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EXPERIMENTAL BEHAVIOUR OF THE REINFORCED CONCRETE BEAMS STRENGTHENED AND REPAIRED WITH STEEL PLATES

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Abstract

The reinforcement of reinforced concrete beams by bonding steel plates on the tension zone of the beams against bending is a common method. Deboning is one of the most important issues that occurs after reinforcing or repairing the beams with steel plates. In this research, three methods are used to attach the steel plate to the assembly for strengthening and repairing; attached by resin, attached by rivets and at the same time attached by resin and rivets. The length of the plates used is 0.75 m, 1.0 m and 1.5 m, with a thickness of 3.0 mm for all specimens. Two shapes of plates used, straight and U-shape. Nine reinforced concrete beams are used to investigate the effectiveness of plate strengthening and repair, in addition to the control one. Two of these beams are loaded to 70% and 100% of the ultimate load of the control beam then repaired with 1.5 m steel plate. The results indicated that when the length of the steel plate is increased from 0.75 m to 1.5m, the ultimate load increased by 0% to 147% of the ultimate load of the control beam. The study shows that the best method for fixing the steel plate to the concrete beam is the fixation by Sikadur 31, where the strength of the beam is increase by 147% of the ultimate load of the control beam.

Keywords: Debonding, Fastening, Repair, , Steel plate, Strengthening.

1.Introduction

Strengthening of reinforced concrete beams is generally required for various reasons, including changes in the use of the structure and design and construction defects. Because of the high tensile and ductility of the steel, steel plates were used as an external strengthening material to strengthen the zone of high bending moment. Despite of wide used of FRP materials in strengthening concrete structure, however, it's cost still high. Therefore, steel plates were used as an enhanced material to strengthen the concrete structure. Several methodologies have been suggested and applied in the literature to this effect.

Increase the bending capacity 45% to 77% of the ultimate load of control beam, [1-6] were used FRP plates by connecting it to the tension face of the beams by wrapping or anchored CFRP sheets. Severe pre-cracked beams had a greater safety reserve in case of sudden failure when strengthened with BFRP plates and steel plates is used and increase the ultimate load to 45.5%, Qin et al. [4]. Steel plates of different thicknesses and methods of fixation were used as a strengthening material for reinforced concrete beams [7-14]. They increase the ultimate load to 164%. Further developments in the use of hybrid CFRP and GFRP reinforcing materials to achieve pseudo ductility have been contributed by Sallal and Rajan [15] GFRP wrapped reinforced concrete beam showed an increase in ultimate load carrying capacity by 74.4% compared to the control specimen. ACI committee 440 [16] is developed a guideline for reinforced concrete members that strengthening with FRP system. Material reduction factors for ultimate limit bending elements had been recommended by ACI 440 [16]. Also, introduced a reduction factor corresponding to the failure mechanism of FRP reinforced concrete beam.

Various methods were used to repair reinforced concrete elements by steel plate or FRP [4, 17]. The damage beams were repaired/ strengthened by injecting epoxy resin or by gluing steel strip/ plates [17].

Reinforced concrete beams had been reinforced with steel plates fixed by bolts/epoxy to study shear strength [18-21]. Their results show that the use of steel plates and bolts as an external reinforcement increases the shear capacity of the beam up to 59%.

The flexure capacity of the beams had been studied using U-shaped or web-bonded steel plate [22, 23]. It was found that, the beam strengthened with web bonded steel plates of 1.6 mm thick, 3 mm thick and 4 mm thick had respectively 26.3%, 47.3% and 78.9% higher load at first crack as compared to control specimen. Reinforced beams with 4 mm thick steel plates joined by one-row bolts and staggered bolts were investigated by Jayaprakash et al. [24]. The ultimate load was increased to 43.3%.

The study focused on methods of strengthening and repairing concrete beams using steel plates of different lengths and using different bonding methods such as epoxy and rivets. The ability to use the steel plates as a strengthening material to the R.C members is the main objective of this study. Then, the behaviour of R.C beams under two - point load is investigated.

