Investigation of the Effect of CFRP Strengthening on the Behavior of Deficient Steel Members under Combined Lateral and Torsional Loading

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ABSTRACT

In recent years, strengthening of steel square hollow sections (SHSs) using carbon fiber-reinforced polymer (CFRP) has attracted the attention of many researchers. Most previous research in this field has been conducted on the behavior of steel members without deficiency in bending, shear and compression, strengthened using CFRP composites. Few studies have been conducted on steel members with deficiency strengthened using CFRP and to the author's knowledge, no research on the behavior of CFRP-strengthened deficient hollow steel members subjected to combined lateral and torsional loading has been presented. The deficiency in steel members may be created due to the errors caused by construction, fatigue cracking, drilling after building for passing of building installations, corrosion, earthquake damage,… and so on. However, this study explored the effect of the use of adhesively bonded CFRP flexible sheets on the structural behavior of SHS steel members having initial deficiencies subjected to combined lateral and torsional loading, using numerical investigation. To study the effects of CFRP strengthening method on recovering the strength lost in the deficient members, seventeen specimens, twelve of which were strengthened using CFRP sheets, were analyzed. To analyze the steel members, three-dimensional (3D) modeling and non-linear static analysis using ANSYS software were applied. The results indicated that the application of CFRP sheets for strengthening of deficient hollow steel members under combined lateral and torsional loading could significantly recover the strength lost due to deficiency.

KEYWORDS: Hollow steel members, Strengthening, CFRP, Numerical investigation, Torsional load, Lateral load.

INTRODUCTION

Over the past decades, retrofitting and strengthening of existing steel structures have become among the serious challenges for structural engineers. Steel structures built in the past often need strengthening due to increased life loads or repair due to corrosion or fatigue cracking. Nowadays, strengthening of steel structures with CFRP sheets has attracted greater attention. CFRP is preferred to strengthen steel hollow sections due to its high tensile strength, high elastic modulus, low weight and ability to be applied to any shape of structure. Several studies have been carried out to employ carbon fiber-reinforced polymer for strengthened steel structures such as flexural strengthening (Idris and Ozbakkaloglu, 2014; Sundarraja and Prabhu, 2013; Teng *et al*., 2015; Al Zand *et al*., 2015; Kabir *et al*., 2016; Haedir *et al*. 2009; Elchalakani, 2014; Andre *et al*., 2012), shear strengthening (Sebastian, 2005), pressure strengthening (Ozbakkaloglu and Xie, 2015; Devi and Amanat, 2015;

Received on 1/10/2017.
Accepted for Publication on 15/7/2018.

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Kumar and Senthil, 2016a; Kalavagunta, 2014; Alam and Fawzia, 2015; Fanggi and Ozbakkaloglu, 2015; Park *et al*., 2013; Ritchie *et al*., 2015; Kumar and Senthil, 2016b; Keykha *et al*., 2015, Keykha *et al*., 2016a, b; Keykha, 2017b), torsion strengthening (Abdollahi Chakand and Zamin Jumaat, 2013; Keykha, 2017c), tensile strengthening (Al-Mosawe *et al*., 2016; Al-Shawaf and Zhao, 2013; Al-Zubaidy *et al*., 2013; Bocciarelli et al., 2009; Colombi and Poggi, 2006; Dawood and Rizkalla, 2010; Sweedan et al., 2013; Teng *et al*., 2012), repairing structures and strengthening structure members damaged due to fatigue (Colombi *et al*., 2014; Ahn *et al*., 2013; Ghaemdoust *et al*., 2016; Ghafoori *et al*., 2012; Jiao *et al*., 2012; Kim and Harries, 2011; Nozaka *et al*., 2005; Zhao and Zhang, 2007).

In another study, Zhou *et al*. (2013) tested a series of notch damaged steel beams strengthened using a carbon fiber hybrid polymeric-matrix composite. Their results showed that the load capacities of the notched steel beams strengthened using CFRP sheets were increased up to 42.9%. Their results also showed that the load capacities of the notched steel beams strengthened using carbon-fiber hybrid-polymeric matrix composite (CHMC) were increased up to 84.9%.

