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The effect of CFRP strengthening on the behavior of deficient steel beams under concentrated and distributed loading

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The method of carbon fiber reinforced polymer (CFRP) strengthening is a technique that is rapidly developed and used for strengthening of steel structures in recent years. Most previous research in the area of CFRP strengthening of steel structures has been conducted on the behavior of flawless steel structures. Based on the author's knowledge, the behavior of CFRP-strengthened deficient square hollow section (SHS) steel beams under concentrated and distributed loads has not been studied. Therefore, this study aims to investigate the behavior and performance of CFRP-strengthened deficient SHS steel beams under concentrated and distributed loads. Finite element method (FEM), using ANSYS, has been employed for modeling of steel beams. Ten steel beams, two non-strengthened steel beams and eight CFRP-strengthened steel beams have been analyzed. The results indicate the dimensions and number of composite layers is being effective on the ultimate capacity of the SHS steel beams. Also, the results have shown that in deficient steel beams CFRP can significantly be recovered the strength lost due to deficiency.

Keywords: Deficient steel beam, CFRP strengthening, Concentrated load, Distributed load, FEM.

1 Introduction

Due to increasing cost of wages and structural material, the cost of rebuilding has increased. Therefore, the cost of rebuilding for people and governments has become an important issue. Furthermore, the maintenance cost of antiquities is more important than the cost of rebuilding. It can be concluded that retrofitting and strengthening of existing structures seems necessary. Strengthening and repairing of the steel structures are different. The use of carbon fiber reinforced polymers is one of the ways in this area. Past research showed that the use of CFRP composite is a perfect solution to overcome the existing short comings in the area of strengthening and repairing structures[1-5]. In recent years, numerous studies have been conducted on the behavior of steel columns strengthened with CFRP composite materials[6-12]. Also, some other studies have been conducted to investigate the bending[13-15], shear[16], tensile[17] and torsional[18-19] behavior of CFRP strengthened steel beams.

Keykha[20] analyzed the slender and stocky steel columns which were strengthened by CFRP sheets, under eccentric compression load. Also, in another study Keykha[21] investigated the behavior the slender and stocky steel columns under combined compression and lateral load (combination of compression and bending). The results of these studies showed that the use of CFRP composite as a reinforcing material did not have the same effect on the behavior of these steel columns.

Karimian *et al*.[22] investigated the effect of CFRP sheet on strengthening steel columns with circular hollow section (CHS) having initial horizontal or vertical deficiency. Their results showed that deficiency can reduce the ultimate capacity of these steel columns. The results showed that the impact of horizontal deficiency on the ultimate capacity of steel columns is higher than the vertical one. In another study, Huang *et al*.[23] evaluated the damaged CHS steel columns. In this study, 22 specimens were strengthened with CFRP composite materials or grout, under axial compression. The results showed that the behavior of damaged CHS steel columns can be effectively rehabilitated in both of the method of CFRP strengthening and grout.

Keykha[24] analyzed and investigated the behavior of CFRP-strengthened steel frames without deficiency. All steel frames investigated in these studies had a square hollow section. The results of these investigations showed that CFRP strengthening (with length and suitable position) increases the ultimate capacity and plasticity of these frames.

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Awaludin and Sari[25] analyzed and tested the behavior of deficient SHS steel beams that were strengthened with CFRP composite sheet. The deficiency in these steel beams was an artificial crack with width and depth 3 mm and 25 mm, respectively, that was considered on the tension side of SHS steel beams (at mid-span). The results of this study showed that the method of CFRP strengthening can be a suitable method for increasing the ultimate capacity of deficient SHS steel beams, if the deficiency in these steel beams was completely covered with CFRP composite sheets.

