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ANALYSIS OF FRP STRENGTHENING WEB-OPENING IN A STEEL I-BEAM UNDER STATIC LOADING

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ABSTRACT
Erecting opening in a steel beam web yields to strength and stiffness problems. This paper discusses retrofitting of web opening in steel beams under static load using FRP composites, to bring back the beam strength and stiffness. The study was carried out via a three-dimensional non-linear finite element model. Two different web opening shapes; circular and rectangular; in two different positions; shear zone and mid-span; were concerned in the analysis. Existence of web opening reduced the capacity of the steel I-beam and caused stress concentration around the opening as well, especially at shear zone which lead to vierendeel failure. The adequate strengthening length, strengthening scheme, FRP types, FRP thickness and FRP material properties were studied to come to a conclusion for the most appropriate strengthening technique to bring back the strength of the original steel I-beam. The results revealed that all the strengthened steel I-beams showed a better behavior, a lower stresses concentration around the web opening and presented a higher load capacity. The applicability of the suggested retrofitting limitations on any beam to recover its original capacity was assured by examining the best revealed results on other beams with different dimensions and material properties.

Key words: Steel I-beam; Web opening; Fiber Reinforced Polymer (FRP); Strengthening; Static Load; Finite Element

INTRODUCTION

In residential buildings, existence of ducts and pipes underneath the floor slabs lead to uneconomic floor height. The most suitable solution is passing the required utilities through openings in the web of the steel beams [1]. Existence of web opening affects the strength badly, alters the stress distribution within the member and affects its behavior. Many attempts were carried out to overcome these deficiencies. The traditional solution is using steel plates for strengthening the web opening. Serious difficulties are faced when using this solution, for example the need of lifting heavy equipment to attach the plates, accommodate complex profiles is difficult and welding procedures is complicated. Moreover, the attached steel plates may corrode and residual stresses are formed. In the contrary, using FRP materials do not produce any of these drawbacks. FRP material is famous of its environmental degradation-resistance and has high elastic modulus in addition to its high strength/weight ratio [2].

The study of FRP strengthening steel beams was mainly concerned with attaching the FRP plates to the lower flange of the beam. Many researchers used this technique for strengthening small scale steel beams [2-4] or full scale beams [5-7] by using externally bonded FRP. They registered the increase in the load carrying capacity of the examined beams. A number of researches proposed numerical analysis and finite element analysis of similar strengthened steel beams presented the same results [8-9].

Bounded studies focused on strengthening steel I-beam web using FRP material. Ahmed [10] presented numerically the utility of CFRP strips to the webs of thin-walled I-section steel beams on the beam's flexural strength. The results showed that attaching CFRP strips improved the ultimate capacity of the beam up to 9%.

[11] suggested three strengthening methods to retrofit light steel beam using CFRP plates on the web sides under end bearing loads. They found that the strengthening using CFRP increases significantly the web buckling ability and curb against web rotation. Mustafy and Ahsan [12] presented finite element model for steel rectangular hollow section (RHS) outwardly strengthened with CFRP sheets which were surrounded outside the RHS. The results proved that CFRP sheets noticeably increased constraints against web rotation, improved the web crippling resistance, increased section strength and the failure mode was modified from web buckling to web yielding. Five steel I-beams were retrofitted using CFRP as shear strengthening on one or both sides of the web and examined by Narmashiri et al [13]. It was observed that the load carrying capacity increased, but the shear strain, deformations, lateral deflection and vertical deflections were reduced. Ghareeb et al [14] investigated numerically the effect of bonding CFRP laminates to the webs of thin walled I-section steel beams on the beam's flexural durability. They found that the local buckling of the beam's web was delayed and the ultimate load was increased by about 24%. Increasing value of the elastic modules of CFRP strips led to improving the effectiveness of the materials by additional 5%. Seven steel I-beams strengthened using CFRP strips with diagonal or vertical patterns on one side and both sides were studied by Rigi and Narmashiri [15]. The largest load carrying capacity and resistance were achieved using the diagonal reinforcement in both sides. Other seven simply steel beams retrofitted using CFRP plates to the web were tested by El-Sayed et al [16]. The results showed that the vertical deflection and web strain were reduced in case of attaching CFRP plates in diagonal direction in spite of the improvement in the beam critical load.
Due to the scarcity of researches concerning the handled topic, and due to the importance and the need of upgrading the steel I-beams with web opening using FRP material with its aforementioned advantages, a comprehensive study on the strengthening of web opening of steel beam is conducted herein. A three dimensional, nonlinear finite element model is presented for steel beams with different opening shapes; circular or rectangular; exist in different positions in the beam; shear zone or at mid-span. The effect of strengthening web openings using FRP composites to enhance the overall behavior of the steel beam and to restore the original capacity was studied.

2. FINITE ELEMENT MODELING

2.1. General

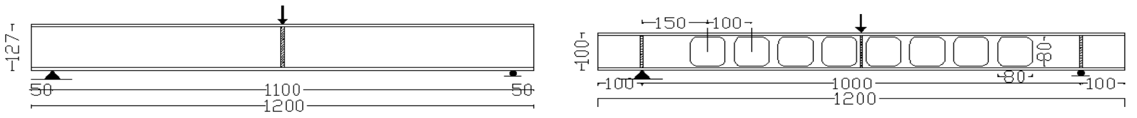
Accurate simulation of the actual behavior of steel beams strengthened by FRP materials requires proper choice for the elements which represent each component of the studied beams. These components are the steel beam flanges, steel beam web, FRP laminates and the adhesive which join the FRP laminates to the steel beam. Moreover, the choice of mesh size which arranges for accurate results with acceptable computational time is important as well.

2.2. Finite element type and mesh

Four-node shell element was utilized to simulate the steel I-beam web. This element is suitable for analyzing thin to moderately-thick shell structures. Each node has six degrees of freedom: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. It is well-suited for linear large rotation and large strain nonlinear applications. Eight-node solid element from ANSYS [17] program library was found to be very efficient in modeling the steel beam flanges. The element has three degrees of freedom at each node. The element has plasticity, stress stiffening, large deflection, and large strain capabilities. It can be used in different shapes for simulating irregular regions. The FRP plates were modeled by using eight-node solid-shell elements which can perfectly be used to simulate thin to moderately thick sections. The adhesive layer between the steel beam and the FRP plates was modeled by using an eight-node solid element with special lineaments of showing cracking to predict the debonding that could happen between steel web and FRP plates. A fine mesh with aspect ratio within the recommended range (1:3) was utilized for all simulated components. A finer mesh was utilized at positions of predicted maximum stresses. Convergence test was performed until accurate results accompanied with reasonable computational time was guaranteed. At the loading and support positions, steel plates were utilized to avoid any undesired premature failure. Solid elements with three degrees of freedom at each node of its eight nodes were used for modeling the plates.

