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Shear Resistance Of Reinforced Concrete Deep Beams With Opening Strengthened By CFRP Strips

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Abstract :

Carbon fiber reinforced polymer (CFRP) as an external reinforcement is used extensively to address the strength requirements related to flexure and shear in structural systems. In this paper, the behavior and performance of reinforced concrete deep beams with opening strengthened with externally bonded CFRP strips failed in shear is presented. The experimental work includes testing eight reinforced concrete deep beams.

The variables considered in the experimental study include the effect of fiber orientation (90° or 45° CFRP strips with respect to beam longitudinal axis), the effect of using longitudinal CFRP strips with vertical CFRP strips and effect of anchoring the vertical CFRP strips. Test results were discussed based on shear resistance – mid span deflection, strain in CFRP and maximum crack width of beams. Experimental results reveal that externally CFRP strips can significantly increase the ultimate shear capacity and limit the shear crack width and increase the stiffness of the deep beams with opening.

Keywords: shear, deep beams, CFRP, strengthening.

مقاومة القص للعتبات الخرسانية المسلحة العميقة ذات الفتحات المقواة بشرائح ألياف الكاربون البوليميرية

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الخلاصة

تستعمل ألياف الكاربون البوليميرية كتسليح خارجي بكثرة لتغطية متطلبات مقاومة الانحناء والقص للأنظمة الإنشائية، يتضمن البحث دراسة سلوك وأداء العتبات الخرسانية المسلحة العميقة ذات الفتحات المقواة بشرائح الكاربون البوليميرية الخارجية والتي تفشل بالقص. يتضمن الجانب العملي فحص ثمانية نماذج من العتبات الخرسانية المسلحة العميقة.

إن المتغيرات التي تم أخذها بنظر الاعتبار في الدراسة العملية هي، تأثير تغير اتجاه شرائح الكاربون البوليميرية لتعمل زاوية قدرها 90° أو 45° بالنسبة للمحور الطولي، تأثير استعمال شرائح من كاربون بوليميرية طولية مع الشرائح العمودية وأيضا تأثير أسلوب تثبيت الشرائح العمودية، تم مناقشة نتائج الفحص اعتمادا على مقاومة القص – الهطول في منتصف النموذج والانفعال في شرائح الكاربون البوليميرية وقياس الحد الأقصى للتشققات في النماذج. تدل النتائج العملية على إن شرائح الكاربون البوليميرية الخارجية تعطي زيادة مهمة لمقاومة القص القصوى وتحد من تشققات القص وتزيد الصلادة للعتبات العميقة ذات الفتحات.

1. Introduction

Reinforced concrete deep beams occur as common structural elements in many structures from tall buildings to offshore gravity structures. They are used as panel beams, foundation beams and more recently, as deep grid walls in offshore gravity – type concrete structures. The term "deep beam" applies to any beam, which has a span / depth ratio less than about 4 [1].

In the design of reinforced concrete deep beams, it is sometimes necessary to provide web opening for service or access. Deep beams as other structural member may need upgrading or rehabilitation programs so that they can cope with the extra loads. Externally strengthening with advanced composite materials, namely, carbon fiber reinforced polymers (CFRP) represents the state-of-the-art in upgrading or rehabilitation techniques. Carbon fiber reinforced polymer (CFRP) laminates [2] are becoming widely used in upgrading and rehabilitation of reinforced concrete members. CFRP offers the design engineer excellent properties not available in traditional materials. This strengthening composite is light in weight, corrosion resistant and possesses higher strength and stiffness compared to steel. The ease of handling and application gives CFRP an advantage over traditional materials for certain applications.

Many papers present the experimental behavior and strength of R. C. beams in shear strengthening with CFRP [3, 4, 5, 6].

Belal [7] studied the influence of strengthening and repairing deep beam with CFRP, experimental results showed a significant improvement in the behavior and carrying capacity of reinforced concrete deep beam.

2. Research Significant

The present paper is intended to provide experimental information about the behavior and shear strength of R. C. deep beam with opening strengthened with different configuration of CFRP. An experimental program of 8 deep beams is described.

3. Experimental Program

3.1 Test Beam Details, Materials, and Strengthening Schemes

A total of eight reinforced concrete deep beams were tested under two concentrated loads. Each beam was 800 mm long with an overall cross – section of 80 mm x 320 mm. The beams were simply supported on a span L of 660 mm giving an L/D ratio of 2, which is less than 4 as recommended by the provisions of the ACI code 318 – 08 for deep beam requirements. All the deep beams designed to fail in shear and they had the same flexural and shear reinforcement, the reinforcing details of the test beams are shown in **Figure. (1)** and the steel mechanical properties are listed in **Table (1).**

Table (1) Reinforcing Steel Properties

Bar Diameter (mm)	Modulus of Elasticity * (MPa)	Yield Stress ** (MPa)	Ultimate Strength ** (MPa)
16	200000	540	654
6	200000	294	515

(*) Assumed value

(**) Each value is an average of three specimens (each 40 cm length)

The details of the tested beams are summarized in **Table (2);** beam (B1) was a solid beam. This was included to provide a basis for comparison of the strength and behavior of the beam with opening. The remaining beams contained two square opening, 65 mm x 65 mm, one in each shear span. They were located symmetrically about the beam axes as shown in **Figure (2).** Beam B2 was a deep beam with opening (reference beam), this beam without strengthening. Six of the deep beams with opening (B3 – B8) strengthened by CFRP strips of 40 mm wide and spaced at 100 mm c/c with different configurations. **Figure.(3)** show the strengthening scheme of the tested beams and Table (2) shows the description of the tested beams.