To increase the stiffness of R.C. beams, beams are composed with other material has properties batter than concrete in tension such as steel plate. This process led to decrease deflection and increase the load capacity of the beam compared with non - composite beam.

2. Experimental Program

2.1. Material properties and specimens

Nine simply supported reinforced concrete beams with rectangular cross section area are tested in this study. All beams are of the same cross-section with width, height and length (200, 250 and 1700 mm), respectively. The reinforcement details for all the beams are the same as 2 Ø 12 mm at the top and bottom in flexure reinforcement and Ø10 mm spaced by 80 mm in stirrups. Figure 1 shows details of control beam.

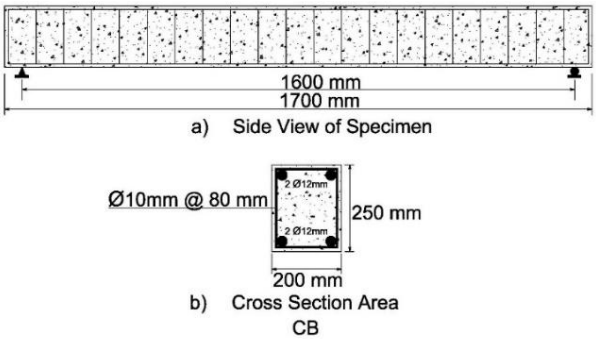

Fig. 1. Details of the control specimen CB.

The properties of the materials used in this research are shown in Tables 1-4. The cement used in this study is ordinary Portland cement (ASTM Type I). Fine and coarse aggregates are in accordance with ASTM C33-03 [25]. Super plasticizer (Sika - ViscoCrete - 180G) is used as (1 kg for 100 kg cement).

The adhesive used for the strengthening the beams by the steel plates is of type Sikadur - 31 CF Slow, an epoxy resin with two components. Sika - anchorFix - 2Tropical is an adhesive used to fix the rivets to specimens. The width and thickness of steel plate that used for the tested specimens is 200 mm and 3 mm, respectively.

The experimental program has considered three parameters which are: length of steel plates (0.75 m, 1.0 m, and 1.5 m), configuration of strengthening (straight and U - shape), type of fixing steel plates to the beams (resin, rivet, and resin and rivet together).

Table 1. Properties of the materials.

Material	Dimension	Yield Strength (MPa)	Ultimate Strength (MPa)	Compressive Strength (MPa)
Concrete	-	-	-	35
Main Steel	D = 12 mm	480	680	-
Stirrup	D = 10 mm	480	680	-
Steel Plate	t = 3 mm	310	378	-
Sika - ViscoCrete - 180G	-	-	-	-
Sikadur - 31 CF Slow	-	13 (7 days, +35 °C)	27 (7 days, +35 °C)	54 (7 days, +35 °C)
Sika - anchorFix - 2Tropical	-	15 (7 days, +20 °C)	29 (7 days, +20 °C)	70 (7 days, +20 °C)
Sikadur-52 LP	-	-	27 (7 days, +30 °C)	70 (7 days, +30 °C)

Table 2. Chemical analysis and main compounds of the used ordinary Portland cement.

Chemical analysis	Percentage %, by weight	Limit of ASTM C150 [26]
(CaO)	62.83	
(SiO_2)	20.5	
(Al_2O_3)	5.36	6.0 Max.
(Fe_2O_3)	1.12	6.0 Max.
(MgO)	3.58	6.0 Max.
(SO_3)	1.45	3.0 Max.
(K_2O)	0.61	
(Na_2O)	0.23	
(L.O.I)	1.02	3.0 Max.
(I.R)	0.49	0.75 Max.
(L.S.F)	0.91	
Main compounds (Bogues equations)		
C_3S	40.9	
C_2S	27.91	
C3A	2.17	8 Max.
C_4AF	10.35	

Table 3. Physical properties of the used ordinary Portland cement.

Physical property		Test results	Limit of ASTM C150 [26]
Specific surface area (Blaine method), m^2/kg		312	260 (Min.)
Setting time (Vicat apparatus), min.	**Initial**	75	45 (Min.)
	Final	310	375 (Max.)
Soundness (Autoclave expansion), %		0.31	0.8 (Max.)
Compressive strength, MPa	**3-day**	10.7	7 (MPa)
	7-day	16.8	12 (MPa)

Table 4. Sieve analysis results of fine aggregate.

