Jordan Journal of Civil Engineering, Volume **10**, No. **2**, **2016**

Repair Effectiveness of Damaged RC Beams with Web Opening Using CFRP and Steel Plates

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ABSTRACT

This paper presents an investigation conducted on repairing damaged Reinforced Concrete (RC) beams with a large rectangular web opening using externally bonded plates. Carbon Fiber Reinforced Polymer (CFRP) and steel plates were used as repair materials with two types of configuration - hexagonal and rectangular - for each material. The beams contain a rectangular web opening at one of the shear spans. The externally bonded CFRP sheet and steel plate were found to be effective in repairing RC beams with a large rectangular web opening. The results showed that CFRP plates perform better than steel plates and that the rectangular configuration is better than the hexagonal one.

KEYWORDS: Web opening, CFRP plates, Steel plates, Repair configuration.

INTRODUCTION

Transverse openings in concrete beams represent a means of accommodating utility services in a building structure. These openings are necessary to accommodate essential services, like water supply, electricity, telephone and computer network. These ducts and pipes are usually placed underneath the soffit of the beam and, for aesthetic reasons, are covered by a suspended ceiling; thus creating a dead space. On each floor, the height of this dead space that adds to the overall building depends on the number and depth of ducts. The ability to accommodate such services through a member, instead of below or above the member, results in a compact design and an overall saving in terms of total building height, which leads to an economical design.

The presence of transverse openings will change the simple beam behaviour into a more complex behaviour, because of a sudden change in the dimension of the cross-section of the beam. However, as the opening represents a source of weakness, the failure plane always passes through the opening. The ultimate strength, shear strength, crack widths and stiffness may also be seriously affected (Mansour et al., 1994). Furthermore, the provision of openings produces discontinuities or disturbances in the normal flow of stresses, which leads to stress concentration and early cracking around the opening region. Similar to any discontinuities, special reinforcement, enclosing the opening close to its periphery should therefore be provided in sufficient quantity to control crack widths and prevent possible premature failure of the beam (Mansour et al., 1991; Tan et al., 1996). On the other hand, Reinforced Concrete (RC) structures may be damaged. Most of them suffer from various deteriorations, such as cracks, concrete spilling and large deflection. Many factors are at the origin of these

Accepted for Publication on 30/11/2014.

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deteriorations, such as ageing, corrosion of steel, earthquakes, environmental effects and accidental impacts on the structure. The cost of replacing these structures is overwhelming. Nowadays, it is necessary to find repair techniques suitable in terms of low cost and fast processing time. Carbon Fibre Reinforced Polymer (CFRP) and steel plates are some of the famous repairing systems that we will therefore use in this study for repairing RC beams with large rectangular openings.

The use of CFRP materials for structural repair and strengthening has continuously increased in recent years, due to the advantages of these materials. These advantages include: high strength-to-weight ratio, high durability, electromagnetic neutrality, ease of handling, rapid execution with less labour and availability in size. One method for providing enhanced shear capacity is to adhesively bond steel plates to the concrete surface. The technique of using externally bonded steel plates has been used worldwide for over 30 years, and since 1975 in the UK. Advantages of external reinforcement over other methods include: a minimum effect on headroom, low cost, ease of maintenance and the ability to strengthen parts of the structure whilst still in use (Jumaat and Alam, 2007). Many studies have been carried out on strengthening and repairing the spoiled beam, due to shear failure, using different techniques, such as plate bonding using steel plates or FRP materials.

Many studies have been carried out for strengthening RC beams with openings. When strengthening the RC beams with Glass Fibre Reinforced Polymer (GFRP), the ultimate shear failure load of the strengthened opened beams having an opening diameter-to-depth ratio of 0.54 was greater than the ultimate shear failure load of the solid control beam (Abdelhafez and Abou-Elezz, 2002). The application of CFRP sheets, according to the arrangement parallel to the opening edges, greatly decreases beam deflection, controls cracks around openings and increases the ultimate capacity of the beam (Abdalla et al., 2003). Both shear span-to-depth ratio and concrete compressive strength of T-beams with openings have pronounced effects on the load-bearing capacity of the tested beams (Zainab et al., 2005). External strengthening of a beam opening using steel plates or CFRP sheets is more efficient than internal strengthening of the opening using internal steel reinforcement (Allam, 2005). In beams with inclined full-depth FRP rods, the analytical compressive stresses demonstrate the two strut mechanisms associated with each FRP rod, which function as a load-resistant mechanism of the beam. It is also found that placing FRP rods far away from the opening does not provide a strengthening effect on the beam (Pimanmas, 2010). External strengthening with CFRP sheets around the opening was found to be very effective in improving the beam shear resistance and stiffness (El-Maaddawy, 2010).

Research Significance

There are many studies available on RC beams with circular and rectangular web openings. Also, many studies have been conducted on strengthening and repair of solid RC beams with externally bonded steel and FRP plates. However, studies on strengthening or repair of RC beams with web openings using externally bonded steel or FRP plates are very limited. Thus, the authors believe that this detailed study to investigate the effectiveness of CFRP and steel plates with different repair configurations for damaged RC beams with a large rectangular opening is carried out for the first time and will be very useful to structural engineering.

Experimental Procedure

The test program consisted of casting and testing of four RC beams. All the beams have a clear span of 2.1 m (6.889 ft.), as well as a cross-section of 175 × 450 mm (6.88 × 17.7 in); four of these beams have a rectangular web opening and one was a solid beam without opening. Ready mix concrete was used, and the average compressive strength of the concrete on the day of testing was 26 MPa (3.77 ksi). Table 1 shows the mechanical properties of the used materials. The tensile strength and modulus of elasticity of the steel plates were 375 MPa (54.39 ksi) and 200 GPa (29007.5 ksi), respectively, whereas the tensile strength and modulus of elasticity of CFRP plates were 2800 MPa (406.1 ksi) and 165 GPa (23931.23 ksi), respectively. Table 2 shows the dimensions and configuration types of externally bonded CFRP and steel plates.

Table 1. Mechanical and geometrical properties of the used materials

Material	Diameter mm (in)	Compressive Strength MPa (ksi)	Ultimate Tensile Strength MPa (ksi)	Modulus of Elasticity MPa × 10^3 (ksi)
Concrete	_	26 (3.77)	_	20 (2900.7)
Steel bars	12 (0.47)	_	406 (58.88)	200 (29007.5)
	10 (0.39)	_	400 (58)	200 (29007.5)
	6 (0.236)		380 (55.11)	200 (29007.5)
CFRP	_	_	2800 (406.1)	165 (23931.2)
Steel	_	_	380 (55.11)	200 (29007.5)

In order to repair damaged RC beams, the concrete surface treatment is very important to guarantee a perfect bonding between concrete and externally bonded plates. Roughness equipment is used on the concrete surface to obtain a suitable face and to have as much friction as possible with the externally bonded plates. The surface is cleaned using air pressure to avoid any residues or dust on the surface. This is because the substrate must be sound, dry, clean and free of laitance, ice, standing water, grease, oils, old surface treatments or coatings as well as all loosely adhering particles. The surface of externally bonded steel plates was also sandblasted to eliminate rust. A special cleaner (acetone) was used to remove carbon dust from the bonding face of the CFRP plate.

The well-mixed Sikadure adhesive (SIKADURE 30) was then trawled onto the surfaces of the concrete specimen to form a thin interface layer. The same adhesive was also applied with a special "dome" - shaped spatula onto the CFRP (SIKA CARBODUR) and steel plates. The plates were then positioned on the prepared concrete surfaces. Using a rubber roller, the plates were gently pressed into the adhesive until the material was forced out on both plate sides. The surplus adhesive was then removed.

Test Setup

All beams were tested as simple supported beams subjected to a four-point load, as illustrated in Figure 1. A universal testing machine with 300 kN (67.44 kips) capacity was used to apply a concentrated load on a steel distribution I-beam, which was used to generate the two concentrated loads on the beam. The load was applied gradually with a speed of 0.5 kN / sec. (0.112 kips /sec.) and was then released with the same speed. Two linear variable differential transformers (LVDT) were used in each test to monitor vertical deflection at two locations; the edge of the opening and the mid-span of the beam, as shown in Figure 1.

