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FLEXURAL BEHAVIOR OF STEEL CONCRETE COMPOSITE BEAM WITH WEB OPENINGS AND STRENGTHENED BY CFRP LAMINATES

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Abstract. The present study is aiming to investigate the structural behavior of simply supported composite beams in which a concrete slab is connected with steel beam by headed stud shear connector or by using epoxy layer as a shear connector. The main variables are the locations and numbers of web openings and methods of strengthening by CFRP laminates or by steel plate. During the test, samples were loaded by one or two line load across the width of the concrete slab; deflection and strain at mid-span were observed versus load.

In the theoretical investigation, the tested samples were numerically modeled and then analyzed using the finite element method. The numerical models were carried out in three dimensions by software package (ANSYS V 12.1). Parametric studies were carried out to investigate the effect of opening diameters, opening locations, methods of strengthening, compressive strength of concrete on the behavior of composite beams.

The results show that the web openings decrease the strength of composite beams in the range of (5-15) % and the deflection of experimental tests show ductile behavior for all beams and increased ductility for strengthened beams.

1- INTRODUCTION

The web opening is necessary to decrease the height of multistory building by decreasing height of every floor from reducing necessary depth for service ducts and make it include the web depth by passing through web opening. A decrease in building height reduces both the exterior surface and the interior volume of building, which lowers the operational and

maintenance cost. On the negative side, web opening can significantly reduce the shear and bending capacity of composite beams.
Clawson and Darwin [1] presented an experimental investigation to study composite beam with concentric rectangular web openings. **M. Hamoodi and W. Hadi**[2] investigated six composite beams contain various number, location and shape (rectangular and squares) of openings. **A. Fam and et. al.** [3]investigated the strengthening of intact steel–concrete composite girders and the repair of notched steel beams, using carbon-fiber-reinforced polymer (CFRP) materials with Young's modulus varying from 150 to 400 GPa. **Bouazaouia and et al.** [4] investigated the bonding connection in steel–concrete composite beams for the case of static loading and high-strength concrete. The 3-point bending test performed on a large beam confirmed that bonding is very efficient. **S. F. Resan**[5] investigated the structural behavior of simply supported composite beams, in which a Ferro cement slab is connected together with aluminum beam by adhesive epoxy layer.
In order to have more information about composite beams, nine structure of composite beams using circular web openings with various diameters and locations, the effect of opening strengthening using CFRP laminate and the effect of using various types of shear connector on composite beam were tested in the present work. The experimental results compared with nonlinear finite element analysis to evaluate the behavior and strength of the tested composite beams utilizing the package software program (ANSYS V 12.1).

2- EXPERIMENTAL STUDY

The composite beams were constructed from a concrete slab and steel I-section. Each beam had a constant span of 1.25m center to center. For the concrete slab, the width was 320mm and the depth was 75mm. The effective width was specified according to the AISC (LRFD) [6]. The slab reinforcement was following the ACI building code requirements [7]. Steel ratio designed depending on requirements for temperature and shrinkage for longitudinal and transverse directions. In each direction; one layer of 6mm diameter was located at center of slab cross section with 100mm center to center spacing.
The total depth of IPE-140 steel I-section was 140mm. The flange had 73mm width and 6mm thickness, while the web had 128mm depth and 5mm thickness, as shown in Figure (1).
The experimental work included eight composite beams; the beams were divided into two groups according to shear connector technique. The first group consisted of two composite beams. Adhesive epoxy technique was used to connect the concrete slab to the steel beam in each composite beam of this group. The two composite beams were different from each other in the thickness of adhesive epoxy layer. The second group consisted of six composite beams. A headed stud technique was used to connect the concrete slab to steel beam, in each composite beam of this group. One composite beam of this group was without any opening which utilized as control beam for comparison purpose, whereas the other five composite beams included opening in the steel beam. The six composite beams where different from each other in the location and number of openings, loading condition, in addition to the strengthening of opening using CFRP. The details of all the composite beams shown in Figure (2).

