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Technical Note

Repair effectiveness of CFRP and steel plates in RC beams with web opening: effect of plate thickness

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Abstract

The effect of steel plate thickness on the repair effectiveness of RC beam is presented in this paper. A total of four beams were tested, one beam repaired by CFRP with a thickness of 1.2 mm and used as a control beam, and three beams repaired by a steel plate. Steel plates with a thickness of 2 mm, 3 mm, and 4 mm were used in repairing the beams. The maximum load-carrying capacity, deflection at mid span and edge of the opening, strain in steel bars, strain in externally bonded plates, crack patterns, and failure modes were observed on each beam. The externally bonded CFRP sheet and steel plates were found to be effective in the repairing of RC beams with large rectangular web opening. The results show that increasing steel plate thickness has little effect on the maximum load capacity. The CFRP plate is more effective than steel plate in increasing the load capacity of beams.

Keywords: *Web opening, CFRP plate, Steel plate, Repair.*

1. Introduction

A transverse opening in concrete beams represents a means of accommodating utility services in a building structure. The ability to accommodate such services through a member, instead of below or above the member, results in compact design and overall saving in terms of total building height. The behaviour of a beam with web opening is complex because of the sudden change in cross section of the beam. The opening becomes a source of weakness as the failure plane passes through the opening [1]. Furthermore, the provision of openings leads to stress concentration and early cracking around the opening region, due to the discontinuities or disturbances in the normal flow of stresses. Similar to any discontinuity, special reinforcement should therefore be provided in sufficient quantity to control crack width and to prevent possible premature failure of the beam, [2]. On the other hand, many RC structures are damaged and are suffering various deteriorations, such as cracks, concrete spilling, and large deflection. These deteriorations are caused by many factors, such as ageing, corrosion of steel, earthquakes, environmental effects and accidental impacts on the structure. The cost of replacing these structures is overwhelming. Thus, it is necessary to find repair techniques that are cheaper and faster. Carbon Fibre Reinforced Polymer (CFRP) and steel plate are the commonly used repair materials. These two plates are used in this study as repair materials.

Externally bonded steel plate to the concrete surface is one of the methods used for enhancing the shear capacity of RC beams. The technique of using externally bonded steel plates has been used worldwide since 1975. The advantages of external bonded material over other methods include minimum effect on headroom, the ability to strengthen a part of the structure when it still in use, low cost and easy application, [3]. Carbon Fibre Reinforced Polymer (CFRP) materials are becoming widely used for the strengthening of RC structures. The advantages of using externally bonded CFRP plates include their high strength to weight ratio, ease of handling, anti corrosion, availability in any size, high durability, and electromagnetic neutrality. Many studies have been carried out on the strengthening and repairing of soiled RC beam at shear zone using different technique such as steel plate bonding [4, 5] or FRP materials [6–11].

Moreover, some studies have been carried out on the strengthening of the RC beam with opening. External strengthening with CFRP sheets around the opening was found to be very effective in improving the beam shear capacity and stiffness, [12]. External strengthening of a beam with opening using steel plates or CFRP sheets is more efficient than internal strengthening of the opening using internal steel reinforcement, [13]. Both the shear span to depth ratio and concrete compressive strength of

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T-beams with an opening have a pronounced effect on the load capacity of the tested beams, [14]. In beams with inclined FRP rods, the analytical compressive stresses demonstrate the two strut mechanisms associated with each FRP rod that 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, [14]. The interfacial shear stresses found to be influenced by the geometry parameters such as thickness of the FRP plate and properties of the adhesive layer [15], where the interfacial shear stress concentrations and levels increase obviously with the increase of the thickness of the FRP plate. The cross sectional shape found to has a significant influence on the effectiveness of the CFRP confinement under concentric loading [16], where member with the circular cross section benefited the most, followed by the member with the square cross section. The gain in load capacity of RC members with rectangular cross sections due to CFRP confinement depends on the aspect ratio of the cross section. However, studies on repair of RC beams with web opening are still very limited. Therefore, the objective of this study is to investigate the effects of steel plate thickness on the repair effectiveness of RC beams with web opening, as well as the comparison of repair using steel and CFRP plate.

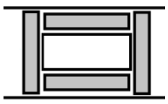
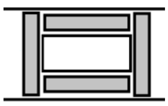
2. Experimental Work

The test program consisted of casting and testing of four RC beams. All RC beams have a clear span of 2.1 m, and a cross sectional dimensions of 175 × 450 mm (width*depth). All RC beams have a rectangular web opening with dimensions of 160*400mm (depth * width). A total of four beams were tested, one beam repaired by CFRP with a thickness of 1.2 which used as a control beam and three beams repaired using steel plates of 2 mm, 3 mm, and 4 mm thicknesses. Ready mix concrete was used and the average compressive strength at age of 28 days was 26 MPa. Table 1 shows the mechanical properties of used material. The tensile strength and modulus of the elasticity of the steel plate are 375 MPa and 200 GPa, respectively. The tensile strength and modulus of the elasticity of CFRP laminates are 2800 MPa and 165 GPa, respectively. Table 2 shows the dimensions and repair configuration of externally bonded CFRP and steel plates. 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 residue or dust on the surface. This is because the substrate must be sound, dry, clean and free from laitance, ice, standing water, grease, oils, old surface treatments or coatings, and all loosely adhering particles. The surface of an externally bonded steel plate was also sandblasted to eliminate the rust. A special cleaner (Acetone) was used to remove carbon dusts from the bonding face of the CFRP plate. The well-mixed sikadure adhesive (SIKADURE 30) was then trawled onto the surface of the concrete specimens to form a thin interface layer. The same adhesive was also applied with a special dome shaped spatula onto the CFRP and steel plates. The plates were then positioned on the prepared concrete surfaces. The plates were gently pressed into the adhesive, using a rubber roller, until the material was forced out on both sides of the plates. The surplus adhesive was then removed.