For each beam, one strain gauge was attached to the main flexure steel bars below the opening. In case of a solid beam, the strain gauge was attached to the main flexure steel bar in the middle of the shear span with a distance of 425 mm (16.73 in) away from the support and 425 mm (16.73 in) away from the concentrated load, as shown in Figure 2 (a). For beam B1 and beam B3, six strain gauges were attached directly to the CFRP and steel plate on the sides of the beams to monitor strain variation in CFRP and steel plates, as shown in Figure 2 (b). Four strain gauges were attached directly to CFRP and steel plates in beam B2 and beam B4, as shown in Figure 2 (b), (c). All the used electrical devices (load cell, LVDT and strain gauges) were attached to the date logger in order to monitor the variation in load, deflection and train values, corresponding to applied loads. The reading was taken out at each 5 kN (1.124 kips) load step up to the ultimate applied load. All the beams were subjected to failure load at the pre-repair stages.

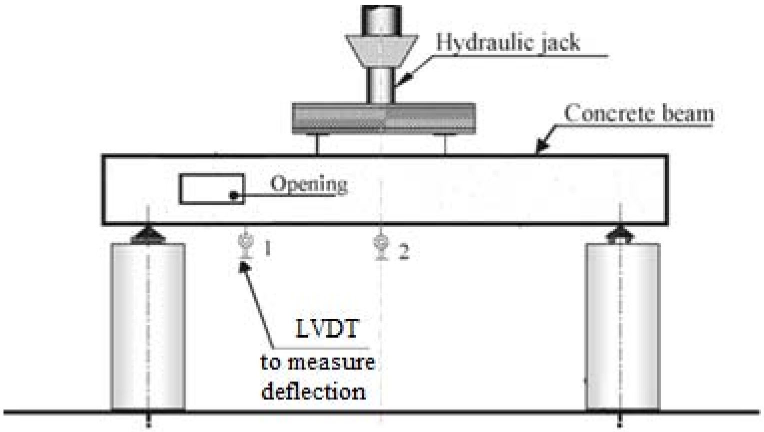


Figure (1): Test setup

Table 2. Configuration types and dimensions

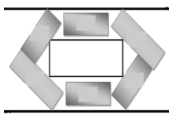
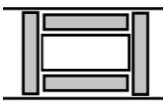
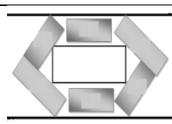
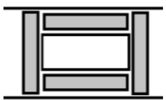
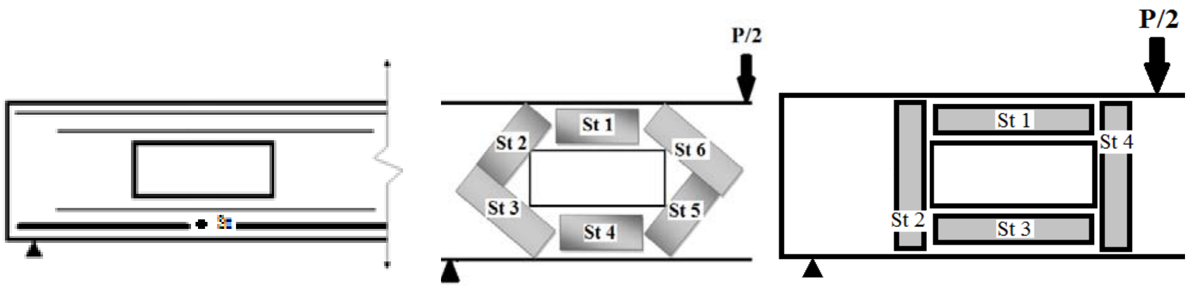
Beam	Repair Material	Type	Configuration	Plate Thickness, mm (in)	Plate Width, mm (in)
S1	N/A	N/A	N/A	N/A	N/A
B1	CFRP	Type A (hexagonal)		1.2 (0.047)	100 (3.937)
B2	CFRP	Type B (rectangular)		1.2 (0.047)	100 (3.937)
B3	Steel	Type A (hexagonal)		3 (0.118)	100 (3.937)
B4	Steel	Type B (rectangular)		3 (0.118)	100 (3.937)

Table 3. Load capacity of RC beams

Beam	Repair Material	Configuration	Maximum Load kN (kip)		Repair Effectiveness [(Lpost-Lpre)/Lpre].%
			Pre-repair (Lpre)	Post-repair (Lpost)	
S1	N/A	N/A	143.4 (32.23)	N/A	N/A
B1	CFRP	Type A(hexagon)	124.0 (27.87)	154.6 (34.75)	25 %
B2	CFRP	Type B (rectangular)	125.2 (28.14)	178.5 (40.13)	43 %
B3	Steel	Type A(hexagon)	124.4 (27.96)	128.7 (28.93)	4 %
B4	Steel	Type B (rectangular)	129.0 (29)	167 (37.54)	30 %



(a) flexural steel bar (b) hexagonal configuration (c) rectangular configuration

Figure (2): Locations of strain gauge

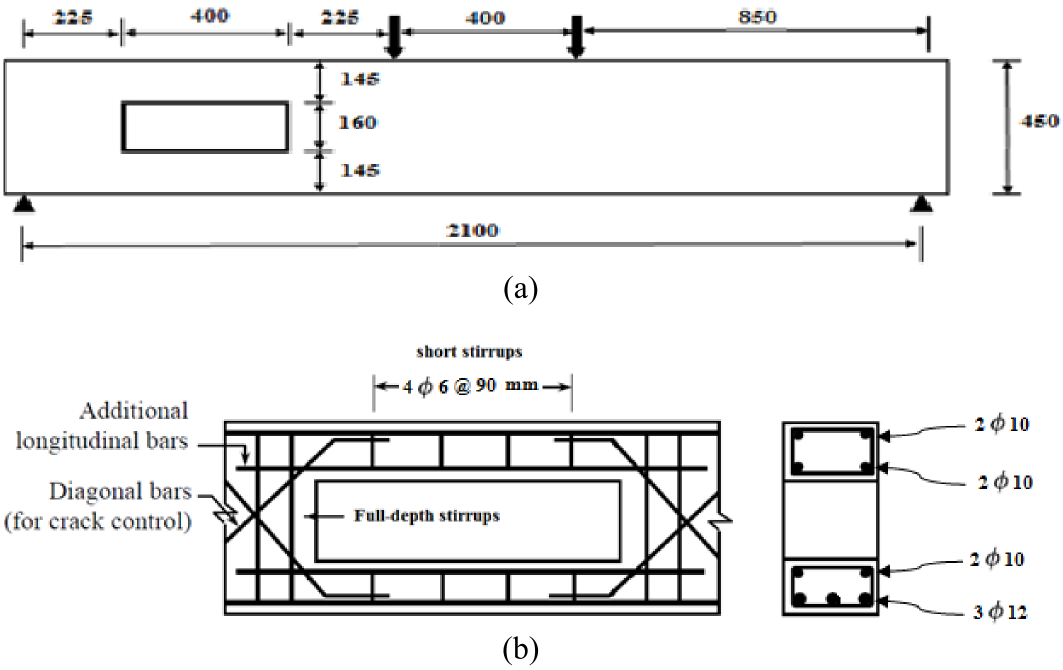
Beam Description

All of the RC beams with web openings contain a large rectangular opening with a size of 160 × 400 mm (6.3 × 15.7 in) (depth × width). The opening was located in the middle of the shear span with a distance of 225 mm (8.85 in) away from the support and 225 mm (8.85 in) away from the concentrated load. The distance between the two concentrated loads is 400 mm (15.7 in) and the shear span is 850 mm (33.46 in), as shown in Figure 3. Beams with openings were designed according to the plastic hinge method (Mansur and Tan, 1999). The beams were reinforced with three steel bars, with a diameter of 12 mm (0.47 in) as major reinforcement in the tension zone and two with a 10 mm (0.39 in) diameter in the compression zone. Additional longitudinal bars were provided as two 10 mm (0.39 in) diameter steel bars at the top and bottom chords of the opening, and diagonal bars for crack control were also added at the corner of the opening. Steel stirrups of a 6 mm (0.236 in) diameter were used at 90 mm (3.54 in) spacing along the top and bottom chords.

RESULTS AND DISCUSSION

The effects of two configurations of CFRP and steel plates on the repair effectiveness are presented in this section. Rectangular and hexagonal configurations of CFRP and steel plates were investigated. The thicknesses used for CFRP and steel plates are 1.2 mm

(0.047 in) and 3 mm (0.118 in), respectively. The results are presented and discussed with regard to the maximum load capacity of the beam, deflection at the mid-span and edge of the opening, strain in steel bars, strain in externally bonded plates, as well as crack patterns and failure modes.