The same concrete mix was used to the whole investigation. It was designed to have average cubic compressive strength of 43 N/mm^2 at 28 days. The mix properties by weight were (1 cement: 1.6 sand: 2.6 gravel), 0.35 water cement ratio and used 5 litter/m^3 AdditiveflocreteSP90S.

3- EXPERIMENTAL RESULTS OF COMPOSITE BEAMS

The behavior of the tested composite beams is explained and shown in figures. Each test was observed from the beginning of the test until failure. The cracking, load deflection curve and mode of failure are all explained in the following. The load-deflection curves for all tested specimens are shown in Figure (3). The ultimate loads, first transverse and longitudinal cracking and other details are given in Table (1).

3.1- Beam CB control

Beam CB control was fabricated without any web opening. The point load (P) (line load across the slab width) was applied in increments.

The test indicated linear load – deflection relation up to (62 %) of the ultimate load followed by ductile failure. The ultimate strength of the beam was (212) kN, At failure, excessive deflection occurred due to yielding of the steel beam at mid span which was followed, as result, by crushing of concrete slab at center.

The slip between the concrete slab and the steel section was (0.012) mm.

3.2- Beam CBO1

The beam CBO1 is constructed with one central circular opening, 80 mm diameter (equal to 58 % steel depth), the slab concrete and steel beam connected together with headed stud shear connector.

Load – deflection curve indicated linear relation up to first cracking of concrete section, which took place after applying (68 %) of the failure load. However, yielding may have occurred firstly at the bottom tee of the web opening due to tensile stresses. The top tee yielding occurred due to tensile stresses also but after failure of beams due to increase of crack width of concrete, as showing in Figure (6).

Beam CBO1 failed after applying load of (183) kN. It means that there is a reduction of (14 %) in the ultimate strength compared with the beam CB control; this variation is due to the effect of the opening at mid span.

3.3- Beam CBO2

Beam CBO2 has two openings with diameters of each one (40) mm (equal to 29 % steel depth) concentrated at mid span; the type of shear connector is headed stud.

Beam CBO2 failed after applying load of (205) kN. It means that there is reduction of about (5 %) in its ultimate strength compared with the guide beam CB control. The result showing the effect of two openings on ultimate strength is lower than that of one opening (Beam CBO1) with same cut out web percent of beam depth. The load-deflection curves for CB control, CBO1 and CBO2 beams have same behavior for all growth curves except beam CBO1 which suffers fast curvature after first crack of concrete. This gives a conclusion that the beam CBO1 exposed to suddenly steel yielding after first crack load at mid span due to the effect of web opening.

3.4- Beams CBSO1 and CBSO2

Beam CBSO1 contained one opening at mid span with diameter (80) mm (equal to 58 % of steel depth) while beam CBSO2 contained two openings with diameters of each one (40) mm (equal to 29 % of steel depth) concentrated at mid span and the two beams strengthened by CFRP laminate. The concrete slab connects with steel beam by headed stud shear connector.
Beam CBSO1 failed after applying a load of (205) kN. It means that there is increasing about (12%) in its ultimate strength compared with the guide beam CBO1 while beam CBSO2 failed after applying a load of (215) kN, as shown in Figure (5). It means that there is increasing about (5%) in its ultimate strength compared with the guide beam CBO2.

These result shows that the CFRP laminate is effective on the composite beam by increasing ultimate strength, increase deflection after ultimate load and change type of failure from steel yielding followed by crushing of concrete in beams CBO1 and CBO2 to concrete crushing in beams CBSO1 and CBSO2.

3.5- Beam CBEO2 II

Beam CBEO2 II contained two openings with diameters of each one (80) mm (equal to 58 % of steel depth) and located at end span and used two concentrated point load at third span.
Beam CBEO2 II failed at applying load (230) kN. The failure type of this beam is lateral torsion buckling at openings as shown in Figure (6). This beam does not contain any cracks in concrete slab. For comparison this beam with another types of beams, two beams are taken; the first one beam without openings with two point load and the second beam contain openings similar to CBEO2II and strengthened it by steel plate. These beams are taken as numerical work in step (4.3.1).