Sieve size, mm	Passing (%) fine aggregate	Passing (%) ASTM C33 [25]
4.75	97	95-100
2.36	88	80-100
1.18	65	50-85
0.6	37	25-60
0.3	6.8	5-30
0.15	1.12	0-10

Table 5. Sieve analysis results of coarse aggregate

Sieve size, mm	Passing (%) fine aggregate	Passing (%) ASTM C33 [25]
19	100	100
12.5	94	90-100
9.5	65	40-70
4.75	2.4	0-15
2.36	1.03	0-5

2.2. Strengthening and repairing of the specimens

The detailing of unstrengthen control beam shown in Fig. 1. Figure 2 illustrates the details of the repairing methods used in this study. The beams are divided into four groups: the steel plates with length (0.75 m, 1.0 m and 1.5 m) are used in the first group of the beam SB1, SB2 and SB3, respectively to investigate the effect of the plate length. To study the effect of the steel plate configuration, the 1.5 m straight steel plate is used in the beam SB3 and the 1.5 m U-shape steel plate (three separated plates are fixed on the three sides) is used in the beam USB. The purpose of the third group is to examine the effect of the method of connecting steel plates to beams. Three beams are used in this group, SB3, SB4, and SB5 that connected to the beams by Sikadur 31, rivet and Sikadur 31, and rivet (fixed in concrete by Sika - anchor Fix - 2Tropical) with Sikadur 31, respectively. Repairing beams represented by group four, which has two beams; first one, the beam RB0.7 similar to control beam after loaded it to 70% of the ultimate load, the repair done by fixing the 1.5m steel plate to the tension zone of beam by Sikadur 31. Second one is the beam RB1.0 also similar to the control beam after loading it to 100% of the ultimate load, the repair done by injecting the cracks by Sikadur-52 LP and use 1.5m steel plate in the tension zone fixed it by Sikadur 31. Table 6 illustrates these details.

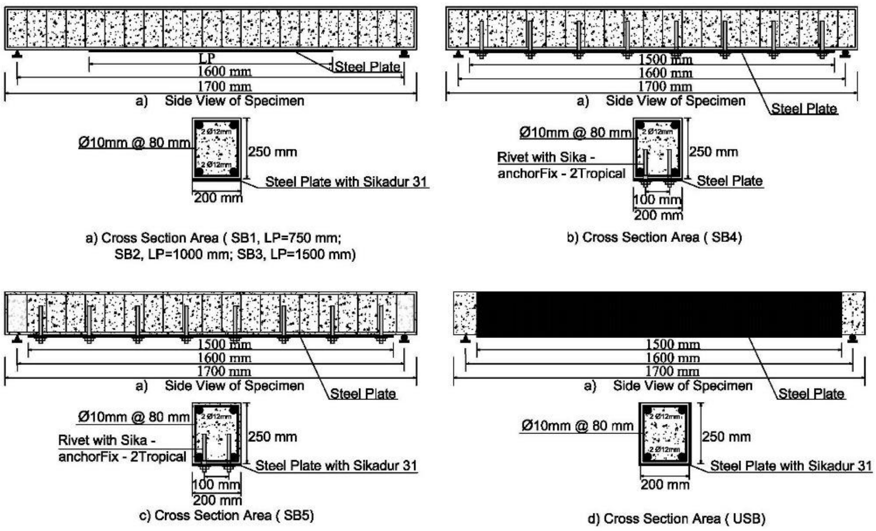

Fig. 2. Details of strengthening and repairing for the specimens.

Table 6. Details of the teste's specimens.

