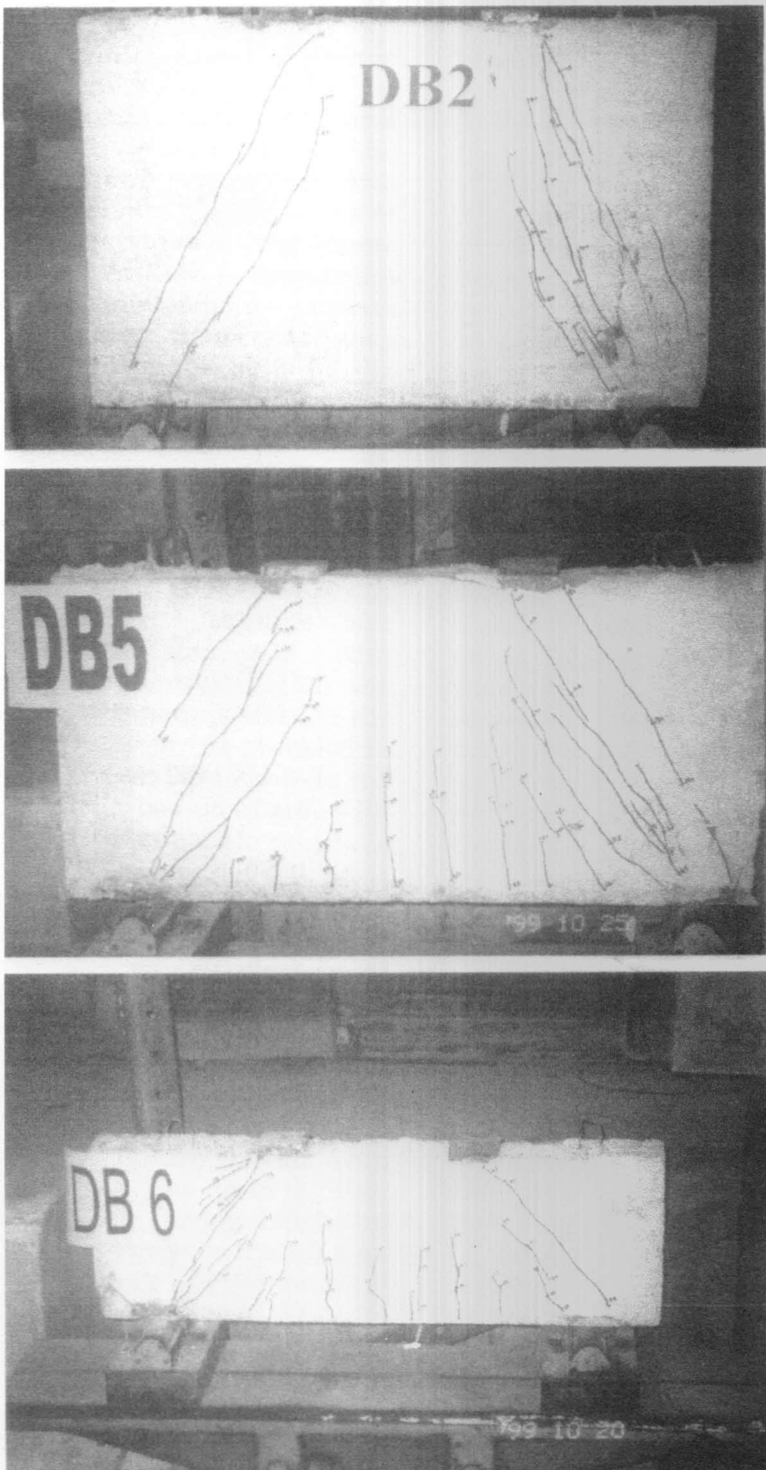

Fig. 7. Cracking patterns for tested deep beams without openings

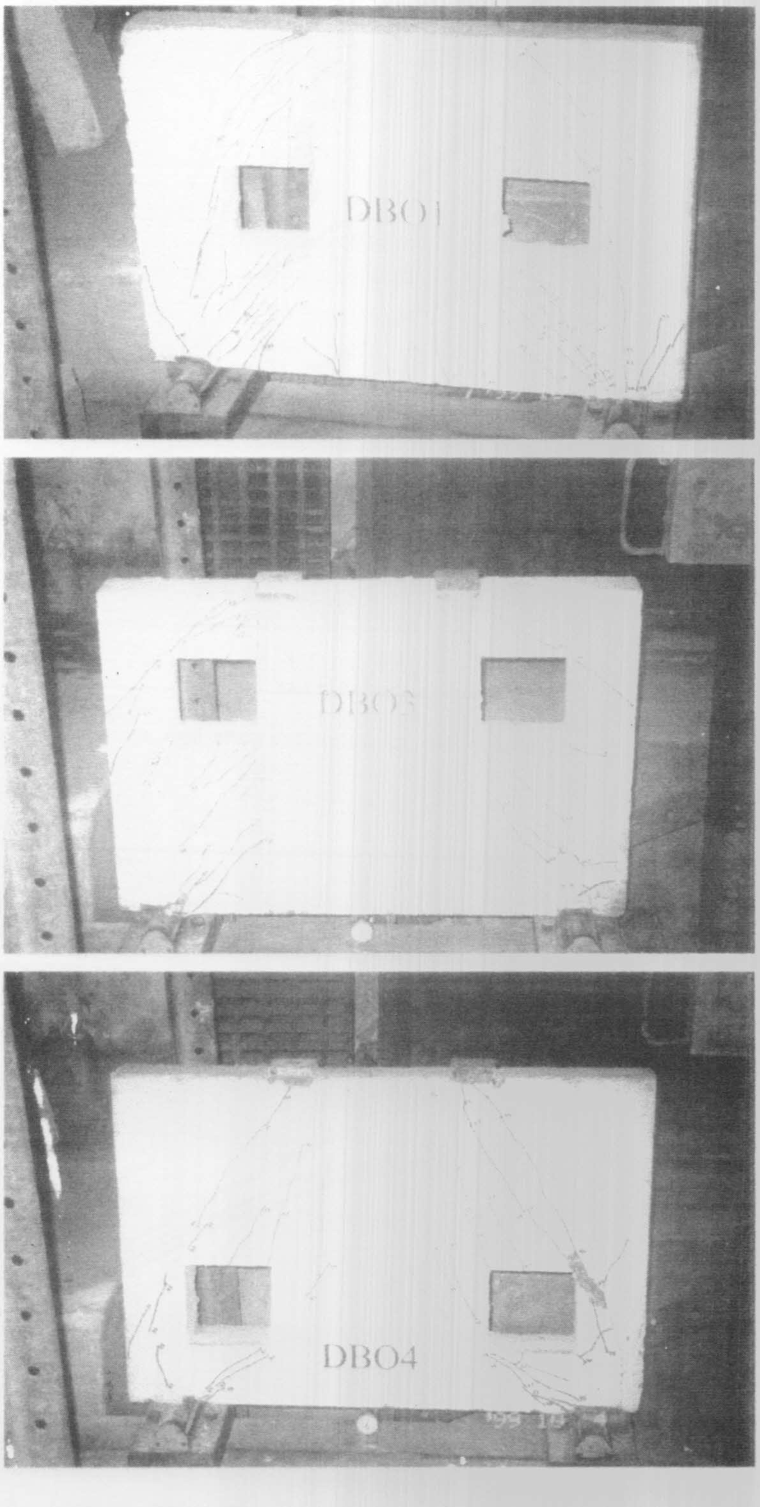

Fig. 8. Cracking patterns for tested deep beams with openings

3. 1. Effect of web reinforcement pattern

The effect of web reinforcement pattern is studied through deep beams group (I), including deep beams DB1, DB2, DB3, and DB4. Deep beam DB1 is considered as the control beam for this group, without any web reinforcement. Fig 4 shows a comparison of load vs. mid-span deflection for deep beams group (I). It is observed that: (i) deep beam DB1 with no web reinforcement exhibits greater mid-span deflection than other deep beams with web reinforcement both in the elastic and post-elastic ranges of loading. Such decrease in the mid-span deflection reflects an increase in the beams stiffness as a result of the presence of web reinforcement; (ii) vertical web reinforcement is more effective in controlling beam mid-span deflection than horizontal web reinforcement. Beam DB2 with vertical web reinforcement exhibits less deflection than deep beam DB3 with horizontal web reinforcement; and, (iii) the most effective web reinforcement pattern is the orthogonal web reinforcement as provided in deep beam DB4. Deep beam DB4 exhibits the least deflection among all beams in group (I), both in the elastic and post-elastic ranges of loading. The values of mid-span deflections at failure for deep beams DB1, DB2, DB3, and DB4 are 3.66 mm, 3.35 mm, 3.51 mm, and 3.24 mm., respectively. Therefore, deep beam DB4 with both horizontal and vertical web reinforcement exhibited the least deflection at failure. Kong et al. [18] pointed out that deflection in deep beams is not a problem if its value at failure does not exceed $l_e/200$. Since mid-span deflection at failure for all deep beams in group (I) was less than $l_e/200$, therefore, for deep beams having height to effective span ratio (h/l_e) greater than 0.8 as defined in the Egyptian Code of Practice (ECP [2]), deflection is not a problem.