2.3. Model verification

Three experimental tests were used to verify the proposed finite element model. Two beams were tested by (Deng and Lee 2007) and one beam was tested by Morkhade and Gupta [18]. Shape and dimensions of tested beams are shown in Fig. 1. The first two beams were 127×76 UB13 (T_W=4 mm, T_F=7.6 mm, B_F=76.2 mm, and H_W =127 mm) with a length of 1.2 m. The design and ultimate strengths were 320 MPa and 370 MPa, respectively, while the elastic modulus was 190 GPa, and the Poisson's ratio was 0.3. One of them (S300) was tested without strengthening, while the second beam (S305) was strengthened by a single CFRP plate attached to the bottom flange of the beam. The CFRP strip had a length of 500 mm, a width of 76.2 mm, a thickness of 3 mm and a modulus of elasticity EX of 212 GPa, while EY = EZ = 8 GPa. The Poisson's ratio was considered 0.3 and the shear moduli were Gyz = 3076.9 MPa and Gxy =Gxz = 4884.8 MPa. The used adhesive was Sikadur-31 with a thickness of 1 mm, a shear modulus of 2.6 GPa, a tensile strength of 30 MPa and a modulus of elasticity of 8 GPa. The third steel I-beam tested by (Morkhade and Gupta 2015) was used to ensure the validity of the model to simulate the steel beam with web opening. The beam dimensions were (T_W=4.7 mm, T_F=5 mm, B_F=55 mm, and H_W =100 mm) and it was 1.2 m long as. The flanges had modulus of elasticity, design strength and ultimate stress of 204 GPa, 364 MPa and 491 MPa respectively. While those of the web were 199 GPa, 329.5 MPa and 440 MPa respectively. The Poisson's ratio was 0.3.



(a) Steel beam tested by Deng and Lee 2007 (b) Steel beam tested by Morkhade and Gupta 2015

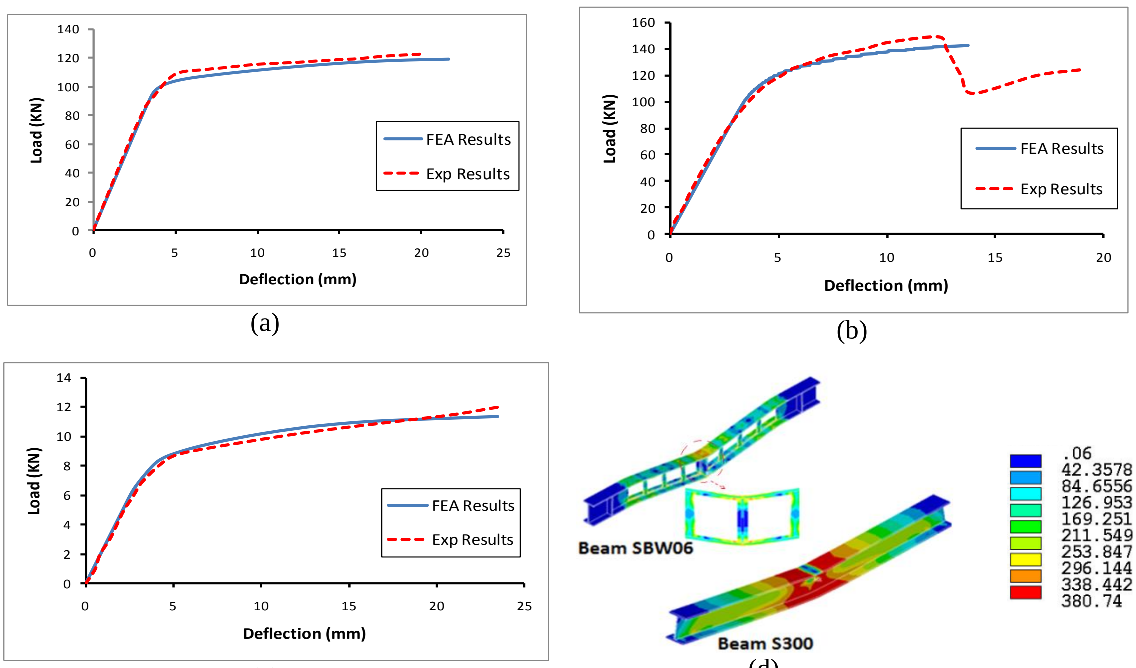
Fig. 1 Tested steel beams

2.4. Material modeling, boundary conditions and load application

Following the testing procedures conducted by Deng and Lee [3] and Morkhade and Gupta [18], the steel I-beams were modeled as an elastic–plastic material with strain hardening, by using bi-linear stress-strain relationship for steel beam material. CFRP plates were modeled as orthotropic material with the above mentioned properties. The boundary conditions were set to simulate simply supported beams. Boundary conditions for simply supported beams were set to the modeled beams. The loads were applied in increments using the load-step and sub-step loading options available in ANSYS program, with the same loading scheme adopted in the tested beams.

Table -1 Comparison between F.E and experimental results

Beam	**Pu (KN)**		**δ (mm)**		P_{FE}/P_{EXP}	δ_{FE}/δ_{EXP}	**Failure Mode**
	EXP	**FE**	**EXP**	**FE**			
S300	122.6	119	20.07	22	0.97	1.09	Bending
S305	149.1	143.15	12.43	14	0.96	1.12	CFRP plate debonding
SBWO6	12	11.375	23.5	23.51	0.95	1.00	Bending and vierendeel
Mean					0.96	1.07	-
COV					0.012	0.06	-



(a) (b) (c) (d)

Fig. 2 Model verification: (a) Load-deflection curves, (S300), (b) Load-deflection curves, (S305), (c) Load-deflection curves, (SBWO6), (d) Von-mises Stresses and deformed shapes of (S300) & (SBW06)

