



Behavior of Deficient Steel Members Strengthened Using CFRP Under Combined Compressive Load and Torsional Moment

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ABSTRACT: Strengthening steel structures using carbon fiber reinforced polymer (CFRP) has attracted the attention of many researchers in recent years. Most previous research in this area has carried out on the behavior of the steel members without deficiency in bending, shear, and compression. The deficiency in steel structures may be created due to the errors caused by construction, fatigue cracking, and so on. In addition, steel structures may be located under combined loads in their lifetime. This study explored the effect of CFRP strengthening on the structural behaviors of square hollow sections (SHS) steel members having initial deficiencies under combined compressive load and torsional moment. To the author's knowledge, there is no independent article in this area. In this study, 17 specimens were analyzed. To analyze the specimens, three dimensional (3D) modeling and nonlinear static analysis using ANSYS software were applied. The results indicated that application of CFRP sheets for the strengthening of the deficient hollow steel members under combined compressive load and torsional moment could recover the strength lost due to deficiency, significantly. The maximum recovery percentage of the compressive load and torsional moment capacity of the specimens was 256.00% and 139.96%, respectively.

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1- Introduction

In the past decades, retrofitting and strengthening structures have become one of the serious challenges for structural engineers. Steel structures built in the past decades may be needed to strengthen due to the increase of life loads, repairing due to corrosion or fatigue cracking. Nowadays, strengthening steel structures by carbon fiber reinforced polymer (CFRP) sheets has attracted greater attention. CFRP is preferred to strengthen steel structures due to its high tensile strength, high elastic modulus, low weight, and ability to be applied to any shape of structures. Several studies have been carried out to employ carbon fiber reinforced polymer for flexural strengthening [1-7], shear strengthening [8], compression strengthening [9-20], tensile strengthening [21-26] of steel structures. The results indicated that application of CFRP sheets could increase the ultimate capacity of these structures. Several other studies have been carried out to employ CFRP for repairing and strengthening steel members damaged due to fatigue cracking [27-32]. In these studies, the results showed that application of CFRP composite could recover the strength lost due to fatigue cracking of these members, significantly.

In another study, Keykha [33] presented a numerical study to investigate the behavior of square hollow sections (SHS) steel frames. The SHS steel frames were strengthened using CFRP composite on bottom and/or all four corner sides. The results showed that the coverage length and the number of CFRP layers have a significant effect on increasing the ultimate load capacity of the SHS steel frames. Also, the results showed that the location of CFRP composite had no similar effect on increasing the ultimate load capacity and the mid span deflection of the SHS steel frames. CFRP strengthening significantly increased the ductility capacity of the SHS steel frames. The maximum percent of the increase in the ductility capacity was about 826%. Investigations of Keykha in this study showed that in the SHS steel frames of thin walled under the contracted loads while the CFRP sheet is located at the bottom surface of the SHS steel frames due to the buckling failure occurs at the top flange, the CFRP sheet has no considerable impact on the ultimate load capacity of the SHS steel frames.

Zhou et al. [34] tested a series of the notch damaged steel beams strengthened using a carbon fiber hybrid polymeric-matrix composite. Their results showed that the load capacity of the notched steel beams strengthened with CFRP sheets was increased up to 42.9%. Their results also showed that the load capacities of the notched steel beams strengthened with Carbon-fiber Hybrid-polymeric Matrix Composite (CHMC)

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were increased up to 84.9%

Awaludin and Sari [35] carried out a numerical and experimental investigation on the non-linear behavior of the SHS steel beams with simple boundary conditions. The investigated steel beam in this research had an artificial crack (width 3 mm, depth 25 mm) at mid-span on tension side, and the steel beams externally repaired with CFRP sheet. Their studies showed that the repair of the steel beams having an artificial crack with CFRP sheets is a suitable solution for increasing the ultimate load capacity of these beams. In beam B (the repaired beam using 1000 mm length of CFRP sheet at bottom surface), CFRP sheet was not very effective on the ultimate load capacity due to the artificial crack was not completely covered with CFRP sheet. In beam C (the repaired beam using 1000 mm length of CFRP sheet at bottom surface and both side faces of 25 mm depth), CFRP sheet was very effective on the ultimate load capacity of the SHS steel beam due to the artificial crack was completely covered with CFRP sheet.