For all tested deep beams in group (I) the first crack was diagonal crack started within the shear spans at the middle third of the beam height. Diagonal cracks then propagated towards the supports and the loading points. The load at which the first diagonal crack occurred is listed in Table 2 for all tested deep beams. For deep beams in group (I) the first diagonal crack occurred at a load ranging between 34 and 38% of the failure load. The first diagonal crack for deep beam DB1, without web reinforcement, occurred at 225 kN whereas such load was 315 kN for deep beam DB4 with vertical and horizontal web reinforcement indicating an effect for the presence of web reinforcement on diagonal cracking load. This is in contrast to previous investigations [13]. Also, the first diagonal crack for deep beam DB2 with vertical web reinforcement occurred at 300 kN whereas such load was 275 kN for deep beam DB3 with horizontal web reinforcement. Therefore, vertical web reinforcement is more effective than horizontal web reinforcement since it increases the cracking load. It should be noted that the web reinforcement pattern plays an important role in controlling the development rate of diagonal cracks. For deep beam DB1 without web reinforcement diagonal cracks propagated rapidly. Again, in deep beam DB4 with orthogonal web reinforcement the rate of propagation of diagonal cracks was more controlled than other deep beams in group (I). Also, vertical web reinforcement is more effective than horizontal web reinforcement in controlling the rate of diagonal cracks propagation.

