Strengthening of RC beams with large openings in the shear zone

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This paper presents results from an experimental study including testing nine reinforced concrete beams in order to investigate the efficiency of external strengthening of such beams when provided with large openings within their shear zones. Firstly three beams were considered. One of these beams was solid without any openings and was considered as a control beam. The second beam was provided with one opening within the shear zone but without any strengthening and was also considered as a control beam whereas the third beam was provided with an opening at the same location and having the same dimensions. However, such third beam was internally strengthened with steel reinforcement along opening edges. Secondly, six beams provided with openings at the same location and having the same dimensions like the second and the third beams were considered. Such six beams were externally strengthened with steel plates or Carbon Fiber Reinforced Plastics (CFRP) sheets along the opening edges. It was found that both type of material used for strengthening and its configuration scheme significantly affects the efficiency of strengthening in terms of beam deflection, steel strain, cracking, ultimate capacity and failure mode of the beam. Test results revealed that the efficiency of external strengthening of beams with openings increased significantly when such strengthening was applied to both inside and outside edges of the beam opening than that in the case of strengthening the outside edges only. Furthermore, it was found that using steel plates for strengthening beams with openings is much more efficient than that in the case of CFRP sheets. Using steel plates not only restored the beam full shear strength but also changed the mode of failure from shear mode to flexural one. Finally, theoretical analysis was performed for all tested beams with openings in order to calculate the ultimate shear force carried by such beams. Equations presented by Egyptian code in addition to empirical formulas found in the literature were used to perform the theoretical analysis. Good agreement was observed between the theoretical results and the experimental ones.

هذا البحث يعرض نتائج دراسة معملية لعدد تسع عينات من الكمرات الخرسانية المسلحة وذلك بغرض دراسة تأثير التقوية الخارجية لهذه الكمرات عندما تكون مزودة بفتحات في منطقة القص. في المرحله الأولي تم إعتبار ثلاثة كمرات إحداهما بدون أي فتحات لتكون كمرة مرجعية والثانية مزودة بفتحة في منطقة القص ولكن بدون أي تقوية وتم أيضا" إعتبارها كمرة مرجعية أما الكمرة الثالثة فقد تم تزويدها بفتحة في منطقة القص في نفس المكان وبنفس ابعاد الفتحة الخاصة بالكمرة الثانية ولكن تم تسليحها داخليا" بحديد تسليح حول مكان الفتحة. في المرحله الثانية تم إعتبار عدد ستة كمرات خرسانية مزودة بفتحات في نفس المكان وبنفس الأبعاد الموجودة في الكمرة المرجعية الثانية ولكن تم تقوية الفتحات لهذه الكمرات باستخدام أشكال مختلفة من كل من الألواح المعدنية ولفات ألياف الكربون. أوضحت النتائج كفاءة استخدام هذه المواد في التقوية الخارجية لهذه الفتحات وذلك من خلال نتائج الترخيم والإنفعالات الحادثة في حديد التسليح والتشرخ وكذلك كل من الحمل الأقصي وشكل الإنهيار. أوضحت النتائج أيضا" أن كفاءة التدعيم للكمرات ذات الفتحات تكون أعلي في حالة تدعيم الفتحات من الداخل والخارج عنها في حالة التدعيم من الخارج فقط. وقد أوضحت النتائج أيضا" أن استخدام الألواح المعدنية في تدعيم الفتحات أفضل من استخدام لفات الياف الكربون وذلك ليس فقط لأنها تحتفظ بكفاءة عالية للكمرة ولكن أيضا " لأنها تغير شكل الإنهيار من انهيار القص الي إنهيار الإنحناء. أخيرا" تم عمل دراسة نظرية لحساب حمل القص الأقصي للكمرات ذات الفتحات وذلك باستخدام معادلات الكود المصري لتصميم وتنفيذ المنشآت الخرسانية الي جانب استخدام بعض النماذج النظرية الموجودة في الأبحاث السابقة وقدأثبتت نتائج الدراسة النظرية التوافق الجيد بين نتائج الدراسة النظرية والنتائج المعملية.

Keywords: Beams with openings, Carbon fiber reinforced plastics, Reinforced concrete, Shear strength, Steel plates, Strengthening

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1. Introduction

Generally, accommodating essential services to existing buildings like telephone lines, electricity cables, natural gas pipes, computer networks and air conditioning pipes needs the creation of utility ducts. Because floor height is in most cases limited, it is necessary to pass these ducts through transverse openings in the floor beams webs. Such openings may be square, rectangular or circular. Circular openings are commonly used for telephone lines, electricity cables, natural gas pipes, and computer networks whereas square or rectangular openings are used for air conditioning ducts. The presence of an opening in the web of a reinforced concrete beam leads to many problems in the beam behaviour such as: (i) reduction in the beam stiffness; (ii) excessive cracking; (iii) excessive deflection; and (iv) reduction in the beam strength [1]. Furthermore, the presence of openings leads to a high stress concentration at the opening corners. The reduction in the beam stiffness as a result of the presence of openings changes the beam forces behaviour to a more complex one [1] and leads to a considerable redistribution of the internal forces especially in the case of continuous beams [2,3].

The degree of change in the beam behaviour as a result of the presence of an opening depends on many factors such as; shape and size of the opening; position of the opening; and type of loading. However, it was found that the size of opening is the most important parameter that affects the beam behaviour. Openings were classified according to their size into two main categories: small openings [4,5] and large openings [6,7]. Mansur and Hasnat [4] considered circular and square openings as small ones. Somes and Corely [6] suggested that a circular opening may be considered large when its diameter exceeds 0.25 times the depth of the beam web. Although no clear-cut line was found in the literature between the two categories, Mansur and Tan [8] suggested that the classification of an opening to either small or large depends on the effect of such opening in the structural response of the beam. An opening may be considered small when the presence of such opening does not change the beam type behaviour. On the other hand, when the presence of the opening leads to change in the beam type behaviour to a frame type behaviour then such opening will be considered as large one.

The presence of an opening through the web of a beam results in dividing the beam element at the location of the opening into two members. One of these members is located above the opening (upper chord) whereas the other is located below the opening (lower chord). It was found that two modes of failure always take place for beams provided with large openings. The first mode of failure is a shear failure mode takes place in the upper and lower chords. However, the second mode of failure takes place as a result of the formation of subsequent plastic hinges at the four corners of the opening [8].

Strengthening of beams provided with openings depends mainly on whether those openings are pre-planed or post-planed. In the case of pre-planed openings, both the upper and lower chords are designed and reinforced to resist the internal forces that they are subjected to. The design of such chords depends on the position of opening and the type of loading. Also, special steel reinforcement is provided around the opening edges and extended with enough length beyond the opening corners to resist the stress concentration. Both the reinforcement provided for the upper and lower chords and the special reinforcement provided around the opening are considered as internal strengthening. On the other hand in the case of post-planed opening created in an existing beam, external strengthening will be necessary for the upper and lower chords and also for the opening corners and edges to protect it against stress concentration.

Different materials in several studies found in the literature were used for the external strengthening of reinforced concrete beams deficient in shear [9-11] or flexure [12-14] or both [15]. The materials used for strengthening were either traditional steel plates or fiber composites. Many types of fiber composites were used such as Glass fiber and carbon fiber polymers in the form of sheets or laminates. These materials were applied by bonding it to the external surfaces of the beams with different configurations and layouts. Previous studies generally revealed that the external strengthening of beams could significantly enhance their shear and flexural strength. Furthermore, such strengthening increases beam stiffness and controls the propagation of cracks. However, it was found that one of the disadvantages of external strengthening is the debonding of the externally bonded materials at their ends. This is due to the lack of anchorage and the stress concentration that controlled the failure of the strengthened beams. Comparatively, very little research efforts found in the literature were directed towards the study of strengthening of beams provided with openings. Mansur et al. [16] studied external strengthening of T-beams provided with small circular openings close to the support. The type of material used was FRP plates in the form of a truss around the position of the opening. Abu Amirah et al. [17] studied external strengthening of reinforced concrete beams having a large rectangular opening in the shear zone. CFRP sheets were used for strengthening and the effect of the aspect ratio of the opening on the beam behaviour was studied. They concluded that the depth of the opening has a great influence on the beam strength. Furthermore, they found that the application of Carbon Fiber Reinforced Plastics (CFRP) sheets around the opening could significantly improve the beam capacity.