Previous studies show that the CFRP composites as a strengthening material of steel structures have suitable role. Although good researches have been done to strengthen the steel structures using CFRP composites, but it seems that a little research has been done on deficient steel beams, and based on the author's knowledge, no independent research has investigated the behavior of CFRP-strengthened SHS steel beams with two-span in length, under concentrated and distributed loads. To fill the knowledge gap in this area, this study aims to investigate the impact of CFRP using as strengthening materials on the behavior of deficient SHS steel beams with two-span in length, using numerical investigations. To determine the ultimate capacity and recovering the strength lost in the deficient SHS steel beams, ten hollow steel beams were modeled and analyzed, one non-strengthened steel beam was without deficiency as control steel beam, one non-strengthened steel beam was having initial deficiency, and eight CFRP-strengthened steel beams were having initial deficiency. The coverage length, the width, and the number of CFRP composite layers were implemented to evaluate and obtain the ultimate capacity of deficient SHS steel beams strengthened with CFRP composite.

2 Materials Used

2.1 SHS steel

In this research, SHS steels with dimensions of 2100 mm × 100 mm × 100 mm and with a thickness of 5.0 mm were used. Some properties of consumable steel such as yield stress, ultimate stress and modulus of elasticity were 280 N/mm^2, 375 N/mm^2 and 200000 N/mm^2, respectively. These values were predicted from the values used in the works done by Keykha[20,21,24].

2.2 CFRP composite

To model steel beams strengthened by CFRP sheet in ANSYS software, SikaWrap-200C was applied. As shown in Table 1, some properties of consumable CFRP such as modulus of elasticity, ultimate tensile strength and thickness are 230000 N/mm^2, 3900 N/mm^2 and 0.111 mm, respectively.

2.3 Adhesive

The applied adhesive in this study is the Sikadur-330. Some properties of used epoxy are shown in Table 2.

3 Numerical Simulation

3.1 Method description

The SHS steel beams were modeled in full 3D using ANSYS. All materials (steel beams, CFRP and adhesive) were simulated by using 3D solid elements (triangle elements of ten-nodes 187). To analyze specimens, nonlinear static analysis was used. In this type of analysis, the load was incrementally applied until the plastic strain in an element reached to its ultimate strain. The properties of the consumable materials were defined according to their nature. Some materials have linear properties while some others have nonlinear properties. The SHS steel beams have nonlinear properties so it was defined as nonlinear material. Also, CFRP and adhesive have linear properties so they were defined as linear materials. In addition, the used CFRP (SikaWrap-200C) is unidirectional composite[19-21, 24]. To mesh the SHS steel beams in ANSYS software, a meshing map was used. Hence, to analyze the SHS steel beams from the solid element of 187 with the mesh size of 25 was used. These element and mesh size were used in the previous study done by Keykha [19-21, 24] that the results of the analysis were satisfactory.

Table 2 — Properties of adhesive (Sikadur-330)

Tensile strength (N/mm^2)	Modulus of Elasticity (N/mm^2)		Elongation at break (%)
	Tensile	Flexural	
30	4500	3800	0.9

Table 1 — Properties of CFRP composite (SikaWrap-200C)

Nominal thickness (mm)	Modulus of Elasticity (N/mm^2)	Ultimate tensile strength (N/mm^2)	Ultimate tensile elongation (%)	Thickness (impregnated with Sikadur-330) (mm)
0.111	230000	3900	1.5	0.9 per layer

3.2 Validity of numerical results

In this research, the numerical results have been validated with the experimental results obtained by Awaludin and Sari [25]. In numerical method, the beams were strengthened and analyzed as the experimental method (as shown in Figs 1 and 2). Comparison of the numerical results with the laboratory results showed that the numerical results have a good accuracy, as showed in Table 3.