Although previous investigations, [3] and [13], reported the occurrence of flexural cracks in addition to diagonal cracks, however for all tested deep beams in group (I) no flexural cracks were detected. This is probably due to the fact that in all these previous investigations deep beams tested had a height to effective span ratio less than 0.8. Such ratio h/l_e was taken as 0.8 for all tested deep beams in group (I) which satisfies the definition of deep beams presented in the Egyptian Code for Practice (ECP [2]).

Modes of failure of deep beams were classified by Tan et al. [13] into three categories as follows: (i) crushing of strut failure where more than one inclined crack exists, the concrete portion between the inclined cracks is in compression forming a concrete compression strut, which crushes under high compression; (ii) shear compression failure where the concrete portion above the upper end of the inclined crack experiences high compression. When the inclined crack further propagates upwards, the concrete above the crack fails by crushing accompanied by a loud noise; and, (iii) diagonal splitting mode characterized by a critical diagonal crack joining the loading point and the support point.

According to this classification failure modes of all tested deep beams are listed in Table 2. The Table also lists failure loads for all deep beams tested. The failure load for deep beam DB1 without web reinforcement was 630 kN. Deep beam DB1 is considered as the control beam for deep beams group (I). The failure load for DB1, $P_{ult(DB1)}$, represents the pure concrete contribution for all beams in this group. Therefore, to obtain the web reinforcement contribution to shear strength for any beam in the group $P_{ult(DB1)}$ is subtracted from the failure load of this beam. Therefore, the vertical web steel contribution (deep beam DB2) is 160 kN representing about 25% enhancement in the failure load of the beam. Such contribution was 90 kN for horizontal web reinforcement (deep beam DB3) representing about 14% enhancement in the failure load. The most effective contribution was in the case of orthogonal web reinforcement pattern (Deep Beam DB4). The failure load increased in this case by 280 kN representing an enhancement of about 44%.

3.2. Effect of height to effective span ratio (h/l_e)

The effect of height to effective span ratio (h/l_e) is studied through deep beams group (II), including beams DB4, DB5, and DB6. Deep beam DB4 is considered as the control beam for this group as it has a height to effective span ratio $h/l_e = 0.8$, which complies with the definition of deep beams presented in the Egyptian Code for Practice (ECP [2]). The shear span to depth ratio a/d was taken as 0.417 for deep beam DB4. Fig. 5 shows a comparison of load vs. mid-span deflection for beams group (II). It is observed that deep beam DB4 (h/l_e = 0.8) exhibits smaller mid-span deflection than other beams in the group having h/l_e ratio less than 0.8. Such decrease in the mid-span deflection is observed in both the elastic and post elastic ranges of loading. This is expected since increasing the ratio h/l_e results in an increase in the beam stiffness and hence a decrease in the beam deflection. The values of mid-span deflections at failure for beams DB4, DB5, and DB6 are 3.25 mm, 4.28 mm, and 4.96 mm. For beams DB5 and DB6, having a height to effective span ratio h/l_e = 0.6 and 0.4 respectively, the deflection at failure becomes close to the limit, $l_e/200$, presented by Tan et al. [12]. Therefore, deflection should be considered in the design of beams having a height to effective span ratio smaller than 0.8.

The effect of height to effective span ratio (h/l_e) on the cracking loads of beams group (II) is presented in Table 2. For deep beam DB4 ($h/l_e = 0.8$) the first diagonal crack occurred at a load 315 kN, representing about 34% of the failure load. Also, no flexural cracks were detected for deep beam DB4 up to the beam failure. However, on decreasing h/l_e ratio to 0.6 (beam DB5) the first crack was flexural crack occurred at a load 150 kN representing about 21% of the failure load, then diagonal cracks occurred later at a load 225 kN representing about 32% of the failure load. The same behavior was detected for beam DB6 with a height to effective span ratio $h/l_e = 0.4$. The first flexural crack in this case occurred at 75 kN representing about 19% of the failure load, then diagonal cracks occurred later at a load 100 kN, representing about 25% of the failure load. It should be noted that for beams DB5 and DB6 the propagation of flexural cracks stopped at a certain limit whereas diagonal cracks continued propagation leading to a pure shear failure of the beams. It should be also noted that the rate of crack propagation for deep beam DB4 ($h/l_e = 0.8$) was more controlled than other beams in group (II). The modes of failure for beams group (II) are presented in Table 2. It was found that the mode of failure was also affected by the ratio h/l_e. Deep beam DB4 ($h/l_e = 0.8$) failed in a shear compression mode whereas for beams DB5 ($h/l_e = 0.6$) and DB6 ($h/l_e = 0.4$) the mode of failure was crushing of strut.