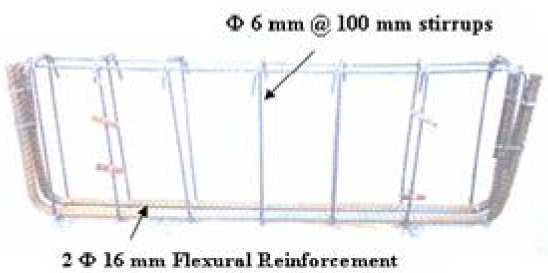


Fig. (1) Details of Test Beam Reinforcement

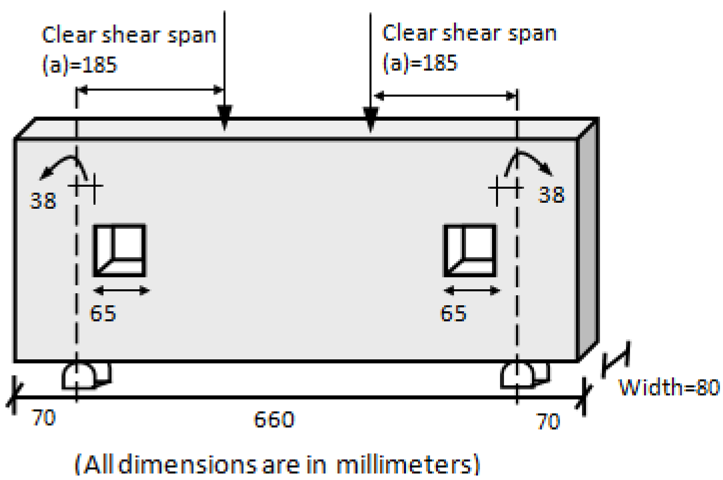


Fig. (2) Details of deep beams with web openings

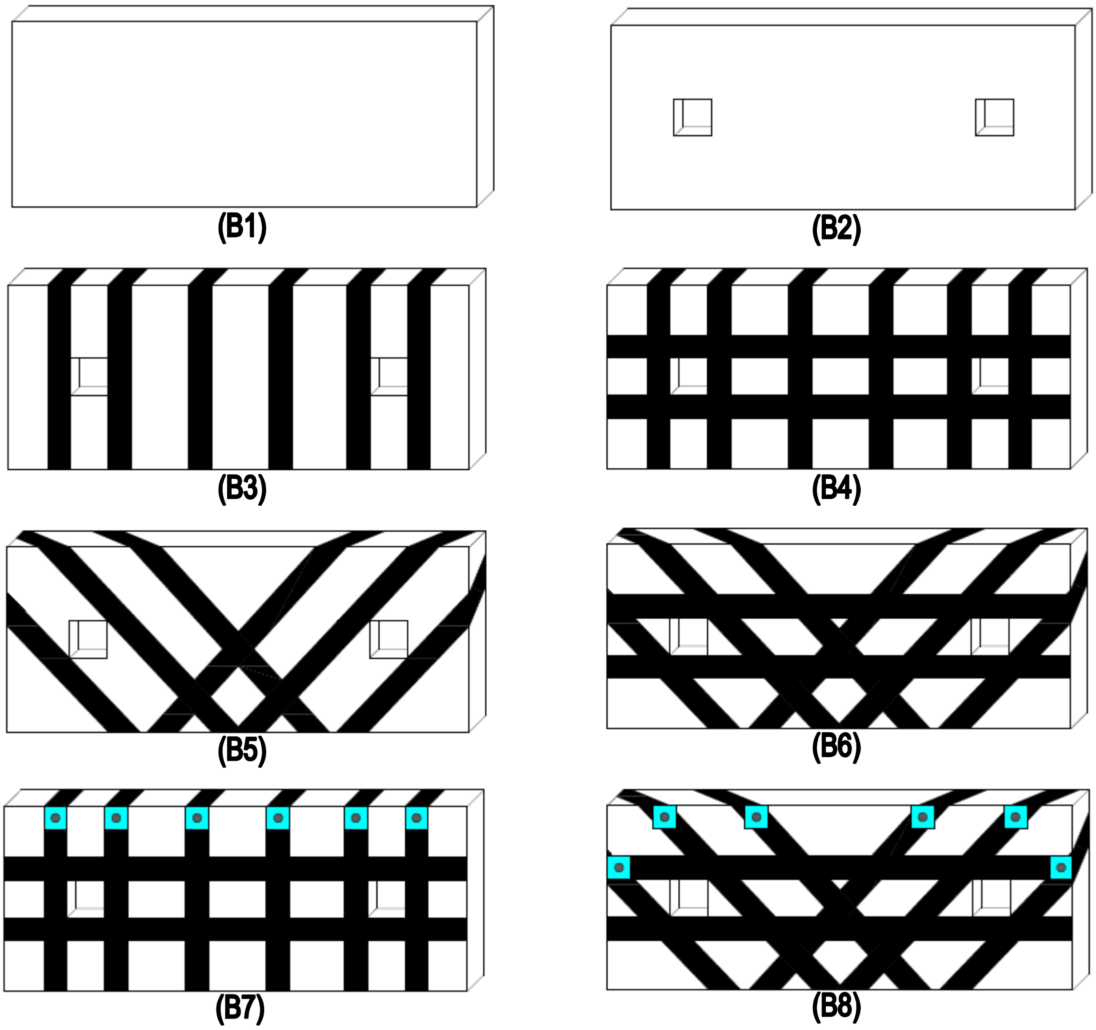


Fig (3) . Strengthening Scheme of the Tested Deep Beams

The beams were cast in a horizontal position using plywood moulds. Three 150 mm x 300 mm cylinder were cast to determine a compressive strength of concrete. The concrete compressive strength are listed in **Table (2).**

Carbon fiber laminate CFRP of type Sika Wrap Hex – 230 C and epoxy based impregnating resin of type Sikadur – 330 have been used to externally strengthen the reinforced concrete deep beams in shear.