Table 1 Mechanical properties of materials

Material	Diameter (mm)	Compressive strength (MPa)	Ultimate tensile strength (MPa)	Modulus of elasticity (MPa) × 10^3
Concrete	_	26	_	20
	12	_	406	200
Steel bars	10	_	400	200
	6		380	200
CFRP	_	_	2800	165
Steel plate	_	_	380	200

Table 2 Configuration types and dimensions

Beam	Repair material	Configuration	Plate Thickness (mm)	plate Width (mm)
B1	CFRP		1.2	100
B2	Steel plate		2	100

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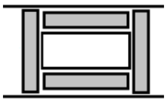
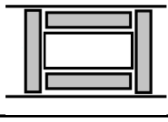
B3	Steel plate		3	100
B4	Steel plate		4	100

2.1. Test set-up

All beams were tested as simple supported beams subjected to a four-point load, as illustrated in Fig. 1. A universal testing machine with 300 kN capacity was used in order to apply the 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 4 kN/min and was then released with the same average. Two linear variable differential transformers (LVDT) were used in each test to monitor vertical deflection at two locations, edge of the opening and mid-span of the beam as shown in Fig. 1. For each beam, one strain gauge was attached to the main flexure steel bars below the opening, as shown in Fig. 2 (a). For all the beams, two strain gauges were attached directly to the CFRP and steel plate on the sides of beams to monitor strain variation in CFRP and steel plates, as shown in Fig. 2 (b). All the used electrical devices (load cell, LVDT, and strain gauges) are attached to the date logger in order to monitor the variation in load, deflection and train values, corresponding to applied loads. The readings were carried out at each 5 kN load step and up to the ultimate applied load. All the beams were subjected to failure load at the pre-repair stages. The beams were then unloaded by bringing back the loading to zero.

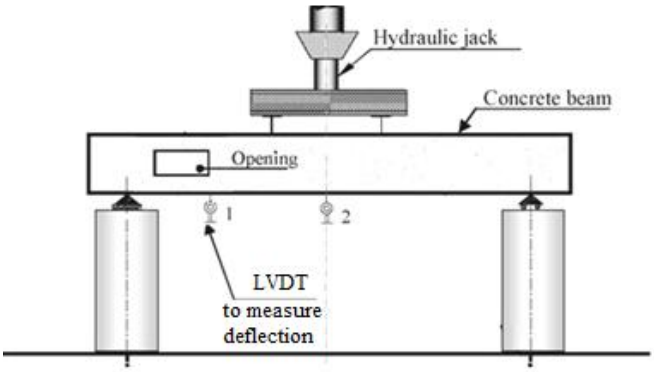
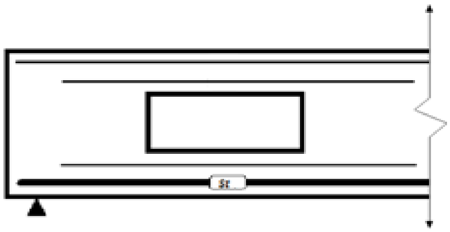
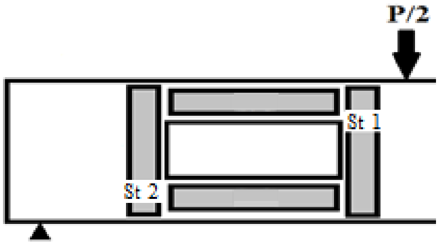


Fig. 1 Test set-up



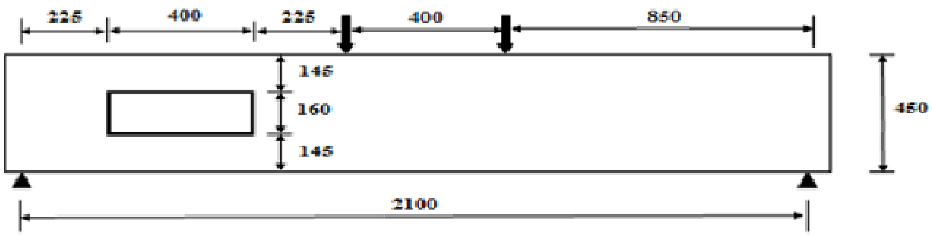
(a) Flexural bar



(b) Externally bonded plates
Fig. 2 Locations of strain gauge

2.2. Sample description

All the RC beams contain a large rectangular opening with a size of 160 × 400 (depth × width) mm. The opening was located at the mid of the shear span with a distance of 225 mm away from support and 225 mm away from the concentrated load. The distance between the two concentrated loads is 400 mm and the shear span is 850 mm, as shown in Fig. 3 (a). Beams with an opening were designed according to the plastic hinge method, [17]. The beams were reinforced with three steel bars with a diameter of 12 mm as a major reinforcement in the tension zone and two of a 10 mm diameter at the compression zone. Additional longitudinal bars were provided as two 10 mm 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 diameter were used at 90 mm spacing along the top and bottom chords.