Failure loads for beams group (II) are listed in Table 2. It is observed that such loads are significantly affected by the h/l_e ratio. The failure load decreased from 910 kN (DB4) to 710 kN (DB5) as a result of decreasing h/l_e ratio from 0.8 to 0.6. Such decrease in the failure load represents about 22% reduction in the failure load. On decreasing the ratio h/l_e again to 0.4 (DB6) the failure load further decreased to 395 kN which represents about 56.6% reduction in the failure load. Therefore, it is concluded herein that the h/l_e ratio plays an important role on controlling the behavior of deep beams.

3. 3. Effect of web openings

The effect of the presence of two symmetric square web openings, located within the two shear spans, on the behavior, shear strength, and failure mode of simply supported reinforced high strength concrete deep beams is studied through deep beams group (III), including deep beams DBO1, DBO2, DBO3, and DBO4. Deep beam DB4 (group I) will serve as the control beam for group (III) as it has the same dimensions, longitudinal reinforcement, and web reinforcement ratios, but without web openings. Fig. 6 shows load vs. mid span deflection for deep beams group (III), compared to the control beam DB4. It is observed that: (i) all deep beams in group (III), having web openings, exhibit greater deflection than deep beam DB4 without web openings, both in the elastic and post elastic ranges of loading. This is expected since the presence of web openings results in a reduction in the beam stiffness and hence increase in the beam deflection; (ii) deep beam DBO2, having two web openings 250 x 250 mm located within the two shear spans at the mid height of the beam, exhibits greater deflection than other deep beams in the group; (iii) the presence of web openings within the shear spans located vertically at the bottom third of the beam results in a significant increase in the beam deflection; and, (iv) the optimum vertical location for the web openings is at the mid height of the beam. Deep beam DBO1, having two web openings 200 x 200 mm located within the two shear spans at the mid height of the beam, exhibits smaller deflection than other deep beams in the group. On moving the openings location vertically upwards (DBO3) or downwards (DBO4), the deflection increases significantly. Therefore, it is concluded herein that if the designer is to provide web openings within the shear spans, the optimum position of such openings for deflection control will be at the mid height of the deep beam.

The presence of web openings significantly affects the cracking loads, cracking patterns, and the sequence of crack propagation. The first crack in all deep beams with openings (group III) was cracking at the openings corners (points A and B in Fig 3.). This is in accordance to other reported findings [18]. Such corners of the opening are opened by the applied load whereas the other two corners of the opening are closed by the load. The load at which such cracks occurred are listed in Table 2, referred to as cracking around openings load. It is observed that such loads were affected by the openings size and location. Such load was 175 kN for deep beam DBO1, having two openings 200 x 200 mm located at the mid height of the beam, representing about 24% of the failure load. However, on increasing the openings size to 250 x 250 mm (deep beam DBO2) the cracking around openings load was reduced to 150 kN representing about 31% of the failure load. On moving the location of the openings 200 x 200 mm upwards or downwards such load increased to 200 kN. Such load represents about 31% of the failure load for deep beam DBO3 and 42% of the failure load for deep beam DBO4. It should be noted that the propagation of cracks around openings stopped at a certain limit and the failure mode of the beams was not affected by such cracks. Diagonal cracks occurred later within regions 1 and 2 shown in Fig. 3. The diagonal cracking loads are also presented in Table 2 for all beams tested in group (III). Diagonal cracks continued propagation leading to the failure of the beams. All deep beams tested with web openings failed in a crushing of strut mode. This means that the mode of failure was affected by the presence of web openings since the control beam DB4 without web openings failed in a shear compression mode. Cracking patterns for deep beams group III are shown in Fig. 8.

Failure loads of deep beams are significantly affected by the presence of web openings. Such loads are further affected by the size and location of the openings. Significant reduction in the failure load is observed in Table 2 for deep beams DBO1, DBO2, DBO3, and DBO4 in comparison to the control beam DB4 without web openings. Such reduction was 19%, 47%, 30%, and 48% respectively. The effect of openings size may be detected comparing deep beams DBO1 (200 x 200 mm) and DBO2 (250 x 250 mm). Such comparison shows a 34.5% reduction in the failure load as a result of increasing the openings size. The effect of openings location can be concluded comparing deep beams DBO1 (openings located at the mid height of the beam), DBO3 (openings located at the upper third of the beam), and DBO4 (openings located at the lower third of the beam). All openings in the three beams have a size 200 x 200 mm. The comparison reveals that: (i) the optimum vertical position of the openings is at the mid height of the beam (DBO1); (ii) moving the openings to the upper third of the beam (DBO3) results in a 13.5% reduction in the failure load in comparison to DBO1; and, (iii) moving the openings to the bottom third of the beam (DBO4) results in a 36% reduction in the failure load in comparison to DBO1. Therefore, it is concluded herein that the worst location for the web openings is within the lower mid third of the beam and the designer should avoid placing web openings close to such location. This is in contrast to other reported findings [18].