3.6- Beam CBP5 and CBP7

Beams CBP5 and CBP7 were fabricated steel beam connected with concrete slab by epoxy adhesive layer with thickness (5 and 7) mm, respectively. For beam CBP5,as the load increased, to (125) kN (equal to (83 %) of the ultimate load of this beam), transverse cracks at the center of the bottom face of the slab and end slip between concrete and steel is occurred while beam CBP7,end slip between steel beam and concrete slab occurred at 100% of the ultimate load of this beam. The crack and end slip continued to increase as the load increased. Figure (7) shows slip between concrete and steel.

Load – deflection curve in Figure (3) shows linear relation up to the beginning of separation between concrete slab and steel beam, which took place after applying about (77 and 86 %) of the failure load for beams CBP5 and CBP7, respectively. The ultimate load of beam CBP5 is (150) kN while the failure load of beam CBP7 occurs at (175) kN. It means that there is increasing about (17 %) in its ultimate strength compared with the beam CBP5 and decreased about (17 %) in its ultimate strength compared with the beam CB control.

4- FINITE ELEMENT ANALYSIS

4.1- Modeling of Composite Beam

In the finite element model, solid element (solid 45) was used to model both steel I-section and steel plate at the support and loading points but with different material properties. In addition, (solid 65) was used to model the concrete slab. Link element (link8) was employed to represent the steel reinforcement in tested beams. The interface between the concrete slab and the steel beam was idealized by representing each stud as one nonlinear spring element (combine 39) at the actual location of the shear stud. Shell element (shell 41) was used to represent the CFRP in the specific beams, while (contact52) was used to descript the epoxy layer.

4.2- Results of Finite Element Analysis

The results from the ANSYS Finite Element Analyses (F.E.A.) were compared with the experimental data. The analysis of specimens takes into account the variation in material properties. This comparison shows a good agreement between experimental work and F.E.A. where identical results were obtained before yielding, while the difference was shown near failure for load-deflection curve while the first cracking load, ultimate load and ultimate mid-span deflection have acceptable data between them, as shown in Table (2).

4.3- Parametric Study

Due to the agreement produced from using the present model to analyze the composite beams tested as described in (4-2), the same configuration of the composite beams was selected in this parametric study. All dimensions and material properties observed through the tests were considered. The parametric study will be chosen as follows:

4.3.1- Shear strengthening for beam using externally steel plate:

To study the effect of strengthening of openings at edge span, the specimen CBEO2II was taken and strengthened with plate steel section with thickness 5 mm around the openings as CBSEO2II, Figure (8) shows that. As compared with the results of ultimate load and load deflection curve from ANSYS program for the CBSEO2II, CBEO2II and CBII specimens, it is found that they are identical till the yield point and after this point the ultimate load of strengthened specimen (CBSEO2 II) increased and load deflection decreased if it is compared with specimen (CBEO2II), the ultimate load of specimens CBII, CBSEO2II and CBEO2II are (260, 240 and 233 kN), respectively.

4.3.2- Effect of Diameters and Locations of Openings:

To study the effect of opening circular hole with different diameters and locations on the behavior of composite beam. Three holes were made on the composite beam with different diameters as a percent from the depth of steel I-section (50%, 70% and 90% of the depth of steel I-section for CBO50, CBO70 and CBO90, respectively) with different locations as a percent from the location of the span (L/4, L/3 and L/2). The table (3) shows the effect of opening on ultimate load as a comparison with control beam.

Table (3) shows that the specimen CBO50 ultimate load is less than CB control by small amount and this percentage is almost equal even with changing opening location for the length span. The deflection of CBO50 is less than CB control when the hole is located in the middle (L/2) and more than CB control when the hole in the (L/3 and L/4). The effect of openings in ultimate load are very clear in CBO70 more than CBO50 especially when the hole at mid-span (L/2). The CBO90 is very weak in ultimate load in comparison with CB control, the opening location is very effective on ultimate load for all cases where the beam is weaker when openings at mid-span and stronger at quarter-span.