Keykha [36, 37] investigated the effect of CFRP strengthening on the behavior of the SHS steel columns and beam-columns. In these studies, the specimens were stocky and slender steel members which were under combined compression and flexural moment. All SHS steel members were investigated in this study were without deficiency. Results showed that the CFRP composite has no similar effect on the behavior of slender and stocky SHS steel members. Results also showed that the Effect of CFRP location has an impact on the axial behavior of the slender steel members.

Abdollahi Chahkand and Zamin Jumaat [38] carried out an experimental and theoretical study on the behavior of CFRP strengthened SHS steel beams in pure torsion. They tested six CFRP strengthened steel specimens under torsion. The tested CFRP strengthened specimens had some different strengthening configurations. The results also showed that using CFRP could improve the plastic and elastic torsional strength of the CFRP strengthened SHS steel beams.

Huang et al. [39] investigated the compressive behavior of damaged circular hollow section steel columns repaired by CFRP or high-strength grout. They tested a total of 22 specimens, including bare steel specimens, CFRP repaired and grout repaired specimens under axial compression loading. Finite element analysis was also performed and analyzed with test results. The results indicate that the behavior of damaged steel columns can be effectively re-habilitated by either CFRP or grout jacketing.

Keykha [40, 41] investigated the behavior of the steel members having initial deficiencies subjected to pure torsional moment. In these studies, the orientations of the deficiencies in the steel members were different. The results indicated that in specimens strengthened using coverage percentage of CFRP sheet less than 100%, when the number of CFRP layers were more than two, CFRP layers were not effective in the torsional capacity.

In another investigation, Keykha [42] strengthened the SHS steel members having initial deficiencies under combined axial compression and lateral loading using CFRP composite. In analyzed deficient specimens, the deficiencies had different orientation. The results indicated that the initial deficiencies in the SHS steel members decrease the ultimate load capacity of these members. When the deficiency was considered in the width direction of steel members, the deficiency had a high

impact on decreasing the ultimate load capacity of the steel members. Therefore, in the steel members with a transverse deficiency, CFRP had a considerable impact on the ultimate load capacity.

From the previous researches, it can be observed that there were investigations done with the use of CFRP composite as a strengthening material for steel members. Also, the behavior of the steel members having initial deficiencies subjected to pure torsional moment or compression load was investigated. It seems that there is a lack of understanding on the behavior of the deficient hollow steel members subject to combined compressive load and torsional moment. Therefore, this article is aimed at developing the knowledge in this area. For this purpose, this study explored the effect of the use of adhesively bonded CFRP flexible sheets on the structural behaviors of the SHS steel members having initial deficiencies under combined compressive load and torsional moment, using numerical investigations. To obtain accurate results, seventeen members were analyzed, one non-strengthened steel member was without deficiency as a control specimen, four non-strengthened steel members with different length and orientation of deficiencies, and twelve strengthened steel members with different length and orientation of deficiencies. The coverage length and the number of layers of CFRP composite, length, width, and orientation of deficiencies were implemented to examine the ultimate capacity of the deficient hollow steel members under combined compressive load and torsional moment.

2- Materials properties

2- 1- SHS steel

The steel square hollow section having a dimension of 60 mm × 60 mm was used in this research. The length and thickness of the steel square hollow section were 1600 mm and 3 mm, respectively. The yield strength mean value was 240 N/mm² and the ultimate tensile strength mean value was 375 N/mm². These values were retrieved from studies conducted by Keykha et al. [18, 20]. The dimensions and material properties of the SHS steel used in this study are also given in Table 1.