The properties of carbon fiber laminate and epoxy used are shown in **Table (3)** and **Table (4).**

Table (2) Summary of Specimen Details and Concrete Compressive Strength

Beam No.	Details of Strengthening	Anchoring of CFRP	Compressive Strength of Concrete (f_c') (MPa)
B1	Solid deep beam (control beam) without strengthening	---	30
B2	Deep beam with opening (control beam) without strengthening	---	31
B3	Deep beam with opening strengthened with 90° CFRP strips	---	28
B4	Deep beam with opening strengthened with 90° CFRP strips and longitudinal CFRP strips	----	30
B5	Deep beam with opening strengthened with 45° CFRP strips	----	32
B6	Deep beam with opening strengthened with 45° CFRP strips and longitudinal CFRP strips	---	30
B7	Deep beam with opening strengthened with 90° CFRP strips and longitudinal CFRP strips	With anchoring 90° CFRP	28
B8	Deep beam with opening strengthened with 45° CFRP strips and longitudinal CFRP strips	With anchoring 45° CFRP	30

Table (3) Properties of CFRP

Type	Tensile Strength (MPa)	Elongation at Failure (%)	Tensile Modulus (GPa)	Thickness (mm)
Sika Wrap Hex-230C	3500	1.5	230	1.3

Table (4) Properties of Epoxy Resin

Type	Mixing Ratio by Weight	Tensile strength (MPa)	Flexural Modulus (MPa)
Sikadur -330	A : B 4 : 1	30	3800

4. Testing Procedure

The eight simply supported deep beams were tested up to failure using 3000 KN capacity hydraulic testing machine. Each beam was loaded by application of a single point load from the testing machine to the upper midpoint of the loading member. The single load was then divided equally between two point loads that were transferred to the concrete beam through two steel bars of Φ 30 mm located at the end of the loading member as shown in **Figure. (4).** Loading was applied in small increments of (5 KN). At each load stage, the deflection reading at mid span of the beam was recorded using dial gage of accuracy of (0.01 mm). The cracking width was recorded with increasing loads and the strain of the CFRP was recorded at each (15 KN) interval using demec points.

Fig. (4) Test Setup

5. Anchoring of CFRP

To avoid (or delay) bond failure and given the limited anchoring length available, the CFRP is preferably wrapped or anchored. This aspect is of importance in the locations shown in **Figure. (5).**

Strengthened beams (B7 and B8) were selected to illustrate the contribution of anchoring the CFRP to the ultimate shear. They were drilled to make a hole of diameter (6 mm) (bolt diameter).

Square plates of (50 mm) width and a thickness of (2 mm) were drilled with a hole of (6 mm) diameter (bolt diameter) in the center of each plate. They were fixed on the CFRP in the locations shown in **Figure (5),** the bolts of diameter (6 mm) were used to anchor the plates on the CFRP.

Fig (5) Anchoring of CFRP

5.1 Steel Plate

Mild steel plates (2 mm thickness) were used to anchor the CFRP strips. Three specimens were tested according to ASTM C370-05a [8] to determine tensile properties. The results of tests are listed in **Table (5).**

Table (5) Properties of Steel Plate

Steel plate thickness (mm)	Modulus of elasticity (GPa)	Yield stress (MPa)	Strain at yield stress (microstrain)	Ultimate stress (MPa)
2	200	240	1200	340

5.2 Bolts

M 6 x 1 mm was chosen to be used to anchor the steel plate and CFRP on concrete specimens.

Direct shear test and tensile strength test were carried out to find the mechanical properties of the bolts as described below.

5.3 Direct Shear Test

This test was carried out on the bolt as shown in **Figure (6).** The failure was observed by cutting the bolt at the face of the applied shear. Three specimens were tested and the average of the three records was taken. The shear strength was (235 MPa) with a deformation equal to (1.0 mm).

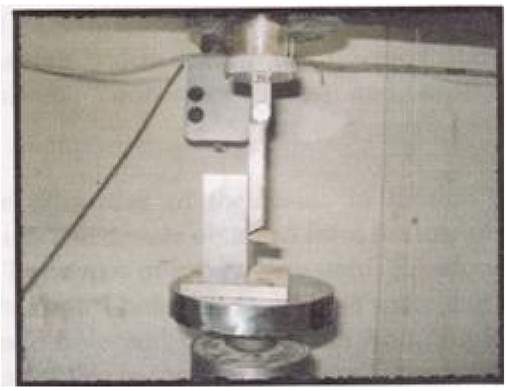


Fig (6) Direct Shear Test of the Bolt

5.4 Tensile Strength Test

Three specimens of the bolts were tested according to ASTM C370-05a [8] the results are listed in **Table (6).**

Table (6) Properties of Bolt

Bolt diameter* (mm)	Modulus of elasticity (GPa)	Yield stress (MPa)	Strain at yield stress (microstrain)	Ultimate stress (MPa)
6	200	560	2930	690

6. Test Results and Discussion

6.1 Effect of Web Opening

The behavior of the deep beams with web openings in regard to the cracking and ultimate load capacities could be explained as follows: For solid deep beams and deep beams with web openings, most of the applied load is transmitted directly from loading point to the reaction point along the "load path". If this path was intercepted by the opening, the reduction in the carrying capacity would depend by an opening on whether this load path could be successfully re-routed, primarily along the path ABC shown in **Figure. (7)**. Some of the load might be transmitted along a secondary path AEC, which, however, is comparatively ineffective because a substantial tensile force along EE' would be required except when the angle θ between AE and EC is small. When the force in BC of the primary path reaches a sufficiently high value, the critical lower diagonal crack would occur. For a given applied load, the force in BC depends on the angle which it makes with the horizontal (angle ϕ), which depends on the location of the opening. It is therefore reasonable to expect that the capacity of the beam would be affected by the location at which the load path is intercepted by the opening. In the absence of the opening, the upper and lower paths in **Figure. (7)** become one, which is the natural load path joining the loading and the reaction point [9, 10].