4 Model Description

In Fig. 3, boundary conditions, loading scenarios, and strengthening methods of the SHS steel beams are shown. To investigate the behavior of the deficient SHS steel beams strengthened using CFRP sheets, three types of the width of CFRP sheet were considered, and these types were type 1, 2, and 3. The width of CFRP sheet in type 1, 2 and 3 was 100, 200, and 400 mm, respectively (see Fig. 3c). The length of CFRP sheet in all the deficient SHS steel beams strengthened using CFRP sheets was 500 mm (as shown in Fig. 3a). Also, one and two CFRP layers were used for strengthening the deficient SHS steel beams. CFRP sheets were located in the center support on the top surface or around of the deficient SHS steel beams (see Fig. 3a and b). Two types of loading for the deficient SHS steel beams were selected. Type 1 loading was two concentrated loads to the distance of 1000 mm from each other (as shown in Fig. 3b). Type 2 loading was a uniform distributed load in all length of the deficient SHS steel beams (as shown in Fig. 3a). All models were prepared as the SHS steel beams with three supports. For example, Figs 4 and 5 show 3D finite element model of the SHS steel beams prepared using ANSYS software (specimens DBC1-500-100 and DBC1-500-200). Two concentrated loads and uniform distributed load were applied in the finite element models.

5 Description of Specimens

For easy naming of specimens, the specimens were nominated by the names of BC0, DBC0, DBC1-500-100, DBC1-500-200, DBC1-500-400, DBC2-500-100, DBC2-500-200, DBC2-500-400, BC1-500-400,

Table 3 — Comparison of the ultimate capacity of beams in both laboratory [30] and numerical analysis

Model label	CFRP sheet (mm)	Experimental (kN)	FE-analysis (kN)
Beam A	NA	10.93	11.01
Beam B	1000 × 100	13.17	14.12
Beam C	1000 × 150	20.87	21.30

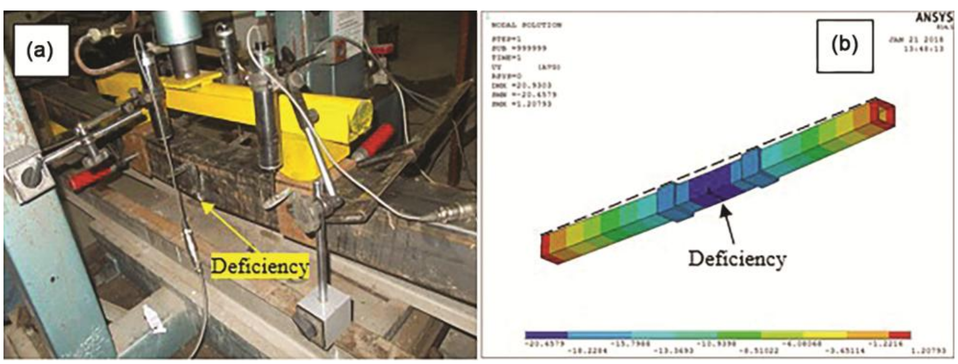

Fig. 1 — Deformed shape of beam A (a) Experimental [30] and (b) Numerical simulation.

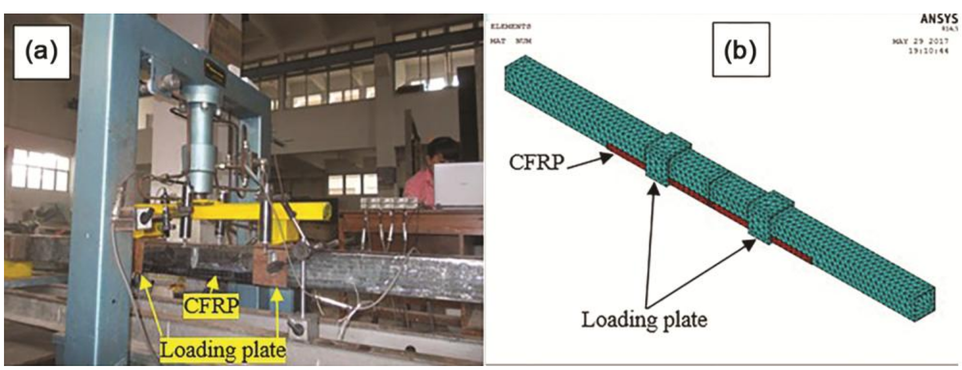

Fig. 2 — Comparison of beam C strengthened by CFRP sheet (a) Experimental [30] and (b) Numerical simulation