Table 1. Sizes and properties of the SHS steel

Dimensions (h × b × t) (mm)	Length L (mm)	Modulus of Elasticity (N/mm ²) Mean value	Stress (N/mm ²)	
			Yielding (F _y)	Ultimate (F _u)
60 × 60 × 3	1600	200000	240	375

2- 2- CFRP composite

The consumed CFRP in the present research is SikaWrap-200C. The SikaWrap-200C is a unidirectional carbon fiber. This CFRP is a carbon fiber reinforced polymer having the modulus of elasticity of 230000 kN/mm² and the tensile strength 3900 N/mm². The thickness of this CFRP sheet is 0.111 mm. These values were retrieved from studies

conducted by Abdollahi Chahkand and Zamin Jumaat [38]. The properties of CFRP used in this research, SikaWrap-200C, is shown in Table 2.

2- 3- Adhesive

The adhesive used in this study is suggested by the supplier of CFRP product. The adhesive is commonly used for the SikaWrap-200C, called Sikadur-330. The Sikadur-330 is a two-part adhesive, a hardener and a resin. In this type of adhesive, the mixing ratio of the hardener and resin is 1:4. The Sikadur-330 also has a modulus of elasticity about 4500 N/mm² and a tensile strength about 30 N/mm². These values were retrieved from studies conducted by Keykha et al. [33, 43]. The properties of the epoxy used in this study are shown in Table 3.

3- Finite element analysis and modeling specimens

3- 1- Model description

Non-linear finite element models were prepared using ANSYS to investigate the structural behavior of the SHS steel members strengthened by CFRP sheets in length. All models were prepared as steel members of fixed-free ends. The longitudinal deficiencies were in two types. Type 1 had a length, width, and depth of 100, 6 and 3 mm, respectively. Type 2 had a length, width, and depth of 100, 12 and 3 mm, respectively. Also, the transverse deficiencies were in two types. Type 1 had a length, width, and depth of 50, 6 and 3 mm, respectively. Type 2 had a length, width, and depth of 50, 12 and 3 mm, respectively. Figure 1 shows the boundary conditions, combined load, and the strengthening scenario adopted for the deficient SHS steel members in this study. Because of the many variables in modeling specimens, the investigation of the fiber orientation was not considered in this study. Therefore, the fiber orientation was considered in the direction of the length of the strengthened specimen (longitudinal orientation).

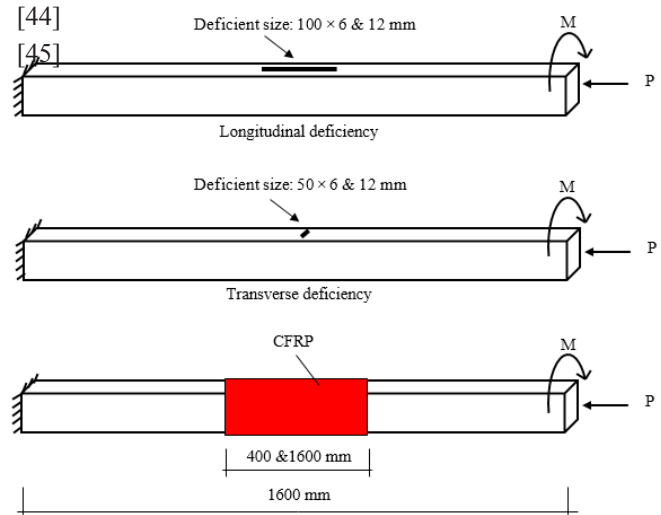


Figure 1. A schematic view (not to scale) of strengthened and non-strengthened SHS steel members having deficiency

Figure 2, for example, shows the three dimensional (3D) finite element model of the prepared specimens using ANSYS. Due to the hollow cross section of the specimens, P-load (axial load) was applied as axial compression on cross section at the free end. To apply torsional moment (M), four concentrated loads were evenly applied on four sides of the specimens at the free end. The concentrated loads were applied so that to organize a torsional moment at the free end of the specimens (see Figure 2). At the beginning, axial pressure value and each one of four concentrated loads applied to organize torsional moment were selected 500 N/mm² and 40000 N, respectively. The number of load sub-steps was defined 25 in ANSYS. All loads gradually increased from zero until that time the SHS steel members achieved their ultimate capacity.