In a numerical study, Keykha (2017e) investigated the effect of CFRP location on flexural and axial behaviors of SHS steel columns. The main purpose of this study was to obtain the ultimate compressive and compressive-flexural load (interaction loads) of SHS steel columns strengthened using CFRP in different locations. Forty three steel columns, which were strengthened using CFRP, were analyzed, using nonlinear static analysis under compressive axial load and flexural moment interaction. The results showed that the location, the coverage percent and the number of layers of CFRP are effective on the ultimate load of SHS steel columns under combined axial compression load and flexural moment. The results also showed that moving the location of CFRP with a percentage of defined coverage can have different effects on the ultimate compression load of SHS steel columns.

Idris and Ozbakkaloglu (2016) investigated the seismic behavior of square FRP–concrete–steel columns under combined axial compression and reversed-cyclic lateral loading, using an experimental study. In this study, square double-skin tubular columns (DSTCs) exhibited a ductile behavior under combined axial compression and reversed-cyclic lateral loading. The important influence of the axial load level on the column behavior was evident with an increase in the load level leading to a significant decrease in the lateral deformation capacity of DSTCs. In the DSTC with a larger inner steel tube, the lateral displacement capacity was lower than in the DSTC with a smaller inner steel tube. The results also indicated that the axial load level, inner steel tube size and presence of a concrete filling inside the inner steel tube have an effect on the plastic hinge lengths of the DSTCs. The results also indicated that the dimensions of the inner steel tube have an effect on the plastic hinge length through their influence on buckling behavior of the tube. The results of this study showed that the provision of a concrete filling inside the inner steel tube can significantly increase the progression and length of the plastic hinge region.

In a similar study, Ozbakkaloglu and Idris (2014) investigated the seismic behavior of FRP concrete–steel DSTCs, using an experimental study. They tested DSTCs that were made using high-strength concrete subjected to constant axial compression and reversed-cyclic lateral loading. The results indicated that the DSTCs made are capable of developing very high inelastic deformation capacities subjected to simulated seismic loading. The results also indicated that the presence of a concrete filling inside the inner steel tube significantly and positively affects the seismic behavior of the DSTCs. In this study, the results indicated that the FRP-tube material has an effect on the lateral displacement capacity of the DSTCs with the specimens confined by FRP tubes manufactured using fibers with higher ultimate tensile strains.

In another study, Keykha (2017d) investigated numerically the behavior of SHS steel frames. The SHS steel frames were strengthened using CFRP composite on the bottom and/or all four corner sides. The results showed that the coverage length and the number of layers of CFRP composite have a significant effect on increasing the ultimate load of the SHS steel frames. Also, the results showed that the location of CFRP composite has no similar effect on increasing the ultimate load and the amount of mid-span deflection of the SHS steel frames. CFRP strengthening significantly increased the ductility capacity of the SHS steel frames. The maximum percentage of increase in the ductility capacity was about 826%. When the CFRP sheet was located at the bottom face of the SHS steel frames, due to buckling failure that occurred at the top flange, the CFRP sheet has no considerable impact on the ultimate load capacity of the SHS steel frames.

Ghaemdoust *et al.* (2016) applied CFRP sheets for the strengthening of SHS steel compression members with initial deficiency to gain load-bearing capacity. They carried out two schemes of strengthening and unidirectional CFRP orientation in both the longitudinal and transverse directions. Their results showed that using CFRP sheets increases ultimate load-bearing capacity up to 55.49%. They observed that strengthening using CFRP sheets under compression loads can rise the ductility of the strengthened SHS steel columns. They also observed that using a larger number of CFRP layers delays local buckling.

In another investigation, Keykha (2017a) strengthened SHS steel beam-columns having initial deficiencies under combined axial compression and lateral loading using a CFRP composite. When analyzing deficient specimens, deficiencies had different orientations. The results indicated that the initial deficiencies in the SHS steel beam-columns decrease the ultimate load-carrying capacity of these steel members. When the deficiencies were considered in the direction of the width of these steel members, the deficiency had a high impact on the ultimate load capacity of those members. Therefore, in the steel beam-columns with a transverse deficiency, CFRP had a considerable impact on the ultimate load capacity of these beam-columns.

Abdollahi Chahkand and Zamin Jumaat (2013) carried out an experimental and theoretical study on the behavior of CFRP-strengthened SHS beams in pure torsion. They tested six CFRP-strengthened steel specimens under torsion. The tested CFRP-strengthened specimens had some different strengthening configurations. The research results of Abdollahi Chahkand and Zamin Jumaat (2013) showed that using CFRP could improve the plastic and elastic torsional strengths of CFRP-strengthened SHS steel beams.