Table -2 Strengthening details of all studied steel beams under static load

Beam designation	Opening Shape	Opening Position	Loading Pattern	FRP Type	FRP Length (mm)	FRP Thickness (mm)	Strengthening Method	P_U (KN)	P_U/P_{solid}	Failure Mode
CB1	-	-	4PB	-	-	-	–	165	1	B
CB2	C	S	4PB	-	-	-	–	149.4	0.90	V&B
CB3	R	S	4PB	-	-	-	–	93.4	0.56	V&B
CB4	R	S	4PB	-	-	-	–	96.6	0.58	V&B
CB5	C	M	4PB	-	-	-	–	159	0.96	B
CB6	R	M	4PB	-	-	-	–	153.4	0.92	B
CB7	-	-	3PB	-	-	-	–	112.5	1.00	B
CB8	C	M	3PB	-	-	-	–	102.6	0.91	B
CB9	R	M	3PB	-	-	-	–	58.2	0.51	B
BSCL1	C	S	4PB	CFRP	95.25	3	P1	152.2	0.92	B
BSCL2	C	S	4PB	CFRP	200	3	P1	157.4	0.95	B
BSCL3	C	S	4PB	CFRP	350	3	P1	158.6	0.96	B
BSCL4	C	S	4PB	CFRP	500	3	P1	161.8	0.98	B
BSCL5	C	S	4PB	CFRP	600	3	P1	164.6	0.99	B
BSCL6	C	S	4PB	CFRP	800	3	P1	169	1.02	B
BMCL1	C	M	4PB	CFRP	95.25	3	P1	159.8	0.96	B
BMCL2	C	M	4PB	CFRP	200	3	P1	162.6	0.98	B
BMCL3	C	M	4PB	CFRP	350	3	P1	175.4	1.06	B
BMCL4	C	M	4PB	CFRP	600	3	P1	189.8	1.15	B
BMCL5	C	M	4PB	CFRP	800	3	P1	189.8	1.15	B
BMCL1-3PB	C	M	3PB	CFRP	95.25	3	P1	110	0.97	B
BMCL2-3PB	C	M	3PB	CFRP	250	3	P1	127	1.12	B
BMCL3-3PB	C	M	3PB	CFRP	600	3	P1	140.2	1.24	B
BMCL4-3PB	C	M	3PB	CFRP	800	3	P1	140.2	1.24	B
BSRL1	R	S	4PB	CFRP	600	3	P1	139	0.84	V&B
BSRL2	R	S	4PB	CFRP	800	3	P1	139.4	0.84	V&B
BSRL3	R	S	4PB	CFRP	1000	3	P1	151.8	0.92	V&B
BSRL4	R	S	4PB	CFRP	1200	3	P1	151.8	0.92	V&B
BSRL3-4L	R	S	4PB	CFRP	1000	12	P1	165	1.00	V&B
BSR-UL	R	S	4PB	CFRP	1000	3	P1	149	0.90	V&B
BMRL1	R	M	4PB	CFRP	285.8	3	P1	163	0.98	B
BMRL2	R	M	4PB	CFRP	600	3	P1	186.6	1.12	B
BMRL3	R	M	4PB	CFRP	800	3	P1	187	1.13	B
BMRL1-3PB	R	M	3PB	CFRP	600	3	P1	88.4	0.78	B
BSC1	C	S	4PB	CFRP	610	3	P1	165	1.00	B
BSC2	C	S	4PB	CFRP	498.2 H & 111.8 V	3	P2	164.4	0.99	B
BSC3	C	S	4PB	CFRP	610	3	P3	181	1.09	B
BSC4	C	S	4PB	CFRP	305	3	P3	158.6	0.96	B
BSR1	R	S	4PB	CFRP	610	3	P1	140	0.85	V&B
BSR2	R	S	4PB	CFRP	498.2 H & 111.8 V	3	P2	150.2	0.91	V&B
BSR3	R	S	4PB	CFRP	610	3	P3	154.6	0.93	V&B
BSR4	R	S	4PB	CFRP	1000 H & 111.8 V	3	P2	161	0.97	V&B
BSCT1	C	S	4PB	CFRP	610	3	P1	158.2	0.96	B
BSCT2	C	S	4PB	CFRP	305	6	P1	158.2	0.96	B
BSR4 T1	R	S	4PB	CFRP	1000 H & 111.8 V	4	P2	166.6	1.01	V&B
BSC-C1	C	S	4PB	CFRP-100	610	3	P1	162.2	0.98	B
BSC-C2	C	S	4PB	CFRP-212	610	3	P1	165	1.00	B
BSC-C3	C	S	4PB	CFRP-350	610	3	P1	167.4	1.02	B
BSC-C4	C	S	4PB	CFRP- 500	610	3	P1	168.9	1.03	B
BSC-B1	C	S	4PB	BFRP-25	610	3	P1	159.4	0.97	B
BSC-B2	C	S	4PB	BFRP-46	610	3	P1	159.8	0.97	B
BSC-B3	C	S	4PB	BFRP-90	610	3	P1	161	0.98	B
BSC-B4	C	S	4PB	BFRP-105	610	3	P1	161.8	0.98	B
BSC-G1	C	S	4PB	GFRP-17	610	19	P1	161.8	0.98	B
BSC-G2	C	S	4PB	GFRP-40	610	19	P1	163	0.99	B
BSC-G3	C	S	4PB	GFRP-64	610	19	P1	165.4	1.00	B
BSC-G4	C	S	4PB	GFRP-95	610	19	P1	167.8	1.02	B
BSR-C1	R	S	4PB	CFRP-100	498.2 H & 111.8 V	3	P2	146.2	0.89	V&B
BSR-C2	R	S	4PB	CFRP-212	498.2 H & 111.8 V	3	P2	150.2	0.91	V&B
BSR-C3	R	S	4PB	CFRP-350	498.2 H&111.8 V	3	P2	151.2	0.92	V&B
BSR-C4	R	S	4PB	CFRP- 500	498.2 H&111.8 V	3	P2	152.2	0.92	V&B
BSR2-G	R	S	4PB	GFRP-95	498.2 H&111.8 V	19	P2	165	1.00	V&B
BSR2-BSP	R	S	4PB	BSP	498.2 H&111.8 V	7	P2	161.9	0.98	V&B
BSR2-BSP T1	R	S	4PB	BSP	498.2 H&111.8 V	9	P2	165.1	1.00	V&B

CB1-F	-	-	4PB	-	-	-	−	470.8	1.00	B
CB2-F	C	S	4PB	-	-	-	−	423.7	0.90	V&B
CB4-F	R	S	4PB	-	-	-	−	273.9	0.58	V&B
CB5-F	C	M	4PB	-	-	-	−	454.2	0.96	B
CB6-F	R	M	4PB	-	-	-	−	436.8	0.92	B
BSCL-F	C	S	4PB	CFRP	1555.2	7.2	P1	480.0	1.01	B
BMCL-F	C	M	4PB	CFRP	585	7.2	P1	472.1	1.00	B
BSR-T-F	R	S	4PB	CFRP	1223.5 H&305V	9.5	P2	471.8	1.00	V&B
BMRL-F	R	M	4PB	CFRP	801.9	7.2	P1	472.7	1.00	B

2.5. Comparison of finite element results with experimental

To validate the proposed finite-element model, a comparison between the experimental data and the finite-element results was conducted. The comparison based on the ultimate load, mid-span deflection and mode of failure, as detailed in Table 1. Good agreement is noticed between the two groups of results. The maximum variance observed between the FE results and the experimental results was about 5%. The mean value of the load ratios was about 0.96 and the corresponding coefficient of variation (COV) was 0.012. Deflections in the finite element models of specimens (S300) and (S305) were higher than the experimental data. This may be due to the lack of material properties data reported by (Deng and Lee 2007). While the deflection value in the finite element model for specimen (SBW06) was almost the same. The COV for deflection results was about 0.06, as detailed in Table 1. Fig 2 shows that the finite element model successfully predicted the Load-deflection of the studied beams.

3. WEB OPENING EFFECT ON STEEL I-BEAM BEHAVIOR UNDER STATIC LOADING

In order to study the effect of using FRP material in retrofitting the steel I-beam, the effect of erecting an opening in the web of the steel beam should be studied first. Nine beams were utilized for this purpose. The beams had the same dimensions and material propertied tested by Deng and Lee [3]. Six beams were studied under 4-point bending (4PB) and three beams were studied under 3-point bending (3PB); as illustrated in Fig. 3. Two different opening shapes; circular and rectangular; in two different locations; shear zone and mid-span; were presented in the analysis. The circular opening diameter was 63.5 mm which equal 0.5 of beam height; however the rectangular web opening had 63.5 mm depth which equal 0.5 of beam height and 190.5 mm length which equal 1.5 of beam height. The opening positions, opening shapes and loading patterns of the steel I-beams are shown in Fig. 3.