(mm/25.4 in)

Figure (3): Beam description (a) Opening location (b) Steel reinforcement at the opening

Effect on Load Capacity

The maximum loads carried by the beams at pre- and post-repair stages are given in Table 3. It can be seen that the maximum load after repair is higher than the maximum load observed at the pre-repair stage. Thus, it is clear that both CFRP and steel plates, which are externally bonded around the web opening of RC beams, are effective in increasing the load capacity of repaired beams. The results indicated that CFRP plates with both configurations (hexagonal and rectangular) can sustain more load at post-repair stage than the solid beam can. The increase in maximum load at the post-repair stage is reported in terms of repair effectiveness, which is the ratio between increase in load in the post-repair stage and the maximum load at the pre-repair stage, expressed as a percentage. It can be seen that the maximum load after repair for beams repaired by steel plates with rectangular configuration is higher than the maximum load observed from the control beam.

The results of this study are in good agreement with (Anders et al., 2003), who concluded that repair-damaged beams may not only recover their original capacity, but can even reach a capacity above that they had before. The results are also in agreement with (Yasmeen et al., 2011), who found that the maximum load of retrofitted beams reached a value of about 23% over their original capacity. Agreement also exists with (Sinan et al., 2005), who found that all steel plate configurations significantly improve the strength and stiffness of RC beams. The results indicated that CFRP plates can sustain more load at the post-repair stage than steel plates. Therefore, CFRP plates are more effective in repairing RC beams with web openings. The contribution of the externally bonded plates depends on the material properties, configuration, surface interaction and distribution of stress on the interface between plate and concrete.

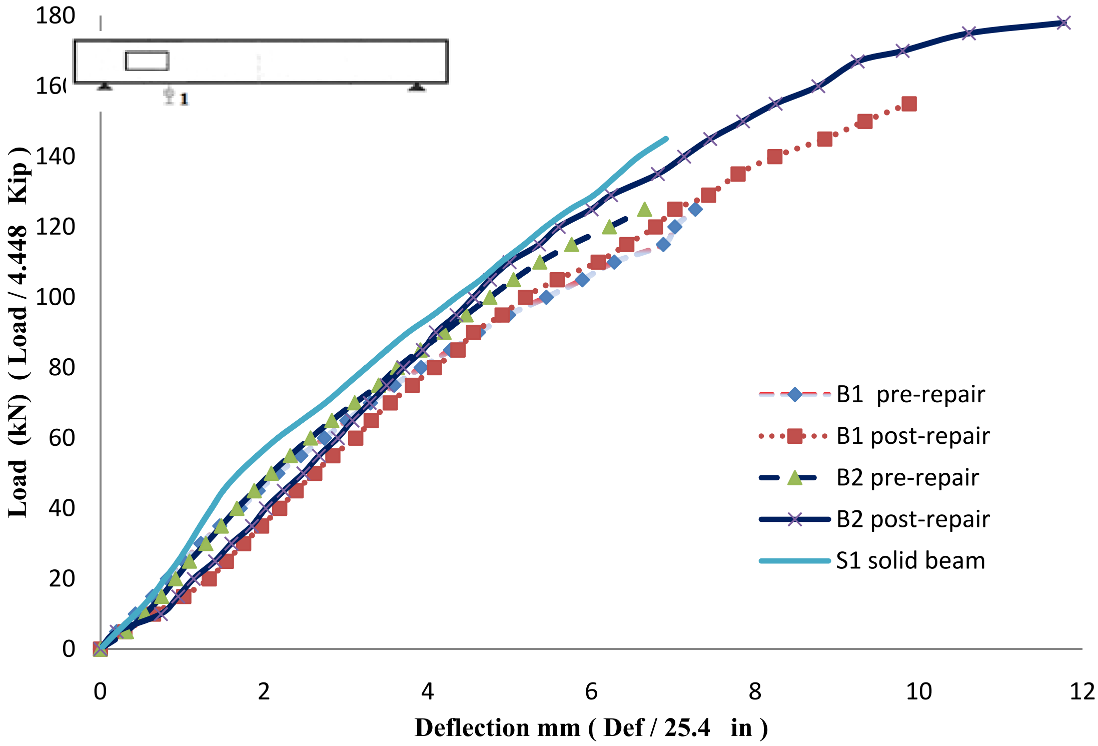


Figure (4): Load *vs.* deflection curves at the edge of the opening for beams repaired by CFRP

This can be attributed to the fact that the surface preparation of CFRP plates is carried out by the manufacturer and is hence of better quality. On the other hand, the surface preparation of steel plates was accomplished in the laboratory using sandblasting. This might have caused surface imperfection in the steel plate, which can result in irregularity and non-uniform stress distribution on the adhesive layer. This is exactly what happened in this study; the use of sandblasting caused bending in the steel plate, which can have an effect on the repair effectiveness. The repair effectiveness is found to be 43% and 30% for rectangular configuration in CFRP and steel plates, respectively, as shown in Table 3. For hexagonal configuration, the repair effectiveness was 25% and 4% for CFRP and steel plates, respectively. Therefore, it is clear that rectangular configuration applied around a web opening is capable of sustaining a 43% higher load than that of pre-repair load, because the rectangular configuration contributed more of an area for top and bottom chords than hexagonal configuration. The results are in good agreement with (Sinan et al., 2005), who found that the increase in the bonding area on the shear span significantly reduces the propagation of shear cracks. The results are also in agreement with (Hemdan et al., 2003), who found that for beams strengthened with CFRP, the percentage of the increase in ultimate capacity ranges from 2% to 60%, depending on the strengthening configuration. Hemdan et al. (2003) also found that configuration having horizontal and vertical CFRP laminates around the opening is the best configuration in the enhancement of ultimate capacity. Based on the results of this study, an externally bonded CFRP plate with rectangular configuration is the best suggestion for the repair of RC beams with a web opening.

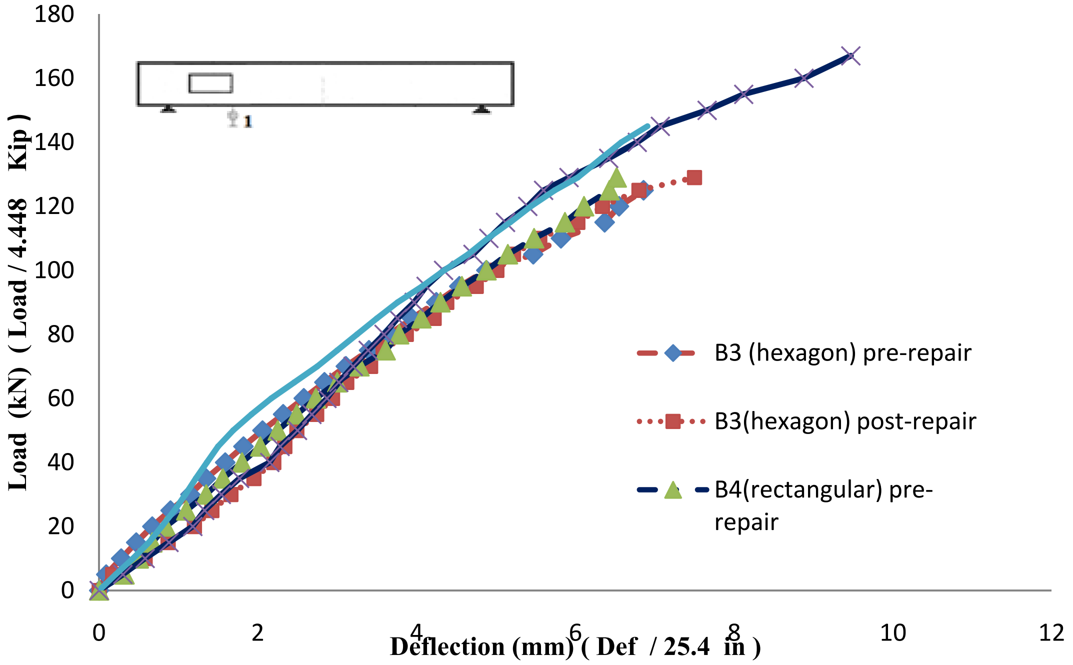


Figure (5): Load *vs.* deflection curves at the edge of the opening for beams repaired by steel plates