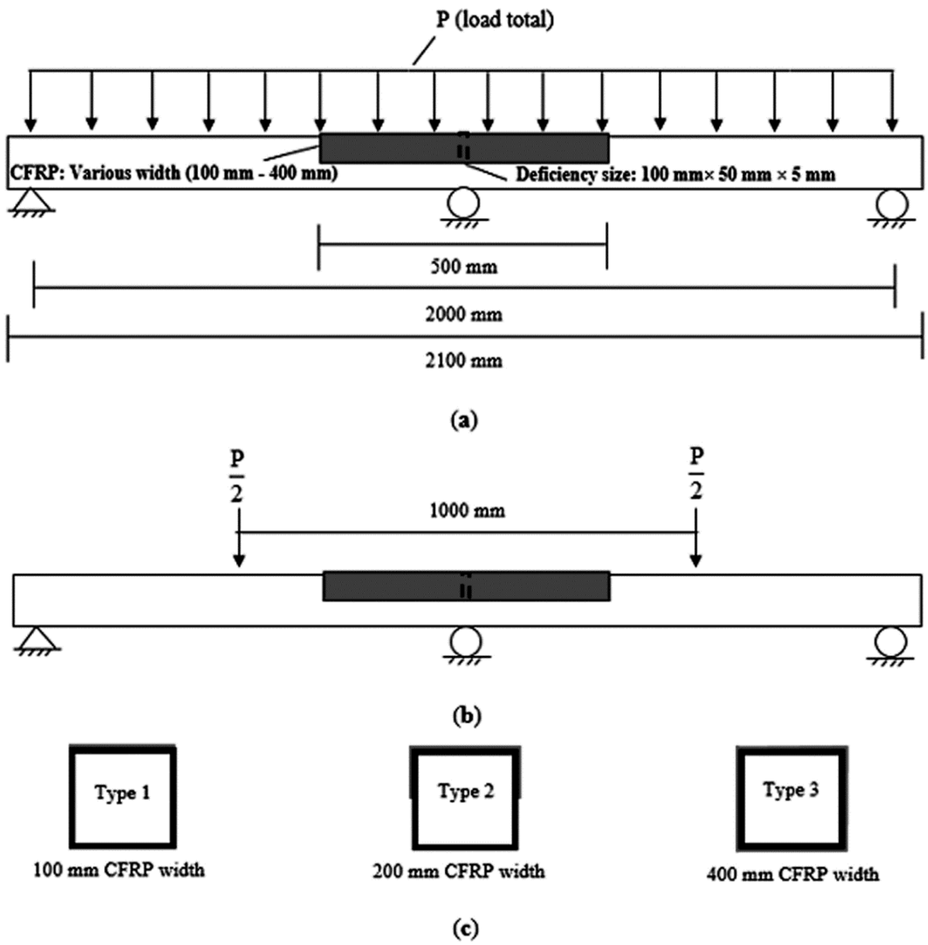

Fig. 3 — The boundary conditions, the loading scenarios and the strengthening methods of the SHS steel beams.

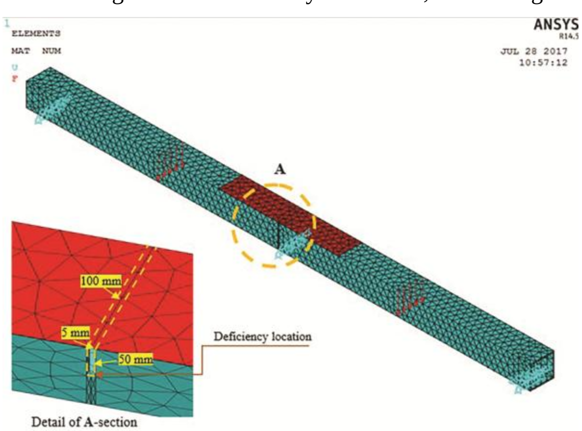

Fig. 4 — Finite element modeling of specimen DBC1-500-100 under concentrated loads.