Keykha (2017c) analyzed ten specimens; one non-strengthened specimen without deficiency as control column, three non-strengthened and six strengthened specimens with different orientations in deficiencies. The number of layers of CFRP composite and the orientation deficiencies were implemented to examine the torsional capacity of the deficient SHS steel members subject to torsional load. When the deficiency was located in the direction of the 45-degree angle, the deficiency had a high decreasing impact on the torsional capacity of the steel members. The maximum percentage of increase in the torsional capacity of the SHS steel members having initial deficiencies was 44.86%.

From past research, it can be observed that there were investigations carried out with the use of CFRP composite as a strengthening material for steel members. The deficiency in steel members may be created due to errors caused by construction, fatigue cracking, drilling after building for passing of building installations, corrosion, earthquake damage,… and so on. It seems that there is a lack of understanding of the behavior of deficient hollow steel members subject to lateral and torsional loading. 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 SHS steel members having initial deficiencies under lateral and torsional loading, using numerical investigations. In order to obtain accurate results, seventeen beams were analyzed; one non-strengthened beam without deficiency as a control, four non-strengthened beams with different lengths and orientations of deficiencies and twelve strengthened beams with different lengths and orientations of deficiencies. The coverage length and the number of layers of CFRP composite, as well as length, width and orientation of deficiencies were implemented to examine the lateral and torsional load capacity of the deficient hollow steel members under lateral and torsional loading.

MATERIAL PROPERTIES

SHS Steel

A steel square hollow section having dimensions of 60×60 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 is 240 N/mm^2 and the ultimate tensile strength mean value is 375 N/mm^2. These values were retrieved from studies conducted by Keykha *et al*. (2015).

CFRP Composite

The CFRP consumed in the present research is SikaWrap-230C. The SikaWrap-230C is a unidirectional carbon fiber. This CFRP is a carbon fiber-reinforced polymer having a modulus of elasticity of 238 kN/mm^2 and a tensile strength of 4300 N/mm^2. The thickness of this CFRP sheet is 0.131 mm. These values were retrieved from studies conducted by Keykha *et al*. (2015, 2016a).

Adhesive

The adhesive used in this study is suggested by the supplier of CFRP product. The adhesive is commonly used for SikaWrap-230C and is called Sikadur-330. 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. Sikadur-330 has a modulus of elasticity of about 4500 N/mm^2 and a tensile strength of about 30 N/mm^2.

MODELING SPECIMENS

Model Description

Non-linear finite element models were prepared using ANSYS to investigate the structural behavior of the SHS steel members strengthened using CFRP sheets in length. All models were prepared as steel members of fixed-pinned ends. The dimensions of longitudinal deficiencies were 100×6×3 mm and 100×12×3 mm (two types). Also, the dimensions of transverse deficiencies were 50×6×3 mm and 50×12×3 mm (two types). Figure 1 shows the boundary conditions, combined loading and the strengthening scenario adopted of the deficient SHS steel members in this study.

NOTE: In pinned support as shown in Figure 1, axial transmission and rotation in all directions are released.

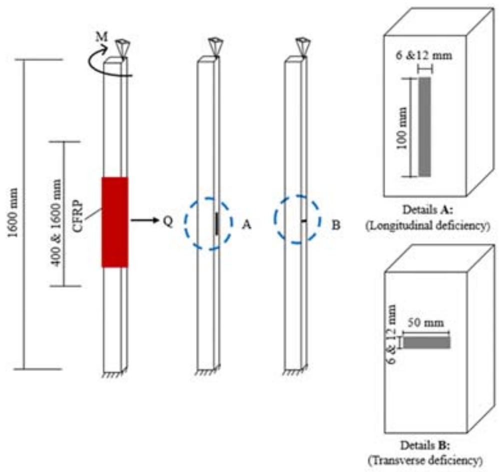


Figure (1): A schematic view (not to scale) of strengthened and non-strengthened SHS steel members having deficiency

Figure 2, for example, shows the 3D finite element model of the prepared specimens using ANSYS. Due to the hollow cross-section of the specimens, loads (T-loads) were evenly applied on four sides of the specimen at the pinned end (as shown in Figure 2). T-loads were applied in order to organize a torsional moment (**M**) at the pinned end of the specimen. The concentrated lateral load (concentrated load of **Q**) was applied in the mid-span of the specimen, as shown in Figures 1 and 2. These loads (loads of **Q** and **M**) were applied on the specimens as simultaneous loads and were gradually increased until the SHS steel members reached their ultimate capacity.