Table (7) shows that the cracking load and ultimate load of deep beam with web opening (Beam B2) decrease by (54.5 %) and (35.6 %), respectively, as compared with the deep beam without web opening (Beam B1).

Figure (8) shows the deflection response of B1 and B2.

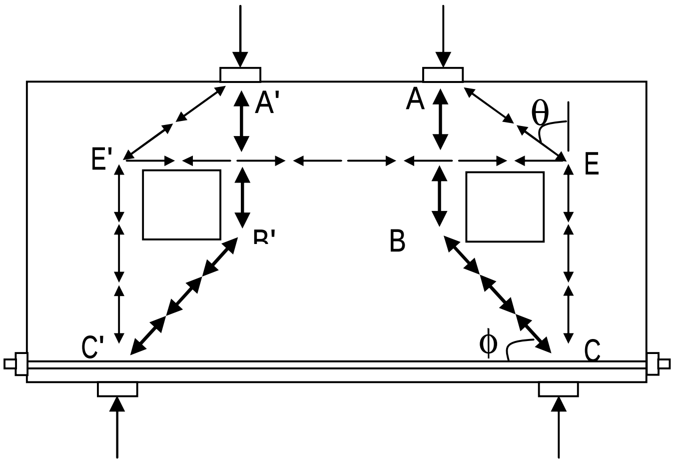


Fig (7) load – Transmission Paths [9]

Table (7) Cracking Load and Ultimate Load of Deep Beams B1, B2

Beam No.	Cracking Load V_{cr} (KN)	Percentage Decrease in Cracking Load with Respect to B1	Ultimate Load V_u (KN)	Mid – Span Deflection (mm)	Percentage Decrease in Ultimate Load with Respect to B1
B1	27.5	---	225	3.7	---
B2	12.5	54.5	145	2.05	35.6

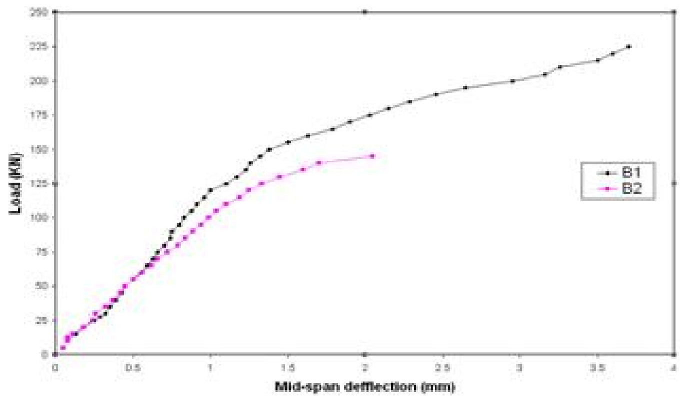


Fig (8) Load – Deflection Curve for Deep Beams B1 and B2

6.2 Effect of Strengthening with CFRP

6.2.1 Effect of Fiber orientation (90º CFRP, 45º CFRP)

Table (8) shows that test beam B5, strengthened with 45º CFRP strips provided higher cracking load and ultimate load as compared to test beam B3, strengthened with 90º CFRP strips, the increase was (25 %) and (18.8 %)respectively. This is due to the fact that the inclined web reinforcement in deep beam had effectively arrested the growth of diagonal cracks, so that the usual diagonal – cracking failure could not occur [11].

Figure. (9) show the load – deflection curves of beam B3 and beam B5. Deep beam B5 behaved in a stiff manner, although both beam B3 and beam B5 show a slightly higher stiffness in the post cracking stage of response as compared with the deep beam B2, without strengthening. Also beam B3 and beam B5 have some improvement in ductility as compared to bam B2, without strengthening.

Table (8) Cracking Load and Ultimate Load of the Strengthening Deep Beams

Beam No.	Cracking Load V_{cr}(KN)	Percentage Increase in Cracking Load with Respect toB2	Ultimate Load V_u(KN)	Mid – Span Deflection (mm)	Percentage Increase in Ultimate Load with Respect toB2
B2	12.5	---	145	2.05	---
B3	20	60	172.5	4.25	19
B4	21	68	215	4.7	48.3
B5	25	100	205	2.9	41.4
B6	27	116	287.5	5.15	98.3
B7	30	140	270	6.5	86.2
B8	34	172	317	5	118.6