(a)

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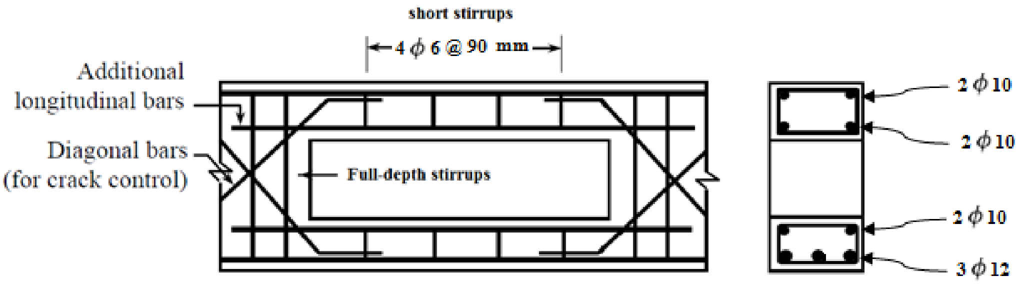

(b)

Fig. 3 Beams description, (a) Opening location, (b) Steel reinforcement at the opening

3. Result and Discussion

The effects of steel plate thickness on the repair effectiveness of damaged RC beams with web opening are presented in this section. The results are presented and discussed with regard to maximum load-carrying capacity of the beam, deflection at the mid span and edge of the opening, strain in steel bars, strain in externally bonded plates and cracks patterns and failure modes.

3.1. Effect on load capacity

The load capacities of the beams at the pre and post repair stage are shown in Table 3. The increase in maximum load at the post-repair stage is reported in terms of repair effectiveness, which is the ratio between the increase in load at the post-repair stage and the maximum load at the pre-repair stage expressed as a percentage. Table 3 shows that the repair effectiveness of beams repaired by steel plate with thicknesses of 2 mm, 3 mm, and 4 mm was 28%, 30%, and 32%, respectively. Therefore, it is clear that all steel plate thicknesses bonded around the web opening show positive effect on repaired RC beams with web opening. The results of this study are in agreement with Anders et al. [18], who found that repairing the damaged RC beams may not only recover its original capacity but can reach capacity above what it had before. The results are also in good agreement with Yasamen et al. [19], who concluded that the increase in maximum load of retrofitted beams reached a value of about 23 % over its original capacity.

From Table 3, it can be seen that the repair effectiveness of the beam repaired by CFRP was 43%. The results indicated that CFRP plate sustains more load at the post-repair stage than all steel plate thicknesses. Thus, it is clear that CFRP is more effective than all steel plate thicknesses. The contribution of the externally bonded plates depends on the material properties, configuration, surface interaction, and the distribution of stress on the interface between plate and concrete. This can be attributed to the fact that the surface preparation for CFRP plates is done by the manufacturer and hence of better quality. However, the surface preparation for steel plates was done in the laboratory using sandblasting. This might have caused surface imperfection in steel plates, which can result in irregularity and non-uniform stress distribution on the adhesive layer. This is exactly what happened in this study, when the use of sandblasting caused bending in the steel plate, which can have an effect on the repair effectiveness.

It can be seen from Table 3 that the increase in steel plate thickness from 2 mm to 4 mm gives an increase in repair effectiveness of 4 % only. Therefore, it is clear that increasing steel plate thickness has a little effect on the maximum load capacity. The increase in steel plate thickness has increased the load capacity by increasing the cross-sectional area of externally bonded plates. However, the increase was insignificant due to the fact that all the beams repaired by steel plates failed by a concrete diagonal shear crack, which cause the externally bonded plate to debond before reaching its ultimate strength. The results show that change the repair plate material from steel to CFRP plate is more effective than change steel plate thickness.

3.2. Effect on load deflection relationship

The load-deflection relationship at the mid span and below the edge of the opening is presented in this section. All the beams showed lower deflection at the mid span as compared to the deflection at the edge of the opening. For deflection at the edge of the opening, the reduction in deflection values found to be 10 % for CFRP, as shown in Table 4. For steel plates, the reductions in deflection were 7 %, 9 %, and 10 % for thicknesses of 2 mm, 3 mm and 4 mm, respectively. Thus, it is clear that the externally bonded plates applied around the web opening are capable of reducing 10 % of the deflection at pre-repair stage.

The beam B2, which was repaired by a steel plate with a thickness of 2mm, shows an effect on deflection at the edge of the opening, where at load of 128 kN the deflection is 6.98 mm and 6.49 mm at pre and post repair stages, respectively. For beam B3, good effect on the load capacity and a good effect on deflection were proved. The highest value of deflection was 6.52 mm obtained at the edge of the opening and it was at the pre-repaired stage at a failure load of 129 kN. However, at the post-repair stage, the deflection for the same load of 129 kN was 5.92 mm. As shown in Fig. 4, which shows the load against deflection at edge of opening curves at pre and post repair stages, the highest effect on deflection was for beams B1 and B4, while the lowest effect on deflection was for beam B2. The value of deflection for beam B1 at the pre-repair stage was 6.58 mm at a failure load of 125.2 kN, while the deflection was 5.95 mm at the post-repair stage at the same load of 125.2 kN.