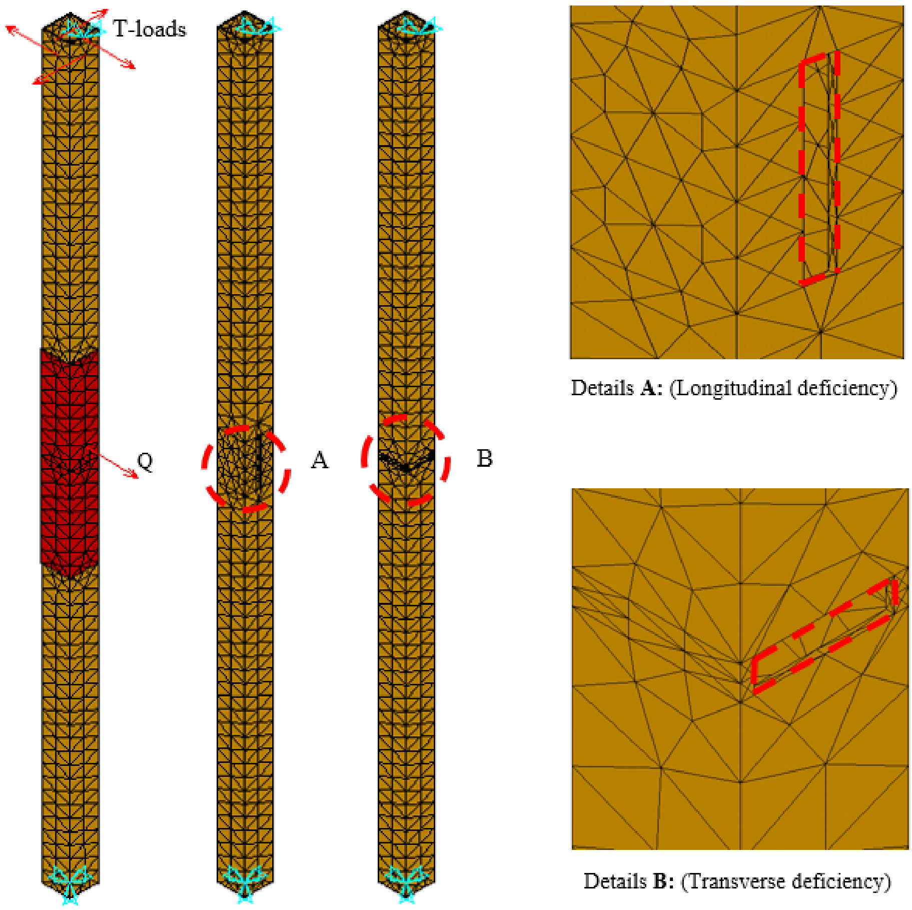


Figure (2): A view of finite element modeling of strengthened and non-strengthened specimens having deficiency in ANSYS

Finite Element Analysis

To simulate the SHS steel members, full three-dimensional modeling and non-linear static analysis method using ANSYS were applied. The SHS steel members, CFRP sheets and adhesive were simulated using the 3D solid triangle elements (ten-node 187). Non-linear static analysis was carried out to achieve failure. In this case, the load was incrementally applied until the plastic strain in an element reached its ultimate value (element is killed). Linear and non-linear properties of materials were defined. The CFRP sheets material properties were defined as linear and orthotropic because CFRP materials have linear properties and they were unidirectional. Also, the adhesive was defined as linear because the adhesive used has linear properties (Keykha, 2017b, d). The SHS steel members were defined as materials having non-linear properties. For meshing, map meshing was used. Therefore, the solid element of 187 with a mesh size of 25 was used for the analysis of the specimens. In previous research, this element and meshing were used by Keykha (2017b, d), showing good agreement between the numerical and experimental results.