Group No.	Beam Symbol	Steel Plate Length (m)	Type of Fixing	Shape of Plate
Control	**CB**	-	-	-
1	**SB1**	0.75	Sikadur 31	Straight
	SB2	1.0	Sikadur 31	Straight
	SB3	1.5	Sikadur 31	Straight
2	**SB3**	1.5	Sikadur 31	Straight
	USB	1.5	Sikadur 31	U - Shape
3	**SB3**	1.5	Sikadur 31	Straight
	SB4	1.5	Sikadur 31+Rivets	Straight

	SB5	1.5	Sikadur 31+Rivets with Sika - anchor Fix - 2Tropical	Straight
4	**RB0.7**	1.5	Sikadur 31	Straight
	RB1.0	1.5	Sikadur-52 LP + Sikadur 31	Straight

2.2.1. Installation of the steel plates

The external strengthening of the specimens by steel plate is performed in accordance with the procedure described below:

- Firstly, the steel plate is cut within the required lengths. Prepare the surface of the steel plate followed by removing any dust or other contaminant prior to installation.
- Both parts, component A (white) and component B (black) of the adhesive (Sikadur-31) are mixed with a ratio of 4: l respectively. The adhesive is then applied on the surface of both concrete and the steel plate.
- The steel plate is then installed onto the concrete.
- The adhesive is then left to harden for at least 7 days before testing the beam.

2.2.2. Repairing procedure

After loading the beam to the 70% or 100% of ultimate load of control beam, the cracks are cleaned from debris by air blower. Epoxy ports are then fixed along the considered crack. The surface cracks and the port are fixed by applying an epoxy paste type Sikadur 31. The beam is left after this stage for 30-45 minutes to ensure complete curing of the paste. The injection process starts by pumping epoxy type Sikadur 52 LP into the port until the epoxy starts to flow out the port, then plugged the ports with a cap. A curing period of approximately 24 hours is provided after the injection procedure. Figure 3 shows these procedures.

Fig. 3. Injection procedure.

2.3. Test set-up and instrumentation.

The beams are tested up to the failure load, except that the RB0.7 beam is loaded at 70 % of the ultimate load. The capacity of the 2000 kN hydraulic jack is used with the four-point load test. A 50 mm dial gauge of 0.01 mm accuracy is fixed at the middle of the span to measure the mid-span deflection as illustrated in Fig. 4.

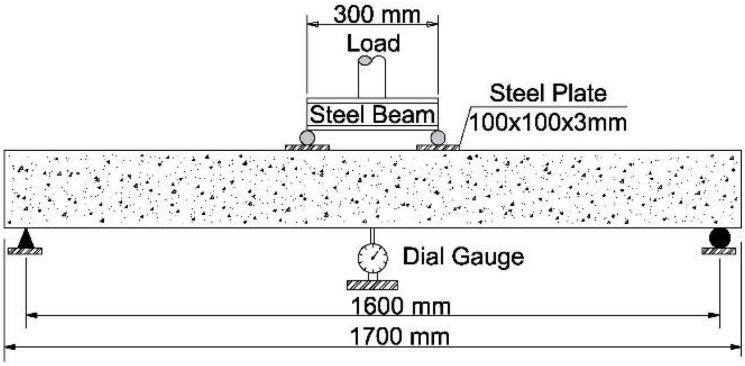

Fig. 4. Test set-up.

3. Discussion of the Results

3.1. Load - deflection curves of the test's specimens

The load-deflection curves of the concrete beams are shown in Figs. 5 and 6. Table 7 summarizes the test results of the specimens.