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Table 4 Maximum load and deflection values at edge of opening

Beam	Repair Material	Thick. (mm)	Pre-Repair Stage		Post Repair Stage				
			Max. load (kN)	Def. (mm)	load (kN)	Def. (mm)	Reducing in def.	Max. load (kN)	Def. (mm)
B1	CFRP	1.2	125.2	6.65	125.2	6.00	10 %	178.5	11.76
B2	Steel plate	2	128	6.98	128	6.49	7 %	163.4	11.85
B3	Steel plate	3	129.0	6.52	129.0	5.92	9 %	167	9.78
B4	Steel plate	4	129.3	7.05	129.3	6.33	10 %	170	9.8

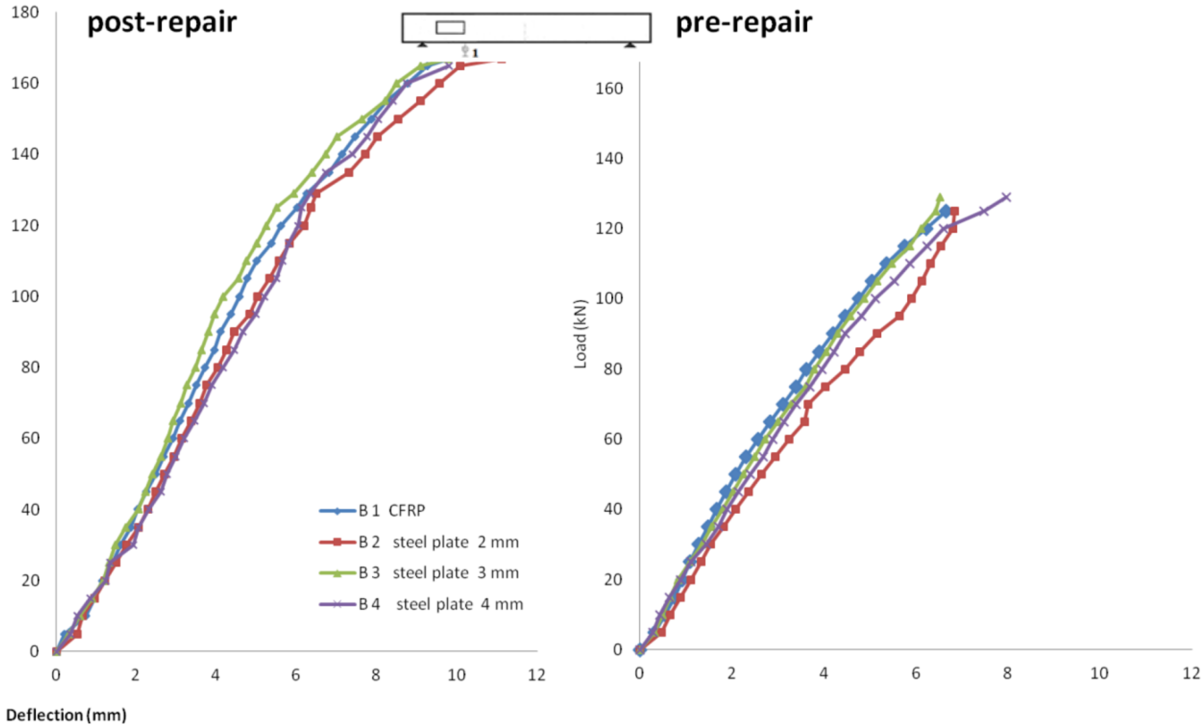

Fig. 4 Load–deflection curves at the edge of the opening at pre and post repair stages

For beam B3, the value of deflection at the pre-repair stage at failure load of 129 kN was 6.35 mm, while at post-repair stage it was 5.85 mm at the same load of 128 kN. The value of deflection for beam B4 at the pre-repair stage was 6.74 mm at a failure load of 129.3 kN, while at the post-repair stage the deflection was 6.14 mm at the same load of 129.3 kN. The result shows that the influence of steel plates on deflection at the edge of the opening increases with the increase in steel plate thickness. The results indicate that the CFRP and steel plates have good effectiveness in reducing the deflection for the repaired beams at the edge of the opening and mid-span of the beam. From Fig. 5, which shows the load against deflection at mid-span curves at pre and post repair stages, it can be seen that curves for repaired beams show somewhat similar behaviour because both CFRP and steel plates around the opening serve in resisting stress concentration at opening corners. Thus, it is delaying the cracking and controlling width and propagation of cracks. The highest value of deflection was obtained was located at the edge of the opening. The results are in agreement with Tan et al. [20], 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 contribution to the stiffness of beams was caused by the CFRP and steel plate outside the cracking region. The result shows that increasing steel plate thickness has little effect on reducing the deflection.

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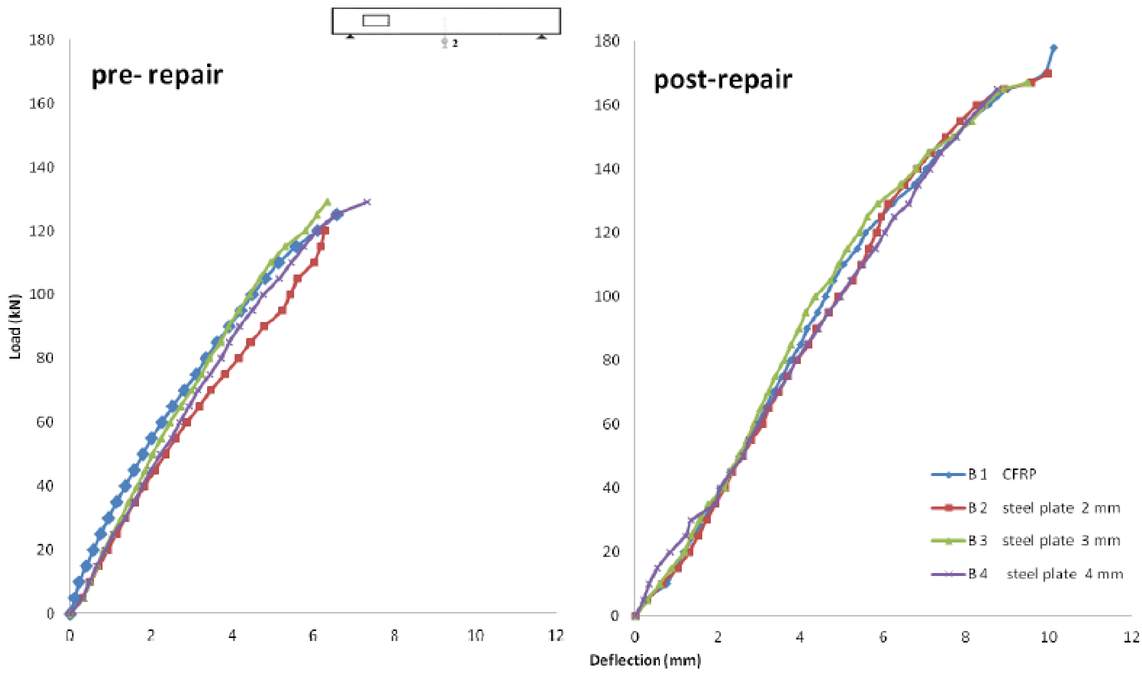