In this paper, a detailed experimental investigation was conducted. The main objectives of the experimental investigation were: (i) to study generally the behaviour of reinforced concrete beams provided with openings within the shear zone; (ii) to investigate the efficiency of internal strengthening of beams with openings using internal steel reinforcement around the opening; and (iii) to study the reliability of external strengthening of beams with openings using either steel plates or CFRP sheets. Furthermore, the effect of strengthening scheme was studied. Four different schemes of steel plates and two different schemes of CFRP sheets were considered and the results were compared. Finally, theoretical analysis was performed in order to evaluate the internal forces created in the upper (top) and lower (bottom) chords of the opening. Moreover, the ultimate shear force carried by the upper chord of the opening was theoretically calculated using equations presented in the Egyptian code for design of concrete structures and other theoretical models found in the literature for all tested beams with openings. Theoretical results were compared to the experimental ones.

2. Experimental study

2.1. Test beams

The experimental program included testing nine reinforced concrete simply supported beams. All tested beams had a rectangular cross section of 150 mm width and 400 mm height. All tested beams had a total length of 3200 mm and a clear span of 3000 mm. The first tested beam (B1) was made solid without any openings and thus was considered as the control beam. The other eight tested beams (B2 to B9) were provided with one rectangular opening. The dimensions and location of the opening were kept the same for the eight beams. The length of the opening was 450 mm and its height was 150 mm. The openings were located within the shear zone of the beams starting at a distance of 300 mm from the support. The lower edge of the opening was located vertically at a distance 100 mm from the extreme bottom fiber of the beam. Therefore, the height of the lower chord was 100 mm and that of the upper chord was 150 mm. Fig. 1 shows the dimensions of beams with openings (B2 to B9).

The bottom reinforcement provided for all tested beams consisted of three bars diameter 16 mm high tensile steel whereas the top reinforcement consisted of two bars diameter 12 mm high tensile steel. All tested beams were provided with vertical stirrups of diameter 8 mm mild steel at a spacing 150 mm. In the case of beams with openings (B2, B4 to B9), the vertical stirrups in the lower and upper chords were in the form of (U) and inverted (U) in order to represent the case of post-planed openings.

Tested beam (B3) was internally strengthened, thus, it was provided with vertical stirrups along the upper and lower chords of its opening in addition to longitudinal and transverse steel reinforcement along its horizontal and vertical edges. Such special reinforcement around the opening of beam B-3 was designed based on the internal forces of the observed Vierendeel behaviour of chord members at the opening. Therefore, the upper chord of the opening was provided with bottom reinforcement of two bars diameter 16 mm high tensile steel and the lower chord of the opening was provided with upper reinforcement of two bars diameter 16 mm in addition to one bar diameter 12 mm high tensile steel. Furthermore, both the upper and lower chords of the opening were provided with vertical stirrups of diameter 8 mm mild steel at a spacing 50 mm. Moreover, both the inner and outer vertical edges of the opening were provided with one vertical two- branch stirrup diameter 16 mm high tensile steel. Fig. 2 shows the details of reinforcement for all tested beams.

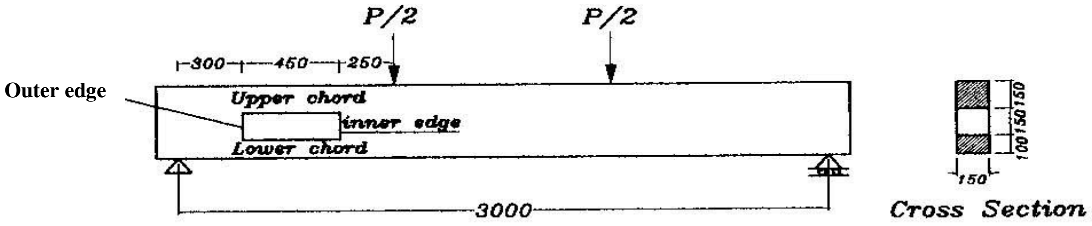
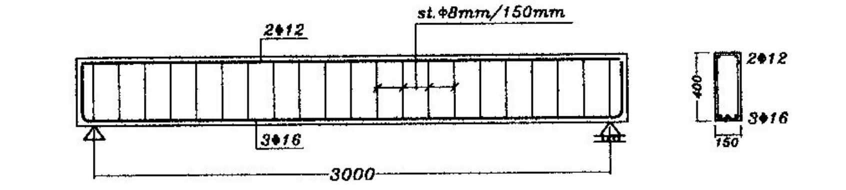
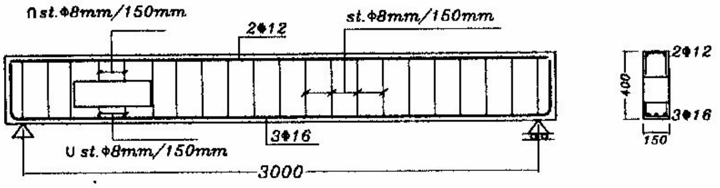


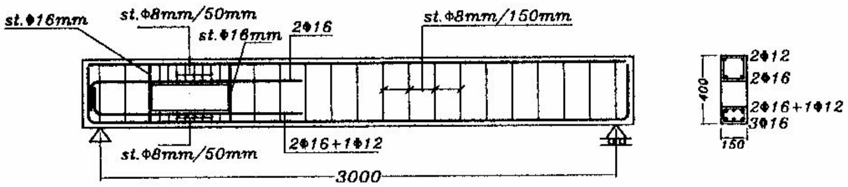
Fig. 1. Dimensions of beams with openings.



(a) Solid beam B1



(b) Beams B2,B4,........,B9



(c) Beam B3

Fig. 2. Reinforcement details of test beams.

2.2. External strengthening schemes

Two different strengthening materials were used for external strengthening of beams with openings (B4 to B9), namely steel plates or CFRP sheets. Four beams (B4 to B7), were strengthened using steel plates having a thickness of 4 mm with four different configuration schemes. Two beams B8 and B9 were strengthened using CFRP sheets with two different configuration schemes. The schemes applied for the external strengthening of the six beams B4 to B9 are presented in fig. 3 and will be explained as follows:

For tested beam B4 two steel plates with openings were bonded to the concrete surface around the opening at both sides of the beam using an epoxy adhesive. The two steel plates were bonded covering both upper and lower chords and extending to a distance 200 mm beyond the vertical edges of the opening. The same strengthening configuration was applied to beam B5. However, in this case the steel plates were bonded to the concrete using 10 mm diameter steel bolts in addition to the epoxy adhesive in order to increase the bond between the steel plates and the concrete beam. To achieve that, holes were first drilled and prepared at the positions of the steel bolts. Then the holes were filled with epoxy adhesive and the bolts were placed in the holes.

The strengthening configuration used for beam B6 was similar to that for beam B4. However, for beam B6 four steel plates were bonded to the inner sides of the opening using epoxy adhesive in addition to the two steel plates previously described for beam B4. Such inner steel plates were extended 20 mm outside the opening from the two sides of the beam Furthermore, in the case of beam B6 the steel plates placed around the opening were connected to those placed at the inner sides of the opening using steel angles of 20 mm size. Such angles were previously welded to the edges of the steel plates placed around the opening and were connected to the steel plates placed at the inner sides of the opening using 6 mm diameter bolts as shown in fig. 3. The strengthening configuration for tested beam B7 was similar to that applied for beam B6. However, in the case of beam B7, 10 mm diameter steel bolts were used to anchor the steel plates placed around the opening to the concrete in addition to the epoxy adhesive.