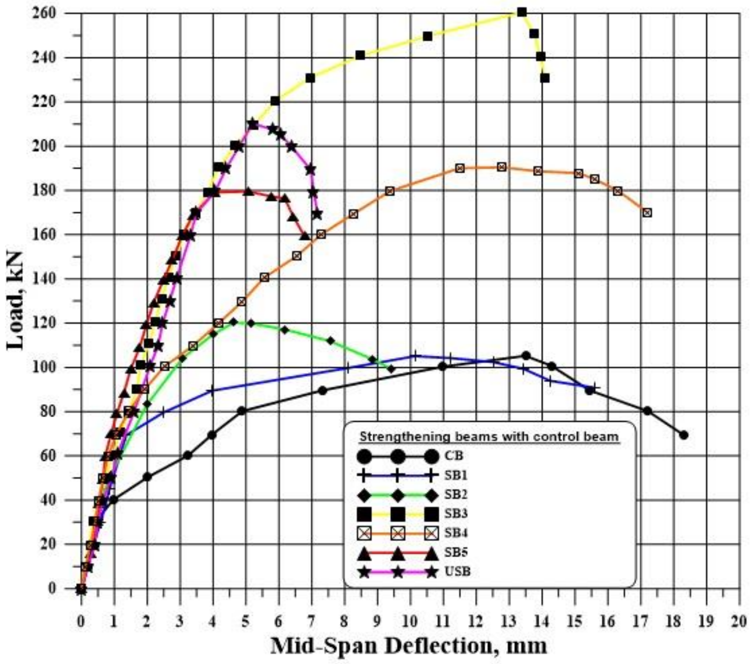

Fig. 5. Load - deflection curves for the strengthening beams.

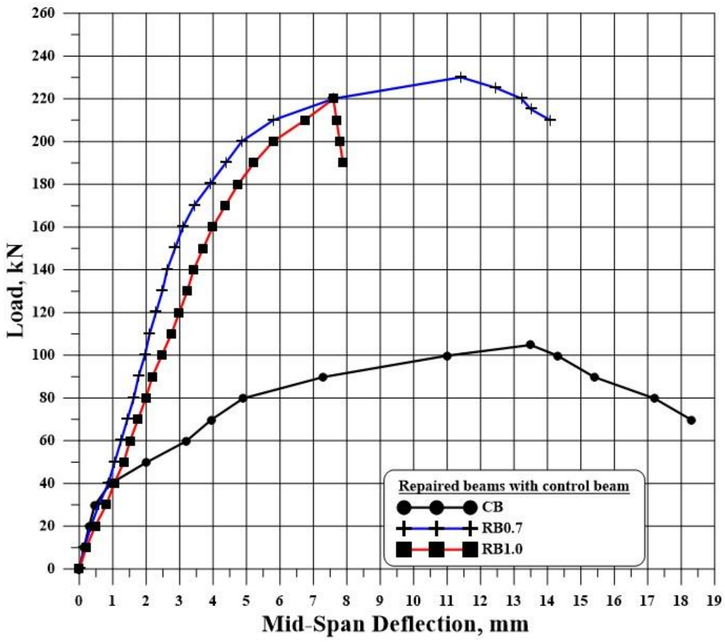

Fig. 6. Load - deflection curves for the repairing beams.

Table 7. Summary of the results.

Beam No.	First Crack Load, kN	Ultimate Load, kN	Ultimate Def. Δu, mm	Strengthening Ratio* %	Mode of Failure
CB	36	105	13.5	-	Flexure
SB1	45	105	10	0	Shear and delamination
SB2	50	120	4.6	14.3	Shear and delamination
SB3	160	260	13.4	147	Shear and debonding
SB4	70	190	11.5	81	Flexure
SB5	140	180	4	71	Shear and delamination
USB	170	210	5.2	100	Debonding and delamination
RB0.7	150	230	12	119	Shear and delamination
RB1.0	90	220	8	110	Shear and delamination

* Strengthening ratio= (Ultimate Load of the beam - Ultimate Load of CB)/ Ultimate load of CB

The ultimate load of the control beam (CB) is 105 kN, which failed by flexure with a maximum deflection of 13.5 mm, as shown in Fig. 7.

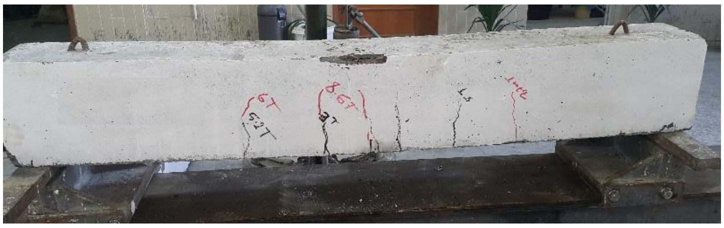

Fig. 7. Control beam.

From the end of the steel plat for the beam SB1, the shear crack started at a load of 45 kN, and then this crack developed horizontally, and several cracks appeared above the steel plat, where it met the main horizontal crack. The ultimate load occurred at 105 kN when the deflection is 10 mm, as shown in Fig. 8.