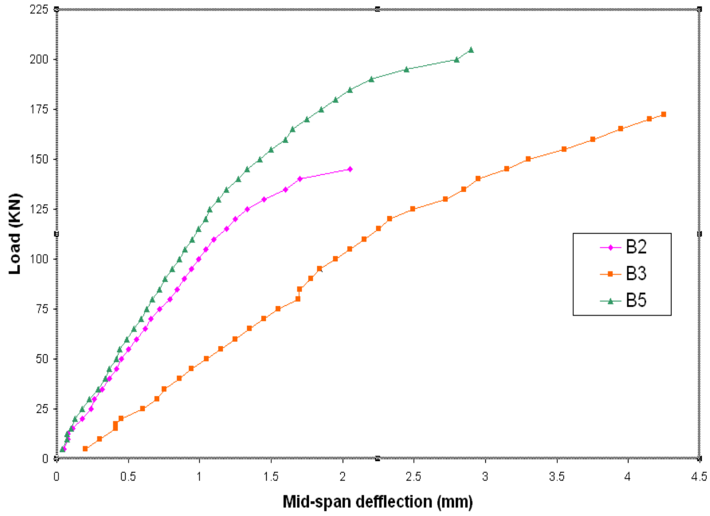


Fig (9) Load – deflection Curves: Effect of Fiber Orientation

6.2.2 Effect of Strengthening in Both Longitudinal and Transverse Directions

Beam B4 was strengthened with longitudinal CFRP strips and with 90º CFRP strips similar to test beam B3. From **Table (8),** it can be seen that test beam B4 increase the cracking load and ultimate load by (5 %) and by (24.6 %) respectively, as compared with beam B3. **Figure. (10)** shows the deflection curves of these two beams. Beam B4 shows a higher stiffness in the post cracking stage of response as compared with beam B3.

Beam B6 was strengthened with longitudinal CFRP strips and with 45º CFRP strips similar to test beam B5. From **Table (8),** it can be seen that test beam B6 increase the cracking load and ultimate load by (8 %) and by (40.2 %) respectively, as compared with beam B5. **Figure. (11)** shows the deflection curves of these two beams. Beam B6 shows a higher stiffness in the post cracking stage of response as compared with beam B5.

Test results reveals that strengthening using CFRP strips arranged longitudinally and wrapped with transverse CFRP strips (90º strips or 45º strips) will not enhance significantly the cracking strength but will increase both the ultimate strength and post – cracking deflection and ductility of the beam.

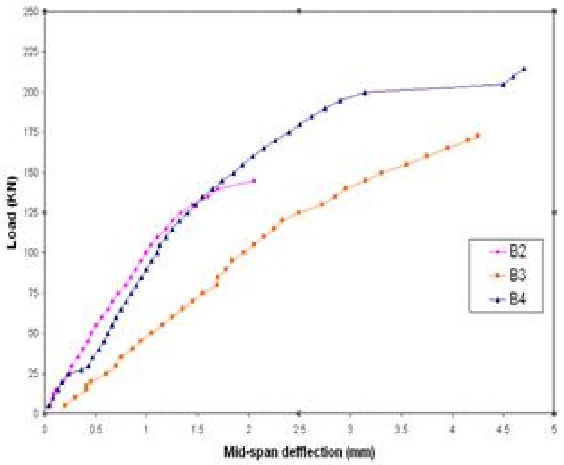


Fig (10) Load – Deflection Curves: Effect of Strengthening in Both Longitudinal and Transverse Direction (90º CFRP)

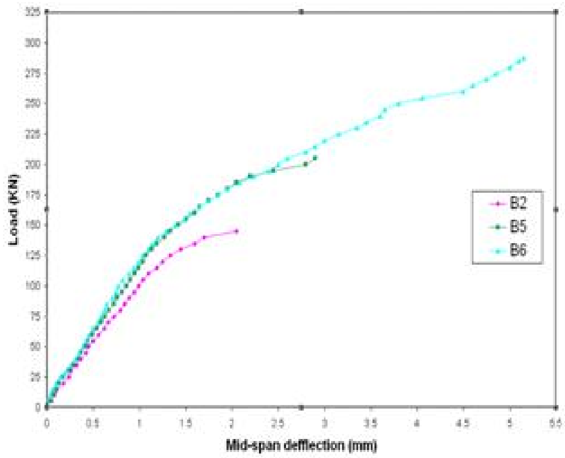


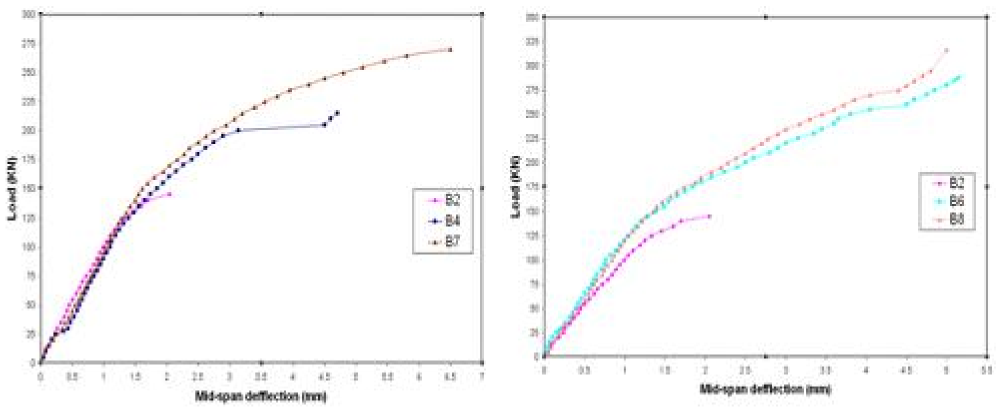
Fig (11) Load – Deflection Curves: Effect of Strengthening in Both Longitudinal and Transverse Direction (45º CFRP)

6.2.3 Effect of Anchoring CFRP Strips

Beam B7 and beam B8 were used to illustrate the effect of anchoring CFRP strips on the behavior of deep beams with opening.

From **Figure. (12a)** and **Table (8),** it can be seen by using anchors in beam B7, the CFRP contribution to the ultimate shear resistance of the beam was increased by (25.6 %) (beam B7 versus beam B4). But the increase was (10.3 %) (beam B8 versus beam B6, **Figure.(12b)**).