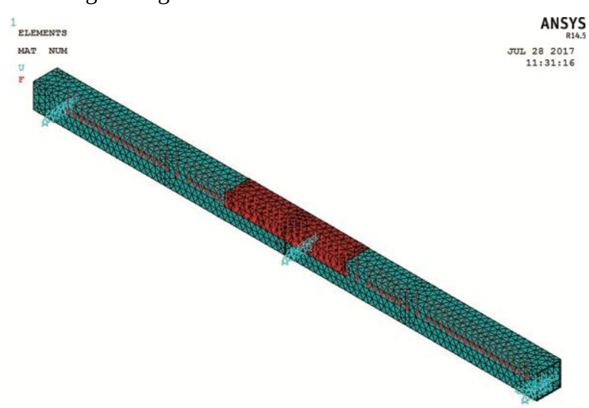

Fig. 5 — Finite element modeling of specimen DBC1-500-100 under uniform distributed load.

and BC2-500-400. For example, the specimen DBC1-500-100 indicates a deficient SHS steel beam strengthened with one layer and 500 mm CFRP length on the top surface. The width of CFRP in this specimen is 100 mm (see Fig. 3c, Type 1). Similarly, the specimen DBC1-500-200 indicates a deficient SHS steel beam strengthened by one layer and 500 mm CFRP length on top surface and both side faces of 50 mm depth. In this specimen, the width of CFRP sheet is 200 mm (see Fig. 3c, Type 2). The specimen DBC2-500-200 is similar the specimen

DBC1-500-200 strengthened by two CFRP layers. The specimen DBC1-500-400 indicates a deficient SHS steel beam strengthened by one layer and 500 mm CFRP length on all faces (see Fig. 3c, Type 3). The width of CFRP in this specimen is 400 mm. The specimens BC1-500-400 and BC2-500-400 indicate that they are without deficiency and are strengthened by one and two layers and 500 mm CFRP length, respectively. In these specimens, the width of CFRP sheet is 400 mm. The control specimen name is BC0 (the SHS steel beam without deficiency). Also, the specimen DBC0 is a non-strengthened deficient specimen. In all deficient specimens, deficiency dimensions were 100 mm × 50 mm × 5 mm (see detail of **A**-section in Fig. 4).

6 Results and Discussion

6.1 The results of the ultimate capacity and recovery

The analysis results of all specimens are shown in Table 4. In the strengthened steel beams, CFRP sheets were applied in the middle support on the top surface, on the top surface and both side faces, or around all faces. For all strengthened specimens, CFRP layers had a constant coverage length. Also, the width of CFRP layers in the strengthened deficient specimens was variable (100 - 400 mm). The results show that, when CFRP does not fully cover the defect length, it cannot be very effective in the capacity of the specimens. The increase percent of the ultimate capacity in the SHS steel beams is increased, with increasing the number of CFRP layers. In strengthened deficient specimens subjected to uniform distribution loading, the ultimate capacity is almost recovered by one CFRP layer. In the strengthened deficient specimens subjected to two concentrated loads, composite is more effective in recovering the capacity than in the case when the strengthened deficient specimens were under uniform distributed load. In all strengthened deficient specimens, the max recovery percent in the ultimate capacity happened for the specimen DBC2-500-400, and was 51.94%. The maximum ultimate capacity of the strengthened steel beams happened for the specimen BC2-500-400 subjected to uniform distributed load, and was 339.89%. As shown in Table 4, the results show that the impact the number of CFRP layers in strengthened deficient steel beams subjected to concentrated loads is more than in the case when the strengthened deficient steel beams are under the uniform distributed load.