Table 2. Properties of CFRP composite

CFRP Sheet: SikaWrap-200C				
Fabric design 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

Table 3. Properties of adhesive

Adhesive: Sikadur-330			
Tensile strength (N/mm ²)	Modulus of Elasticity (N/mm ²)		Elongation at break (%)
	Tensile	Flexural	
30	4500	3800	0.9

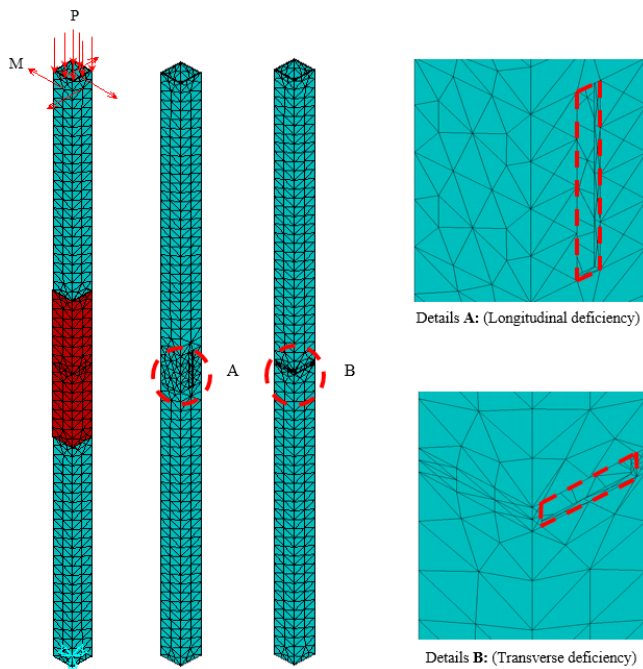


Figure 2. A view of finite element modeling of the strengthened and non-strengthened specimens having a deficiency in ANSYS

3- 2- Finite element analysis

To simulate the SHS steel members, the full three dimensional modeling and non-linear static analysis methods using ANSYS were applied. The SHS steel members, the CFRP sheets, and the adhesive were simulated using the 3D solid triangle elements (ten-nodes 187). Non-linear static analysis was carried out to achieve the steel members to their failures. In this case, the load was incrementally applied until the plastic strain in an element reached to its ultimate value (element is killed). Linear and non-linear properties of materials were defined. The material properties of the CFRP sheet were defined as linear and orthotropic because the CFRP materials have linear properties and they were unidirectional. Also, the adhesive was defined as linear material because the used adhesive has linear properties. The SHS steel members were defined as the materials having nonlinear properties. For meshing, the map meshing was used. Therefore, the solid element of 187 with the mesh size of 25 was used for analysis of the specimens. In previous research, this element and meshing were used by Keykha [33, 43], showing a good accurateness between the numerical and experimental results.

3- 3- Validity of software results

It is necessary to validate the calculation of software. In this study, the software results were validated and calibrated by the experimental results of Abdollahi Chahkand and Zamin Jumaat [38] and Keykha et al. [18, 20]. For the analysis of the specimens, as mentioned in the previous section, the solid element of 187 with the mesh size of 25 was selected. From the studies conducted by Abdollahi Chahkand and Zamin Jumaat [38] and Keykha et al. [18, 20], the ultimate capacity of the Type 1 and specimen C2-40, obtained from experimental, theoretical, and numerical results, is also displayed in Table 4. As mentioned in the

Introduction section, Abdollahi Chahkand and Zamin Jumaat [38] carried out an experimental and theoretical study on the behavior of the SHS beams strengthened using CFRP sheets in pure torsion moment. Figure 3 shows the ultimate load-displacement curves of specimen C2-40 in the laboratory, theoretical, and numerical analysis. As shown in Table 4 and Figure 3, a good accuracy is seen between the experimental and numerical results.