Figure. (12) shows that the presence of anchors increase the post – cracking deflection and absorption capacity when compared to deep beam B4 and beam B6 without anchors. Since no failure was observed in the anchoring system, their true capacity cannot be determined.



(a) Load – Deflection Curves: Effect of Anchoring 90º CFRP Strips

(b) Load – Deflection Curves: Effect of Anchoring 45º CFRP Strips

Fig .(12) Effect of Anchoring

6.3 Crack Patterns and Mode of Failure

Three different modes of failure have been identified for deep beam with web opening [12].

Mode A is the typical shear failure of a solid deep beam by diagonal cracking along a line joining the loading and reaction points as shown in **Figure (13a).** When the opening intersects the natural load path failure occurs, either in mode B or mode C.

Mode B is characterized by sudden collapse due to diagonal cracking along the two critical paths joining the loading as well as reaction points with the furthest corners of the opening as shown in **Figure(13b).**

In contrast, failure in **Mode C** occurs in a gradual manner. It is caused by deformation mainly in the shear span relative rotation of three distinct segments of the beam as shown in Fig (13c) [12].

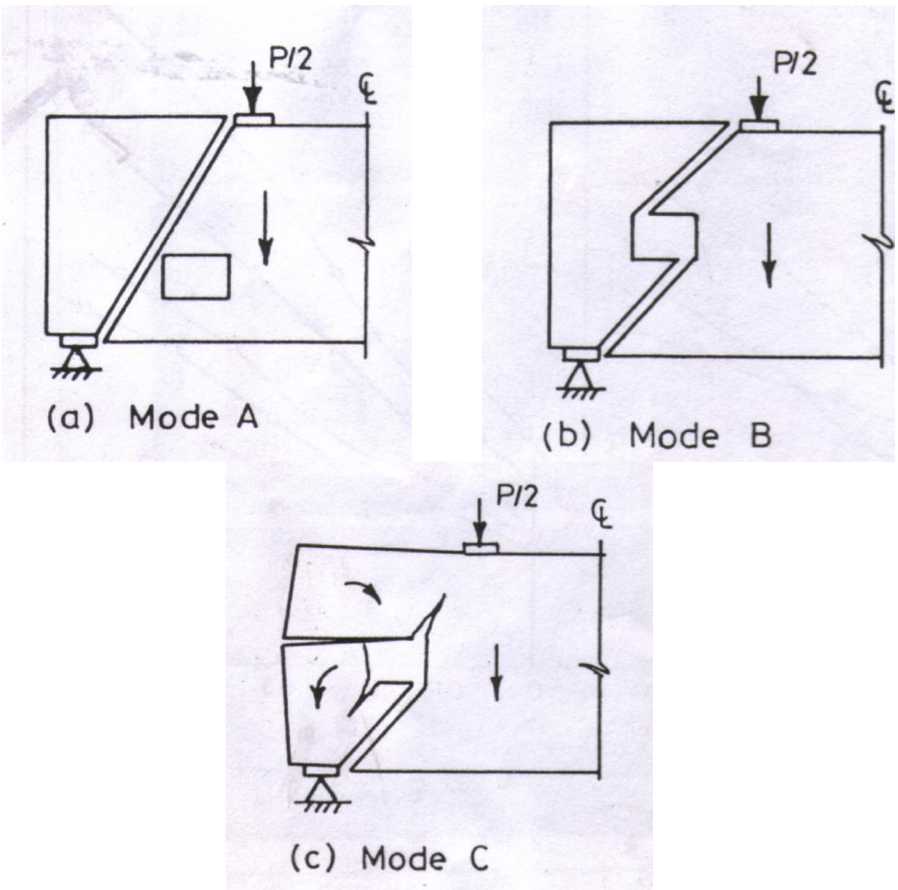


Fig (13) Observed Failure Modes for Deep Beams with Web Opening [12]

All the tested beams failed in shear. **Figure (14)** shows the cracking patterns at failure.

For beams with web opening, the cracks were initiated at corners of the opening. These cracks propagated toward the support and loading points. As the applied load was increased, new diagonal cracks, approximately parallel to the original ones, were developed with simultaneous widening and extension of the existing cracks. As the deep beams with opening strengthened with 90º CFRP strips, the mode of failure controlled by crushing the concrete between CFRP strips. This mode of failure improved by using longitudinal CFRP with vertical 90º CFRP (beam B4). The tearing of CFRP will control the mode of failure of beam B4.

The mode of failure of beam B5 with 45º CFRP strips was the tearing of the CFRP followed by crushing of concrete near the opening.

The mode of failure of beam B6 with 45º CFRP strips and longitudinal CFRP was also the tearing of CFRP followed by crushing of concrete near the opening.

One way to improve the performance of the strengthening scheme of beam B4 or beam B6 is to anchor the ends of the 90º CFRP strips or 45º CFRP strips. By the use of anchors in beam B7 or beam B8, the premature failure mode was prevented as shown in **Figure (14).** Rather than peeling of CFRP sheets. Crushing of concrete in beam B7 and beam B8 was observed.