Fig. 8. SB1 Beam delamination.

The beam SB2 has a similar behaviour to the beam SB1, but the first cracks appear at the 50 kN while the maximum mid-span deflection is 4.6 mm at 120 kN ultimate load, as shown in Fig. 9.

Fig. 9. SB2 Beam failure.

At 160 kN the micro cracks appear in the beam SB3 in the region of bending moment. The micro cracks continue with increased loading, but suddenly, large shear cracks appeared at the end of the steel plate and the shear failure occurred with debonding at the ultimate load 260 kN, as shown in Fig. 10.

Fig. 10. SB3 Beam pattern.

The plates used in the beams SB1 and SB2 did not contribute significantly to increasing the strength because the plates are within the boundaries of the flexure area. The plates prevented the cracks from appearing in the area of its presence and the crack crawled to find a weak area (end of the plate) and the crack formed and caused an early failure of the beam as shown in Figs. 8 and 9. The plate in the beam SB3 covered the entire area of the flexure, so the flexure crack did not find a weak area to appear and the mechanism of failure turned to other types such as delamination and debonding as shown in Fig. 10.

The reason for the appearance of cracks on one side as shown in Fig.10 may be due to the heterogeneity of concrete. Moreover, the first crack appeared on the left side, and thus that side became weaker than the other.

In the case of the beam SB4, flexural cracks started at 70 kN and when the load is 190 kN, the flexural failure occurred. As cracks appeared around bolt areas due to the load concentration, and these cracks extended with the increase in the load until failure. the specimen has lost its strength at load 190 kN but has not failed because of the steel plate and rivets still in contact with the beam and carry the tensile load until the flexure occurs with delamination. Figure 11 shows this case.

Fig. 11. SB4 Beam pattern.

The flexure cracks started to appear under the load of 140 kN in the beam SB5. The shear crack developed at the load 180 kN at the end of the steel plate and the failure occurred due to the shear and delamination of the plate, this means that the failure is caused by the insulation of the plate fixation with concrete, not the failure of the plate. The mid - span deflection is 4 mm at this load, as shown in Fig. 12.

Fig. 12. SB5 Beam failure.

From the end of the steel plate a vertical crack appeared adjacent to the steel plate at a load of 170 kN for the beam USB, as shown in Fig. 13. The cracks began to expand with the increase in the load. The failure occurred, because the fixation of the plat in concrete is stronger than the other cases. Because the failure occurs in the small area, it indicates that the use of epoxy material in the fixation gives higher strength than other cases. The crack occurs in the concrete with part of the concrete remaining in this plate indicates the strength of the bond. Large cavities occurred in the beam near the supports. There is a buckling in the steel plate considering the area above the neutral axis is subject to compression and support from one side only. Consequently, there is a debonding and delamination failure in the beam at 210 kN.

Fig. 13. USB Beam debonding.

Beam RB0.7 is repaired after loading to 70% of the ultimate load, then reloaded. The flexural cracks start to appear at the load 150 kN, the cracks differ, because the cracks in the first case are treated with a material of very high resistance, and after the second loading, cracks formed in the concrete, due to the weakness of these areas compared to the repaired area with a material of high resistance. The failure is caused by shear and delamination at the load of 230 kN with deboning in the steel plate. Additionally, shear cracks occurred at the ultimate load, as shown in Fig. 14.

Fig. 14. RB0.7 Beam failure.

The same simulation and behaviour of the RB0.7 beam occurred with the RB1.0 beam. The type of failure is a combination of flexure, shearing, delaminating and deboning in the steel plate at the load 220 kN, as shown in Fig. 15.

Fig. 15. RB1.0 Beam failure.