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 (2013) and Keykha *et al*. (2015, 2016a). To analyze the specimens, as mentioned in the previous section, the solid element of 187 with a mesh size of 25 was selected (Keykha, 2017 b and d). In addition, this element and mesh size were used for the SHS steel beam-columns under loading scenario 1 by Keykha (2017a) in a previous research. Also, from the studies conducted by Keykha *et al*. (2015, 2016a) and Abdollahi Chahkand and Zamin Jumaat (2013), the ultimate load capacity of the type 1 specimens and C0 obtained from experimental, theoretical and numerical results is displayed in Table 1, to validate the calculation of the software. As shown in Table 1, a good agreement in accuracy is seen between the experimental and numerical results.

Table 1. Ultimate load capacity of type 1 specimen (Abdollahi Chahkand and Zamin Jumaat, 2013) and C0 (Keykha *et al*., 2015, 2016a)

Specimen label	Experimental capacity	Theoretical capacity	Numerical capacity	Error (%)
Type 1	2.782 (kN . m)	2.720 (kN . m)	2.784 (kN . m)	0.07
C0	31.80 (kN)	32.86 (kN)	32.060 (kN)	0.82

Specimen Labeling

The steel members included one 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 and four layers of CFRP applied on all four sides of the steel members. The control specimen was analyzed without strengthening to determine the rate of lateral and torsional load capacity increase in strengthened steel members. To easily identify the specimens, the steel members were designated as QM0, QM0-T6, QM0-T12, QM0-L6, QM0-L12, QM2-25-T6, QM4-25-T6, QM2-100-T6, QM2-25-T12, QM4-25-T12, QM2-100-T12, QM2-25-L6, QM4-25-L6, QM2-100-L6, QM2-25-L12, QM4-25-L12 and QM2-100-L12. For example, the designation QM2-100-T12 indicates that it is a steel member with transverse deficiency strengthened by two layers of CFRP fully wrapped around it. In this specimen, the transverse deficiency width is 12 mm. The designation QM2-100-L6 indicates that it is a steel member with longitudinal deficiency strengthened by two layers of CFRP fully wrapped around it. In this specimen, the longitudinal deficiency width is 6 mm. The designation QM4-25-L6 indicates that it is a steel member strengthened by four layers with a CFRP coverage of 25% wrapped around it and with longitudinal deficiency, where the longitudinal deficiency width is 6 mm. The designation QM0-T6 specifies that it is a non-strengthened steel member with transverse deficiency, where the transverse deficiency width is 6 mm. Similarly, the designation QM0-L12 specifies that it is a non-strengthened steel member with longitudinal deficiency, where the longitudinal deficiency width is 12 mm. The control steel member is designated as QM0.

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.