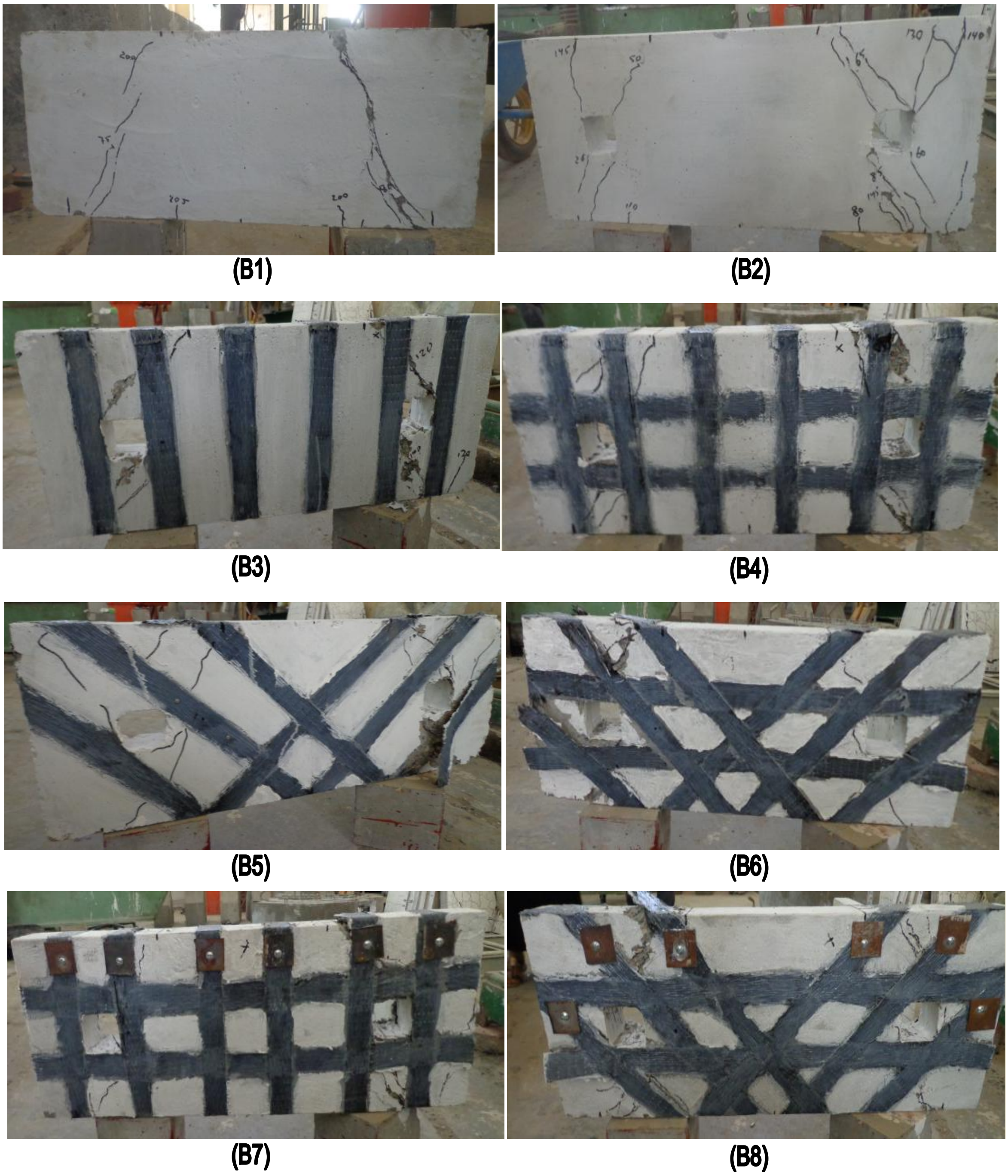


Fig (14) Modes of Failure of the Tested Beams

6.4 Shear Crack Width

Cracks developed on one of the beam faces at various stages of loading were visually inspected, and the width of all the major cracks were measured to determine the maximum value. For the deep beam without opening (B1), maximum crack widths along the major inclined crack in the shear span occurred almost at mid-depth of the beam and propagates toward the support and loading point during subsequent increase in the applied load.

The load verse maximum crack width curves of deep beams are shown in **Figure (15).** It can be seen from **Figure (15)** that the provision of opening resulted in wider cracks throughout the loading range primarily because of stress concentration. Also Fig (15) shows the influence of strengthening with CFRP, the maximum crack width is decreased as strengthening with CFRP.