6.2 Failure modes

In order to show the failure modes of specimens, for example, the failure mode six specimens are shown in Fig. 6. In Type 1 loading (two concentrated loads), as shown in Figs 6d and 6f, two-local buckling at the bottom of loads were observed, in the ultimate capacity of the SHS steel beams. In the mechanics of failure, one of the criteria for failure of specimens is the criteria of *Von Mises* failure (Maximum Von Mises Stress (MVMS)). When non-strengthened specimen having a deficiency (specimen DBC0) was subjected to the uniform distributed load, the MVMS was observed was observed near the deficiency (see Fig. 3a), but when this specimen was subjected to two concentrated loads, the maximum Von Mises stress was observed near the middle support (see Fig. 3b). In all specimens strengthened with CFRP composite, the MVMS was observed near the deficiency (see Figs 6c-6f). As shown in Figs 6c and 6d, the area of the maximum Von Mises stress in the specimens subjected to two concentrated loads is

Table 4 — Specimen details and analysis results

Designation of steel beam	The ultimate capacity (kN)		% of increase or decrease in the ultimate capacity		% of recovery in the ultimate capacity	
	Concentrated load	Distributed load	Concentrated load	Distributed load	Concentrated load	Distributed load
BC0	166.80	289.30	NA	NA	NA	NA
DBC0	120.00	276.20	-28.06	-4.53	NA	NA
DBC1-500-100	135.11	286.94	-19.00	-0.82	12.59	3.89
DBC1-500-200	151.08	294.89	-9.42	+1.93	25.90	6.77
DBC1-500-400	164.09	302.91	-1.62	+4.70	36.74	9.67
DBC2-500-100	153.25	288.40	-8.12	-0.31	27.71	4.42
DBC2-500-200	158.13	292.15	-5.20	+0.99	31.78	5.77
DBC2-500-400	182.33	329.14	+9.31	+13.77	51.94	19.17
BC1-500-400	181.73	325.63	+8.95	+12.56	NA	NA
BC2-500-400	200.98	339.89	+20.49	+17.49	NA	NA