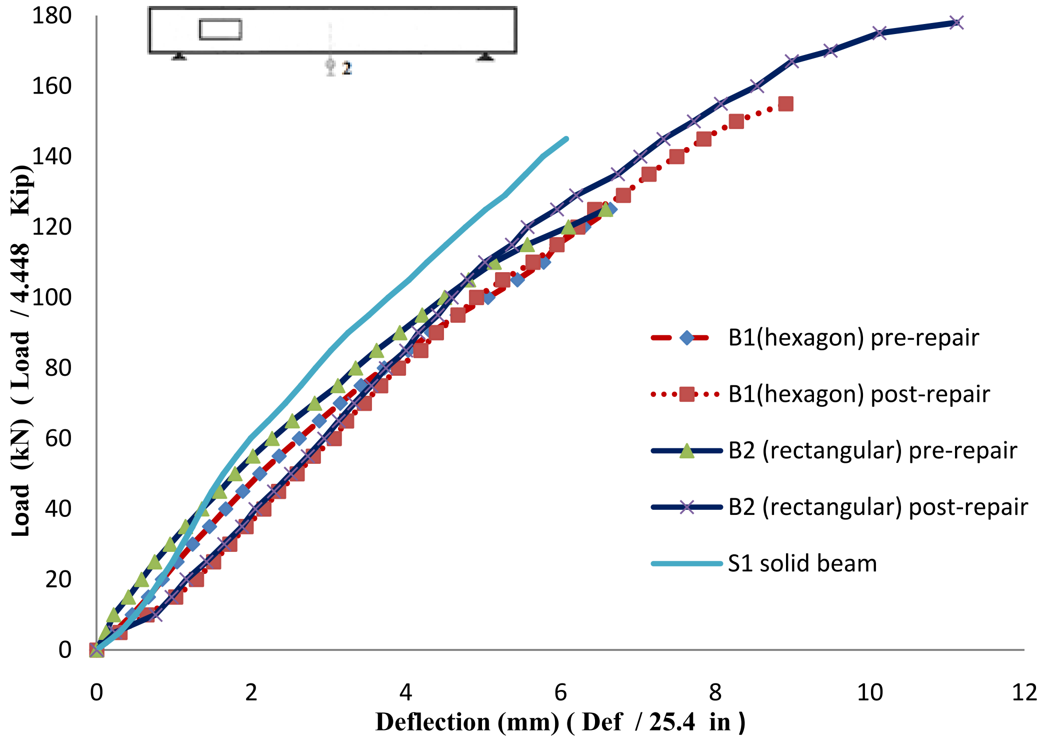


Figure (6): Load *vs.* deflection curves at the mid-span for beams repaired by CFRP

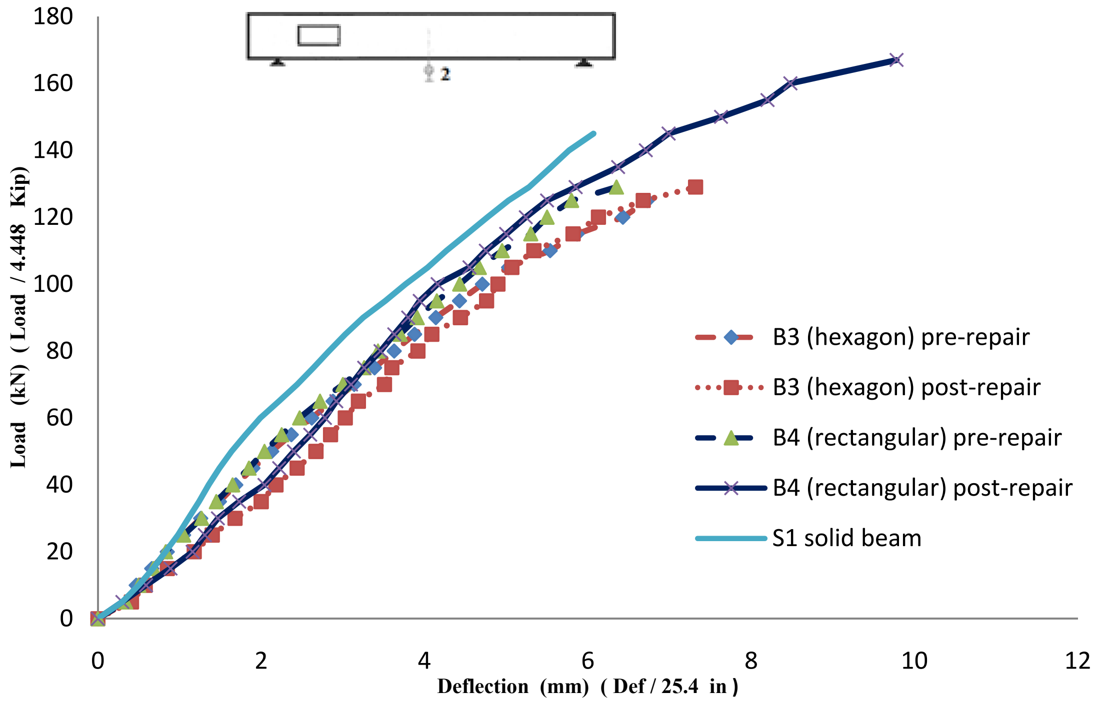


Figure (7): Load *vs.* deflection curves at the mid-span for beams repaired by steel plates

Table 4. Maximum load and deflection values at the edge of the opening

Beam	Pre-repair Stage		Post-repair Stage				
	Max. load kN (kip)	Deflection mm (in)	Pre-repair load kN (kip)	Deflection mm (in)	Reduction in deflection	Max. load kN (kip)	Deflection mm (in)
S1	143.4 (32.23)	6.909 (0.27)	N/A	N/A	N/A	N/A	N/A
B1	124.0 (27.87)	7.27 (0.286)	124.0 (27.87)	7.02 (0.276)	3.5 %	154.6 (34.75)	9.88
B2	125.2 (28.14)	6.65 (0.26)	125.2 (28.14)	6.00 (0.236)	10 %	178.5 (40.13)	11.76
B3	124.4 (27.96)	6.86 (0.27)	124.4 (27.96)	6.80 (0.267)	1 %	128.7 (28.93)	7.50
B4	129.0 (29)	6.52 (0.256)	129.0 (29)	5.92 (0.233)	9 %	167 (37.54)	9.47

Effect on Load Deflection Relationship

The behaviour of load deflection relationship at the mid-span and below the edge of the opening is presented in this section. Figure 4 and Figure 5 show the load against deflection curves at the edge of the opening for beams repaired by CFRP and steel plates, respectively. Figure 6 and Figure 7 show the load against deflection curves at the mid-span for beams repaired by CFRP and steel plates, respectively. The solid beam, as expected, show the highest value of deflection at the mid-span, while beams with openings show the highest value of deflection at the edge of the opening. For deflection at the edge of the opening, the reduction in deflection values is found to be 10% and 9% for rectangular configuration of CFRP and steel plates, respectively, as shown in Table 4. However, for hexagonal configuration, the reduction in deflection values was 3.5% and 1% for CFRP and steel plates, respectively. Therefore, it is clear that rectangular configuration applied around a web opening is capable of reducing 10% higher deflection than that of pre-repair load, because the rectangular configuration contributed more of an area for top and bottom chords than the hexagonal configuration.