Beams B8 and B9 were externally strengthened using CFRP sheets with two different configuration schemes. For tested beam B8 CFRP sheets were applied around the opening at both sides of the beam. At each side of the beam two layers were applied. The first layer was bonded to the upper and lower chords of the opening and was extended 200 mm beyond the vertical edges of the opening. Such layer was placed in a way that the fibers are in the horizontal direction. The second layer had a width of 200 mm and was bonded vertically at the right and the left edges of the opening. Such layer was placed in a way that the fibers are in the vertical direction. In the case of beam B9 one layer of CFRP sheets in the form of U-shape was first bonded along the inner sides of the opening perpendicular to the opening edges and then another layer of CFRP sheets was bonded outside the opening and parallel to the opening edges similar to that used for beam B8. The U-shaped CFRP sheets bonded to the top and the bottom inner sides of the opening were extended vertically to cover the full height of the upper and lower chords. Also, the U-shaped CFRP bonded to the right and left inner sides of the opening were extended horizontally to cover a distance of 200 mm beyond the vertical edges of the opening.

2.3. Materials

The concrete mix used for casting all tested beams was made using ordinary Portland cement, natural sand, and gravel having a maximum size of 25 mm. The mix proportions were 1.0: 1.48: 2.95, respectively by weight. The water cement ratio w/c was kept in the range of 0.5. The average concrete cube compressive strength was 35 MPa. The steel bars used for tested beams longitudinal reinforcement were high tensile steel (diameter 12 and 16 mm) and the steel used for the stirrups was ordinary mild steel 8 mm diameter. The yield stress and the ultimate strength were 400 MPa and 610 MPa, respectively for diameter 16 mm and were 380 MPa and 600 MPa, respectively for diameter

12 mm. The yield stress and the ultimate strength of mild steel bars of 8 mm diameter were 250 MPa and 400 MPa, respectively. The steel plates used for the external strengthening of the openings of tested beams (B4 to B7) were of 4 mm thickness and had a yield stress of 205 N/mm^2 and ultimate tensile strength of 300 N/mm^2. High strength CFRP sheets were used for the external strengthening of the openings of tested beams B8 and B9. The thickness of the CFRP sheets was 0.13 mm and had a tensile strength and modulus of elasticity 3500 and 230000 MPa, respectively. It should be noted that these mentioned properties of the CFRP sheets were taken from the product data sheet provided by Sika Egypt Company. Two-component epoxy adhesive supplied by the same company was mixed according to the proportions recommended by the manufacturer to bond the steel plates and CFRP to the target surfaces of the tested beams.

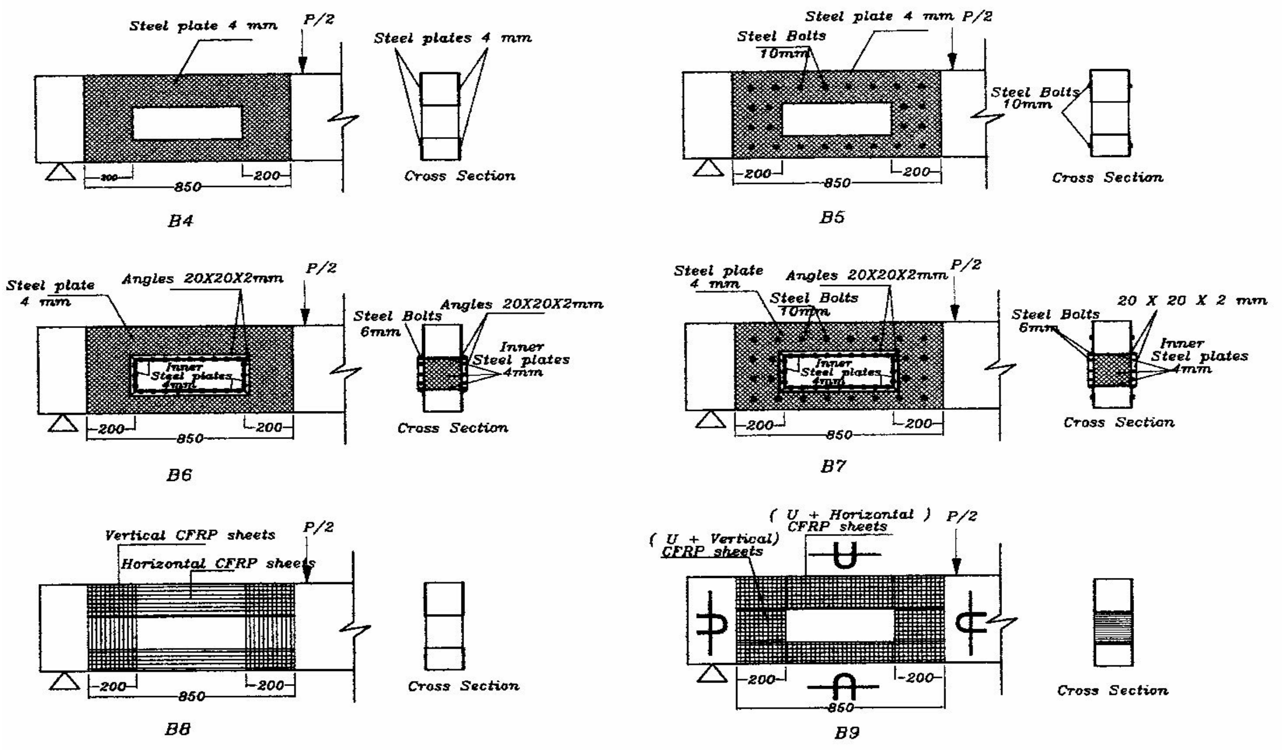


Fig 3. External strengthening schemes used for test beams.

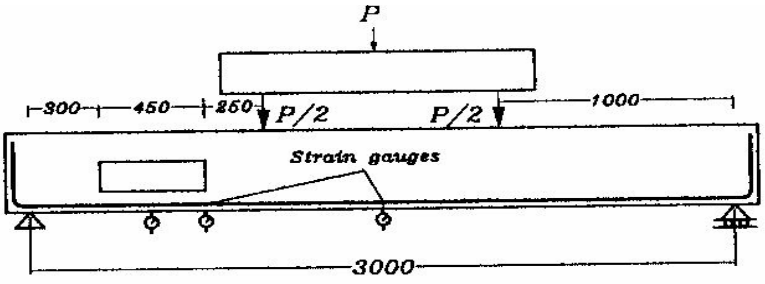


Fig. 4. Loading set-up and instrumentations of test beams.

2.4. Loading setup and instrumentations

All beams considered in the experimental study were tested to failure under the effect of two concentrated loads as shown in fig. 4. The load was applied using a hydraulic jack of 500 kN capacity and was transmitted to the beam by means of distributing steel beam. The load was monitored using an electrical load cell. Deflections of tested beams were measured at three locations by means of mechanical dial gauges. The first dial gauge was placed at the beam mid-span whereas the second dial gauge was placed directly under the inner vertical edge of the opening. The third dial gauge was placed at the middle of the opening. Electrical strain gauges of 10 mm gauge length were used to measure the strain in the longitudinal bottom flexural reinforcement at two locations. The first location was at the beam mid-span whereas the second location was directly under the inner vertical edge of the opening. Fig. 4 shows the loading setup and instrumentations for all tested beams.

3. Test results and discussions

The nine beams chosen in the current experimental program were aimed to achieve many objectives through a comparison between the behaviour of these beams. For example, testing beams B1 and B2 revealed the behaviour of un-strengthened beams with openings in comparison to that of a solid beam. Also, testing beam B3 revealed the behaviour of internally strengthened beam with opening in comparison to a solid beam B1 and un-strengthened beam with opening B2. Furthermore, testing beams B4 to B9 revealed the efficiency of different schemes of external strengthening for beams with openings. This was achieved comparing the behaviour of those beams B4 to B9 to that of a solid beam B1 and un-strengthened beam with opening B2. Also, a comparison between the efficiency of internal strengthening and external strengthening with different schemes was obtained comparing the behaviour of beam B3 to that of beams B4 to B9. Such behaviour of all tested beams will be presented in the following sections. Necessary comparisons will be made between different beams in order to achieve the objectives of the study presented above.