When the beams were analysed under 4PB, the ultimate load of the solid beam (first control beam CB1) was 165 KN with a bending collapse mode. Existence of circular and rectangular openings at the shear zone of the beam reduced the ultimate loads by about 10% and 42% respectively, as in beams CB2 and CB4. Smaller reductions where found when the same openings existed at mid-span; CB5 and CB6; 4% and 8% for circular and rectangular openings, respectively. If the edge of the rectangular opening exists exactly below one of the concentrated loads; as in CB3, more reduction in the ultimate load was noticed in addition to distortion in the opening shape. When the steel I-beams were analysed under 3PB, the failure load of the solid beam CB7 was 112.5 KN. The two critical cases, existing the opening at the middle of the beams were studied. The ultimate load was reduced by 9% in case of circular opening (beam CB8). However, the ultimate load of the beam CB9 reached only about 51% of the original load capacity when a rectangular web opening was under the load directly. A large effect on the beam performance was noticed as shown in Fig. 4. Sever reduction in the ultimate load was noticed especially when a rectangular opening exist in the shear zone. Noticeable increase in the beam deflections in the elastic zone was noticed as well. Web opening caused vierendeel failure in some of the studied beams as listed in Table 2. The above results show how the efficiency of the steel beam was affected by erecting an opening in the web. The following sections will handle a comprehensive parametric study to recover the original capacity of the solid beam by strengthening the web using FRP materials. Table 2 summarizes all data of the studied beams.

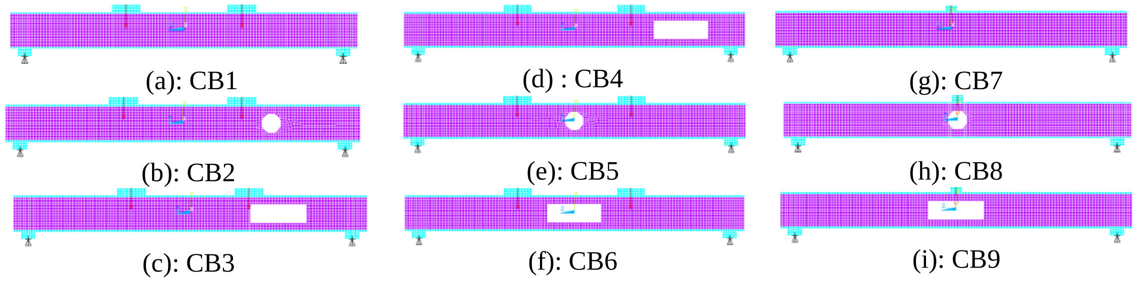


Fig. 3. Loading patterns and opening positions

4. FRP STRENGTHENING OF WEB OPENING

4.1. Strengthening length

In this section, the adequate length of CFRP plates for strengthening web opening in steel beams to recover its original strength will be discussed. Fig. 5 shows the studied opening shapes when they exist in shear zone or at mid-span. The CFRP plates were bonded to the web in both sides above and below the web opening. The CFRP and adhesive properties were the same used as by Deng and Lee 2007, as detailed above. Following the (SEI/ASCE and Darwin, 2003 [19]) requirements in strengthening web openings using steel plates, a minimum strengthening length of FRP plates was considered, which should exceed the web opening by at least a length of ($L_1=a_0/4$), on each side of the opening; where a_0 is the length of the web opening, i.e. the total strengthening length should be more than or equals 1.5 opening length. The maximum available CFRP plate thickness (3 mm), which represents 0.75 tw (web thickness), was utilized to provide sufficient strengthening and help in controlling the opening distortion produced from loading. From the analysis, it was found that this minimum CFRP length was not sufficient in all opening shapes and positions. The CFRP plate lengths were increased gradually to find the adequate length. In case of circular opening under 4PB, CFRP plates of lengths of 200 mm, 350 mm, 500 mm, 600 mm and 800 mm representing 3.15, 5.51, 7.87, 9.35 and 12.6 of opening diameter (D), respectively were used. For steel beam CB2 (steel beam with circular opening at shear zone), The used lengths; in beams BSCL2 - BSCL6; increased the failure load by about 1.87%, 5.35%, 6.16%, 8.3%, 10.17% and 13.1% respectively as indicated in Fig. 6 and detailed in Table 2. The original capacity of the solid beam was exceeded by about 2%, when using a CFRP plate with length of 800 mm. However, existence of circular opening at the middle of the beam was not that critical. The reduction in the steel beam capacity was only about 4% and 9% under 4PB and 3PB, respectively. To obtain the ideal strengthening lengths in these cases, a relation between strengthening length and the load ratio was drawn in Fig. 6-d. A minimum length of 9.6 D was sufficient when the circular opening existed at shear zone. While, when a circular opening existed at the middle of the beam, a length of 3.6 D and 1.85 D were enough to restore the original capacity of the beam under 4PB and 3PB, respectively. It is noteworthy that when the strengthening length exceeds the critical location of stresses concentrations around the web opening, negligible effect of the increase in CFRP plates is achieved. This was noticed when the CFRP lengths reached about 11 D in case of circular opening at the middle of the beam length.

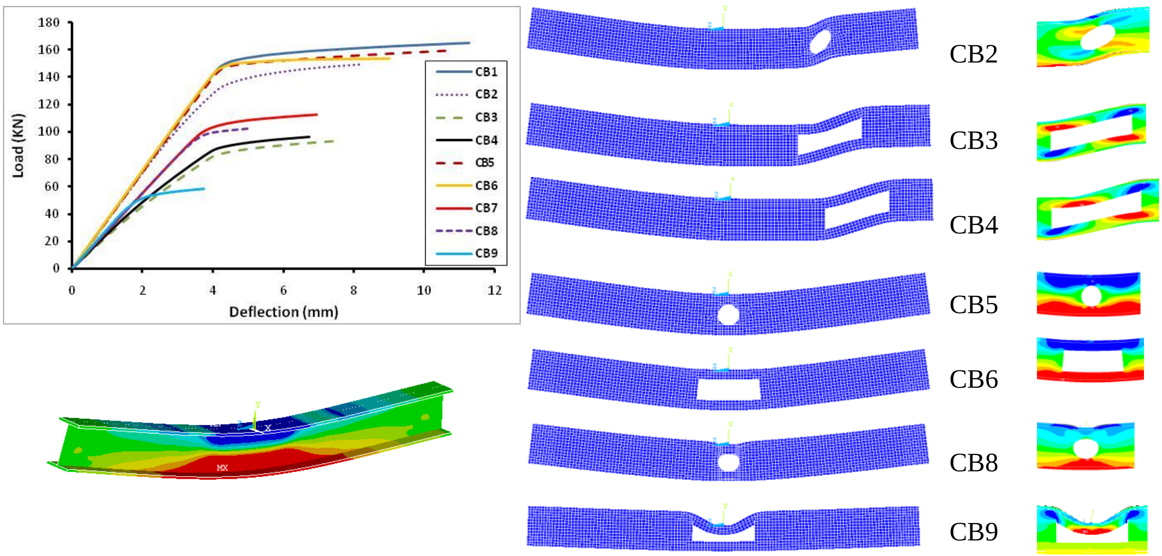
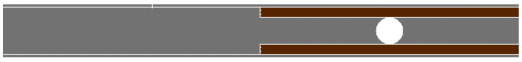


