Steel and Composite Structures, *Vol. 23, No. 1 (2017) 87-94*
DOI: https://doi.org/10.12989/scs.2017.23.1.087

CFRP strengthening of steel columns subjected to eccentric compression loading

Amir Hamzeh Keykha *

Department of Civil Engineering, Zahedan Branch, Islamic Azad University, Zahedan, Iran

(*Received July 15, 2016, Revised December 09, 2016, Accepted December 14, 2016*)

Abstract. Steel structures often require strengthening due to the increasing life loads, or repair caused by corrosion or fatigue cracking. Carbon Fiber Reinforced Polymers (CFRP) is one of the materials used to strengthen steel structures. Most studies on strengthening steel structures have been carried out on steel beams and steel columns under centric compression load. No independent article, to the author's knowledge, has studied the effect of CFRP strengthening on steel columns under eccentric compression load, and it seems that there is a lack of understanding on behavior of CFRP strengthening on steel columns under eccentric compression load. However, this study explored the use of adhesively bonded CFRP flexible sheets on retrofitting square hollow section (SHS) steel columns under the eccentric compression load, using numerical investigations. Finite Element Method (FEM) was employed for modeling. To determine ultimate load of SHS steel columns, eight specimens with two types of section (Type A and B), strengthened using CFRP sheets, were analyzed under different coverage lengths, the number of layers, and the location of CFRP composites. Two specimens were analyzed without strengthening (control) to determine the increasing rate of the ultimate load in strengthened steel columns. ANSYS was used to analyze the SHS steel columns. The results showed that the CFRP composite had no similar effect on the slender and stocky SHS steel columns. The results also showed that the coverage length, the number of layers, and the location of CFRP composites were effective in increasing the ultimate load of the SHS steel columns.

Keywords: steel columns; CFRP; strengthening; eccentric compression load; FEM

1. Introduction

Due to the increasing cost of rebuilding, retrofitting and strengthening existing structures seem necessary. Although the cost of rebuilding is not an important issue, the cost of maintenance antiquities is of great important. Strengthening and retrofitting structures are different. One way that has been welcomed by researchers is the use of carbon fiber reinforced polymers. The use of CFRP is a perfect solution in order to overcome the existing shortcomings and strengthen certain infrastructures such as bridges (ACI 440 2002). Compared to other reinforcement materials, CFRP is preferred to strengthen steel structures due to the fact that it has higher elastic modulus and ability to be applied in any form of structure. Over the past decades, some studies have been done on strengthening and retrofitting steel columns (Teng and Hu 2007, Bambach *et al*. 2009, Haedir and Zhao 2011, Fanggi and Ozbakkaloglu 2015, Park and Yoo 2013, Kim and Harries 2011, Keykha *et al*. 2015, 2016a, b). Other studies have been done on flexural strengthening, shear, tensile and torsional of steel beams (Deng *et al*. 2004, Youssef 2006, Islam and Young 2013, Al-Zubaidy *et al*. 2013, Abdollahi Chakand *et al*. 2013).

In another study, Al Zand *et al*. (2015) strengthened the square CFST (concrete-filled steel tube) beams. The results showed that, for all strengthened CFST models using one layer of CFRP sheet, CFRP had no significant enhancement in the ultimate load values when wrapped along 50, 75 and 100% of the length of samples.

Keykha *et al*. (2016a) strengthened the slender square hollow section steel columns with different boundary conditions using CFRP. They offered a theoretical method to analyze these columns.The results showed that the CFRP composite did not have the same effect on columns with different conditions.

Bhuvaneshwari and Vishruth (2016) strengthened the short hollow circular steel tubes using glass fiber reinforced polymer (GFRP) under axial and eccentric compression. Their test results showed that, for both axial loading and minor eccentric loading, control of localized buckling along with percentage increase in stiffness and energy absorption were significant for strengthened specimens with two layers of wrapping GFRP.