4. Validity of codes of practice predictions

The validity of shear design equations for reinforced concrete deep beams, presented in different codes of practice was assessed using the experimental results from testing ten simply supported high strength concrete deep beams presented earlier. The equations given by the following codes of practice were examined: (i) the ACI Building code (ACI 318 [10]), (ii) the UK CIRIA Guide-2 [19], (iii) the Egyptian code of Practice (ECP [2]), (iv) the CEB-FIP code [20], and, (v) the Canadian code of Practice (CSA) [17].

The ACI code (ACI 318 [10]) presents an equation for the estimation of shear resistance provided by the concrete in reinforced concrete deep beams in the form of:

$$V_C = \left(3.5 - 2.5\frac{M_u}{V_u d}\right)\left(1.9\sqrt{f_c'} + 2500\ \frac{V_u d}{M_u}\right) b d \quad (1)$$

$$V_C < 6\sqrt{f_c'}\, b d \quad (2)$$

Where M_u and V_u = moment and shear at the critical section, d = effective depth, f_c' = cylinder compressive strength of concrete; ρ = main longitudinal reinforcement ratio, and b = beam width.

The ACI code (ACI 318 [10]) presents another equation for the estimation of the shear resistance provided by web reinforcement in deep beams in the form of:

$$V_s = \left[\frac{A_v}{S_v}\left(\frac{1 + \frac{l_n}{d}}{12}\right) + \frac{A_h}{S_h}\left(\frac{11 - \frac{l_n}{d}}{12}\right)\right] f_y\, d \quad (3)$$

Where A_v and A_h = area of vertical and horizontal web reinforcement, S_v and S_h = spacing of vertical and horizontal web reinforcement, l_n = clear span of the beam; and f_y = yield strength of web reinforcement. The ACI Eqs. (1 to 3) are applicable to deep beams subjected to top loading. Deep beams are defined in the ACI code [10] as those beams having a depth to effective span ratio greater than 0.2. The first term in Eq. (1) (3.5 - 2.5 M_u/V_u d) takes into consideration the beneficial effect of shear strength reserve of deep beams after the formation of diagonal cracks [14]. In Eq. (1), the beneficial effect of main longitudinal reinforcement on the shear strength of deep beams is taken into account in terms of the reinforcement ratio ρ. Equations (1 to 3) were developed for reinforced normal strength concrete deep beams. Table 3 presents a comparison of experimental results to the ACI code [10] predictions. The concrete contribution, vertical web reinforcement contribution, and horizontal web reinforcement contribution are investigated separately, then the total failure loads of tested deep beams are compared to code predictions. The code equations were used with all safety factors removed. It is observed from Table 3 that the ACI code predictions for the concrete contribution, (Eqs. (1) and (2) are conservative since the ratio between such prediction and the experimental result is 0.54. Therefore, the ACI equations 1 and 2 are Conservative in the case of high strength concrete deep beams. The ACI code prediction for the contribution of vertical web reinforcement Eq. (3), is also conservative. For deep beam DB2 with vertical web reinforcement, the ratio between the code prediction for vertical web reinforcement contribution to the experimental result is only 0.51. However, the ACI code prediction for the horizontal web reinforcement contribution is extremely unsafe. For beam DB3 with horizontal web reinforcement the ratio between the code prediction for horizontal web reinforcement contribution to the experimental result is about 3.68. Although, the experimental results show that the vertical web reinforcement is more effective than horizontal web reinforcement however, the ACI code underestimates the effect of vertical web reinforcement and severely overestimates the contribution of horizontal web reinforcement. Such unrealistic result from the ACI equation can be explained examining Eq. (3). The vertical web reinforcement contribution is estimated by multiplying $(f_y d A_v/12S_v)$ by a factor say $a_1 = (1 + l_n/d)$, whereas for the horizontal web reinforcement contribution the factor say $a_2 = (11 - l_n/d)$. This is unrealistic at least in the range of $d/l_n = 0.4$ to 0.8 considered in this investigation. At $d/l_n = 0.8$, the factor $a_1 = 2.25$ whereas $a_2 = 9.75$ which means that the contribution of horizontal web reinforcement is 4.33 times the contribution of vertical web reinforcement. Fig. 9 presents the variation of the vertical and horizontal web reinforcement contributions in terms of the factors a_1 and a_2 with the ratio d/l_n. The value of the ratio d/l_n considered is between 0.1 (shallow beams) and 1.0 (deep beams). The following can be observed: (i) for shallow beams ($d/l_n = 0.1$), the contribution of vertical web reinforcement ($a_1 = 11.0$) is much greater than that for horizontal web reinforcement ($a_2 = 1.0$); (ii) at $d/l_n = 0.2$, the contribution of vertical web reinforcement is equal to that for horizontal web reinforcement ($a_1 = a_2 = 6.0$); and, (iii) as the ratio d/l_n increases the contribution of horizontal web reinforcement increases whereas that for vertical web reinforcement decreases, and Eq. (3) starts to be unrealistic.