4.3.3- Effect of Concrete Compressive Strength

To show the effect of compressive strength of concrete on behavior of composite beam, four cases were studied CB40, CB50, CB70 and CB90 for concrete compressive strength 40, 50, 70 and 90 N/mm^2, respectively. The first cracking load for all specimens are 40 kN, so increase in concrete compressive strength is not affected on first cracking load. Table (3) shows the effect of increasing of the concrete compressive strength on ultimate load of composite beam as a compared with control beam (CB control) where the increase in compressive strength of concrete increased the ultimate load of composite beam.

5- CONCLUSIONS

The main concluding remarks that have been achieved from the experimental work and finite element analysis may be summarized as follows:

- The experimental work confirms the general idea that the presence of web opening decreases the strength of composite beams. According to the opening position, its size and number, the reduction in the composite beam strength ranges between (5 % to 14 %).
- The experimental test results confirm that the strengthening technique of CFRP system is applicable and can increase the strength capacity of composite beam. In this study, the effect of CFRP on composite beam deletes the effect of openings on ultimate load where the ultimate load of strengthened beam is approximately equal to load capacity of control beam.
- The experimental work results show that the ultimate strength decreases when using epoxy layer as a shear connector, with 5 mm epoxy layer thickness (beam CBP5) the reduction in ultimate strength equal to 29% if compared with beam CB control and equal to 17% when using 7 mm epoxy thickness (beam CBP7) so with increasing the epoxy thickness there is decreasing in the reduction of ultimate strength.
- The nature of failure in composite beams is ductile especially in strengthened beams with CFRP laminate.
- The presence of end openings reduced ultimate load by about 10 % and 7.7 % for strengthened openings by steel plate if compared with beam without opening under same load condition.
- The effect of openings on ultimate load differs with the difference of diameters and locations where the reduction of ultimate load is within the range of (6.3 % to 43 %), for three diameters (50, 70 and 90%) and three locations (L/4, L/3 and L/2). The

reduction increases with increasing the diameter and with approaching to the middle of span.

– The effect of compressive strength of concrete on ultimate load is a direct proportional where the ultimate strength of composite beam increases with increasing the compressive strength of concrete in a range of (6.3 to 38.3) % for compressive strength of (40 to 90) N/mm^2.

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Table 1: Test results of experimental work

Beam No.	Ultimate Load (kN)	Decrease in ultimate load (% of CB control)	Initial cracking load (% of ultimate load)	Maximum deflection (mm)	Type of Failure
CB control	212	--------	68	15.4	Steel yielding followed by crushing of concrete
CBO1	183	14	68	10.59	Steel yielding followed by crushing of concrete
CBO2	205	5	49	14.18	Steel yielding followed by crushing of concrete
CBSO1	205	5	73	17.31	Crushing in concrete
CBSO2	215	-1	58	26.5	Crushing in concrete
CBEO2 II	230	--------	------	6.34	Lateral torsional buckling at openings
CBP5	150	29	83	12.04	Separation between steel and concrete
CBP7	175	17	100	13.32	Separation between steel and concrete

Table 2: Experimental and numerical results of first crack loads, ultimate load and mid span deflection

Beam No.	First Cracking load (kN)		$\left(\frac{\text{Pcr (EXP)} - \text{Pcr (FEM)}}{\text{Pcr (EXP)}}\right)$ (%)	Ultimate Load (kN)		$\left(\frac{\text{Pu (EXP)} - \text{Pu (FEM)}}{\text{Pu (EXP)}}\right)$ (%)	Mid-Span Deflection at 0.7 of ultimate load		$\left(\frac{(\Delta)\text{EXP} - (\Delta)\text{FEM}}{(\Delta)\text{EXP}}\right)$ (%)
	Pcr (EXP)	Pcr (FEM)		Pu (EXP)	Pu (FEM)		(Δ)EXP	(Δ)FEM	
CB control	145	100	31	212	222	-5	4.5	4.7	-4
CBO1	125	98	22	183	190	-4	3.65	3.5	4
CBSO1	150	111	26	205	210	-2	3.6	3.55	1.4
CBO2	100	70	30	205	211	-3	3.5	3.64	-4
CBSO2	125	103	18	215	220	-2	3.8	3.6	5.3
CBEO2II	----	80	---------	230	233	-1	2.6	3.59	0.3
CBP5	125	102	18	150	168	-12	2.3	3.7	-60(neglect)
CBP7	----	105	-------	175	182	-4	2.7	3.29	21
The Average			24 %			3.8 %			5.1 %