3.1. Cracking patterns and failure modes

Different cracking patterns and failure modes were observed for different beams. For the solid beam B1 the first flexural crack was observed at the position of the maximum positive bending moment between the two concentrated loads at a total load P = 40 kN. As the applied load was further increased more flexural cracks appeared. Then at higher load diagonal shear cracks were observed. Finally, the beam failed in a flexural mode of failure. Different behaviour was observed for the un-strengthened beam with opening B2. In this case, the first crack was observed at the opening corner adjacent to the concentrated load at a total load P = 10 kN. At a total load of 15 kN another crack was observed at the opening corner adjacent to the support. As the applied load was further increased the cracks propagated towards the load and the support and more cracks were observed at the opposite opening corners and some shear cracks were observed at the lower chord of the opening. At a total load of P = 30 kN, flexural cracks were observed on the bottom surface of the beam at the position of inner vertical edge of the opening and also at the beam mid-span. With increasing the applied load two main diagonal shear cracks were observed at the upper and lower chords of the opening and more flexural cracks were formed within the middle part of the beam. The main diagonal crack in the upper chord of the opening started very close to the position of right inner vertical edge of the opening and extended on an angle of about 45 degrees towards the lower edge of the upper chord of the opening. On the other hand, the main diagonal crack in the lower chord started also very near to the inner vertical edge of the opening and extended towards the lower edge of the lower chord approximately along the diagonal line of the lower chord. Finally, the beam failed in a shear mode at the opening along the two previously formed diagonal cracks at its chords. The failure started along the main diagonal crack of the upper chord followed by a shear failure along the main diagonal crack of lower chord.

In the case of test beam B3, the first crack was observed at the opening corner adjacent to the concentrated load at a total load P = 30 kN followed by another crack at the opening corner adjacent to the support at a total load P = 40 kN. It should be noted that the cracking behaviour of the internally strengthened beam with opening B3 was similar to that for the un-strengthened beam with opening B2. However, cracks were observed in the case of beam B3 at higher values of applied load than that of beam B2. Also, in the case of beam B3 wider band of shear cracks were observed along its chords than that in the case of beam B2. Moreover, the main diagonal crack in the upper chord of the opening of beam B3 extended approximately along the diagonal line of the upper chord with inclination angle less than that of the corresponding main diagonal crack observed at 45 degrees inclination angle. Such increase in the number of diagonal cracks and the decrease in the inclination angle of the main crack of upper chord were due to the existence of more stirrups in the upper and lower chords of the opening in the case of beam B3. Also, the increase in the number of diagonal shear cracks reflects a redistribution of stresses beyond the cracking stage due to the existence of the stirrups. Finally beam B3 failed in a shear mode along the previously formed main diagonal shear cracks at the upper and lower chords of its opening.

It should be noted that the crack propagation could not be observed along the opening for beams B4 to B9 due to the existence of materials around the openings used for the external strengthening of those beams. However, the first observed crack for those beams was a flexural crack formed on the bottom face of the beam at mid-span at a total load of P = 40 kN. With the increase of the load a wide band of flexural cracks were observed covering the middle third of the beam and also near to the inner vertical edge of the opening. Different modes of failure were observed for those beams. In the case of beams B4 and B5, failure was initiated by debonding of the end vertical steel plates near to the inner vertical edge of the opening followed by a shear mode of failure. After the removal of steel plates, two main diagonal shear cracks were observed along the upper and lower chords of the openings of those beams. The inclination of both main diagonal cracks was nearly the same as that for beam B3. A similar mode of diagonal shear failure was observed in the case of beams B8 and B9. However, in the case of test beam B8, the failure was started when the fibers separated and warped along the upper and lower chords of the opening and then followed by a sudden diagonal shear failure along main diagonal cracks formed at the upper and lower chords of the opening. In the case of beam B9, a similar behaviour of fibers warping was observed but with higher values of applied load. However the failure started when CFRP sheets debonded at the upper edge of the upper chord above the inner vertical edge of the opening and then followed by a sudden diagonal shear failure along the two main diagonal shear cracks observed at the upper and lower chords. In the case of beams B6 and B7, different mode of failure was observed due to the strengthening scheme provided for these beams. Such scheme provided an enough anchorage for strengthening of both upper and lower chords of the opening. Also such strengthening scheme increased the stiffness of both upper and lower chords against the vertical shear forces. The strengthening scheme provided for beams B6 and B7 transformed the failure mode to a flexural mode of failure rather than a shear mode of failure. Fig. 5 shows all tested beams after failure.

3.2. Efficiency of different strengthening schemes

The ultimate failure load P_u and the corresponding modes of failure are presented in table 1 for all tested beams. Examining the results presented in the table it is clear that the presence of an opening within the shear zone not only reduced the ultimate load capacity of the beam but also changed the failure mode from a flexural mode to a shear mode of failure. The reduction in the ultimate failure load of the beam was about 37 % due to the presence of a 150 mm x 450 mm opening located within the shear span.

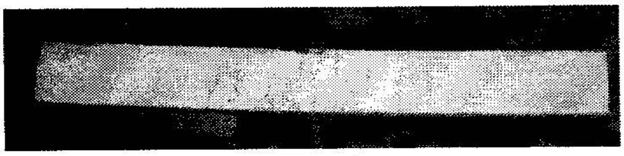
Examining the results presented in the table one can detect the efficiency of external strengthening with different materials and different configuration schemes in comparison to the efficiency of the internal strengthening. Such comparison reflects the difference in the efficiency of strengthening between pre-planed and post-planed openings. Generally, it can be observed from the results presented in the table that either internal or external strengthening of the beam opening could significantly enhance the ultimate load capacity of the beam. However, such enhancement in the ultimate capacity depends on the type of strengthening. For example, in the case of internal strengthening using internal stirrups in the upper and lower chords of the opening in addition to longitudinal and transverse reinforcement along the opening edges (Beam B3), the enhancement in the beam strength was 52 % in comparison to that for the un-strengthened beam B2. Such enhancement in the ultimate load capacity of the beam was due to the increase in the shear strength of the beam as a result of the contribution of the internal stirrups to the shear strength. It should be noted that although the ultimate load capacity of beam B3 increased, however the failure mode was a shear mode like that for the un-strengthened beam B2.

Similarly, in the case of externally strengthened beams with openings using steel plates only outside the opening (B4 and B5) the beams failed in a shear mode after debonding of plates since such scheme of strengthening did not provide enough anchor for plates. The enhancement in the ultimate load capacity of the beam was 52 % and 55 % for beams B4 and B5 respectively in comparison to the un-strengthened beam B2. A comparison between the ultimate load capacities of beams B4 and B5 revealed that the use of steel bolts for bonding the steel plates to the concrete in addition to epoxy adhesive only had a marginal effect on the ultimate load capacity of the beam. Such effect was only about 2%.

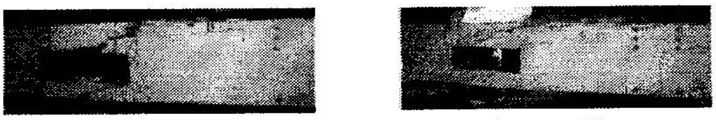
Different results were observed in the case of externally strengthened beams with openings using steel plates inside and outside the opening connected along the edges of the opening using steel angles (B6 and B7). In this case the failure took place in a flexural mode since such strengthening scheme confined the inner edges of the opening, provided enough anchor length of the steel plates around the chords and prevented debonding of steel plates. As a result the shear strength of the upper and lower chords of the opening significantly increased.