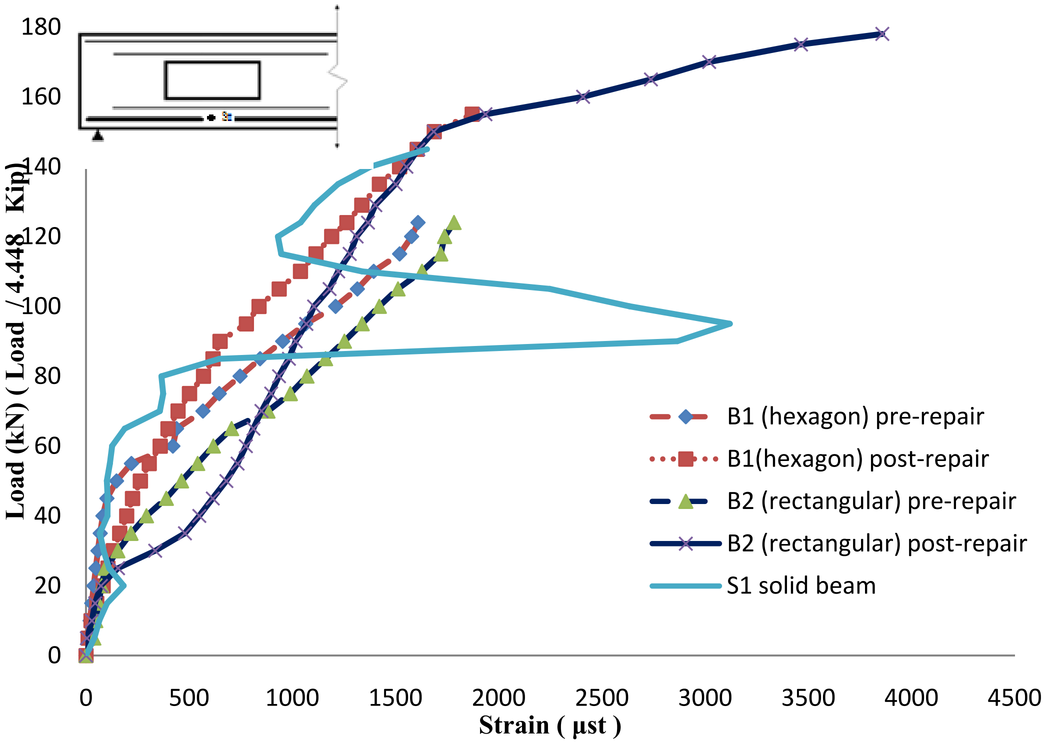


Figure (8): Load *vs.* steel bar strain curves at St for beams repaired by CFRP

For deflection at the mid-span of the beam, the reduction in deflection values is found to be 9% and 7% for rectangular configuration in CFRP and steel plates, respectively, as shown in Table 4. For hexagonal configuration, the reduction was 3% and 1 % for CFRP and steel plates, respectively. Beam B3, which was repaired with a steel plate, according to configuration type A (hexagonal), shows a smaller effect on load capacity and no effect on deflection at the edge of the opening, as can be seen from Figures 4 and 5. This indicates the weakness of this type of configuration for steel plates, because hexagonal configuration contributed a little area on the top and bottom chords. Beam B2 has the highest effect on deflection at the edge of the opening. As shown in Table 4 and Table 5, for deflection at the edge of the opening in the pre-repaired stage at a failure load of 125.2 kN (28.146 kips), the deflection was 6.65 mm

(0.26 in), while at the post-repair stage the deflection for the same load of 125.2 kN (28.146 kips) was 6 mm (0.236 in). For deflection at the mid-span, the value of deflection at the pre-repair stage at a failure load of 125.2 kN (28.146 kips) was 6.58 mm (0.259 in), while at the post-repair stage at a load of 125.2 kN (28.146 kips) the deflection was 5.95 mm (0.234 in), with a reduction of about 10% of deflection at the edge of the opening and mid-span. Rectangular configuration is more effective than hexagonal in reducing the deflection for repaired beams, because the rectangular configuration contributed more of an area than hexagonal configuration, as well as there being a contribution of externally bonded plates in reducing the deflection increase with an increase in the area of these plates.

Table 5. Maximum load-deflection values at the mid-span

Beam	Pre-Repair Stage		Post-Repair Stage				
	Max. load kN (kips)	Deflection mm (in)	Pre-repair load kN (kips)	Deflection mm (in)	Reduction in deflection	Max. load kN (kips)	Deflection mm (in)
S1	143.4 (32.23)	6.069 (0.23)	N/A	N/A	N/A	N/A	N/A
B1	124.0 (27.87)	6.64 (0.26)	124.0 (27.87)	6.44 (0.253)	3 %	154.6 (34.75)	8.91 (0.35)
B2	125.2 (28.14)	6.58 (0.259)	125.2 (28.14)	5.95 (0.234)	9 %	178.5 (40.13)	10.12 (0.398)
B3	124.4 (27.96)	6.73 (0.264)	124.4 (27.96)	6.68 (0.263)	1 %	128.7 (28.93)	7.32 (0.288)
B4	129.0 (29)	6.35 (0.25)	129.0 (29)	5.85 (0.23)	7 %	167 (37.54)	9.78 (0.385)

This indicates the effect of externally bonded CFRP plates with configuration type B (rectangular) on beam deflection at the edge of the opening. This is in agreement with (Hemdan et al., 2003), who found that strengthening configuration having horizontal and vertical CFRP laminates around the opening is the best configuration in reducing deflection. From Figure 6 and Figure 7, it can be seen that curves in deflection for repaired beams show somewhat similar behaviour, because both CFRP and steel plates around openings serve in resisting stress concentration at the opening corners, thus delaying cracking and controlling width and propagation of cracks. It is clear that the rectangular configuration is the more effective parameter than the materials in repair. The highest value of deflection was obtained for beams B1, B2, B3 and B4, located at the edge of the opening. The results are in agreement with (Tan et al., 1982), who found that for beams with an opening, the maximum deflection usually occurs at the high moment end of the opening. The decrease in deflection is smaller for the repaired beams, since the CFRP and steel plates prevent cracks from developing and widening. Furthermore, some contributions to the stiffness of beams are caused by the CFRP and steel plates outside of the cracking region. This means that externally bonded CFRP with configuration type B (rectangular) represents the best material and configuration in decreasing the deflection of the damaged RC beams with a large rectangular opening.

Effect on Steel Bar Strain

The load-strain relationship of steel reinforcement is presented in this section. A strain gauge (St) was attached onto a main steel bar reinforcement at the middle of the opening in the bottom chord. Figure 8 and Figure 9 show the load-steel bar strain of the strain gauge (St) at the pre–repair stage and post-repair stage. In all the beams at the pre-repair stage, the strain gauge (St) shows an increase in strain value with the increase being in applied load and reaching the yielded point strain of the maximum load. At the post-repair stage, the externally bonded CFRP and steel plate shared the strain with steel bars, where the strain gauge (St) reached a strain less than the strain at the pre-repair condition with the same load, but with different reducing percentages dependent on the material and configuration used, as shown in Table 6. For solid beam S1, the strain increases with the increase in the applied load. The steel strain has stopped increasing at 95 kN (21.346 kip) of load stage where strain reached 3120 µst. Hence, there is an abnormal change in strain curves for solid beam as seen in Figure 8 and Figure 9. This may be due to strain gauge damage which needs to be further investigated.

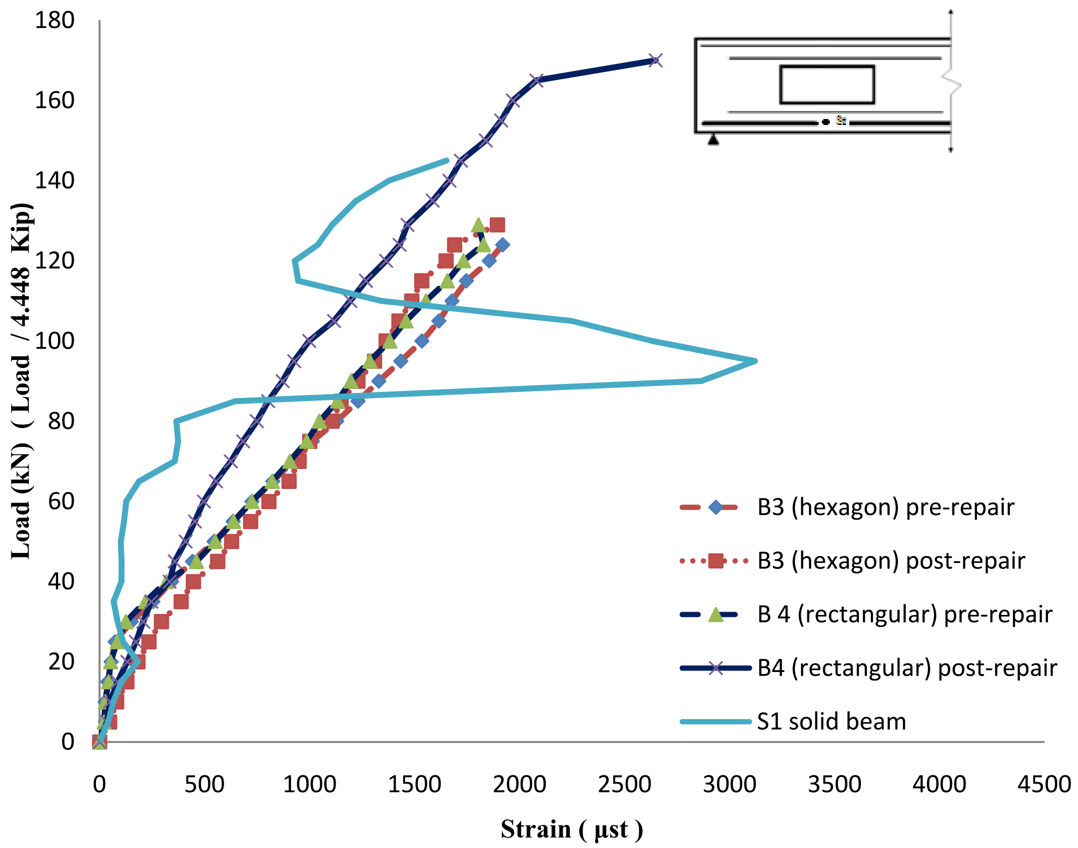


Figure (9): Load *vs.* steel bar strain curves at St for beams repaired by steel plates

The strains in major steel bars at the bottom chord in the middle of the opening at pre-repair and post-repair stages are given in Table 6; the reducing percentages in strains were observed to be 22% and 24% for beams repaired by CFRP for hexagons and rectangles, respectively. However, for beams repaired by a steel plate, the reducing percentages were found to be 13% and 19% for hexagonal configuration and rectangular configuration, respectively. It is clear that the contribution of externally bonded plates to steel bar strain depends on the plate material rather than on the configuration. This is because the strain in steel reinforcement is controlled by the interaction of repair material and concrete. The CFRP plates have better interaction with concrete than steel plates, and hence are able to share the strain in the reinforcement effectively.