Fig 5. Load against deflection curves at the mid-span at pre and post repair stages

3.3. Effect on steel bar strain

The load-strain relationship of steel reinforcement is presented in this section. The strain gauge (St) was attached onto the main steel reinforcement bar at the middle of the opening in the bottom chord. Fig. 6 shows the load against steel bar strain of the strain gauge (St) at the pre and post repair stages. For all the beams at the pre-repair stage, the strain gauge (St) shows an increase in strain value with the increase in applied load and reaches its yielded strain at the ultimate 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 strain values less than the strain at the pre-repair stage at same load. This was subjected to a different in the decrease of strain values percentage a depending on the material and thickness that were used, as shown in Table 5.

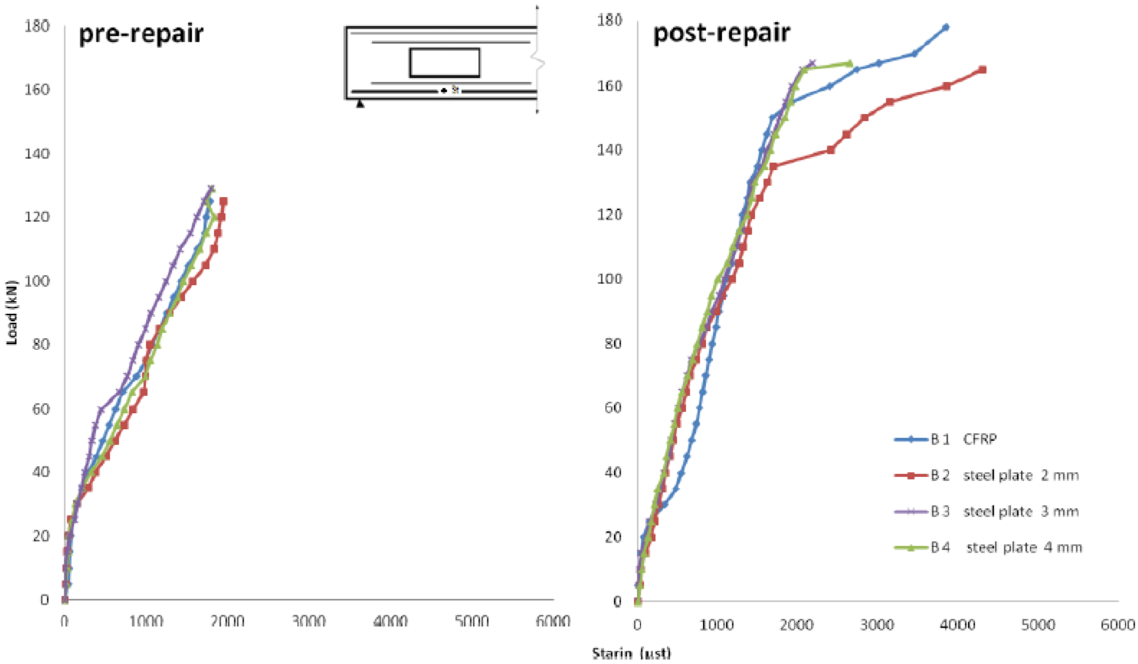

Fig. 6 Load against steel bar strain of (St) at pre and post repair stages

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The strain values in the major steel bar at the bottom chord at the middle of the opening at pre and post repair stages are illustrated in Table 5. The reducing percentage in strain was 24% for beams repaired by CFRP. However, for beams repaired by steel plates, the reducing percentages were found to be 17 %, 19 % and 20 % for thicknesses of 2 mm, 3 mm and 4 mm, respectively. It is clear that the contribution of externally bonded plates on steel bar strain depends on the plate material rather than the thickness of the plates. This is because the strain in steel reinforcement is controlled by the interaction between repair material and concrete surface. The CFRP plates have better interaction with concrete than steel plates and hence are able to share the strain in the reinforcement effectively. Therefore, it is concluded that the CFRP is more effective for repairing of RC beams. The results are in agreement with Hemdan et al. [21], who found that the strengthening RC beams with a web opening by CFRP cause 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 are not very clear, like the flexural zone. The presence of a transverse opening will change the simple beam behaviour into 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 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 makes stress-strain redistribution around the opening and this will add more complexity to shear phenomena.