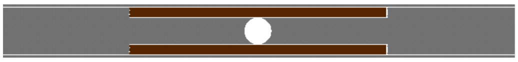
Fig. 4 Results of reference beams;
Load-deflection curves, deformed shapes and stress distributions

As expected, the reduction in the beam capacity was more critical when erecting rectangular opening in the web. A sever reduction in the ultimate capacity accompanied with an increase in the beam deflection from the onset of loading and throughout the loading steps, was observed in beam CB4, as shown in Fig. 7(a). To enhance the beam strength, 3 mm thick CFRP plates with lengths of 600 mm, 800 mm and 1000 mm equivalent to 3.15 L, 4.2 L and 5.25 L, respectively, were studied; (models BSRL1: BSRL3); where L is the rectangular opening length. The maximum increase in the load capacity reached only 92% of the original capacity, as indicated in Table 2. Negligible increase in the beam capacity was noticed when the CFRP plate covered the full length of the beam (1200 mm), as in model BSRL4. Thus, a number of trials were carried out by increasing the thickness of CFRP plates to restore the capacity of the original beam. This was achieved with a strengthening length of 5.25 L with 4 layers of CFRP plates (a total thickness of 12 mm). This means that when rectangular opening existed at shear zone, CFRP plate with thickness equals to triple the steel web thickness to restore the original capacity of the solid beam was required. In beam CB3, where one of the concentrated loads was exactly over the opening edge, the maximum recovered capacity was achieved by using a strengthening length; of 5.25 L (beam BSR-UL) and it reached about 90% of the original beam capacity (beam CB1); as shown in Fig. 7(b). Increasing the number of CFRP layers could not recover the solid beam capacity. High stress concentrations were observed at the corners of the rectangular opening. Beginning of debonding between the steel beam and CFRP plates was noticed at a load of 138.6 KN (about 84% of CB1) at the top of the opening. These results match well with the (SEI/ASCE and Darwin, 2003 [19]) requirements which recommend that the distance between the concentrated load and the opening center line must be not less than half the depth of the steel section.



(a) circular opening at shear zone

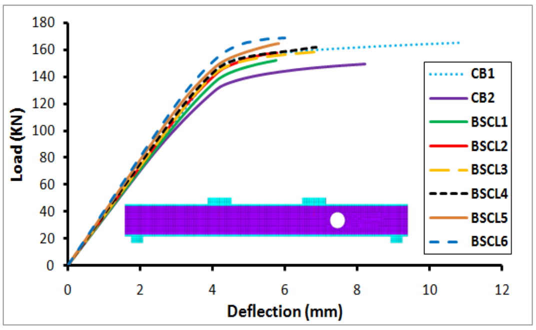
(b) rectangular opening at shear zone



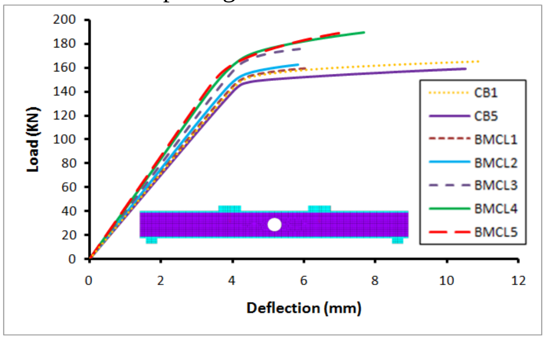
(c) circular opening at mid span

(d) rectangular opening at mid span

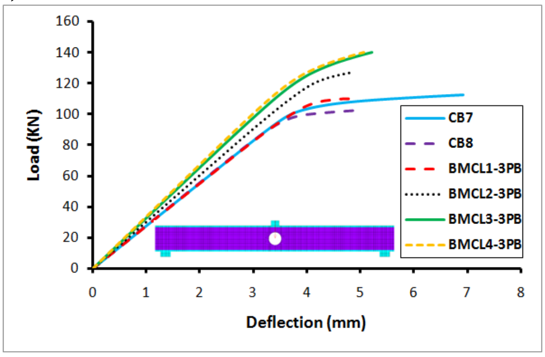
Fig. 5 CFRP plates above and below the opening



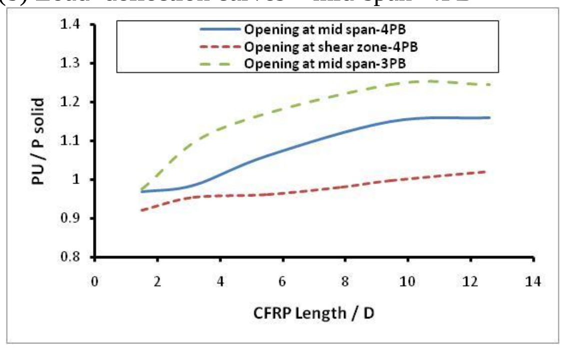
(a) Load–deflection curves - shear zone- 4PB



(b) Load–deflection curves – mid-span- 4PB

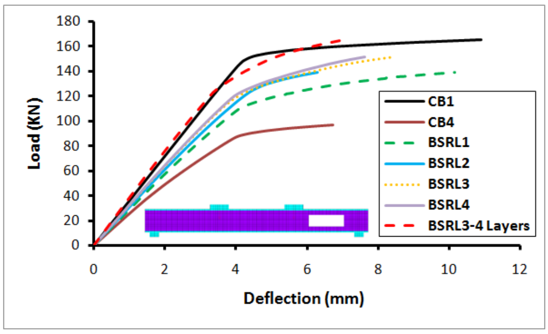


(c) Load–deflection curves – mid-span- 3PB

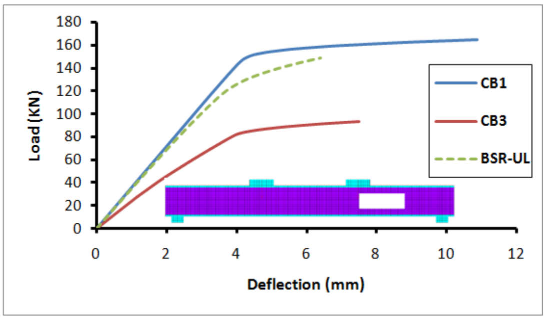


(d) Adequate strengthening length - circular opening

Fig. 6 Strengthening length of circular web opening



(a) Load–deflection curves of CB4 strengthened using CFRP plates



(b) Load–deflection curves of CB3 strengthened using CFRP plates

Fig. 7 Results of strengthening rectangular web-opening at shear zone

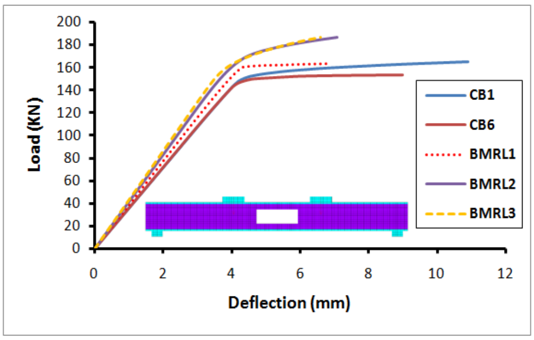
The capacity of the original beam decreased by only about 5.1% when the rectangular web opening existed at mid-span between the two concentrated loads (Beam CB6). The behavior of the two steel beams was typical until yield. Different strengthening lengths were used (beams BMRL1: BMRL3), and the minimum length of