Table 4. Comparison of the ultimate capacity of specimens in laboratory, theoretical, and numerical analysis

Specimen label	Experimental capacity	Theoretical capacity	Numerical capacity	Error (%)
Type 1 [42]	2.782 (kN . m)	2.720 (kN . m)	2.784 (kN . m)	0.07
C2-40 [19, 21]	36.100 (kN)	36.150 (kN)	36.779 (kN)	1.88

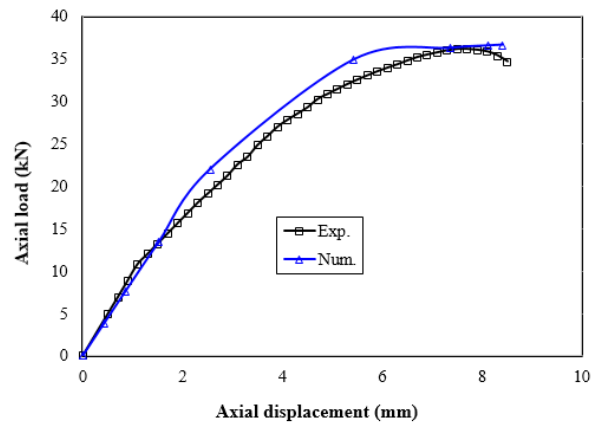


Figure 3. Axial load-axial displacement curve of specimen C2-40

3- 4- Specimens labeling

The steel members included one control specimen, four non-strengthened specimens with different lengths, widths, and orientation of deficiencies, and twelve specimens with different lengths and orientation of deficiencies strengthened with two and four layers of CFRP applied on all four sides of the steel members. The control specimen was analyzed without strengthening to determine the increase percent and recovery in the ultimate capacity of the steel members. To easily identify the specimen, the steel members were designated PM0, PM0-T6, PM0-T12, PM0-L6, PM0-L12, PM2-25-T6, PM4-25-T6, PM2-100-T6, PM2-25-T12, PM4-25-T12, PM2-100-T12, PM2-25-L6, PM4-25-L6, PM2-100-L6, PM2-25-L12, PM4-25-L12, and PM2-100-L12. The first part of the label (PM) stands for the steel members under combined compressive load (P) and torsional moment (M). The second part of the label (0, 2 and 4) stands for the number of CFRP layers. The third part of the label (25, 100) stands for the percent of the CFRP coverage. The fourth part of the label (T, L) stands for transverse (T) and longitudinal (L) deficiency, respectively. The fifth part of the label (6, 12) stands for the width (6, 12 mm) of deficiencies.

For example, the designation PM2-100-T12 indicates that it is the steel member with a transverse deficiency strengthened by two layers of CFRP fully wrapped around it. In this specimen, the transverse deficient width is 12 mm. The designation PM2-100-L6 indicates that it is the steel member with a longitudinal deficiency strengthened by two layers of CFRP fully wrapped around it. In this specimen, the longitudinal deficient width is 6 mm. The designation PM4-25-L6 indicates that it is a steel member strengthened by four layers and 25% of the CFRP coverage wrapped around it with a longitudinal deficiency, its longitudinal deficient width is 6 mm. The designation PM0-T6 specifies that it is a steel member non-strengthened with a transverse deficiency, its transverse deficient width is 6 mm. Similarly, the specimen PM0-L12 specifies that it is a steel member non-strengthened with a longitudinal deficiency, that the longitudinal deficient width is 12 mm. The control steel member is designated as PM0.

NOTE: In this research, the percent of CFRP coverage is defined as the ratio of CFRP length to the SHS steel member length multiplied by 100.