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

Beam	Repair material	Thickness (mm)	Pre-repair stage		Post-repair stage				
			Max. Load (kN)	Strain (μst)	Load (kN)	Strain (μst)	Reducing in Strain	Max. load (kN)	Strain (μst)
B1	CFRP	1.2	125.2	1783	125.2	1366	24 %	178.5	3858
B2	Steel plate	2	128	1956	128	1629	17 %	163.4	4295
B3	Steel plate	3	129.0	1805	129.0	1466	19 %	167	2648
B4	Steel plate	4	129.3	1795	129.3	1438	20 %	170	2184

3.4. Effect on externally bonded plate strain

The behaviour of load-strain relationship for externally bonded CFRP and steel plates is presented in this section. Strain gauge are fixed at two locations , one locations is on the opening corner near the support (ST2) and another location is at the opening corner near the point of applied load (ST1), as shown in Fig. 2(b). The load against strain curves for beams B1, B2, B3 and B4 are shown in Figs. 7, 8, 9 and 10, respectively. The recorded strains indicate that the value of strain for all beams did not reach the ultimate strain of CFRP and steel plates. This is due to the fact that the concrete failed before allowing the repair materials to reach the ultimate strain values. It can be observed from Figs. 7 to 10 that the externally bonded plates start to share the strain in the beam from the start of the applied load. The results are in agreement with Khalifa and Intomio [20], 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 greatly depends on the location of the strain gauge with respect to a crack.

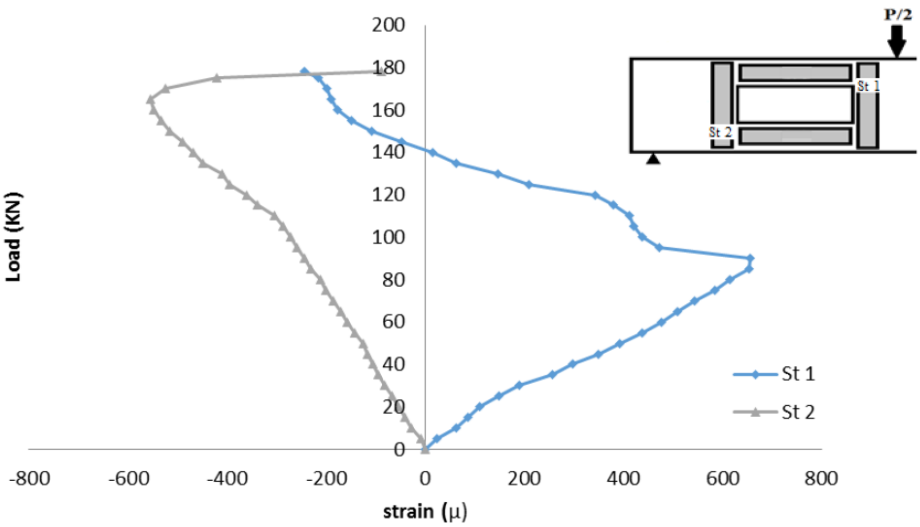

Fig. 7 Load against strain of externally bonded CFRP plates of beam B1

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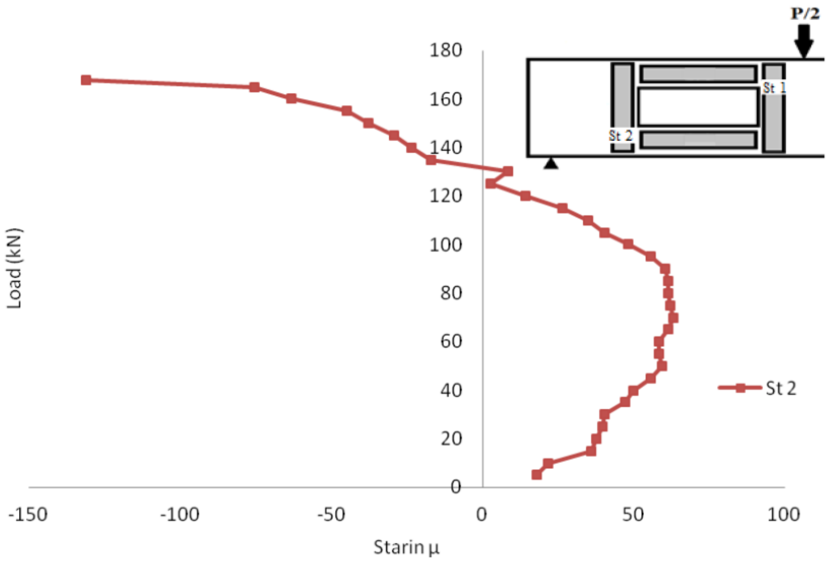