The shear resistance provided by the concrete in reinforced concrete deep beams might be calculated according to the UK-CIRIA Guide-2 [19] using an equation presented in the form of:

$$V_c = C_1 \left(1 - 0.35 \frac{x_e}{h}\right) f_t \, bh \quad . \tag{4}$$

Table 3 Comparison of test results to ACI code (ACI 318-95 [10])

Beam	Concrete contribution V_c (kN)			Vertical web Reinforcement contribution, V_s (kN)			Horizontal Web Reinforcement contribution, V_s (KN)			Total Failure load, (Pult)* KN		
	Exp.	Code	Code/Exp.	Exp.	Code	Code/Exp.	Exp.	Code	Code/Exp.	Exp.	Code	Code/Exp.
DB1	630	340	0.40	-----	-----	-----	-----	-----	-----	630	340	0.54
DB2	630	340	0.54	160	82	0.51	-----	-----	-----	790	422	0.53
DB3	630	340	0.54	-----	-----	-----	90	331	3.68	720	671	0.93
DB4	630	340	0.54	-----	82	-----	-----	331	-----	910	753	0.83
DB5	-----	252	-----	-----	73	-----	-----	227	-----	710	552	0.78
DB6	-----	163	-----	-----	64	-----	-----	135	-----	395	362	0.92

* Total load applied on the beam=2P

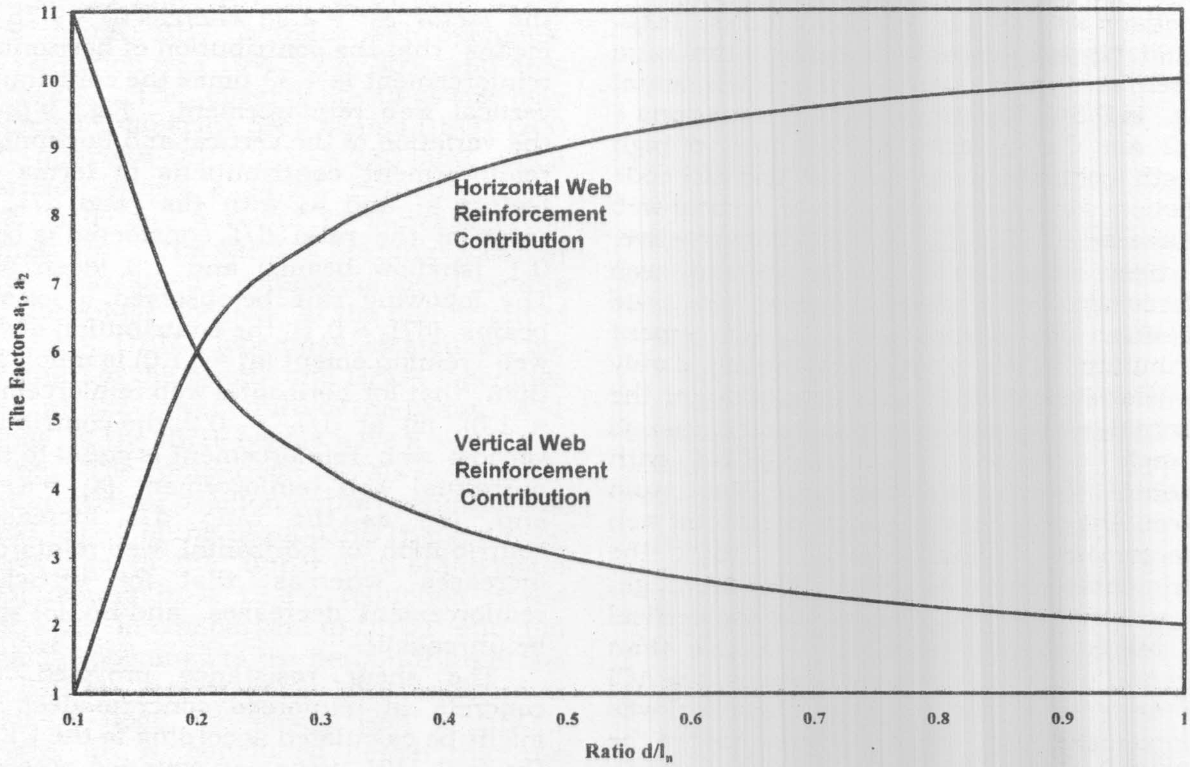

Fig. 9. Variation of vertical and horizontal web reinforcement contributions to shear strength with d/L_n ratio (ACI 318-95).

Where: C_1 = coefficient taken equals to 1.4 for normal weight concrete and 1.0 for lightweight concrete, x_e = clear shear span, h = beam height, and f_t = cylinder splitting tensile strength of concrete.