4- Results and discussion

4- 1- The ultimate capacity results

Table 5 shows the results of numerical analysis of the specimens without strengthening or with two or four layers of strengthening CFRP sheets. The coverage length of Type 1 CFRP is 1600 mm (100% of the length of steel beam) and another Type (Type 2) is 400 mm (25% of the length of steel beam). The center position of CFRP sheet is in the center of steel beam. In Table 5, the ultimate capacity and the recovery percent in the ultimate capacity of specimens are shown. To calculate the ultimate capacity and percentage of increase or decrease in the ultimate capacity of specimens, the ultimate capacity of all specimens was compared with the ultimate capacity of the reference specimen (PM0), while to calculate the recovery percent of the ultimate capacity of specimens, the ultimate capacity of the strengthened specimens was compared with the ultimate capacity of the deficient specimen in its category. For example, percentage of recovery in the ultimate capacity of specimen PM2-25-T6 is compared with specimen PM0-T6. As shown in Table 5, in this specimen (PM2-25-T6), the percentage of recovery in the ultimate compression capacity (PU) and the ultimate torsional capacity (MT) is 39.81% and 39.78%, respectively. Also for example, the percentage of increase in the ultimate capacity of specimen PM2-100-L12 is compared with specimen PM0. In this specimen (PM2-100-L12), the percentage of increase in the ultimate compression capacity and the ultimate torsional capacity is 10.60% and 71.46%, respectively. The results showed, when the deficiency was located in the direction of the length (the longitudinal deficiency) and the width (the transverse deficiency) of steel member, the deficiency had an impact on the decrease in the ultimate capacity of the steel members. In these specimens, as shown in Table 5, CFRP had considerable impact on the ultimate capacity. The results also showed, when the deficiency was located in the direction of the width of steel member, the deficiency had high impact on the decrease in the ultimate capacity of the steel members. Therefore, in the steel member with a transverse deficiency, CFRP had a considerable impact on the ultimate capacity of the specimen. In strengthened specimens, when

the composite coverage percentage is less than 100% and the number of CFRP layers is 4, CFRP is not effective in the ultimate capacity of the strengthened specimens. The Lack of increase in the ultimate capacity was due to the fact that these specimens had recovered with two CFRP layers. For the strengthened specimens, when the CFRP coverage is full, CFRP is more effective in the ultimate capacity. In this study, the maximum percentage of recovery in the ultimate compression capacity and torsional capacity happened for the specimen PM2-100-T12 and was 256.00% and 139.96%, respectively (see Table 5). The maximum percentage of increase in the ultimate compression capacity and the ultimate torsional capacity happened for the specimen PM2-100-L6 and was 10.85% and 71.86%, respectively.

4- 2- Comparison of failure modes

All specimens were subjected to combined compressive load and torsional moment until failure. As mentioned in section 3 due to the hollow cross section of the specimens, P-load was applied as axial compression on cross section at the free end. To apply torsional moment, four concentrated loads were evenly applied on four sides of the specimens at the free end. The concentrated loads were applied so that to organize a torsional moment at the free end of the specimens (Figure 2). In all specimens with longitudinal deficiency that were strengthened using two full layers of CFRP sheets, the maximum Von Mises stress was observed the near of free end these specimens (as shown in Figure 4f). In the rest of the specimens, the position of maximum Von Mises stress was located in place of the deficiency (as shown in Figures 4a-e). In the specimens strengthened by adhesively bonded CFRP sheets subjected to pure torsional moment or compression load, the failure modes were in terms of CFRP rupture [19, 38]. In this study the specimens were also strengthened by adhesively bonded CFRP sheets, so the failure modes of the strengthened specimens were in terms of CFRP rupture

5- Conclusions

In this study, the CFRP sheets with two types of length (400 and 1600 mm) and number of layers (two and four layers) were wrapped around the SHS steel members having initial longitudinal or transverse deficiencies. The ultimate capacity, the percentage of increase in the ultimate capacity, the percentage of the recovery in the ultimate capacity, and the failure modes of the SHS steel members having initial deficiencies were discussed. Based on seventeen analyzed specimens, one non-strengthened specimen without deficiency as a control specimen, four non-strengthened specimens with different lengths, widths, and orientations of deficiencies, and twelve specimens with different lengths and orientations of deficiencies strengthened with two types of length and number of CFRP layer were analyzed, the following conclusions were drawn:

- The initial deficiencies decrease the ultimate carrying capacity of non-strengthened SHS steel members subjected to combined compressive load and torsional moment. When the deficiency is located in the width direction of steel member (the transverse deficiency), the deficiency had high impact on the decrease in the ultimate capacity of the steel member (see Table 5). The maximum percentage of decrease in the ultimate compression capacity and torsional capacity happened

for the specimen PM0-T12 and was 70.59% and 37.12%, respectively.

- The width of deficiency in the SHS steel members with the transverse deficiency is more effective in decreasing the ultimate capacity of the steel members than in the SHS steel members with the longitudinal deficiency.
- In strengthened specimens using CFRP sheets, when the deficiency was located in the width direction of steel members, the CFRP sheets are more effective in increasing and recovering the ultimate capacity of the steel members than in the case when the deficiency was located in the direction of the length of steel members.
- When the CFRP composite coverage percentage is less than 100%, the number of CFRP layers exceeding four is not effective in the ultimate capacity of the steel members. The Lack of increase in the ultimate capacity was due to the fact that the strengthened specimens with the CFRP composite coverage percentage less than 100% had recovered with two CFRP layers.
- In all specimens with the transverse deficiency and all specimens strengthened using CFRP layers with the coverage percentage of CFRP composite less than 100%, the position of maximum Von Mises stress located in the place of the deficiency. In the specimen with the longitudinal deficiency, the maximum Von Mises stress was observed away from deficiencies (near the free end).
- The maximum percentage of increase in the ultimate compression capacity and the torsional capacity happened for the specimen PM2-100-L6 and was 10.85% and 71.86%, respectively. Also, the maximum percentage of recovery in the ultimate compression capacity and torsional capacity happened for the specimen PM2-100-T12 and was 256.00% and 139.96%, respectively.
- By comprising of specimens with the longitudinal deficiency strengthened using CFRP incomplete layers (the composite coverage percentage less than 100%) with the specimens with the longitudinal deficiency strengthened using CFRP full layers, it can be concluded that when the coverage percentage of CFRP composite is 100%, the CFRP composite changes the failure modes of the strengthened specimens from the location of deficiencies to a location near the specimen free end.

Table 5. Analysis results of specimens

Designation of specimen	No. of layers CFRP	CFRP coverage (%)	PU: Compression capacity (kN)	M _T : Torsional capacity (kN-m)	% of recovery in compression capacity	% of recovery in torsional capacity
PM0	0	0	125.339	1.759	NA	NA
PM0-T6	0	0	89.556	1.257	NA	NA
PM0-T12	0	0	36.862	1.106	NA	NA
PM0-L6	0	0	99.026	1.390	NA	NA
PM0-L12	0	0	93.968	1.319	NA	NA
PM2-25-T6	2	25	125.212	1.757	39.81	39.78
PM4-25-T6	4	25	126.195	1.771	40.91	40.89
PM2-100-T6	2	100	128.429	2.794	43.41	122.28
PM2-25-T12	2	25	124.857	1.752	238.71	58.41
PM4-25-T12	4	25	126.102	1.770	242.09	60.04
PM2-100-T12	2	100	131.229	2.654	256.00	139.96
PM2-25-L6	2	25	125.288	1.758	26.52	26.47
PM4-25-L6	4	25	126.195	1.771	27.44	27.41
PM2-100-L6	2	100	138.938	3.023	40.30	117.48
PM2-25-L12	2	25	124.512	1.748	32.50	32.52
PM4-25-L12	4	25	126.195	1.771	34.30	34.27
PM2-100-L12	2	100	138.623	3.016	47.52	128.66