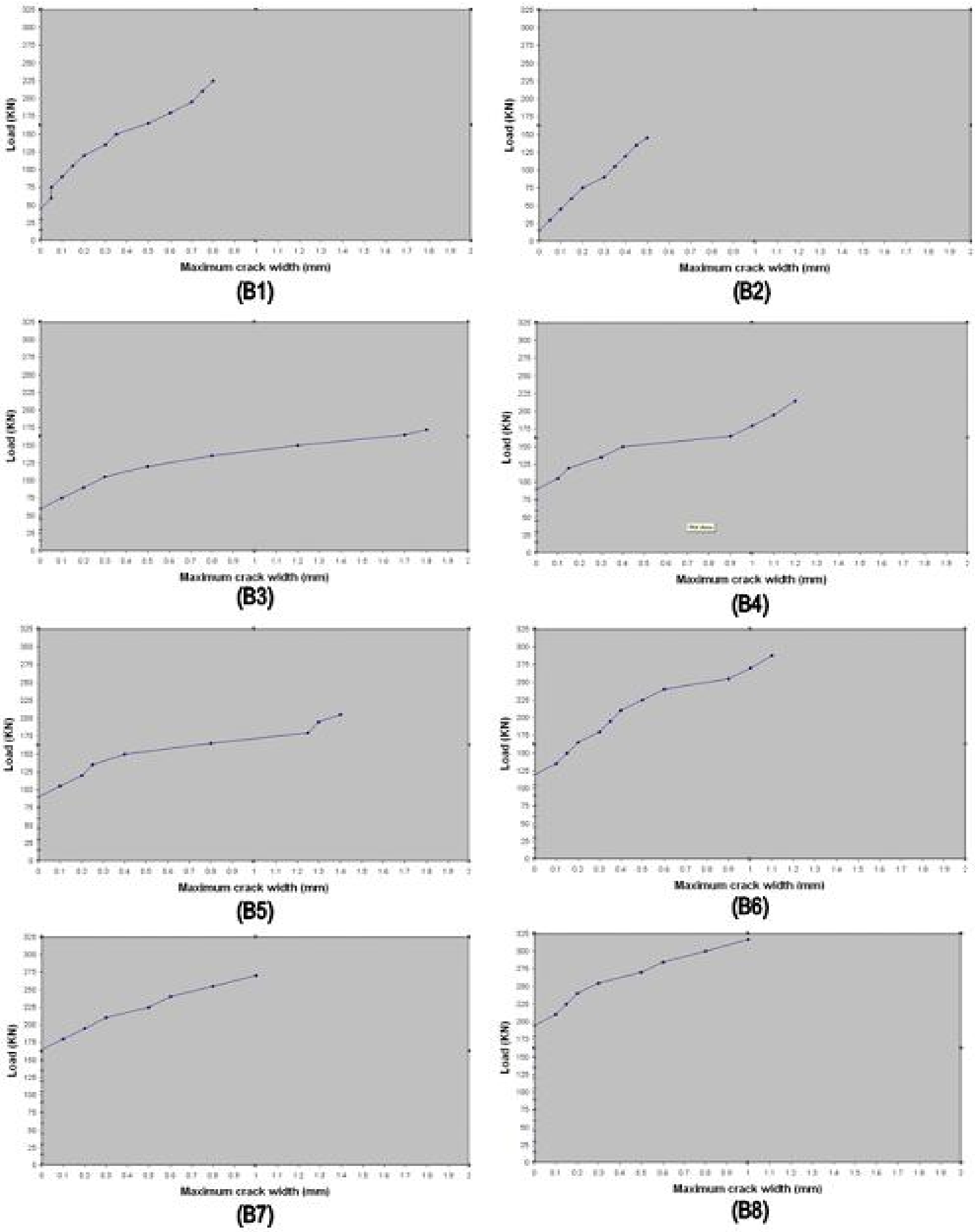


Fig . (15) Load – Shear Crack Width of the Tested Deep Beams

6.5 Tensile Strain in CFRP Strips

The demec points were placed at mid-depth of the vertical strips, 90º strips or 45º strips at region intersect the diagonal shear crack between the load and support.

Figure (16) shows the development of strains which was recorded at each 15 KN interval loading for all strengthening deep beams. It can be observed that the strain in the CFRP were very small before the initiation of the diagonal shear cracks and began to increase very quickly after the formation of the shear crack.

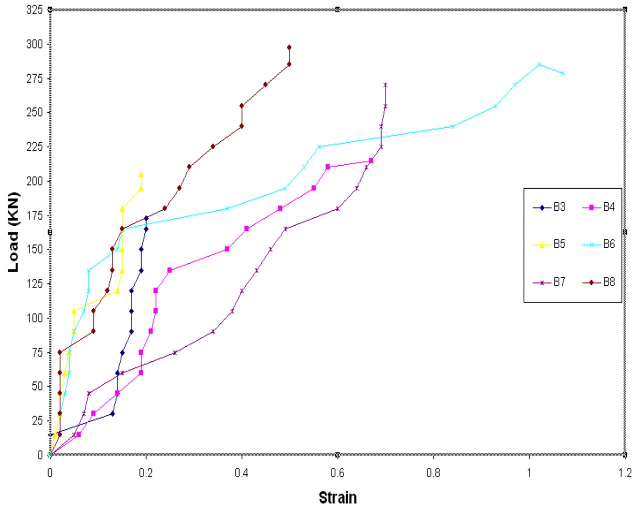


Fig (16) Development of Tensile Strain in Vertical CFRP Strips of the Tested Deep Beams

Conclusions and Recommendation

Based on the experimental investigation reported herein on reinforced concrete deep beams with opening strengthened with CFRP, the following conclusions can be drawn:

(1) Reinforced concrete deep beams with opening strengthened with 45º CFRP strips exhibited higher cracking load and ultimate load as compared with 90º CFRP strips.

(2) Both strengthening scheme (90º CFRP, 45º CFRP) will improve the ductility of the deep beam with opening.

(3) When combining CFRP strips in the longitudinal direction of the deep beam followed by 90º CFRP strips, the results showed that there was an additional increase in cracking load and ultimate load by (5 %) and (24.6 %) respectively.

(4) When combining CFRP strips in the longitudinal direction of the deep beam followed by 45º CFRP strips, the results showed that there was an additional increase in cracking load and ultimate load by (8 %) and (40.2 %) respectively.

(5) Strengthening scheme of 45º CFRP strips with additional longitudinal CFRP strips is more efficient in upgrading the shear resistance of deep beam with opening than 90º CFRP strip with longitudinal CFRP strips.

(6) The additional longitudinal CFRP strips with transverse CFRP strips (90º or 45º CFRP) will improve the post cracking stiffness and ductility of the deep beam with opening.

(7) The bolt anchors of transverse CFRP (90º or 45º CFRP) increased the composite contribution to the shear resistance of deep beam with opening by an additional (25.6 %) for 90º CFRP scheme and (10.3 %) for 45º CFRP scheme. Since no failure was observed in the anchoring system, their true capacity cannot be determined.

(8) Provision of opening resulted in wider cracks throughout the loading range primarily because of stress concentration. But the strengthening with CFRP decreased the maximum crack width.

(9) The strain in the CFRP were very small before the initiation of the diagonal shear cracks and began to increase very quickly after the formation of the shear crack.

Further research is needed to study the effect of strengthening deep beams with different web opening location and different (a/d) ratio.

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