1.5 L (285.75 mm) recovered about 98.8% of its original capacity, as shown in Fig. 8 (a). By interpolation between the strengthening lengths and the ultimate capacity of the beam, a CFRP plate length of 1.65 L could recover the beam original capacity. It is noteworthy that using strengthening lengths exceed the position of maximum stresses under static load, no enhancement in the beam performance could be gained, as indicated in Fig. 8 (a) (beams BMRL2 and BMRL3). If the rectangular web opening was directly under the concentrated load; beam CB9 Fig. 3 (i), sever distortion was found in the beam cross-section. The beam recovered only about 78% of its original load by using a strengthening length of 600 mm; (3.15 L), as indicated in Fig. 8 (b). Increasing the strengthening length could not enhance the beam behavior since the additional length was away from the stressed area and could not prevent the distortion in the beam cross-section, as shown in Fig. 8 (c).

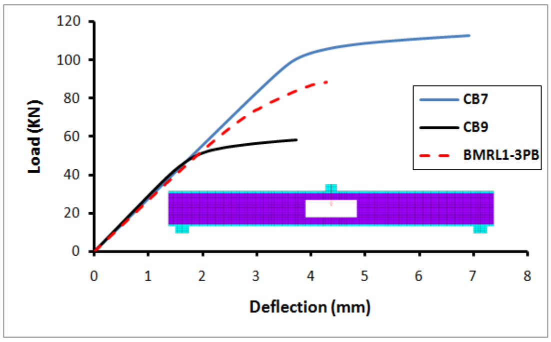
4.2. Strengthening scheme

In this section, three strengthening schemes for FRP plates strengthening steel beam web opening; illustrated in Fig. 9; were studied. The first strengthening scheme was attaching CFRP plates to the web in both sides above and below the web opening of the steel I-beam with a length of 610 mm (about 9.6 D), width of 24.15 mm and a thickness of 3 mm; beams (BSC1 and BSR1) as shown in Fig. 9 (a & b). This length gave the best strengthening effect on the steel I-beam CB2 as discussed above. The second strengthening scheme was attaching the CFRP plates in both sides of the steel I-beam at the top and bottom in addition to two vertical strips at the right and the left of the opening as in beams (BSC2 and BSR2); Fig. 9 (c & d). The thickness, width and the total length of the CFRP plate were kept the same as in the first scheme. The third strengthening scheme was attaching the CFRP plates to the web in both sides in the whole space around the opening, as one part with opening applicable to the beam web opening where the CFRP plates length was kept 610 mm with thickness of 3mm; beams (BSC3 and BSR3) as shown in Fig. 9 (e & f). These schemes were examined to find the ideal strengthening scheme with the minimum adequate length and width of FRP plates, at the critical shear position for both circular and rectangular opening shapes; Beams CB2 and CB4, respectively.

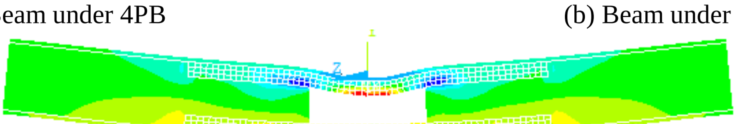
The adequate length for strengthening circular opening at shear zone with the first studied scheme was 9.6 D. Dividing this length into two horizontal strips and two vertical strips (scheme P2); as detailed in Table 2; helped the beam to recover about 99.64% of the original solid beam capacity. Using scheme (P3), which covered the whole space around the web opening had a considerable effect on the behavior of the steel I-beam (BSC3) where the ultimate load of the beam exceeded that of the original beam by 9.7% as shown in Fig 10 (a).



(a) Beam under 4PB

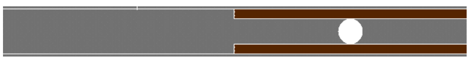


(b) Beam under 3PB



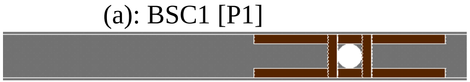
(c) Stress distribution along the steel I-beam (BMRL1-3PB)

Fig. 8 Results of strengthening rectangular web-opening at mid-span



(a): BSC1 [P1]

(b): BSR1 [P1]



(c): BSC2 [P2]

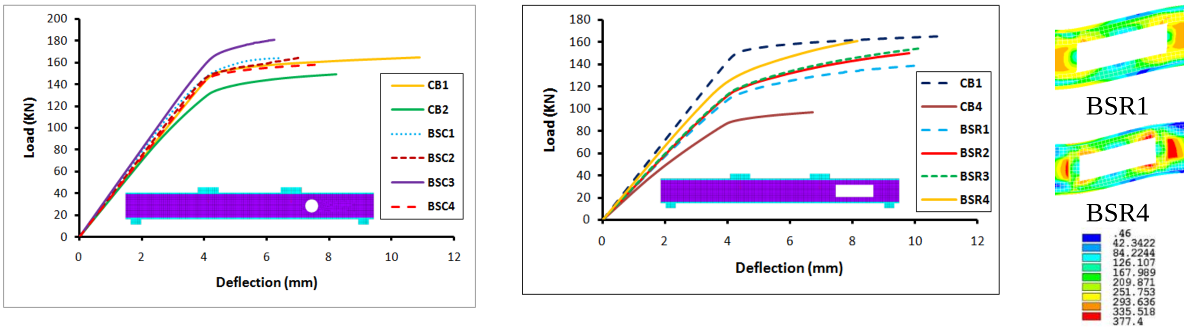
(d): BSR2 [P2]

(e): BSC3 [P3]

(f): BSR3 [P3]

Fig. 9 Strengthening schemes

A noticeable decrease in the beam deflection was occurred in beam (BSC3). This may be explained that the CFRP plate covered all the stresses produced around the opening. In this beam, debonding between the CFRP plate and the steel web started at a load of 153.7 KN, at the edge near to the beam centerline. However, no debonding propagation was observed along the rest of the load steps. In beam (BSC4), the same strengthening scheme (P3) to surround the circular opening in beam but with less CFRP area (the total CFRP area equals to that used in BSC1 and BSC2) forced the beam to sustain only 96% of the desired capacity. This was due to the decrease in the horizontal strengthening length above and below the opening. The strengthened circular opening in the four beams (BSC1 : BSC2) showed a bending mode of failure and no vierendeel failure was observed. Using the CFRP plates with thickness 3 mm with strengthening schemes P1, P2, and P3 on the steel I-beams with rectangular web opening at shear zone, could not recover the beam strength as in beams BSR1, BSR2 and BSR3, respectively, as shown in Fig 10 (b). Similar attitude and deflection were noticed in elastic stage and after steel yielding. Applying two horizontal plates above and below the opening (scheme P1) with length of about 5.25 L, managed to achieve this goal only when four layers of CFRP plates (total thickness 12 mm) were used. 98% of the beam original capacity could be recovered when using 3 mm thick CFRP plates above and below the opening with length 5.25 L in addition to two vertical plates forming scheme P2. Moreover, the vertical CFRP strips decreased the stresses at the opening corners, as shown in Fig. 10 (c), at which debonding started between the CFRP plates and the steel web at a load of about 80% of the ultimate load.