Table 1
Test Results

Test beam	Strengthening material	Strengthening scheme	Total ultimate load (P_u), kN	Strengthening efficiency (%) of B2	Mode of failure
B1	-	Solid (control)	167	-	Flexure
B2	-	No strengthening (control)	105	-	Shear
B3	Steel reinforcement	Internal	160	52	Shear
B4	Steel plates	Outside only	160	52	Shear
B5	Steel plates	Outside only + bolts	163	55	Shear
B6	Steel plates	Inside and outside	170	-	Flexure
B7	Steel plates	Inside and outside + bolts	167	-	Flexure
B8	CFRP Sheets	Outside only	120	14	Shear
B9	CFRP Sheets	Outside and inside	157	49	Shear



(a) Beam B1

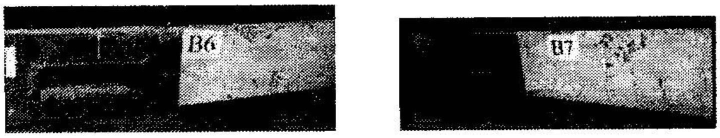


(b) Beam B2

(c) Beam B3

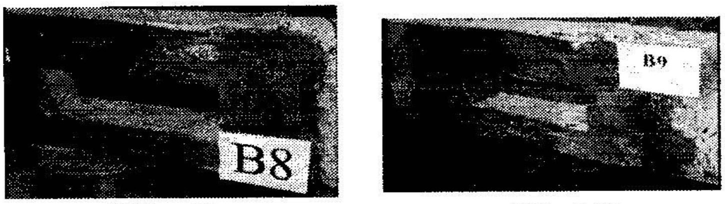
(d) Beam B4

(e) Beam B5



(f) Beam B6

(g) Beam B7



(h) Beam B8

(i) Beam B9

Fig. 5. Test beams after failure.

Results presented in the table for beams B8 and B9 externally strengthened using CFRP sheets revealed that external strengthening using CFRP sheets only outside the opening and parallel to the opening edges (B8) was less efficient than using inside U-shape CFRP sheets perpendicular to the opening edges in addition to outside CFRP sheets parallel to the opening edges (B9). Such strengthening scheme for beam B8 enhanced the ultimate load capacity of the beam by about 14 % in comparison to the un-strengthened beam with opening B2. Such limited enhancement in the ultimate load capacity of the beam may be attributed to the horizontal orientation of the fibers of CFRP sheets at the upper and lower chords of the opening, which did not provide any direct contribution to the shear strength. In this case the direction of the fibers was perpendicular to the direction of the external shear forces in the chords. However, the limited enhancement in the shear strength of the beam was due to the slight improvement in the concrete shear strength since the fibers covered the inclined shear cracks and resist some tensile stresses around the cracks. Comparatively, more enhancement in the ultimate load capacity was observed in the case of beam B9 externally strengthened inside and outside the opening. The enhancement in this case was 49 % in comparison to the un-strengthened beam B2. In this case, the vertical orientation of CFRP fibers along the upper and lower chords in the direction of the external shear forces significantly increased the shear strength of the chords. Also, the presence of U-shaped CFRP sheets in addition to the horizontal outside CFRP sheets along the chord members increased the efficiency of such scheme against debonding which lead to a higher contribution of CFRP sheets to the shear strength of the chord members.

A comparison between the ultimate load capacities of beams with openings externally strengthened with steel plates (B4 and B5) to that externally strengthened with CFRP sheets (B8) revealed that steel plates are more efficient than CFRP sheets since steel is a homogeneous material compared to the unidirectional CFRP sheets. Such homogeneous steel plates can resist not only the external shear force but also tensile stresses in any direction. Furthermore, a similar comparison between the ultimate load capacities of beams with openings externally strengthened with steel plates (B6 and B7) to the corresponding externally strengthened beam with CFRP sheets (B9) confirmed the greater efficiency of steel plates in providing enough shear strength to the opening chords than CFRP sheets. This advantage of steel plates in addition to the economical aspect may lead to a recommendation that steel plates be used for external strengthening with openings rather than CFRP sheets. It is also recommended that the engineer should take into consideration the following when designing external strengthening for a beam with opening: (i) providing enough shear strength to the chords of the opening; and (ii) extending the strengthening material along and beyond the opening corners to overcome the stress concentration and to prevent the formation of plastic hinges at corners.

3.3. Deflections

Fig. 6 shows load-mid-span deflection relationships for all tested beams. Comparing the deflection for beams B1 and B2 revealed a significant increase in the mid-span deflection for beam B2 than that for beam B1. This is due to the decrease in the stiffness of beam B2 as a result of the inclusion of the opening. It can be also observed from the figure that the load-deflection behaviour of all strengthened beams with openings is similar to that of the corresponding solid beam B1 within the elastic range of loading. However, in the post-elastic stage, strengthened beams with openings showed significant deviations in their load-deflection behaviour. The following can be observed: (i) Beam B8 strengthened externally with CFRP sheets only around the opening and parallel to the opening edges had the least stiffness and the least ductility among all strengthened beams; (ii) external strengthening of beams with openings resulted in a much more significant increase in the beam stiffness than that in the case of internally strengthened beam B3; (iii) beams externally strengthened inside and outside their openings showed an increased stiffness and ductility over those strengthened only outside the opening; (iv) external strengthening using steel plates is much more efficient than external strengthening using CFRP sheets; and (v) the use of steel bolts for bonding steel plates to concrete in addition to epoxy adhesive resulted in a decrease in the beam stiffness.

Figs. 7 and 8 show load-deflection relationships for all tested beams with openings at the inner vertical edge and at the middle of the opening, respectively. It is clear from the figures that the external strengthening applied outside only or outside and inside the opening could significantly increase the beam stiffness at the opening compared with the unstrengthened beam B2. Moreover, external strengthening of the opening is more efficient than internal strengthening of the opening in controlling the beam deflection at the opening

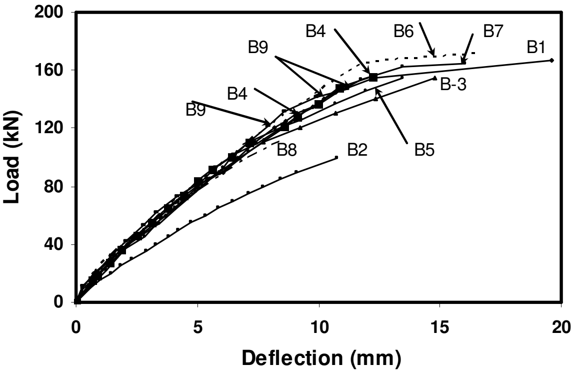


Fig. 6. Load-deflection relationships at mid-span.

and hence increasing the beam stiffness. This may be attributed to the gain of additional inertia due to the composite action induced by the presence of the external material bonded to the concrete surface which leads to an overall higher stiffness of the beam compared to the case of internal steel reinforcement. Furthermore, it can be observed from the figures that external strengthening using steel plates is much more efficient than that using CFRP sheets. This is in general due to the difference in nature between the two materials. In the case of CFRP sheets, fibers are oriented in one direction and to increase the efficiency of such fibers around the opening two layers of CFRP sheets were applied in two perpendicular directions, thus, the material could work in these directions to resist both shear and flexural stresses along the opening in addition to the stress concentration at the opening corners. Comparatively, a steel plate is a continuous homogeneous material and thus it can successfully resist both shear and flexural stresses along the opening as well as the stress concentration at opening corners. The figures also revealed that the externally strengthened beam using CFRP sheets only around (outside) the opening and parallel to the opening edges (B8) had the highest deflection and lowest stiffness among all other externally strengthened beams. Moreover, it is clear from the figures that external strengthening applied inside and outside the opening is much more efficient than that applied outside the opening only. Strengthening applied inside and outside the opening provides better anchorage along the chord members that helps increasing shear strength and also provides sufficient resistance to the stress concentration at the opening corners.