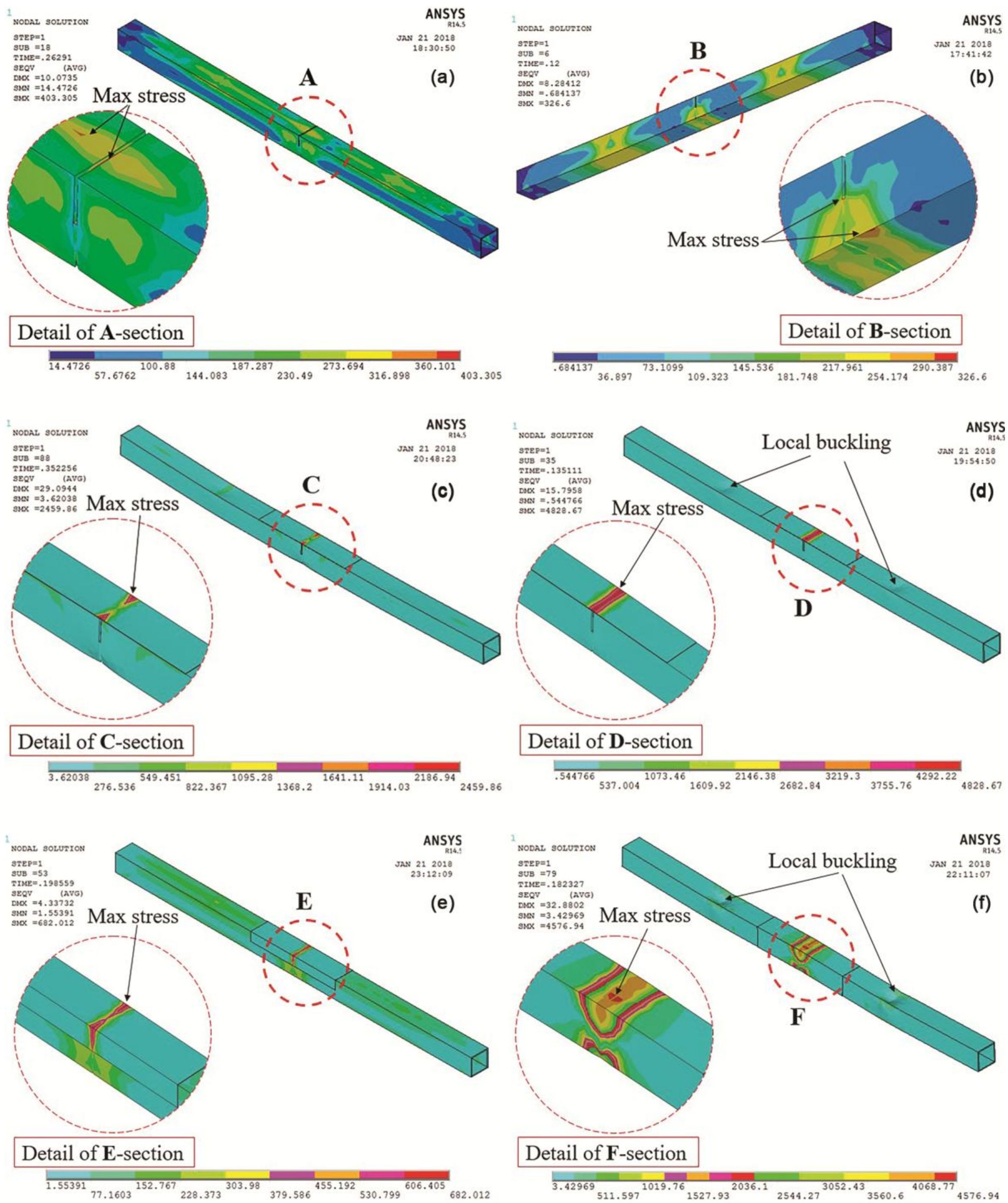

Fig. 6 — Failure modes of specimens (a) Specimen DBC0 under uniform distributed load, (b) Specimen DBC0 under concentrated loads, (c) Specimen DBC1-500-100 under uniform distributed load, (d) Specimen DBC1-500-100 under concentrated loads, (e) Specimen DBC2-500-200 under uniform distributed load and (f) Specimen DBC2-500-400 under concentrated loads.

larger than the specimens subjected to the uniform distributed load.

7 Conclusions

In this study, for all strengthened SHS steel beams, CFRP layers had a constant coverage length but different widths. In these specimens, CFRP sheets were applied with one and two layers and the CFRP sheets were located in the center of the beams (in middle support). Two types of loading for the SHS steel beams were selected, the uniform distributed and concentrated loading. All specimens were separately subjected to the uniform distributed load and the concentrated loads until failure. Based on the obtained results, the failure modes, the ultimate capacity, and the role of CFRP fabrics on recovering the ultimate capacity of the SHS steel beams were discussed. Based on ten analyzed specimens, the following conclusions are drawn:

(i) CFRP composite increases the ultimate capacity of the deficient SHS steel beams. With an increase in the width of CFRP, the ultimate capacity increase.

(ii) The number of CFRP layers has an influence on the ultimate capacity of the deficient SHS steel beams. The effect of the number of CFRP layers in strengthened deficient steel beams subjected to concentrated loads was more observed than in the case when the strengthened deficient steel beams were under the uniform distributed load because the beams subjected to concentrated loads have more deflection than the beams under the uniform distributed load, with the same conditions.

(iii) The results showed that CFRP is a suitable material for recovering the ultimate capacity of the deficient SHS steel beams. The results also show that, when CFRP does not fully cover the defect length, it cannot be very effective in the capacity of the specimens. The increase percent of the ultimate capacity in the SHS steel beams is increased, with increasing the number of CFRP layers.

(iv) In strengthened deficient specimens under the uniform distributed loading, the ultimate capacity is almost recovered by one CFRP layer and 500 mm coverage length.

(v) The maximum ultimate capacity in the strengthened steel beams happened for the specimen BC2-500-400 under the uniform distributed load, and the maximum percentage of recovery in the ultimate capacity happened for the specimen DBC2-500-400.

(vi) When non-strengthened specimens having a deficiency were under the uniform distributed load, the MVMS was observed at the middle supports. In the non-strengthened specimen having a deficiency subjected to two concentrated loads, the MVMS was observed near the deficiency. Also, for the strengthened specimens, the MVMS was observed near the deficiency.

(vii) It is significant to note that the results of this study were obtained based on the FE models, and in the future, it will need more experimental justification.

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