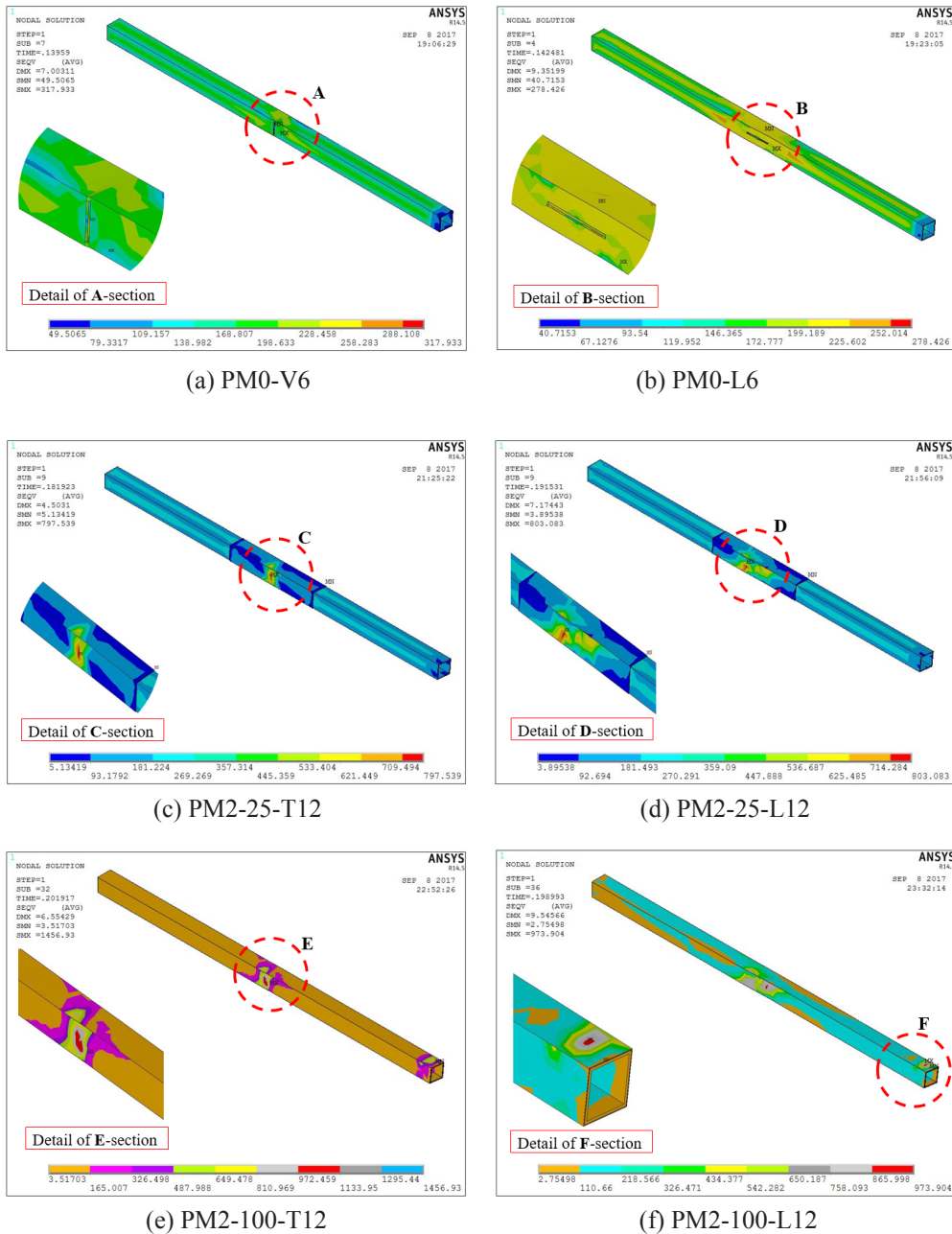


Figure 4. Comparison of the Von Mises stress in the specimens

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