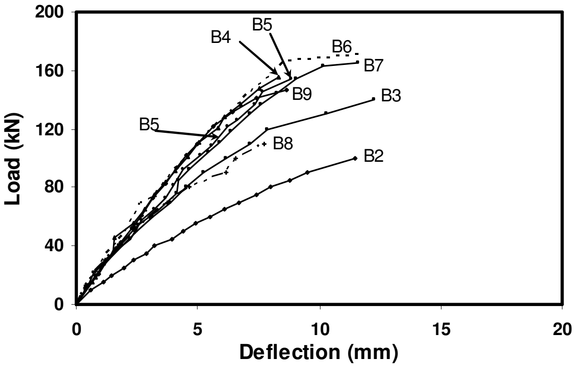


Fig. 7. Load-deflection relationships at the inner edge of the opening.

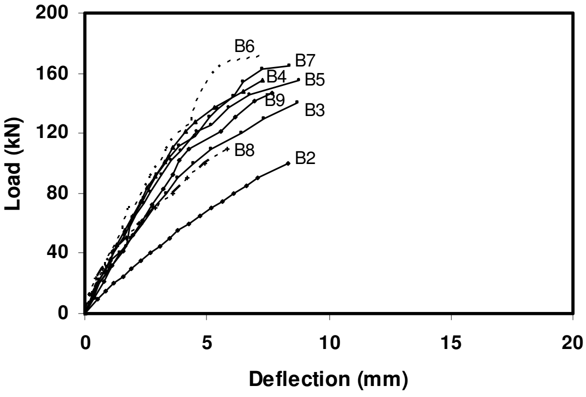


Fig. 8. Load-deflection relationships at the middle of the opening.

It should be noted that using steel bolts to anchor the steel plates to the concrete in addition to the epoxy adhesive resulted in a significant decrease in the beam stiffness at the opening. This can be observed examining figs. 7 and 8. Finally, examining load-deflection relationships presented in figs. 7 and 8, it can be noticed that there are some fluctuations in the curves for strengthened beams. Such fluctuations reflect redistribution of forces through strengthening materials at the opening during loading.

3.4. Strains

Fig. 9 presents load-strain relationships for the bottom flexural steel reinforcement at mid-span. For the solid beam B1 a traditional ductile behaviour can be observed from the relationship. Firstly, the relationship showed a linear trend within the elastic range up to yielding of steel reinforcement took place. Secondly, beyond the point of yielding of steel reinforcement the relationship showed a non-linear trend up to the failure of the beam. However, different load-strain relationship was observed for beam B2 as a result of the presence of an opening within the shear span of the beam. Such relationship reflects a significant reduction in the beam stiffness as a result of the presence of the opening. The load-strain relationship showed a very limited linear elastic range and suddenly failure occurred before the bottom steel reinforcement yields due to the reduction in the shear strength of the beam.

Examining the relationships presented in fig. 9, it is clear that applying either internal strengthening (B3) or external strengthening (B4 to B9) for beams with openings generally increased the stiffness of beams in comparison to the un-strengthened beam B2 or even in comparison to the solid beam B1. However, for those beams the load-strain relationship patterns were different and reflected a reduced ductility of those beams. In the case of beam B3 strengthened with internal stirrups along its upper and lower chords and provided with internal steel reinforcement along its opening edges, almost the same load-strain pattern was obtained in the elastic range like the solid beam B1 up to the point of yielding of bottom steel reinforcement. Beyond the point of yielding and when the plastic range started the beam failed in a shear mode.

On other hand, for beams B4 and B5 strengthened using external steel plates only around the opening the load-strain behaviour reflected the efficiency of such plates in increasing the beam stiffness and also reflected their mode of failure. The load-strain relationship was linear up to failure and the strain in the bottom steel reinforcement did not reach the yield point. Failure in this case took place in a shear mode after debonding of steel plates due to the lack in their end anchorage. Different observations can be obtained for beams B6 and B7 strengthened externally using steel plates inside and outside the opening and connected together using steel angles along the opening edges. In this case, a linear elastic load-strain relationship was observed up to the point of yielding of steel reinforcement followed by failure in a flexural mode. However, less ductility was clearly obtained in comparison to the solid beam B1. It should be noted that such strengthening schemes used for beams B6 and B7 provided enough shear strength to the upper and lower chords of the opening. The existence of the external steel plates decreased the post-elastic behaviour range of the bottom flexural reinforcement before failure. This may be attributed to the transformation of the strain from the steel reinforcement to the strengthening steel plates.

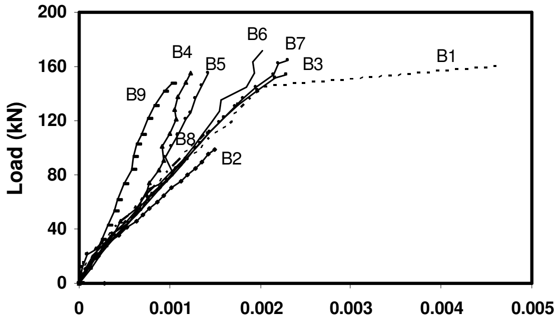


Fig. 9. Load-strain relationships for the tensile reinforcement of tested beams at the mid span.

The difference between the effect of external strengthening using CFRP sheets only around the opening (B8) and using CFRP sheets inside and outside the opening (B9) on the load-strain behaviour can be also detected from fig. 9. The load-strain behaviour of beam B8 reflected a lower contribution of CFRP sheets as they were applied parallel to the opening edges, i.e., the direction of the fibers was horizontal in both upper and lower chord of the opening. In this case the load-strain behaviour was very close to that for the un-strengthened beam B2 except an increase in the beam stiffness induced by such strengthening scheme. On the other hand, the load-strain behaviour of beam B9 reflected the efficiency of such strengthening scheme in increasing the beam stiffness. However, the load-steel strain curve was almost linear and the strain values were very limited up to the failure. Such behaviour was observed due to the shear failure, which occurred as a result of CFRP debonding.

Fig. 10 presents load-strain relationships for the bottom steel reinforcement at the location of the inner vertical edge of the opening for all tested beams with openings. Such load-strain relationships reflect the efficiency of different schemes used for strengthening the beam opening in terms of reducing the steel strain in the bottom flexural reinforcement in comparison to that for the un-strengthened beam with opening B2.

In the case of the un-strengthened beam with opening B2 the lowest stiffness and greatest steel strain were obtained in comparison to all other strengthened beams. The load-strain relationship for beam B2 showed a linear trend up to failure and the value of the steel strain passed the value of steel yield strain. This may indicate the start of the formation of a plastic hinge at this location. It should be noted that fig. 10 indicated that the strengthening scheme for beam B8 provided the lowest efficiency among all strengthened beams. In this case the strain values in the bottom steel reinforcement were the highest among all other strengthened beams. On the contrary, the strain values in the bottom steel reinforcement were the lowest for beams B6 and B7 among all other strengthened beams. This also confirms the transformation of the strain from the internal steel reinforcement to the external strengthening steel plates. Also, load-strain relationships for beams B4 and B5 showed that the strengthening scheme for these beams were less efficient than that used for beams B6 and B7. Moreover, load-strain relationship for the beam B3 showed the efficiency of internal strengthening of beams with openings in increasing the beam stiffness at the opening. Finally, it is clear from fig. 10 that the efficiency of external strengthening of beams with openings using CFRP sheets inside and outside the opening (B9) is much more efficient than that strengthened only around the opening (B8). The load-strain relationship for beam B9 showed higher stiffness of such beam and lower values of the steel strain than that for beam (B8).