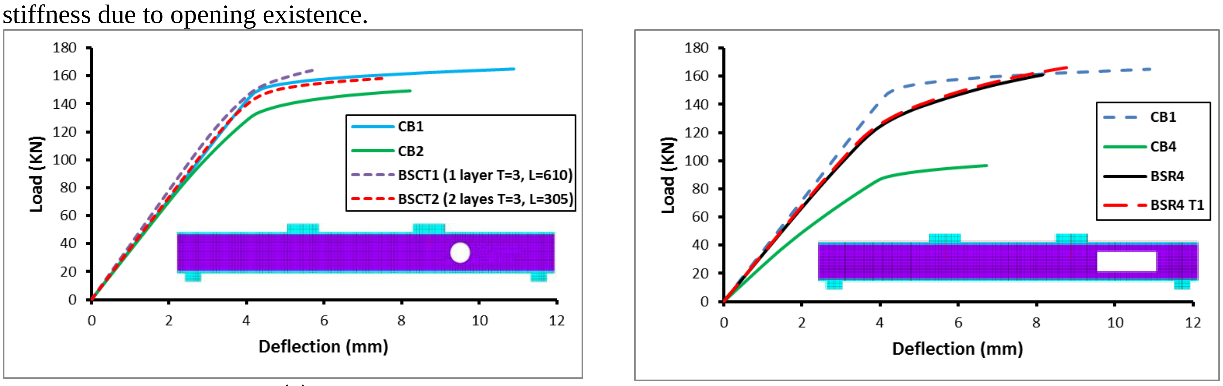


(a) (b) (c)

Fig. 10 Results of different strengthening schemes; (a) Load–deflection curves (circular opening), (b) Load–deflection curves (rectangular opening), (c)Stress distribution around rectangular web opening

4.3 FRP Thickness

In this section, the suitable CFRP plate thickness of the adequate strengthening length was studied. The ultimate load of the solid control beam was recovered when the CFRP plates were provided above and below the circular opening with length of 9.6 D and thickness of 3 mm. When this adequate length was divided into two equal pieces (Beam BSCT2); strengthening length of 4.8 D with total thickness of 6 mm; the beam sustained only about 96% of the original solid beam capacity; as shown in Fig. 11 (a). However, the ductility of the beam was increased by about 31% compared to the beam with 9.6 D strengthening length. This may be attributed to the short CFRP length which is considered brittle material. In case of rectangular opening at shear zone, CFRP plates with thickness of 3 mm and length 5.25 L mm in addition to two vertical strips with length equals the web height recovered only 97% of the desired load (Beam BSR4). Increasing the thickness of the CFRP plates to 4 mm, with this scheme (P2) managed to recover the solid control beam capacity (Beam BSR4 T1). This scheme helped the beam to avoid the progression of the debonding failure that started at a load of 89% of the ultimate load. In addition, the stiffness of the steel I-beam was increased significantly after the sever reduction in beam stiffness due to opening existence.



(a) (b)

Fig. 11 Effect of CFRP thickness on steel I-beam with web opening

4.4. FRP Type

The effect of different types of FRP composites; Carbon Fiber Reinforced Polymer CFRP, Glass Fiber Reinforced Polymer (GFRP) and Basalt Fiber Reinforced Polymer (BFRP); were compared in strengthening the circular and the rectangular web opening in a steel beam at shear zone under static load. Different values of elastic modulus of each FRP type were used. CFRP is known with its high strength while GFRP and BFRP are known with their low cost. All the compared beams were strengthened by horizontal 24.15 wide FRP plates in both sides of the web, above and below the opening with a thickness of 3 mm and a length of 9.6 D for circular opening.

Low, medium, high and ultra-high elastic moduli CFRP plates were used in strengthening four beams with circular opening at shear zone (BSC-C1, BSC-C2, BSC-C3 and BSC-C4) respectively. The elastic moduli of the CFRP plates in the four beams were 100 GPA, 212 GPA, 350 GPA and 500 GPA respectively. The results showed that the ultimate load of the steel beam increased with the increase of the elastic modulus value. Using low modulus CFRP plates recovered 98% of the original capacity of the solid beam. Normal modulus CFRP plates helped the beam to recover the total capacity. Using high modulus and the ultra-high modulus CFRP plates helped the steel I-beam to exceed the desired beam capacity by 2% and 3% respectively. The available elastic moduli of BFRP plates (25 GPa, 46 GPa, 90 GPa and 105 GPa) were used in strengthening four beams (BSC-B1, BSC-B2, BSC-B3 and BSC-B4) respectively. The maximum recovery gained of the steel beam was 98.06% of the original capacity in the fourth beam. The GFRP plates have close elastic moduli to BFRP (17.2 GPa, 40 GPa, 64 GPa and 95 GPa) and their effect was studied in beams (BSC-G1, BSC-G2, BSC-G3 and BSC-G4) respectively. However, GFRP is available in large thicknesses. The maximum available thickness of GFRP plates; 19 mm used by El Damatty et al., [20] was used in this analysis. In spite of the low values of the elastic moduli of the GFRP plates, having large thickness increased the beam strength and managed to restore the original beam capacity in model BSC-G3 and even helped in exceeding the original solid beam capacity in model BSC-G4. Increasing the value of elastic modulus of each FRP type reduced the stresses around the opening by 9%, 3%, 11% in CFRP, BFRP and GFRP, respectively, as shown in Fig. 12.

The same elastic moduli of CFRP plates were used with a total length of 5.25 L around the rectangular opening scheme (P2) in beams (BSR-C1: BSR-C4) as detailed in Table 2. However, increasing the CFRP elastic modulus could not recover the original beam capacity. The large thickness available in GFRP plates (19 mm) with elastic modulus of 95 GPa helped the beam to recover its original full capacity; in addition to a noticeable ductile behavior for the beam; as shown in Fig. 13.