Fig. 8 Load against strain of externally bonded steel plate of beam B2

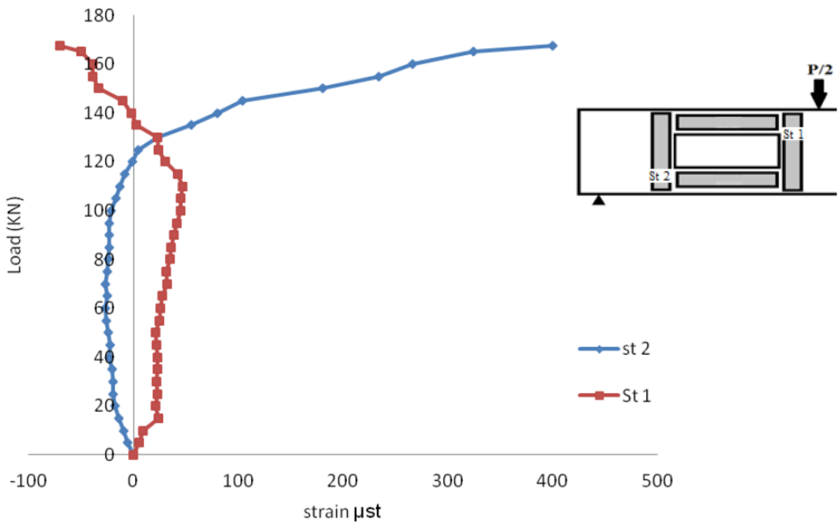

Fig. 9 Load against strain of externally bonded steel plates of beam B3

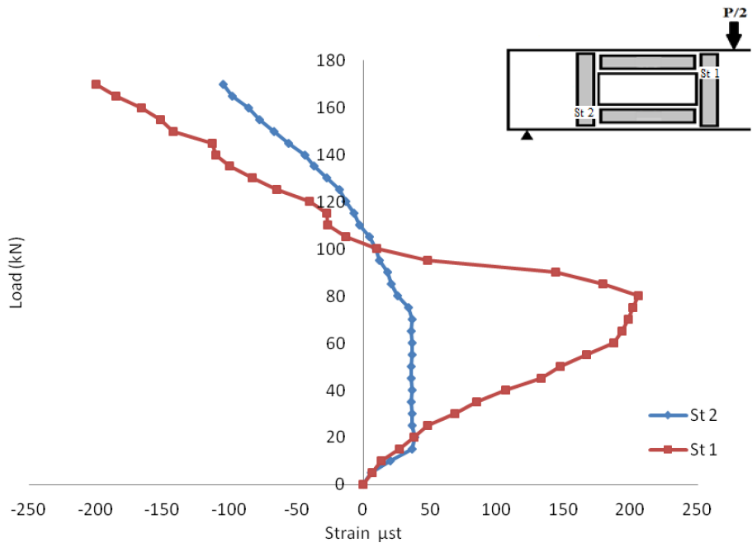

Fig. 10 Load against strain of externally bonded steel plates of beam B4

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As can be seen from Fig. 7, for beam B1 the maximum CFRP strain measured at failure was in strain ST1. For beam B3, the steel plate strain measured at failure was deferent at each location, because the value of the strain greatly depends on the location of the strain gauge with respect to a crack, as shown in Fig. 9. It can be observed from Fig. 10 that for beam B4, the maximum CFRP strain measured at failure was in strain ST1, on the bottom chord of the opening. 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.

3.5. Effect on crack pattern and failure modes

The crack pattern and the failure modes for all beams at pre and post repair stages are presented in this section. Figs. 11 and 12 show the crack pattern and the failure mode for all the beams at the pre and post repair stages, respectively. The failure modes of all the beams are similar because the failure occurs due to failure in concrete as diagonal shear failure before the externally bonded plates reach the ultimate strain. It can be seen from Fig. 11 (b) that the first diagonal crack for beam B2 was observed at the corner of the opening at a load of 35 kN; additional cracks were formed with the increase of the applied load. Failure of the beam occurred when the total applied load reached 128 kN. 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 163.4 kN. At failure, concrete diagonal shear failure was observed around the opening, as shown in Fig. 12 (b).

This mode of failure is called splitting failure, which is due to relatively high longitudinal compressive stress developed at the top of the chords, which created transverse tension, and led to splitting failure, as according to Khalifa and Nanni [22]. The CFRP sheet did not fracture or debond from the concrete surface at the ultimate load. As can be seen from Fig. 11 (d), the first diagonal crack for beam B4 was observed at the corner of the opening at a load of 35 kN, additional cracks were formed with the increase of the applied load. Failure of the beam occurred when the total applied load reached 129.3 kN. As shown in Fig. 12 (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 170 kN. At failure, crushing of the concrete was observed on the top 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 [23] who found that the use of CFRP plates for strengthening of RC beams in the shear results in smaller shear crack width, which implies that the concrete contribution to the ultimate capacity is higher than for un-strengthened beams. A review was done for understanding the debonding failures in FRP bonded to concrete systems and 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 [24].