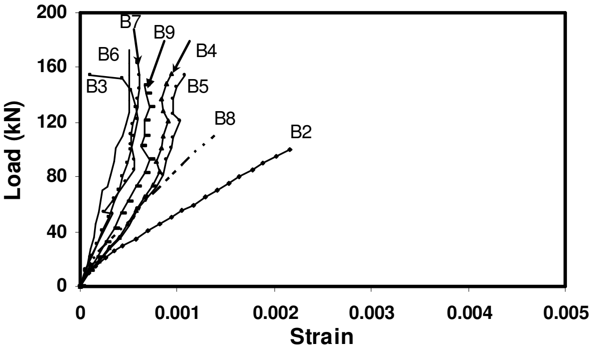


Fig.10. Load-strain relationships for the tensile reinforcement of tested beams at inner edge of the opening.

4. Theoretical analysis

Consider first the behaviour of the beam segment at the location of the opening. An assumption for this behaviour, which was found to be consistent with test results [1,3], is to consider a Vierendeel behaviour having chords above and below the opening. This assumption was considered since the contraflexure points were found nearly at the mid-span of the chord members. Therefore, the internal forces in the upper (top) and lower (bottom) chords of the opening can be easily obtained considering the equilibrium of forces at the opening as shown in fig. 11. The following equations can be obtained from such equilibrium:

$$V_m = V_t + V_b \, , \tag{1}$$

$$N_t = N_b = \left(\frac{M_m}{Z} \right); \; Z = h - 0.5(h_t + h_b) \, . \tag{2}$$

Where V_m= applied shear force at the center of the opening; M_m= applied moment at the center of the opening; V_t= shear force at the top chord of the opening; V_b= shear force at the bottom chord of the opening; N_t= axial compression force in the top chord; T_b= axial tension force in the bottom chord; and Z= the distance between the plastic centroids of the chord members.

The equilibrium of the forces shown in fig. 11 yields:

$$V_m = \left(\frac{P}{2} \right), \tag{3}$$

and

$$M_m = \frac{P}{2}\left(X + \frac{L_o}{2} \right). \tag{4}$$

Also, V_t and V_b can be calculated since they are considered to be the reactions of a two hinged frame laterally loaded by the support reaction ($P/2$) as shown in fig. 11. Based on the dimensions of such two hinged frame determined from the dimensions of the

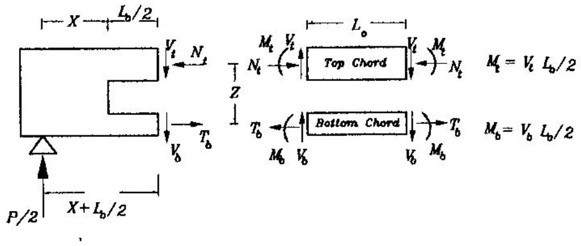


Fig 11. Equilibrium of forces at the opening.

top and bottom chords and the dimensions of the opening, the shear force carried by the top chord was found to be $V_t = 0.74\ V_m = 0.74\ (P/2)$.

Now since failure of most of the beams tested in the current experimental program occurred in the form of shear failure in the opening chords. Also, such failure always started at the top chord of the opening. Therefore, the theoretical analysis will focus on the shear strength behaviour of the top chord of the opening. The main objective of the theoretical analysis will be the calculation of the ultimate shear force of the top chord of tested beams and to compare such theoretical results to the experimental ones. It should be noted that the theoretical shear force of the top chord of tested beams will be calculated in accordance to the Egyptian Code for design and construction of concrete structures ECCS 203-01 [18] and other theoretical models found in the literature.

For a traditional reinforced concrete section, the shear force capacity can be estimated by the addition of the contribution of the internal web reinforcement to the contribution of the concrete. Also, in the case of externally strengthened beams, the contribution of the strengthening material will be added to the shear force capacity of the beam.

Furthermore, since the top chord of the opening is subjected to an axial compressive force in addition to the shear force and bending moment, therefore the ultimate design shear force carried by the concrete can be calculated according to the Egyptian Code [18] using the following equations:

$$V_c = 0.24\sqrt{\frac{f_{cu}}{\gamma_c}}(\delta_c)bd\,, \tag{5}$$

and

$$\delta_c = 1 + 0.07\left(\frac{N_c}{A_c}\right). \tag{6}$$

Where δ_c represents the increase in the shear force capacity due to the effect of the axial compressive force (N_c), and A_c is the area of concrete section. Also, the ultimate design shear force carried by the internal vertical steel stirrups can be calculated according to the Egyptian code [18] as follows:

$$V_{st} = \frac{A_{st}(f_y / \gamma_s)}{b.S} bd\ . \tag{7}$$

Where A_{st} = is the cross sectional area of the stirrups; b = width of the beam; and S = spacing between vertical stirrups. Eqs. (5) and (7) can be used to estimate the ultimate shear force carried by the concrete and the stirrups, respectively by setting the safety factors of materials γ_c and γ_s equal to one.

Also, the contribution of the strengthening material to the total shear force carried by the beam in the case of externally strengthened beams using steel plates, V_p can be estimated using the empirical equation suggested by Sharif et al. [19]. Such equation is in the form:

$$V_p = 2\tau\left(\frac{dh_p}{2}\right), \tag{8}$$

where τ = the interface shear stress along the plate height; h_p = height of steel plate; and d = effective depth of the section.

Sharif et al. [19] suggested a value of the interface shear stress $\tau = \tau_{ave} = 0.80$ N/mm^2 in the case detached side plates (Wings), and $\tau = \tau_{max} = 3.5$ N/mm^2 in the case of connected side plates having a U-shape (Jacket).

Furthermore, the effective shear force carried by the externally bonded CFRP sheets having a U-shape was given by Khalifa et al. [20] in the following form:

$$V_F = 2t_F f_{Fe} d_F\ . \tag{9}$$

Where t_F = thickness of the fiber; d_F = effective depth of the fiber; and f_{Fe} = effective tensile strength of CFRP. Such effective tensile strength of CFRP can be estimated using the following equation:

$$f_{Fe} = R \ f_{Fu} \ , \tag{10}$$

where f_{Fu} = the ultimate tensile strength of the CFRP; and, R = reduction factor. The reduction factor is proposed by Khalifa et al. [20], based on the condition of the CFRP debonding as:

$$R = \frac{0.0042(f_c')^{2/3} W_{Fe}}{(E_F t_F)^{0.58} \varepsilon_{Fu} d_F} \ . \tag{11}$$

Where f_c' = concrete cylinder compressive strength of concrete; E_F = modulus of elasticity of the CFRP (Gpa); ε_{Fu} = ultimate tensile strain of the CFRP; and W_{Fe} = factor based on the effective bond length of the CFRP and the CFRP scheme. This factor W_{Fe} was expressed in the form of:

$$W_{Fe} = d_F - L_e \ . \tag{12}$$

Where L_e = effective bond length of CFRP expressed as:

$$L_e = e^{6.134 - 0.58 \, ln(t_F E_F)} \ . \tag{13}$$

The above presented equations were used to evaluate the contribution of concrete, internal steel stirrups, and external strengthening materials to the ultimate shear force carried by the beam. In the case of the un-strengthened beam with opening B2 it was suggested that the effect of the internal opened stirrups is negligible and therefore the ultimate shear force of the top chord was calculated as the ultimate shear force carried by the concrete only using eqs. (5) and (6). In the case of the internally strengthened beam with opening B3, the shear force carried by the top chord was considered to be the summation of the contributions of the concrete and the stirrups. However, the contribution of the concrete to the total shear force decreases significantly after concrete cracking. Furthermore, at higher levels of concrete cracking the contribution of the concrete to the total shear force may be ignored. The Egyptian code [18] considers only half of the concrete design shear strength to contribute to the total ultimate design shear force carried by the beam section. Also, the Egyptian code recommends a condition for the maximum nominal shear strength of the section not exceeding $= 0.70\sqrt{f_{cu} / \gamma_c}$ or 3 N/mm² whichever the lesser. It is proposed herein based on the results obtained from test beam B3 that the contribution of the concrete shear strength to the total shear force be ignored after concrete cracking. Therefore, the total ultimate shear force will depend only on the contribution of the internal stirrups.