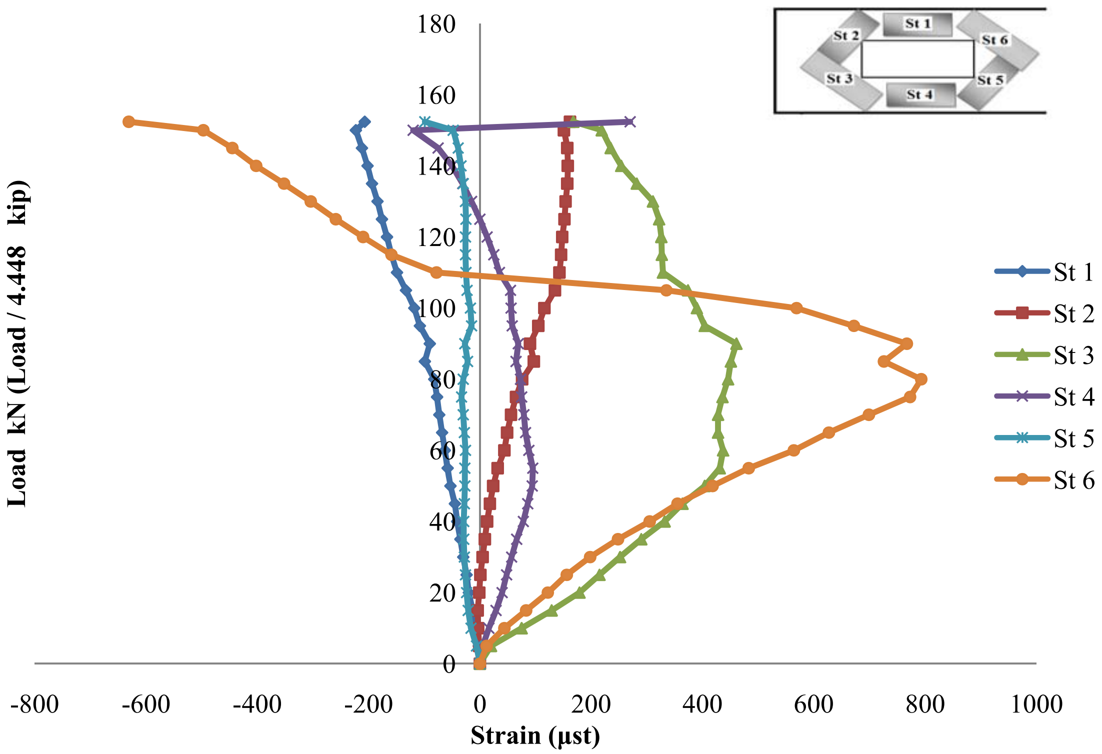


Figure (10): Load *vs.* strain curves of externally bonded CFRP plates for beam B1

Table 6. Strain of the major steel bar (St1) at pre-repair and post-repair stages

Beam	Pre-repair Stage		Post-repair Stage				
	Max. load, kN (kip)	Strain (µst)	Load, kN (kip)	Strain (µst)	Reduction in strain	Max. load, kN (kip)	Strain (µst)
S1	143.4 (32.23)	N/A	N/A	N/A	N/A	N/A	N/A
B1	124.0 (27.87)	1609	124.0 (27.87)	1264	22 %	154.6 (34.75)	1871
B2	125.2 (28.14)	1783	125.2 (28.14)	1366	24 %	178.5 (40.13)	3858
B3	124.4 (27.96)	1920	124.4 (27.96)	1690	13 %	128.7 (28.93)	2007
B4	129.0 (29)	1805	129.0 (29)	1466	19 %	167 (37.54)	2648

Therefore, it is concluded that the CFRP can be suggested for repairing RC beams. The results are in agreement with (Hemdan et al., 2003), who found that strengthening RC beams with web openings by CFRP causes a noticeable reduction in strain relative to ultimate steel bar strain. The mechanism of failure and the stress distribution in the shear zone for solid beams are still complex and not very clear, like in the flexural zone. The presence of a transverse opening will change the simple beam behaviour into a more complex one, because of a sudden change in the dimension of the cross-section of the beam. However, as the opening represents a source of weakness, the failure plane always passes through the opening. The provision of openings produces discontinuities or disturbances in the normal flow of stresses, thus leading to stress concentration and early cracking around the opening region. Furthermore, repairing the beams with externally bonded plates causes stress-strain redistribution around the opening and this will add more complexity to shear phenomena.

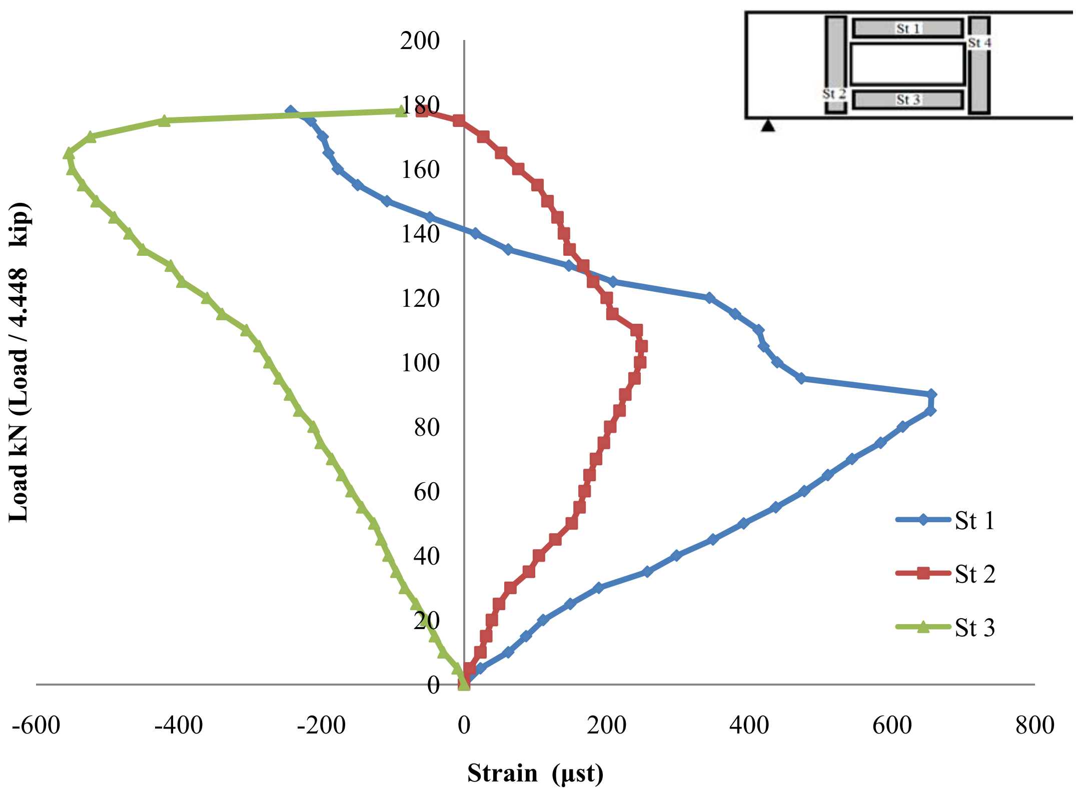


Figure (11): Load vs. strain curves of externally bonded CFRP plates for beam B2

Effect on Load Strain of External Bonded Plates

The behaviour of load strain for externally bonded CFRP and steel plates is presented in this section. For beam B1, the maximum CFRP strain measuring failure was in strain gauge 3 (St3) and strain gauge 6 (St6), on the opening corner near to the support and concentrated load, as shown in Figure 10, which shows the load-strain relationship of externally bonded CFRP plates for beam B1 in six points. The recorded strains indicate that the value of strains for all pieces did not reach the CFRP ultimate strain. It can be observed from Figures 10 to 14 that the externally bonded plates start to share the strain in the beam from the start of the applied load. The strains observed at all locations of the CFRP and steel plates did not reach the ultimate strain of the plates. This is due to the fact that the concrete failed before allowing the repair materials to reach the ultimate strain values. The results are in agreement with (Khalifa and Intomio, 2002), who found that the maximum CFRP vertical strain measured at failure corresponded to 14% of the reported CFRP ultimate strain. This value is not absolute, because it is greatly dependent on the location of the strain gauge with respect to a crack. Figure 11 shows the load-strain relationship of externally bonded CFRP plates for beam B2 in four points. For beam B1, the maximum CFRP strain measured at failure was in strain gauge 1 (St1), on the top chord of the opening. Strain gauge 4 was broken during testing. The recorded strains indicate that the value of strains for all pieces did not reach the CFRP ultimate strain.