The shear resistance provided by web reinforcement in deep beams may be estimated according to the UK-CIRIA Guide-2 [19] using the following equation:

$$V_S = C2\ \Sigma \frac{100\ A_i\ y_i\ \sin^2\ \alpha_i}{h}. \qquad (5)$$

Where C_2 = coefficient taken equals to 130 Mpa for plain bars and 300 Mpa for deformed bars, A_i = area of web bar, y_i = depth at which a web bar intersects the critical diagonal crack, α_i = angle between a web bar and the critical diagonal crack. The equations presented by the UK-CIRIA Guide-2 [19], Eqs. (4) and (5) are applicable for deep beams having a height to effective span ratio greater than 0.5, therefore they are applicable to deep beams DB1 to DB5 tested in the experimental investigation. Comparing the UK-CIRIA Guide-2 predictions for the concrete contribution to shear strength of deep beams DB1 to DB4 revealed that the code predictions are less conservative than that from the ACI code. The ratio of code prediction to experimental result is 0.6 compared to 0.54 for the ACI code. However, the UK-CIRIA Guide-2 predictions for the web reinforcement contribution to shear strength (Eq. 5) are more unrealistic than the ACI code. Examining Eq. (5) and considering two bars, one of them is vertical and the other one is horizontal. The two bars have the same type, area, and depth of intersection with the critical diagonal crack (y_i). In this case, the contribution of each of the two bars will depend on the angle of intersection between the bar and the critical diagonal crack (α_i), which in turn depends on the ratio a/d. For the vertical bar, the angle α_i will be equal to $\tan^{-1}(a/d)$ whereas for the horizontal bar, the angle α_i will be equal to $(90 + \tan^{-1}(a/d))$.

Fig. 10 presents the variation of the vertical and the horizontal web reinforcement contributions, in terms of a factor say $u_1 = \sin^2(\tan^{-1}(a/d))$ for the vertical bar and another factor say $u_2 = \sin^2(90 + \tan^{-1}(a/d))$ for the horizontal bar, while changing the ratio a/d. The range of a/d chosen is between 0.1 and 2, which covers all practical cases of deep beams. Examining fig. 8, the following can be observed: (i) at low values of a/d ratios (a/d < 0.5), the UK-CIRIA Guide-2 [19] predicts that the effect of horizontal web reinforcement is much greater than that of vertical web reinforcement, for example at a/d = 0.2 the factor $u_1 = 0.039$ whereas the factor $u_2 = 0.962$ which means that the effect of horizontal web reinforcement is 25 times the effect of vertical web reinforcement, this is severely unrealistic; (ii) at a/d = 1.0, the code predicts that both the vertical and horizontal web reinforcement have the same contribution to shear strength; and, (iii) for a/d values greater than 1.0, as a/d increases the effect of vertical web reinforcement becomes greater than that of horizontal web reinforcement, for example at a/d = 1.5 the factor $u_1 = 0.692$ whereas $u_2 = 0.308$, which seems realistic according to the current experimental results and also results from previous investigations [3], [13], and [1].

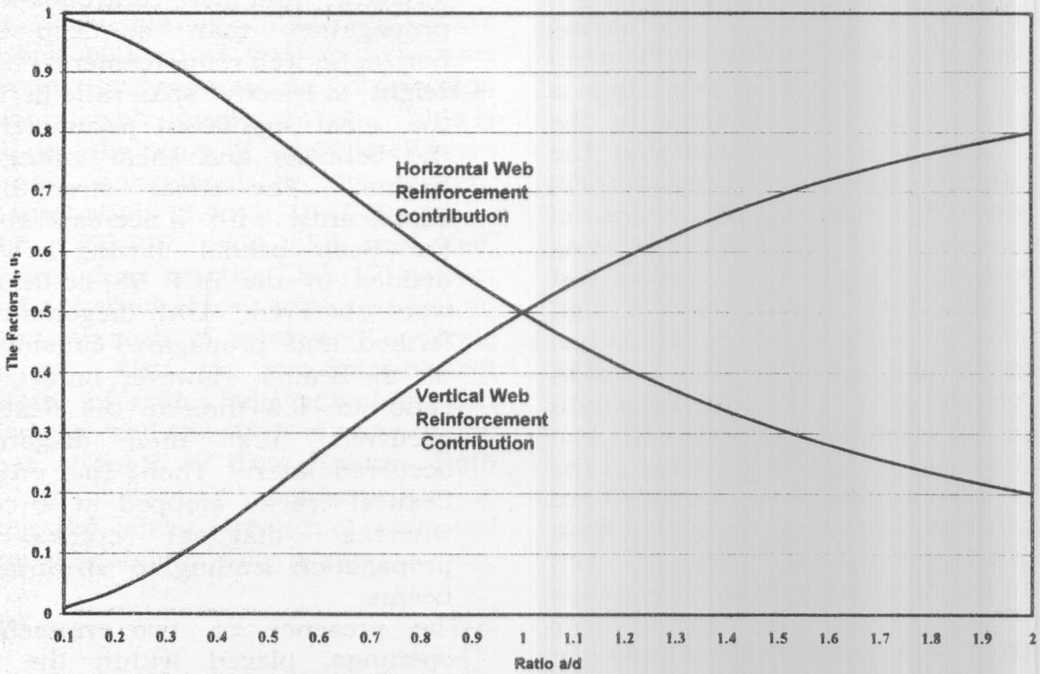

Fig. 10. Variation of vertical and horizontal web reinforcement contributions to shear strength with a/d ratio (UK-CIRIA GUIDE 2)

Results, not presented herein for brevity, showed that the equations presented by the Egyptian Code of Practice (ECP [2]) are also conservative in predicting the concrete contribution to shear strength of reinforced high strength concrete deep beams. Furthermore, the ECP [2] neglects the beneficial effect of main longitudinal tension reinforcement on shear strength of deep beams. The contribution of web reinforcement in reinforced concrete deep beams presented in the Egyptian code of Practice (ECP [2]) in a way similar to that adopted in the ACI code (ACI 318 [10]) which was presented earlier Eq. (3). Therefore, the same observations presented earlier for the ACI Eq. (3) will be applicable to the ECP [2].