In the case of externally strengthened beams with openings using steel plates or CFRP sheets, the ultimate shear force carried by the section will be considered as the summation of the contribution of the shear force carried by the concrete and the effective shear force carried by the external strengthening materials. It should be clearly understood that the consideration of the contribution of the concrete to the total shear force in this case is due to the confinement provided by the external strengthening to the concrete which significantly reduced its cracking. The full contribution of the concrete to the total shear strength should be considered up to the moment of debonding of external strengthening materials.

Based on that the ultimate theoretical shear force carried by the top chords for beams B4, B5, B6, and B7 were calculated using eqs. (5), (6) and (8). Also, the ultimate theoretical shear force carried by the top chord for beam B9 was calculated using eqs.. (5), (6) and (9). It should be noted that in the case of beam B8, the orientation of fibers in the top chord was perpendicular to the direction of the external shear force. As a result there is theoretically no contribution for the external fibers to the ultimate shear force carried by the top chord of the opening.

Table 2 presents a comparison between the experimental and theoretical results for the ultimate shear force carried by the top chord of the opening for tested beams with openings. It can be observed from the results presented in the table that in general the theoretical results were in good agreement with the experimental ones. The theoretical results were always greater than the experimental ones. However, for beam B3, it was found that if half the contribution of the concrete to the shear force is added to the contribution of the steel stirrups, as recommended by the Egyptian code [18], then the theoretical total shear force will be much greater than the experimental one. On the other hand, when the contribution of the concrete to the shear force is ignored and the shear force capacity of the section was calculated only based on the contribution of the steel stirrups alone, a more reliable and conservative theoretical ultimate shear force of the top chord was obtained as shown in the table. It is to be noted that shear reinforcement, in form of vertical stirrups, of both top and bottom chords of the test beam B3 was designed in the test program according to the Egyptian code [18]. Moreover, the experimental results for beams B6 and B7 were much less than the theoretical ones. This is because such beams failed in a flexural mode and they did not reach their full shear strength. Finally, it should be noted that the theoretical models used were reliable since the theoretical results are close to the experimental ones. However, the theoretical model used for the calculation of the contribution of the steel plates to the total shear force ignores the effect of plate thickness. The model only considers the variation of the interface shear stress between the plates and the concrete. The theoretical model used for the calculation of the contribution of CFRP sheets to the total shear force was found to be more reliable since it considers the effect of the thickness of the fibers.

Table 2
Comparison between experimental and theoretical ultimate shear force carried by the top chord of the opening

Test beam	Strengthening scheme at the top chord	Experimental ultimate shear force on the top chord $(V_{ut})_{exp}$, kN	Theoretical ultimate Shear force carried by the top chord $(V_{ut})_{the}$, kN	$(V_{ut})_{exp}$ / $(V_{ut})_{the}$
B2	control	38.85	33.48	1.16
B3	Internal stirrups	59.2	57.6(76.45)*	1.03(0.77)*
B4	Outside steel plates (Wings)	59.2	52.1	1.14
B5	Outside steel plates+bolts (Wings)	60.31	52.1	1.16
B6	Outside and inside steel plates (Jacket)	61.8	101.34 (at flexur failure)	0.61
B7	Outside and inside steel plates + bolts (Jacket)	62.9	101.34 (at flexure failure)	0.62
B8	Outside horizontal CFRP	44.4	34.66	1.28
B9	Inside Vertical U-shape CFRP + Outside horizontal CFRP	58.09	54.93	1.06

( )* Values calculated considering half concrete shear strength

5. Summary and conclusions

An experimental study was conducted including testing nine reinforced concrete beams in order to investigate the efficiency of external strengthening of such beams when provided with large openings within their shear zones. Firstly, three beams were considered. One of these beams was solid without any openings and was considered as a control beam. The second beam was provided with one opening within the shear zone but without any strengthening and was considered also as a control beam whereas the third beam was provided with an opening at the same location and having the same dimensions. However, such third beam was internally strengthened with steel reinforcement along opening edges. Secondly, six beams provided with openings at the same location and having the same dimensions like the second and the third beams were considered. Such six beams were externally strengthened with steel plates or Carbon Fiber Reinforced Plastics (CFRP) sheets along the opening edges. Finally, theoretical analysis was performed for all tested beams with openings in order to calculate the ultimate shear force carried by such beams. Equations presented by Egyptian code in addition to empirical formulas found in the literature were used to perform the theoretical analysis. Based on this study the following conclusions can be drawn:

1. The inclusion of an opening in a reinforced concrete beam within its shear zone significantly decreases its stiffness and ultimate strength. Various cracks are formed around the opening corners due to stress concentration and diagonal cracks are formed along its upper and lower chords due to the lack of its shear strength. Failure in this case suddenly occurs in the form of diagonal shear failure in both the upper and lower chords.
2. External strengthening of beam opening using steel plates or CFRP sheets is more efficient than internal strengthening of the opening using internal steel reinforcement. The external material provides additional stiffness to the section at the opening. The degree of increase in the section stiffness depends upon the type of material used for external strengthening. Also, external strengthening of beams with opening in shear zone could significantly increase its shear strength. However such increase in the shear strength is mainly dependent on the type of material used and its configuration scheme.
3. The use of steel plates for external strengthening of the beam is more efficient than the use of CFRP sheets. The homogeneous properties of the steel plate material lead to a much more reliable resistance to diagonal shear cracks in comparison to that offered by the unidirectional oriented fibers of the CFRP sheets.
4. The use of external steel plates for strengthening the internal and external sides of the beam opening is found much more efficient than external strengthening of external sides only. Such configuration scheme of external strengthening not only restores the full shear strength of the beam but also changes its mode of failure to a flexural mode rather than shear mode.
5. The use of steel bolts to increase the bond between the steel plates used for external strengthening and the concrete has a marginal effect on the beam strength. However, it reduces the beam stiffness due to the holes drilled in the concrete.
6. External strengthening of beam opening using inside U-shape CFRP sheets perpendicular to the opening edges in addition to outside CFRP sheets parallel to the opening edges is more efficient than using outside CFRP sheets parallel to the opening edges only. The horizontal orientation of the fibers of CFRP sheets at the upper and lower chords of the opening does not provide any direct contribution to the shear strength but only marginally enhances the contribution of concrete to shear strength. However, the presence of vertically oriented CFRP fibers along the upper and lower chords in the direction of the external shear force significantly increases the shear strength of the chords. Moreover, the application of U-shaped CFRP sheets in addition to the horizontal outside CFRP sheets along the chord members increases the resistance of such scheme against debonding which leads to a higher contribution of CFRP sheets to the shear strength of chord members.
7. Based on the experimental and theoretical analysis presented herein in this paper, It is recommended that the engineer should take into consideration the following when designing external strengthening of beam with opening: (i) providing enough shear strength

to the chords of the opening; (ii) extending the strengthening material along and beyond the opening corners to overcome the stress concentration and to prevent formation of plastic hinges at corners.

8. For internally strengthened beams with openings, the contribution of the concrete to the total ultimate shear force decreases significantly after concrete cracking. At higher levels of concrete cracking the contribution of the concrete to the total shear force may be ignored. Although the Egyptian code considers half of the concrete shear strength to contribute to the total shear force capacity provided that the nominal ultimate shear strength does not exceed $0.70\sqrt{f_{cu} / \gamma_c}$ or 3 N/mm^2. However, it is recommended herein that such contribution of the concrete be ignored and the ultimate shear force be dependent only on the contribution of the internal stirrups when calculating the ultimate shear force (failure) of the section.

9. The theoretical analysis of tested beams was reliable since the theoretical results were in good agreement with the experimental ones. However, the theoretical model used for the calculation of the contribution of the steel plates to the total shear force ignores the effect of the plate thickness. The model only considers the variation of the interface shear stress between the plates and the concrete. It is recommended herein that more experimental data should be generated in order to develop a more reliable theoretical model for the estimation of the shear force carried by the steel plates. Such model should take into consideration the thickness of the steel plate.

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