RESULTS AND DISCUSSION

Lateral and Torsional Load Capacity Results

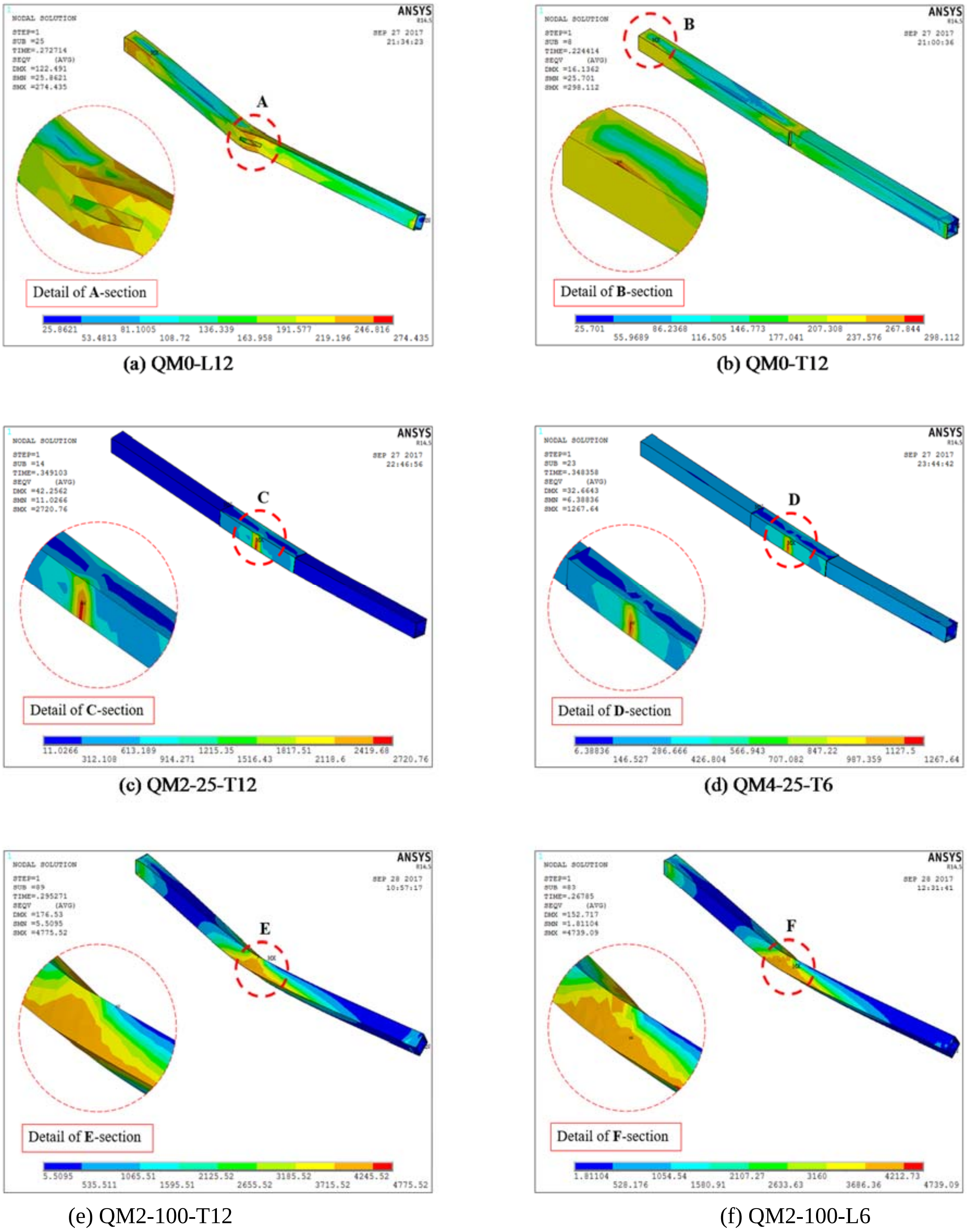
Table 2 shows the results of numerical analysis of the specimens without strengthening or with two or four layers of strengthening. The coverage length of type 1 CFRP is 400 mm (25% of the length of the steel member) and that of (type 2) is 1600 mm (100% of the length of the steel member). The center position of CFRP sheet is in the center of the steel member. In Table 2, lateral and torsional load capacity (**Q_U** and **M_U**, respectively), percentage of increase or decrease in the lateral and torsional load capacity and percentage of recovery in lateral and torsional load capacity of specimens are shown. To calculate lateral and torsional load capacity and percentage of increase or the decrease in lateral and torsional load capacity of the specimens, lateral and torsional load capacity of all specimens was compared with lateral and torsional load capacity of reference specimen (QM0), while for the calculation percentage of recovery in lateral and torsional load capacity of the specimens, lateral and torsional load capacity of strengthened specimens was compared with lateral and torsional load capacity of deficient specimen in its category. For example, the percentage of recovery in the lateral and torsional load capacity of specimen QM2-25-T6 is compared with that of specimen QM0-T6. As shown in Table 2, in this specimen (QM2-25-T6), the percentage of recovery in lateral and torsional load capacity is 59.04% and 59.00%, respectively. The results showed that deficiencies had a considerable impact on the decrease in lateral and torsional load capacity of the steel members. When the deficiency was located in the direction of the width of the steel member (transverse deficiency), the deficiency had more impact on the decrease in the lateral and torsional load capacity of the steel member than in the case when the deficiency was located in the direction of the length of the steel member (longitudinal deficiency). 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 lateral and torsional load capacity of the strengthened specimens. The lack of increase in lateral and torsional load capacity was due to the fact that these specimens had recovered with two CFRP layers. In the strengthened specimens, when the CFRP coverage is full, CFRP is more effective in the lateral and torsional load capacity than in the case when the composite coverage percentage is less than 100%. In this study, the maximum percentage of increase in lateral and torsional load capacity happened for specimen QM2-100-L6 with 136.85% and 83.62%, respectively. Also, the maximum percentage of increase in recovery of lateral and torsional load capacity happened for specimen QM2-100-T12 with 199.26% and 127.97%, respectively.