The equations presented by both the CEB-FIP code [20] and the Canadian Code of Practice CSA [17] neglect the beneficial effect of web reinforcement on the shear strength of reinforced concrete deep beams. Also, the two codes neglect the effects of the main longitudinal tension reinforcement and the effect of a/d ratio on the shear strength of deep beams. Both codes are extremely conservative in predicting the shear strength of reinforced high strength concrete deep beams.

5. Summary and conclusions

Detailed literature review was conducted for the previous experimental and theoretical investigations on reinforced concrete deep beams. A lack of information was observed regarding the behavior of high strength concrete deep beams especially those having height to effective span ratios ranging between 0.4 and 0.8. The effect of web openings is questionable and not well covered in the literature. Also, it was observed that the existing design methods and the empirical equations presented by current codes of practice were developed and calibrated using normal strength concrete deep beams test results, therefore their applicability to high strength concrete deep beams is questionable. An experimental program was conducted in this paper on simply supported high strength concrete deep beams, subjected to two concentrated loads applied on the top of the beams. The experimental study included ten deep beams. The variables considered were size and location of web openings, web reinforcement pattern, and height to effective span ratio. The experimental results for shear strength were compared to current codes of practice predictions. Based on this study the following conclusions can be drawn:

1-Web reinforcement pattern significantly affects the behavior and shear strength of high strength concrete deep beams. The most effective web reinforcement pattern is the orthogonal pattern. Deep beams having such reinforcement pattern exhibited the least deflection both in the elastic and post-elastic ranges of loading. Also, deep beams having orthogonal reinforcement pattern had greater cracking load and shear strength than beams having other reinforcement patterns.

2-Web reinforcement pattern significantly affects the rate of crack propagation and failure mode of high strength concrete deep beams. Such rate was more controlled in the case of deep beams having orthogonal web reinforcement pattern. Also, a deep beam having orthogonal web reinforcement pattern failed in a shear compression mode whereas in the case of deep beams having different patterns the failure mode was crushing of strut.

3-Vertical web reinforcement is much more effective than horizontal web reinforcement. A deep beam with vertical web reinforcement exhibited less deflection, greater cracking load, greater shear strength, and more controlled rate of crack propagation than a deep beam with horizontal web reinforcement.

4-Height to effective span ratio (h/l_e) is one of the most significant parameters affecting the behavior and shear strength of deep beams. The shear strength decreases significantly with a decrease in such ratio. For deep beams having $h/l_e = 0.8$ (as defined by the ECP 98) no flexural cracks were observed. Only diagonal cracks were formed and propagated causing the failure of the beams. However, on decreasing h/l_e ratio to 0.6 then to 0.4 flexural cracks occurred first then diagonal cracks occurred later. Then, the propagation of flexural cracks stopped at a certain limit whereas diagonal cracks continued propagation leading to shear failure of the beams.

5-The presence of two symmetric square openings, placed within the two shear spans, significantly affects the behavior and shear strength of reinforced concrete deep beams. Up to 48% reduction in the shear strength was observed in the case of deep beams with openings in comparison to the shear strength of a deep beam without openings. Also, mid-span deflection increased significantly as a result of the presence of web openings.

6-If the designer is to provide web openings within the shear spans the worst location for it is within the lower third of the beam and the designer should avoid placing openings close to such location. Also, the optimum position for such openings for deflection control is at the mid height of the deep beam.

7-The equations presented by both the ACI 318 [10] and the UK-CIRIA Guide-2 [19] is extremely conservative in predicting the concrete contribution to shear strength of deep beams. Both equations were developed and calibrated using test results from testing reinforced normal strength concrete deep beams. The equations need revisions to make it applicable in the case of high strength concrete deep beams.

8-The equations presented by both the ACI 318 [10] and the UK-CIRIA Guide-2 [19] is severely inappropriate in predicting the contribution of web reinforcement to shear strength. The equations underestimate the contribution of vertical web reinforcement and severely overestimate the contribution of horizontal web reinforcement. This is observed in the range of height to effective span ratio considered in the current experimental study ($0.4 < h/l_e < 0.8$).

9-Both the CEB-FIP code [20] and the Canadian code of practice CSA [17] neglect the beneficial effect of web reinforcement on the shear strength of reinforced concrete deep beams. Also, the two codes neglect the effects of main longitudinal tension reinforcement and the effect of a/d ratio on the shear strength of deep beams. Both codes are extremely conservative in predicting the shear strength of reinforced high strength concrete deep beams.

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