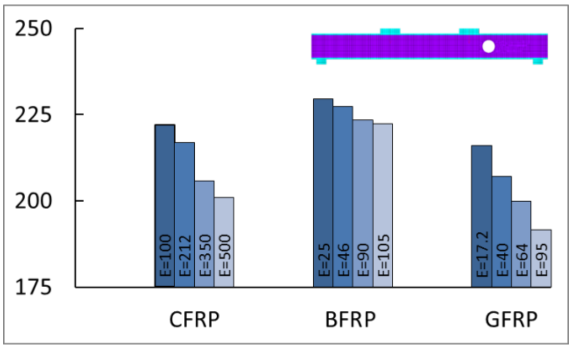


Fig. 12 Effect of FRP Elastic modulus on max stress around web circular opening

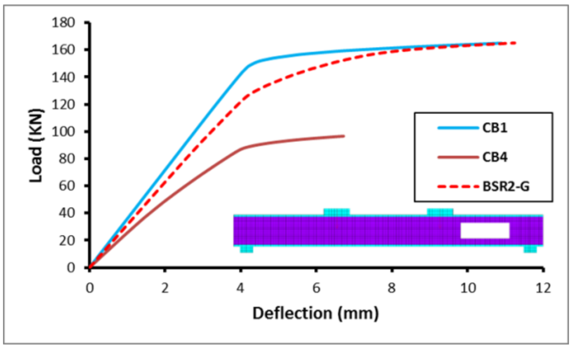


Fig. 13 GFRP strengthening rectangular opening

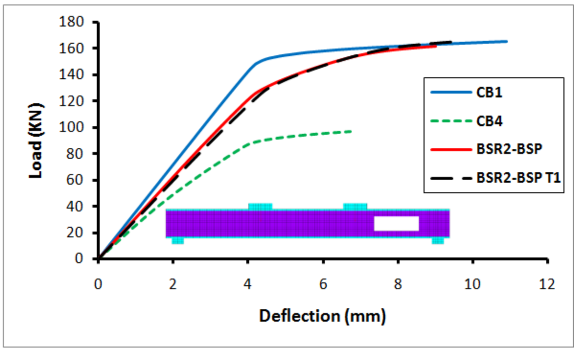


Fig. 14 Strengthening rectangular opening by BSP sandwich plate

A novel technique of using FRP plates for strengthening structures was introduced by Li et al., 2014. This technique depended on using a sandwich plate consists of BFRP and steel (BSP). The sandwich consisted of three layers. The first and the third layers were BFRP each has a thickness of 2 mm with elastic modulus of 105 GPa. The middle layer was steel plate and has a thickness of 3 mm with elastic modulus of 210 GPa; beam (BSR2-BSP). The same strengthening scheme P2 with a total length of 5.25 L was used. The adhesive layer has 1 mm thickness between each two layers. The beam could recover about 98.1% of its original capacity. Increasing the thickness of each BFRP plate to 3 mm; beam (BSR2-BSP T1) managed to recover the desired capacity with a typical beam behavior; as shown in Fig. 14.

5. VALIDATION OF RESULTS ON DIFFERENT BEAM SIZES

The results of the adequate strengthening lengths and the most suitable retrofitting technique were applied to a larger beam. A beam tested by Patnaik et al., [21], with a length of 3.35 m, a flange width of 152.5 mm, a flange thickness of 9.5 mm, a web height of 305 mm, a web thickness of 9.5 mm and an overall depth of 324 mm, was used to perform this investigation. The beam had design and ultimate strengths of 320 MPa and 400 Mpa respectively. The modulus of elasticity was 203 GPa and the Poisson's ratio was 0.3. Six reference beams were considered namely CB1-F : CB6-F, as detailed in Table 2. The beams were studied under four point bending (4PB). Circular openings had a diameter of 0.5 Hw (half the web height), while the rectangular openings had a height of 0.5 Hw and a length of 1.5 Hw. The ultimate load of the reference solid beam (CB1-F) was 470.8 KN with a bending collapse mode. Almost the same reductions in the load carrying capacities of the beams with circular and rectangular openings in shear or mid-span zones were noticed, as detailed in Table 2. The beams were strengthened using CFRP plates with thickness of 7.2 mm, about 0.75 the steel web thickness, as concluded from the current study. Using scheme P1, The recommended adequate strengthening lengths of 9.6 D and 3.6 D in case of a beam with a circular opening at shear zone and at mid-span (Beams BSCL-F and BMCL-F), respectively. These lengths managed to restore the original capacity of the solid control beam (CB1-F), and noticeably reduced the stresses around the opening as shown in Fig. 15. One of the successful strengthening techniques was used for the rectangular web opening at the critical position; shear zone. The opening was strengthened using scheme P2 which surrounds the opening with CFRP length of 5.25 L and thickness equals to the web thickness (BSR-T-F). While a strengthening length of 1.65 L with scheme P1 was sufficient to help the steel I-beam with rectangular web opening at mid-span (Beam BMRL-F) to restore its original capacity.

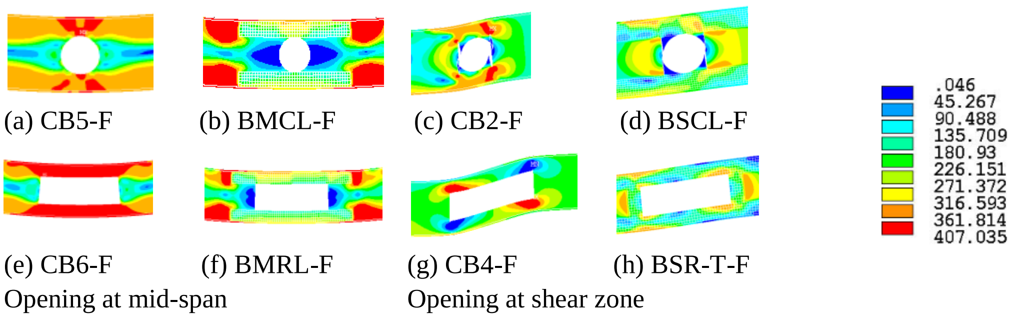


Fig. 15 Stresses around openings before and after strengthening

6. CONCLUSIONS

This study highlights the effect of using FRP plates on strengthening steel I-beams with web opening under static loads. A three-dimensional non-linear finite element model was adopted using ANSYS program. Suitable elements were selected to model the I-beam web, flanges, FRP plates and adhesive layer. The accuracy of the model was verified with some available experimental data from literature. Both shapes of openings; rectangular and circular; either at mid-span or at shear zone were induced and analyzed with and without FRP strengthening to find the appropriate strengthening method to help the beam to sustain its original capacity before opening erection by using different parameters. The dimensions of opening were considered according to the (SEI/ASCE and Darwin, 2003 [19]). The following conclusions were outlined:

- The current study demonstrated the structural efficiency of unstiffened steel I-beam with circular web openings especially at mid-span over the beam with rectangular openings, which showed vierendeel collapse mechanism irrespective to the opening position. Opening should be avoided under concentrated load, especially rectangular shape.
- CFRP is the most appropriate FRP type for strengthening web opening in a steel beam under static loading due to its high elastic modulus which reduces stress concentration around the opening significantly and increases the ultimate load of the beam.
- Strengthening the opening with long CFRP plates of a certain thickness was more effective than using double the thickness with half length.

- The minimum recommended lengths for strengthening circular web opening at mid-span and shear zone in a beam subject to 4PB were 3.6 and 9.6 opening diameter, respectively, with upper and lower CFRP strips with thickness 0.75 I-beam web thickness.
- Rectangular opening in shear zone needed to be strengthened with two horizontal strips in addition to two vertical strips surrounding the web opening with a total length of 5.25 opening length with the same web thickness. The same length was sufficient in two horizontal strips only when the CFRP plate thickness was tripled.
- The availability of GFRP plates with high thickness; 19mm; helped the beam to recover its original strength using strengthening length around rectangular opening in shear zone equals 6.3 opening length in spite of its low elastic modulus.
- The BFRP-Steel-BFRP (BSP) sandwich plate around the opening managed to back-up the original capacity of the beam when the rectangular opening was surrounded by plate length of 6.3 opening length with total thickness of 9 mm.
- The required strengthening length for the rectangular web opening at mid span under 4PB was only 1.65 opening length.

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