Table 2. Analysis results of specimens

Designation of specimen	No. of CFRP layers	CFRP coverage (%)	Q_U: Lateral capacity (kN)	M_U: Torsional capacity (kN-m)	% of recovery in lateral capacity	% of recovery in torsional capacity
QM0	0	0	12.162	1.459	NA	NA
QM0-T6	0	0	9.674	1.161	NA	NA
QM0-T12	0	0	9.325	1.119	NA	NA
QM0-L6	0	0	11.002	1.320	NA	NA
QM0-L12	0	0	10.303	1.216	NA	NA
QM2-25-T6	2	25	15.386	1.846	59.04	59.00
QM4-25-T6	4	25	15.685	1.882	62.14	62.10
QM2-100-T6	2	100	27.968	2.601	189.10	124.03
QM2-25-T12	2	25	15.294	1.559	64.01	39.32
QM4-25-T12	4	25	15.310	1.837	64.18	64.16
QM2-100-T12	2	100	27.906	2.551	199.26	127.97
QM2-25-L6	2	25	15.661	1.853	42.35	40.38
QM4-25-L6	4	25	15.714	1.898	42.83	43.79
QM2-100-L6	2	100	28.806	2.679	161.83	102.95
QM2-25-L12	2	25	15.552	1.806	50.95	48.52
QM4-25-L12	4	25	15.699	1.853	52.37	52.38
QM2-100-L12	2	100	28.215	2.631	173.85	116.37

Comparison of Failure Modes

All specimens were subjected to lateral and torsional loading until failure. As previously mentioned, the T-loads were evenly applied on four sides of the specimen at the pinned end. The T-loads were applied in order to organize a torsional moment at the pinned end of the specimen (see Figure 1). The concentrated lateral load was applied in the mid-span of the specimen. In this section, to compare failure modes of the specimens, for example, several failure modes are shown. In the control specimen (QM0) and all non-strengthened specimens having initial deficiencies subjected to combined lateral and torsional loading, high stress was observed at three locations; near the ends and the mid-span. In these specimens, the maximum von Mises stress was observed near the fixed end (see Fig. 3a and b). In non-strengthened specimens having longitudinal deficiency under combined lateral and torsional loading, as shown in Figure 3a, a rotation was observed near the mid-span of these specimens. In the rest of the specimens, the position of maximum von Mises stress was observed at the mid-span (in place of the deficiencies) of these specimens (see Fig. 3c-f)



(a) QM0-L12 (b) QM0-T12

(c) QM2-25-T12 (d) QM4-25-T6

(e) QM2-100-T12 (f) QM2-100-L6

Figure (3): Comparison of von Mises stress in the specimens

CONCLUSIONS

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

1. The initial deficiencies in SHS steel members decrease lateral and torsional load capacity of these steel members. When the deficiency is located in the direction of the width of the steel member (transverse deficiency), the deficiency had more impact on the decrease in lateral and torsional load capacity of the steel members than in the case when the deficiency is located in the direction of the length of the steel member (longitudinal deficiency).
2. In strengthened specimens using CFRP sheets, when the deficiency was located in the direction of the width of the steel member, the CFRP sheets are more effective in increasing and recovering lateral and torsional load capacity of the steel members than in the case when the deficiency was located in the direction of the length of the steel member.
3. When the CFRP composite coverage percentage is less than 100%, the number of CFRP layers exceeding four is not more effective in lateral and torsional load capacity of the steel members having initial deficiencies than in the case when the number of CFRP layers is two. Lack of increase in lateral and torsional load capacity is due to the fact that SHS steel members have recovered with two CFRP layers.
4. In the strengthened specimens, when the CFRP coverage is full, CFRP is more effective in lateral and torsional load capacity than in the case when the composite coverage percentage is less than 100%. The reason which can be mentioned here is that in all non-strengthened specimens having initial deficiencies subjected to combined lateral and torsional loading, high stress was observed at three locations (not in the mid-span); near of the ends and the mid-span.
5. The maximum percentage of increase in lateral and torsional load capacity happened for specimen QM2-100-L6 with 136.85% and 83.62%, respectively. Also, the maximum percentage of increase in recovery of the lateral and torsional load capacity happened for specimen QM2-100-T12 with 199.26% and 127.97%, respectively.
6. In all the strengthened specimens, the position of maximum von Mises stress was observed at the mid-span (in place of the deficiencies) of these specimens. In the control specimen and all non-strengthened specimens having initial deficiencies subjected to combined lateral and torsional loading, the position of maximum von Mises stress was observed near the ends of these specimens.

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