Concerning past studies, it can be observed that there were investigations done with the use of CFRP composite as a strengthening material for SHS steel beams, and SHS steel columns under centric compression load. It seems that there is a lack of understanding on behavior of CFRP strengthening on steel columns under eccentric compression load. Therefore, this article aimed to develop the knowledge in this area. For this purpose, this study explored the use of adhesively bonded CFRP flexible sheets on retrofitting SHS steel columns under eccentric compression load, using numerical investigations. In order to carefully examine,

∗Corresponding author, Ph.D.,
E-mail: ah.keykha@iauzah.ac.ir

Copyright © 2017 Techno-Press, Ltd.
http://www.techno-press.org/?journal=scs&subpage=6
ISSN: 1229-9367 (Print), 1598-6233 (Online)

Table 1 Sizes and properties of SHS steel

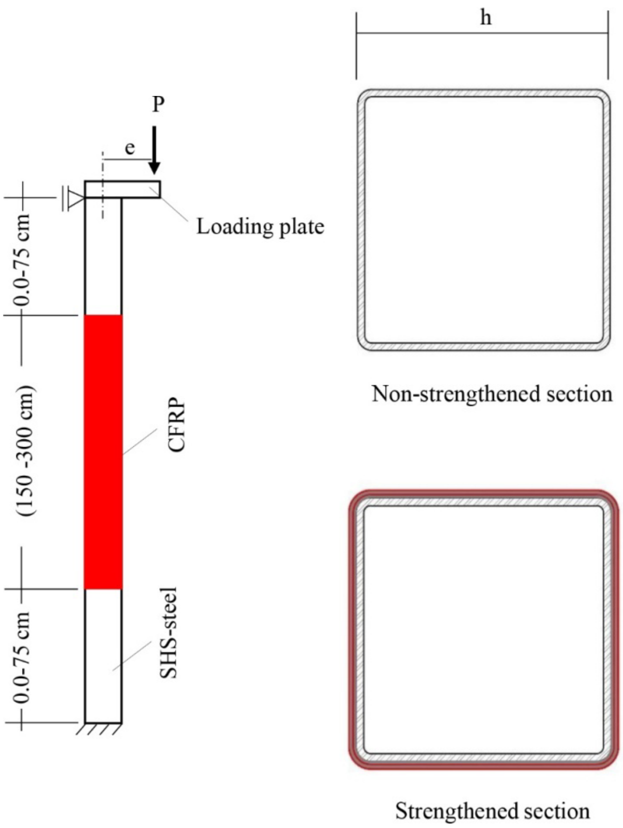
Type section	Dimensions ($h \times b \times t$) (mm)	Length L (mm)	Modulus of elasticity (N/mm^2)	Stress (N/mm^2) Yielding (F_y)	Ultimate (F_u)
A	90 × 90 × 2.5	3000	200000	280	375
B	40 × 40 × 2.0	3000	200000	280	375

Table 2 Properties of CFRP material

CFRP Sheet: SikaWrap-230C				
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)
0.131	238000	4300	1.8	1

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



(a) SHS steel columns-side view Cross section (b)

Fig. 1 Boundary conditions of a SHS steel column strengthened using CFRP

both slender SHS steel columns and stocky were analyzed. The coverage length, the number of layers, and the location of CFRP composite were implemented to examine the ultimate load of the SHS steel columns under eccentric compression load.

2. Material

The dimensions, the section types, and properties of the consumed steel in this study are given in Table 1. The yield strength mean value found by coupon tests is 280 N/mm^2 and the ultimate tensile strength mean value is 375 N/mm^2. The consumed CFRP in the present research is SikaWrap-230C. Properties of CFRP composite are shown in Table 2. Adhesive used in this study is suggested by the supplier of CFRP product. The adhesive is commonly used for the SikaWrap-230C, called Sikadur-330 (Table 3).

3. Finite element modeling

3.1 Model description

Non-linear finite element models were prepared using ANSYS to investigate the structural behavior of the SHS steel columns strengthened by CFRP sheets in length. All models were prepared as fixed-pinned supported columns with a point load (P), at which the point load was applied with different eccentricity (the eccentricity load is shown with e: see Fig. 1). Fig. 1 shows the boundary conditions of the SHS steel columns and the strengthening scenario adopted in this study.