Table 3:Comparison between the control beam and beams have openings and beams with different concrete compressive strength

Beam No.	Ultimate load of Beams (kN)	Decrease in ultimate load (% of CB control (222 kN))
CBO50 (at L/2)	205	7.7
CBO70 (at L/2)	175	21.2
CBO90 (at L/2)	125	43.7
CBO50 (at L/3)	205	7.7
CBO70 (at L/3)	186	16.2
CBO90 (at L/3)	143	35.6
CBO50 (at L/4)	208	6.3
CBO70 (at L/4)	195	12.2
CBO90 (at L/4)	152	31.5
CB40	237	-6.3
CB50	274	-18.9
CB70	324	-31.4
CB90	360	-38.3

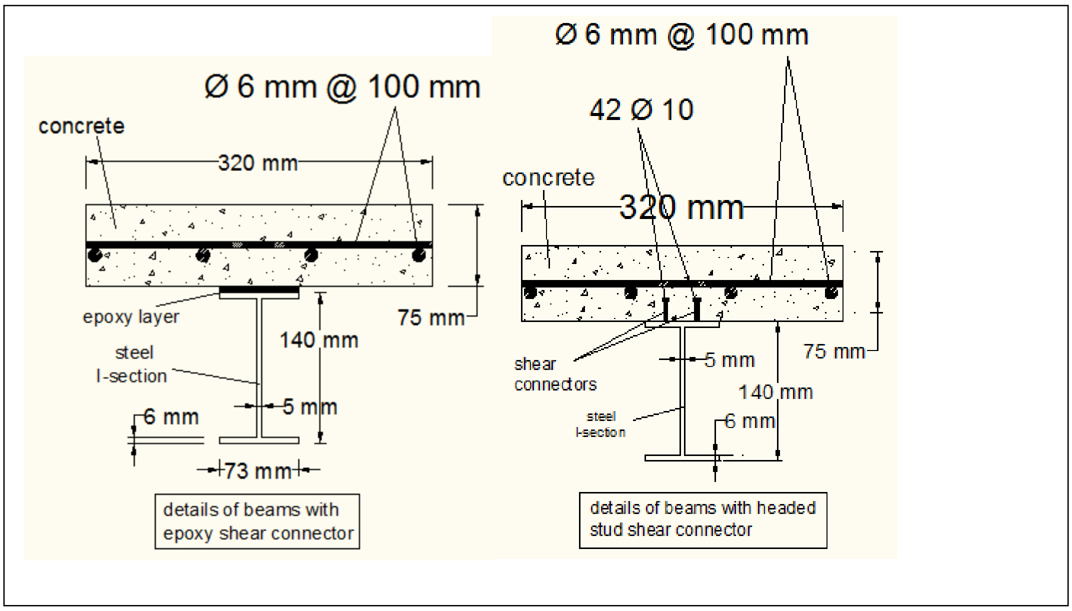

Figure 1: Details of composite beam

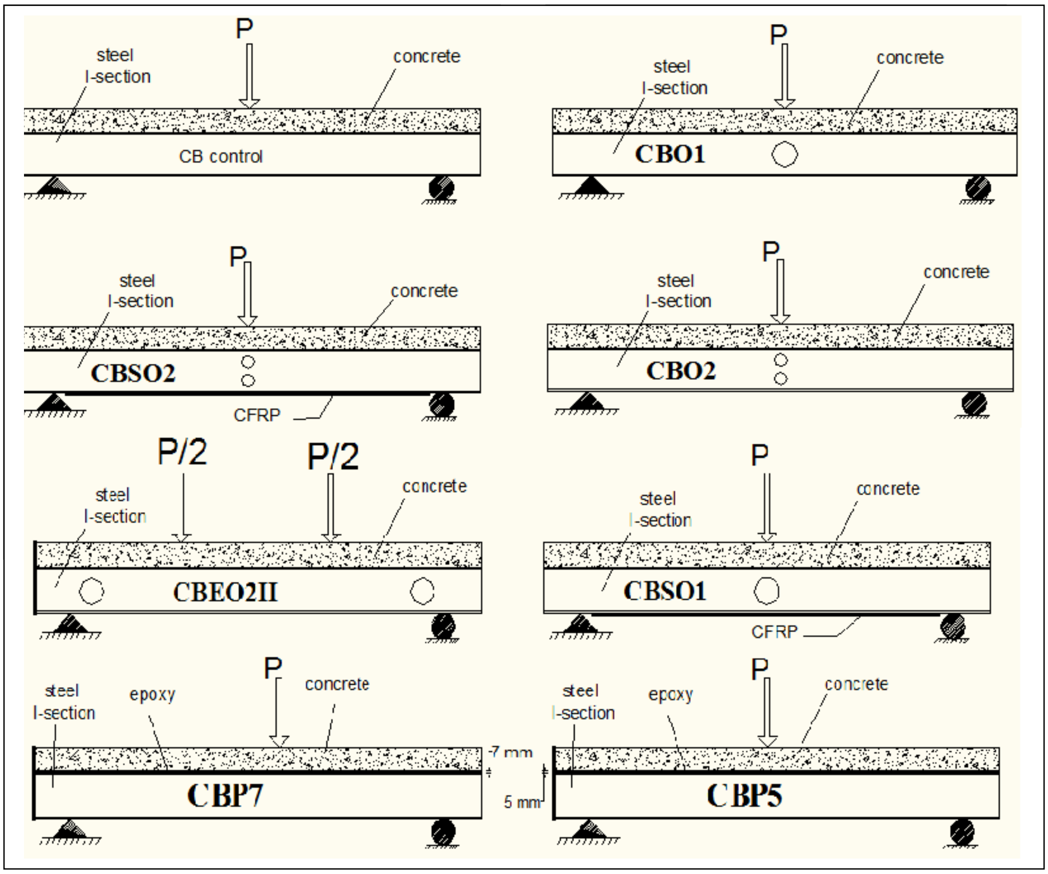

Figure 2: Beams details

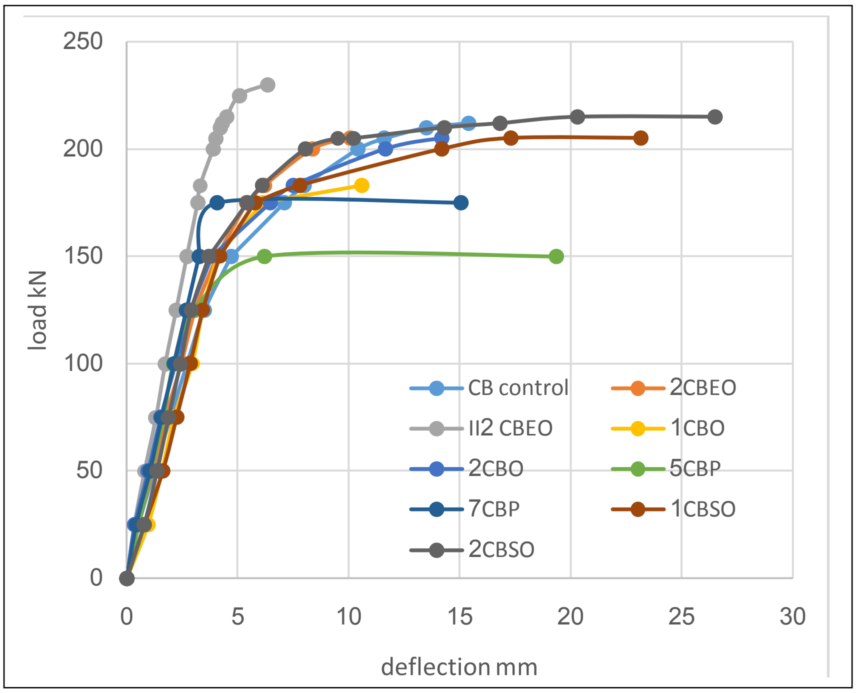