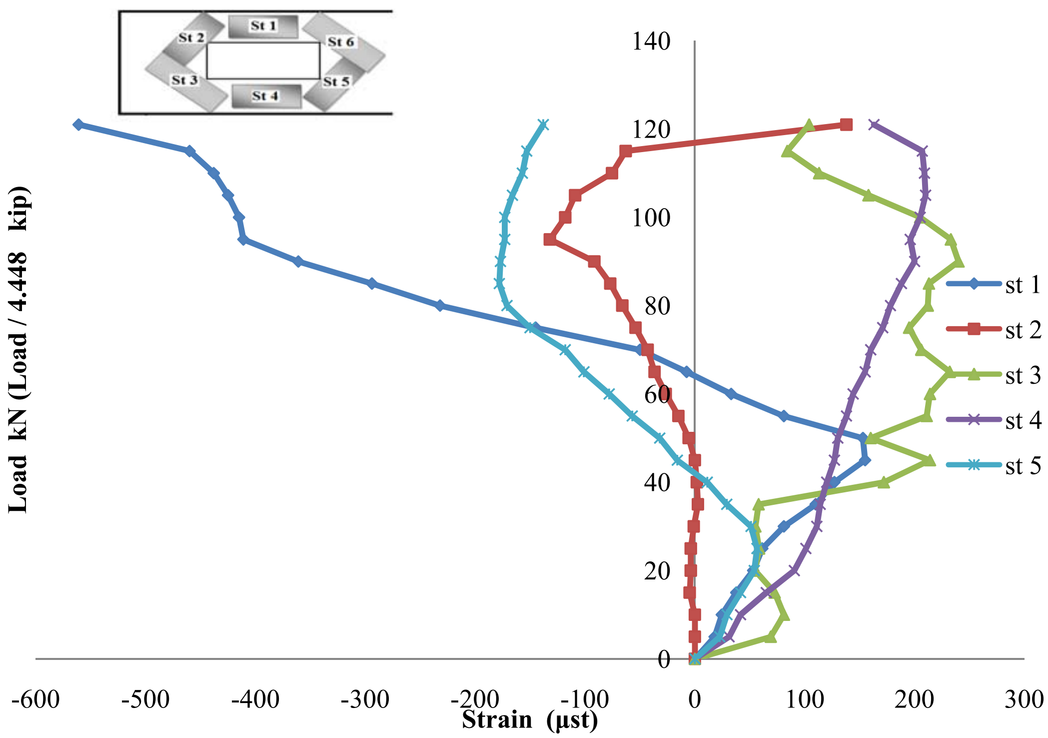


Figure (12): Load *vs.* strain curves of externally bonded steel plates for beam B3

For beam B3, the steel plate strain was measured at failure in six points and found to be of different values, because the value of strain is greatly dependent on the location of the strain gauge with respect to a crack, as shown in Figure 12, which shows the load-steel plate strain relationship for beam B3. In six points, all the pieces did not reach the steel plate ultimate strain, and strain gauge 6 (St6) was broken during the test. Figure 13 shows the load-steel plate strain relationship for beam B4 in four points. For beam B4, the maximum CFRP strain measured at failure was in strain 3 on the bottom chord of the opening. The recorded strains indicate that the value of strain for all pieces did not reach the steel plate ultimate strain**.** Strain gauge 1 (St1) and strain gauge 4 (St4) were broken during the test. The value of strain greatly depends on the location of the strain gauge with respect to a crack. For all specimens, the strain for all pieces did not reach the ultimate strain. CFRP and steel plates were not fractured or debonded from the concrete surface, and this ultimately indicates that CFRP and steel plates could provide additional strength if the beams did not fail by concrete diagonal shear cracks.

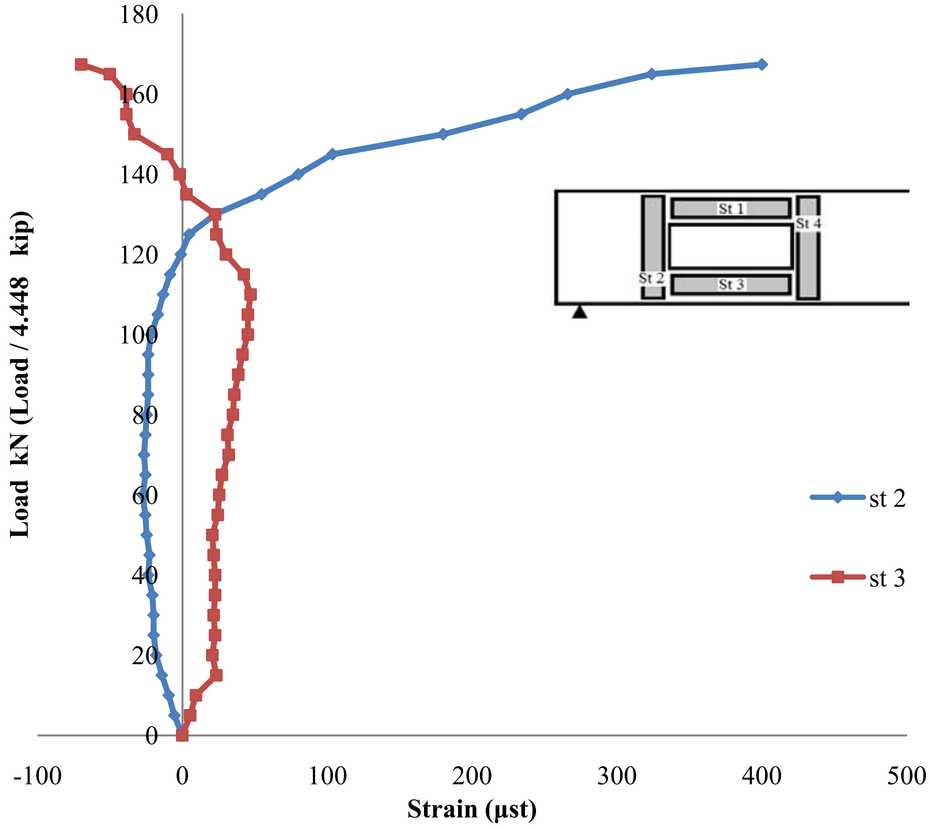


Figure (13): Load *vs.* strain curves of externally bonded steel plates for beam B4