Fig. 2, for instance, shows the three dimensional (3D) finite element model of the prepared specimens using ANSYS (specimen AC2-50). The centric compression load and the eccentric were simultaneously applied to the columns. These loadsgradually increased until the strengthened SHS steel columns achieved their ultimate load capacity.

3.2 Analysis methodology of specimens

To simulate the SHS steel columns, the full three dimensional modeling and non-linear static analysis methods using ANSYS were applied. The SHS steel columns, CFRP sheets, and adhesive were simulated using the 3D solid triangle elements (ten-nodes 187). Non-linear static analysis was carried out to achieve the failures. In this case, the load was incrementally applied until the plastic strain in an element reached to its ultimate strain (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 (Keykha *et al.* 2016a). The SHS steel columns and adhesive were defined as the materials having non-linear 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 *et al.* (2016a), showing a good

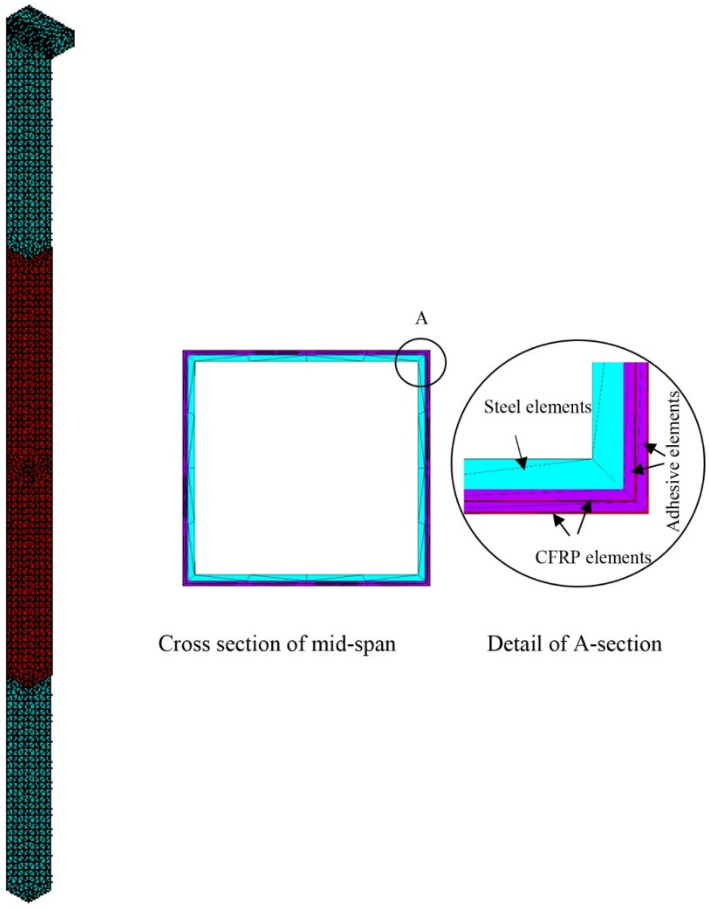
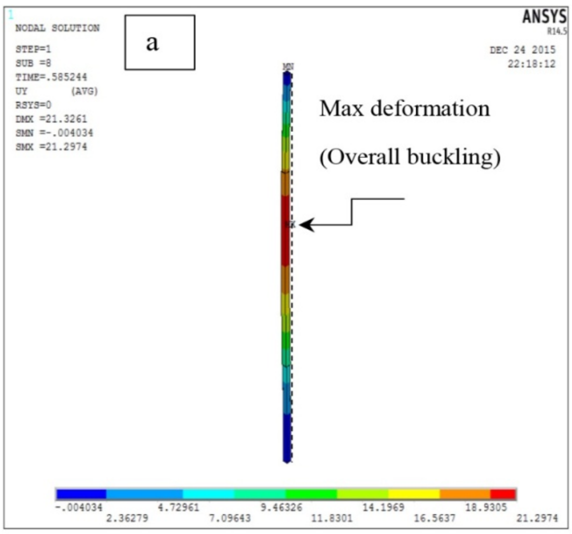


Fig. 2 Finite element modeling of strengthened steel columns (AC2-50)



(a) Numerical

(b) Experimental (Keykha *et al*. 2015)

Fig. 3 Failure mode of specimen BC2-50

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 Keykha *et al*. (2015). 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 (Keykha *et al*. 2016a). Figs. 3(a)-(b) show a simulated specimen using ANSYS software and an experimental tested specimen.