3.2. Effect of the steel plate length

To study the effect of steel plate length on strengthening beams, the beams SB1, SB2 and SB3 are taken. The flexure crack occurred in the mid-span and at the point near the mid-span. Within the strengthened beam, the flexure occurs at the end of the steel plate due to the stress concentration at this point. As the length of the steel plate increase (i.e., the end of steel plate far from the mid span and increase contact area between beam and plate), the stiffness of the beam increase, therefore the beam SB1 and SB2 show a slight increase in strength. As shown in Fig. 16 and Table 3, The strength does not increase in the beam SB1 and the increase in section inertia caused the deflection to decrease by 12.8% (10 mm). The strength of the beam SB2 increased by 14.3% (120 kN), while the mid-span deflection decreased by 66%, to 4.6 mm at ultimate load.

The increase in the length of the plate in the beam SB3 entered the failure region and contributed to an increase in the strength by 147% (260 kN). Although the mid-span deflection did not increase, a reading of 13.4 mm is recorded at ultimate load. Therefore, as the length of the steel plate increases, the beam strength increases for the same type of fastening.

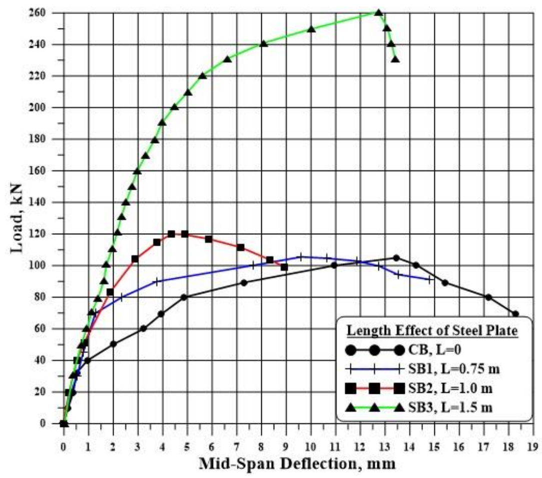

Fig. 16. Length effect of the steel plate.

3.3. Effect of the steel plate position

Specimens SB3 and USB are used to investigate the effect of the steel plate position. As shown in Fig. 17, specimen SB3, which is strengthened with a 1.5 m straight steel plate at bottom face, the strength of the beam increased to 260 kN, which signified a 147% increase in strength. While the USB beam, which has a three-steel plate with a length of 1.5 m in the bottom and two sides of the beam, the strength of the specimen has increased to 210 kN, which increased by 100%. Consequently, the straight shape of the steel plate is the best.

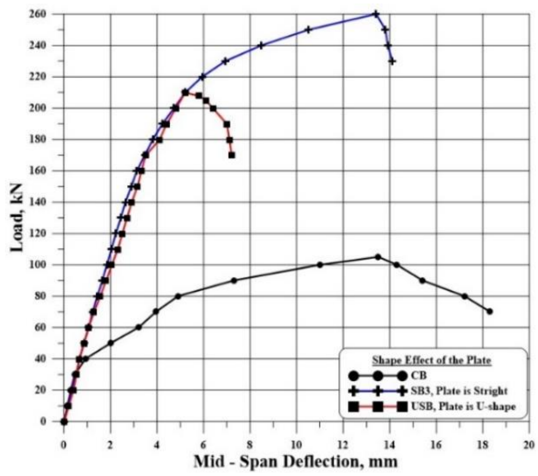

Fig. 17. The Shape effect of the steel plate.

3.4. Effect of the method of fixing the steel plate

Figure 18 shows the effect of the type of the fixing the steel plate. Specimens SB3, SB4 and SB5 are taken to examine the effect of steel plate fixation. the high strength of SB3 beam come from the steel plate fixed by sikadur31, as the ultimate load reached 260 kN, and with a mid -span displacement of 13.4 mm. An increase in strength of 147% is recorded.

In specimen SB4, that used rivets and epoxy (Sika - anchorFix - 2Tropical) to fix the steel plate. The strength increased by 81% of ultimate load, recording an ultimate load of 190 kN and a mid-span deflection of 11.5 mm.

While the method of fixing the steel plate into specimen SB5 is by epoxy (Sikadur 31), together with the rivets grouted by epoxy (Sika - anchorFix - 2Tropical). The presence of rivets in the tension region led to a weakness in this region, and therefore the increase in the strength of the SB5 beam is not at the expected level, reaching 71% in comparison with SB3 and SB4.