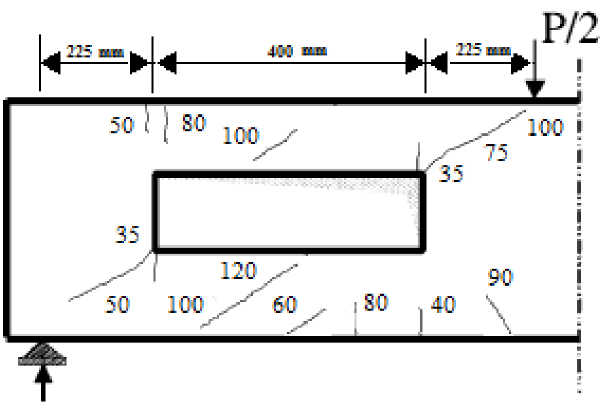


Figure (14 a): Beam B1

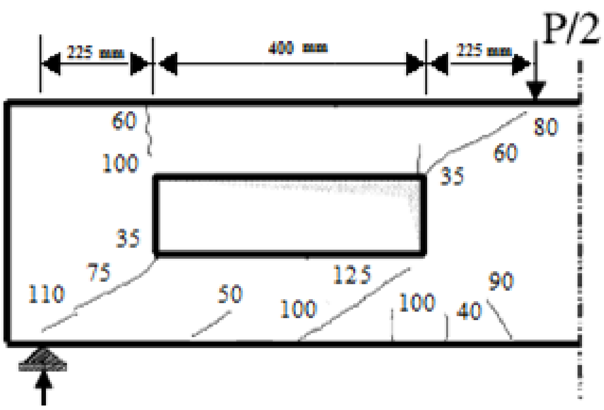


Figure (14 b): Beam B2

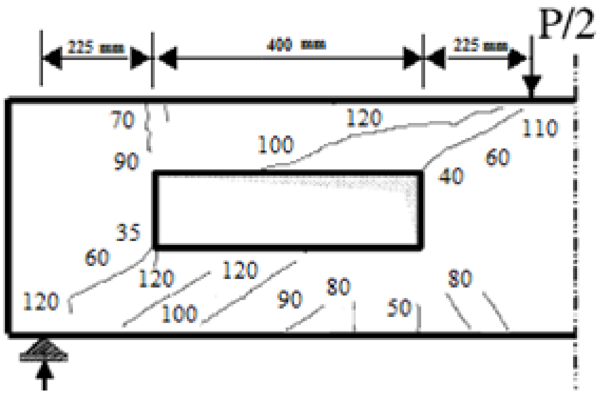


Figure (14 c): Beam B3

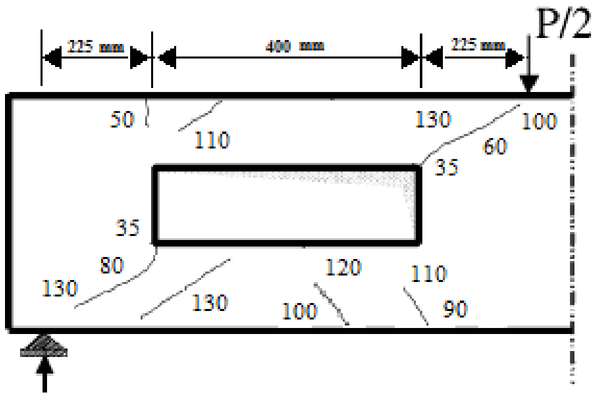


Figure (14 d): Beam B4

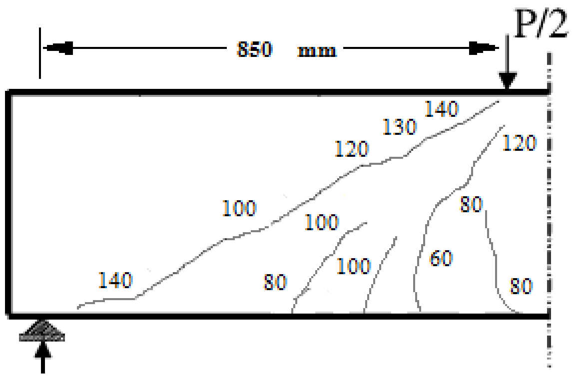


Figure (14 e): Solid beam (mm/25.4) in

Figure (14): Crack pattern and failure modes at the pre-repair stage

Figure (15 a): Beam B1

Figure (15 b): Beam B2

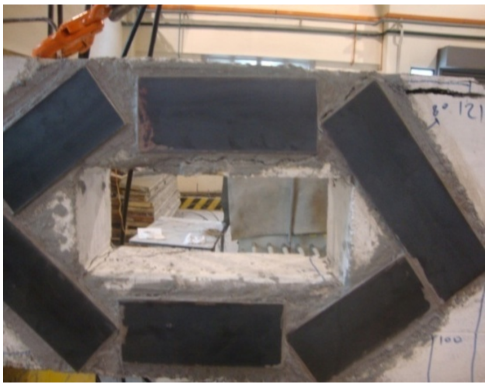


Figure (15 c): Beam B3

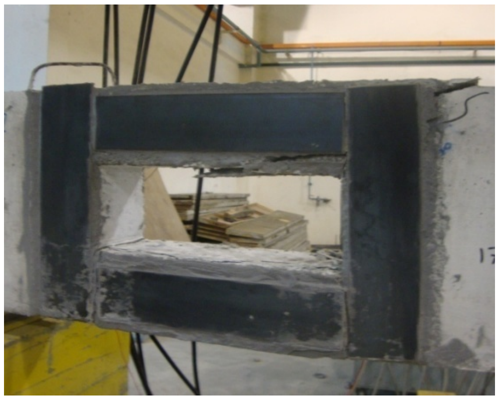


Figure (15 d): Beam B4

Figure (15): Failure modes at the post-repair stage

Effect on Crack Pattern and Failure Modes

The crack pattern and the failure modes of all the specimens at the pre- and post-repair stages are presented in this section. The failure mode for all the beams is similar, because the failure occurs due to a failure in concrete diagonal shear before the externally bonded plates reach the ultimate strain. Figure 14 and Figure 15 show the crack pattern and failure modes for: (a) beam B1, (b) beam B2, (c) beam B3 and (d) beam B4, at pre-and post-repair stages, respectively. For beam B1, the first diagonal crack was observed at the middle span at a load of 45 kN (10.111 kip), where with the increase in the applied load additional cracks were formed. As it can be seen from Fig. 14(e) at a load of 80 kN (17.976 kip), flexural crack at bottom shear span was observed, failure of the beam occurred when the total applied load reached 143.4 kN (32.222 kip) due to a failure in concrete diagonal shear.

It can be seen from Figure 14 (b) that the first diagonal crack for beam B 2 was observed at the corner of the opening at a load of 35 kN (7.865 kip); additional cracks were formed with the increase of the applied load. Failure of the beam occurred when the total applied load reached 125.2 kN (28.146 kip). At the post-repair stage, many cracks were formed at the solid span of the beam, and the failure of the beam occurred at a load of 178.5 kN (40.109 kip). At failure, crushing of the concrete was observed on the top face and bottom face of the chord members, as shown in Figure 15 (b). This mode of failure is called splitting failure, which is due to relatively high longitudinal compressive stress which developed at the top of the chords, creating transverse tension and leading to splitting failure, according to (Khalifa and Nanni, 2002). The CFRP sheet did not fracture or debond from the concrete surface at the ultimate load. As can be seen from Figure 14 (d), the first diagonal crack for beam B4 was observed at the corner of the opening at a load of 35 kN (7.865 kip); additional cracks were formed with the increase of the applied load. Failure of the beam occurred when the total applied load reached 129 kN (29 kip). As shown in Figure 15(d) for beam B4, at the post-repair stage many cracks were formed at the solid span of the beam and the failure of the beam occurred at a load of 167 kN (37.525 kip). At failure, crushing of the concrete was observed on the top face and bottom face of the chord members due to high compressive stress in concrete before the externally bonded plates reach the maximum strain.

The results are in agreement with Lee and Al-Mahaidi, who found that the use of CFRP plates for the strengthening of RC beams in shear results in smaller shear crack width, which implies that the concrete contribution to the ultimate capacity is higher than for un-strengthened beams (Lee and Al-Mahaidi, 2008). A review was done for understanding the debonding failures in FRP bonded to concrete systems. It was concluded that more research is needed for better understanding and quantification of the environmental effects on the debonding failures in FRP-adhesive-concrete systems, according to (Büyüköztürk and Yu, 2006). Most of the FRP/concrete joints were found to fail by crack propagation in the concrete adjacent to the adhesive-concrete interface, starting from the critically stressed position, according to (Chen and Teng, 2003).

CONCLUSIONS

This study investigated the effect of repairing damaged RC beams with a large rectangular web opening using externally bonded CFRP and steel plates with two configurations for each material. The following conclusions can be drawn based on the results of the tested beams in the present study:

- Damaged RC beams with a large rectangular web opening can be effectively repaired by CFRP and steel plates.
- Externally bonded CFRP plates are more effective than steel plates for repairing damaged RC beams.
- Rectangular configuration is more effective than hexagonal configuration for repairing damaged RC beams with a large rectangular web opening.
- The highest value of load capacity increase of 43% was obtained in beam repaired with externally bonded CFRP sheets using configuration type B (rectangular).

The lowest value of load capacity increase of 4% was obtained in beams repaired with steel plates using configuration type A (hexagonal).

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