Figure 3: Load-deflection curves of beams

Figure 4: Beam CBO1 at failure

Figure 5: Beam CBSO2 at failure

Figure 6: Beam CBEO2II at failure

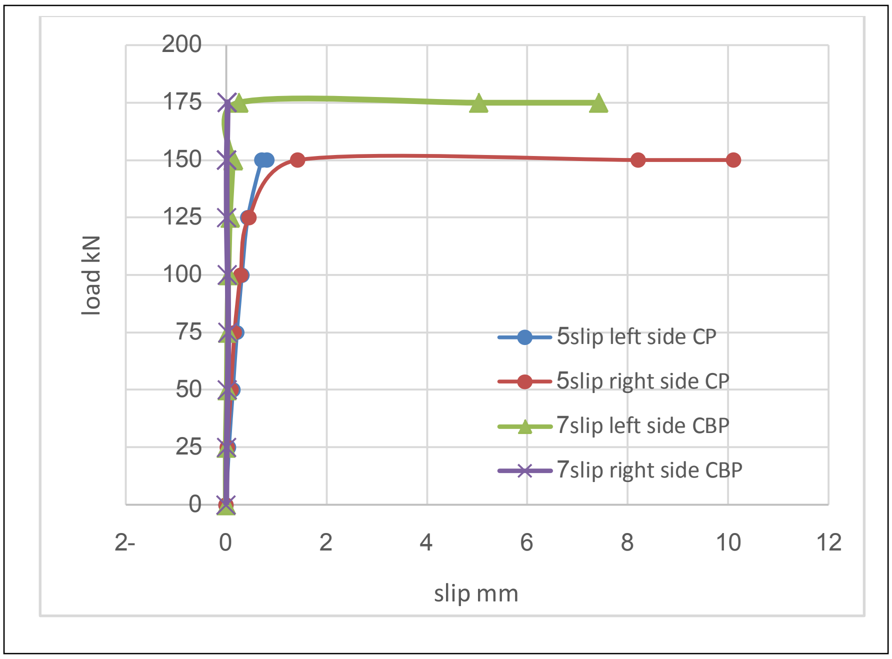

Figure 7: Slip between concrete slab and steel beam at beams CBP5 and CBP7

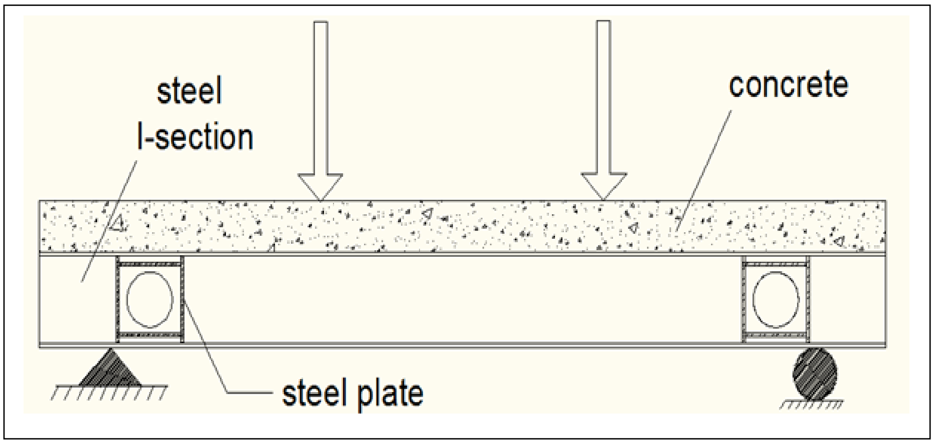

Figure 8: Details of srengthened beam by steel plate (CBSEO2 II)