Noticed from these three beams SB3, SB4 and SB5, the rivets make a weakness in the concrete in the tension area due to making holes in the concrete and thus reduce the stiffness of the beam.

It can be concluded that the method of fastening with Sikadur 31 is the best.

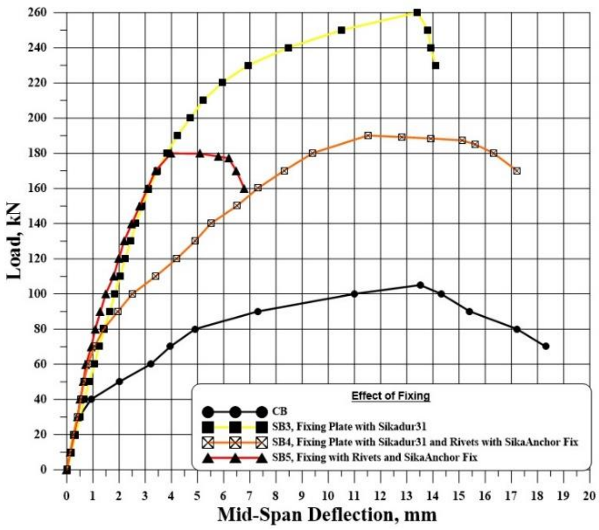

Fig. 18. Effect of the fixing of the steel plate.

3.5. Effect of repairing

In addition to the strengthening of specimens, the repair of specimens is represented by specimens RB0.7 and RB1.0 and showed by Fig.6. The RB0.7, which is repaired by the application of a 1.5-meter-long steel plate in the tension face of beam by Sikadur31, this configuration showed that the strength increase is 119%, recording an ultimate load of 230 kN.

On the other hand, specimen RB1.0, which is repaired in the same way as RB0.7, the increase in strength is 110%, with an ultimate load of 220 kN.

Placing a steel plate on the tension face of the beam gives additional tensile strength that works with reinforced steel bars. In case the reinforcing steel bars are reached to yield, the steel plate may still withstand the stress by the bonding slip force.

Because the RB1.0 beam had more internal cracks, and the reinforcing steel in the tensile zone had some of the yield and the contribution of the steel plate being simple, therefore, the increase in strength between the two specimens (RB0.7 and RB1.0) is 9%.

4. Conclusions

An experimental study is conducted on a number of reinforced concrete beams to investigate the effect of plate length to strengthen the beam and fastening methods. Two beams are also examined after being loaded for 70% and 100% of ultimate load of control beam, and then repaired and tested up to failure.

This study leads to the following conclusions:

- As the length of the steel plate increase from 0.75 m to 1.5m, the beam strength increases, that record a ratio of 147% for the length of the 1.5-meter steel plate.
- Strengthening with straight steel plate better than U - form with different in increasing percent of strength 47%.
- Has been noted for the method of fixing the steel plate, that fixing with Sikadur 31 gives the highest strength rather than the rivet fixation method and Sika - anchorFix - 2Tropical with difference 44.4%.
- The method of repair used in this study gives an increase in strength by 110% of ultimate load of control beam.

Nomenclatures

CB	Control Beam
D	Bar diameter
*RB*0.7	Beam loaded until 70% of ultimate load, then repaired
*RB*1.0	Beam loaded until 100% of ultimate load, then repaired
*SB*1	Beam with 0.75 m straight steel plate fixed with Sikadur 31
*SB*2	Beam with 1.0 m straight steel plate fixed with Sikadur 31
*SB*3	Beam with 1.5 m straight steel plate fixed with Sikadur 31
*SB*4	Beam with 1.5 m straight steel plate fixed with Sikadur 31+Rivets
*SB*5	Beam with 1.5 m straight steel plate fixed with Sikadur 31+Rivets (fixed inside concrete by Sika - anchorFix - 2Tropical)
t	Thickness of steel plate
USB	Beam with 1.5 m three separated steel plate fixed with Sikadur 31

Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CFRP	Carbon Fiber Reinforced Polymer
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
RC	Reinforced Concrete

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