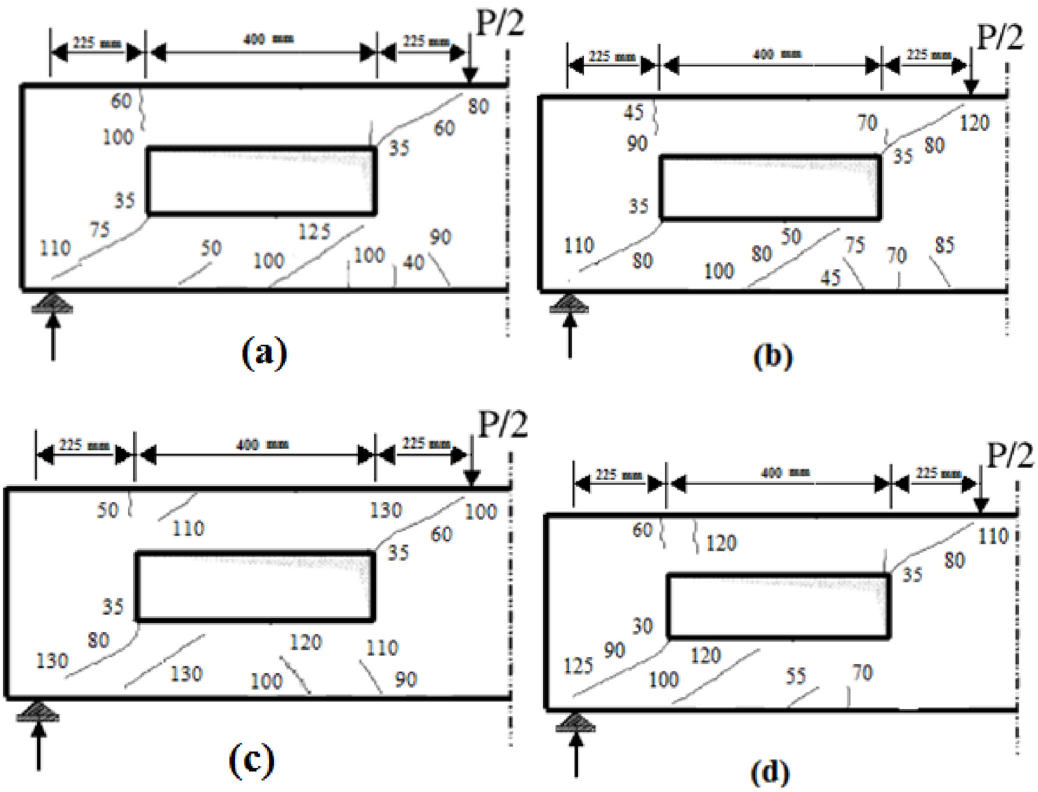

Fig. 11 Crack patterns and failure modes of beams at the pre-repair stage (a) Beam B1, (b) Beam B2, (c) Beam B3, (d) Beam B4

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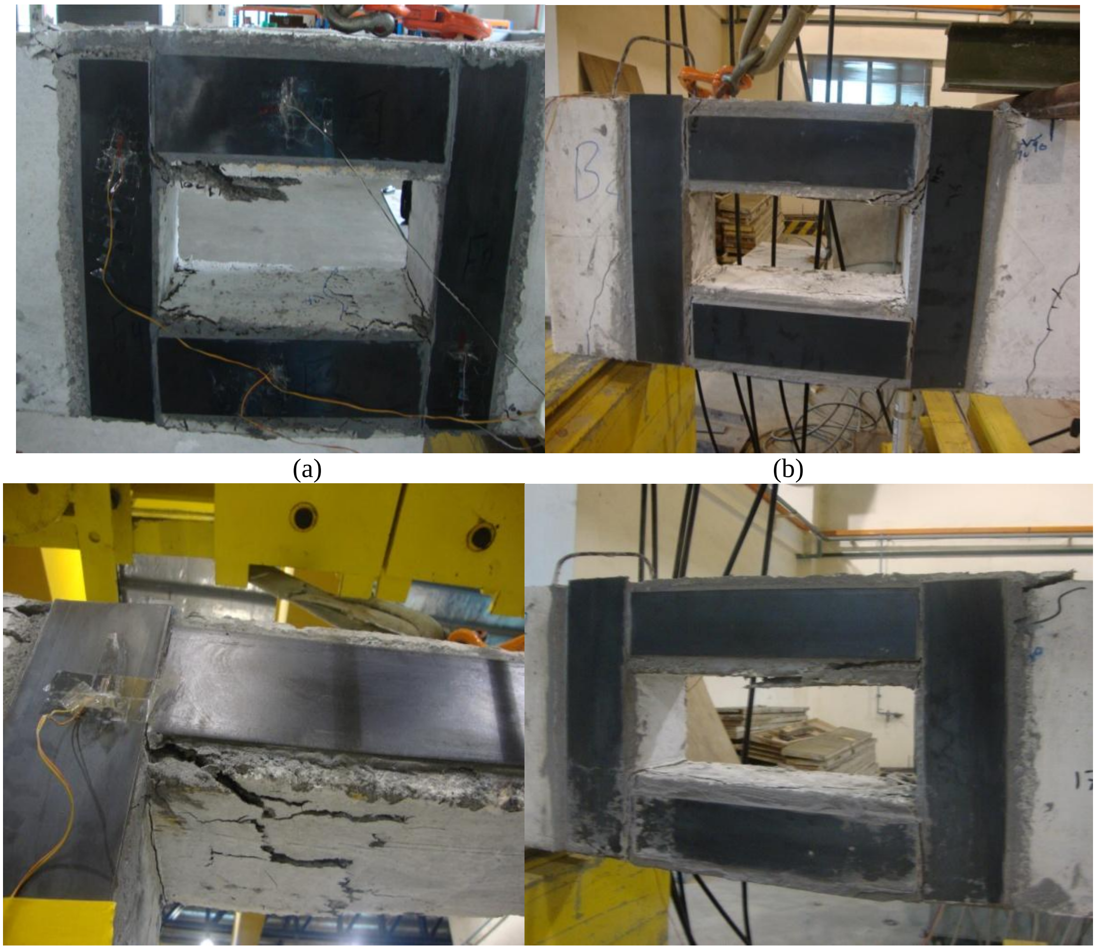

(a) (b)

(c) (d)

Fig. 12 Failure modes of beams at the post-repair stage (a) Beam B1, (b) Beam B2, (c) Beam B3, (d) Beam B4

4. Conclusion

The following conclusions can be drawn from the results of the investigation:

1. CFRP and steel plates can effectively be used to repair the damaged RC beams with a large rectangular web opening.
2. Externally bonded CFRP plates are more effective than steel plates in repairing the damaged RC beam.
3. An increase in the steel plate thickness has a little effect in increasing the maximum load capacity.

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