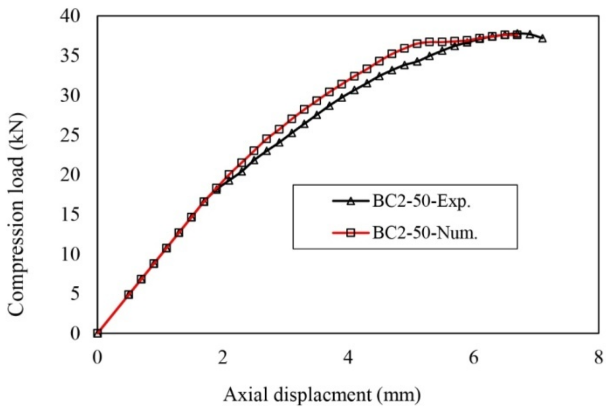


Fig. 4 Compression load-displacement curve of specimen BC2-50, experimental and numerical

The compression load-displacement curve of the specimen BC2-50, obtained from both experimental and numerical results, is also displayed in Fig. 4. As shown in Fig. 4, good accuracy is seen between the experimental and numerical results.

3.4 Description of specimens

The columns are included two control specimens and eight specimens strengthened with one and two layers of CFRP applied on all four sides of the columns. In each type (Type A and Type B) of columns, one specimen, that is control specimen, was analyzed without strengthening to determine the increase rate of the ultimate load in strengthened steel columns. To easily identify the specimen, the columns were designated by the names such as AC0, AC1-50, AC2-50, AC1-100, AC2-100, BC0, BC1-50, BC2-50, BC1-100 and BC2-100. For example, the specimens AC2-100 and BC2-100 indicate that they were strengthened by two layers of CFRP fully wrapped around the columns Type A and B. The specimen AC2-50 indicates that it is a Type A column strengthened by two layers and the CFRP coverage 50% wrapped around the column. The specimen BC1-50 also specifies that it is a column Type B strengthened by one layer and the CFRP coverage 50% wrapped around the column. Similarly, the specimen BC2-50 specifies is a column Type B strengthened by two layers and the CFRP coverage 50% wrapped around the column. The control columns Type A and B are designated as AC0 and BC0.

4. Results and discussion

4.1 The ultimate load results

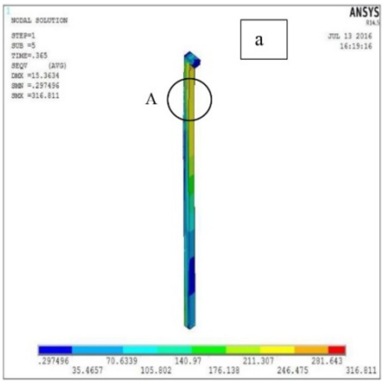
Tables 4-5 shows the numerical analysis results of the specimens in Type A and B without strengthening or with one or two layers of CFRP sheet strengthened. The coverage lengthof CFRP varies based on the length ofcolumns. The center position of CFRP sheet is in the center of column.The results showed that CFRP is not effective in the ultimate loadin Type A columns (stocky columns) when the composite coverage percentage is less than 100%. For Type A columns, when the CFRP coverage is full, CFRP is effective in the ultimate load. With an increase in the ratio of eccentricity load (e/h), the ultimate load of columns decreases. In these columns (the columns of Type A with a coverage percentage 100% of CFRP) when that e/h is greater than a half, CFRP is not effective in the ultimate load of column. For the Type A columns, the maximum percentage of increase of the ultimate load happened for the specimen AC2-100 (35.77%) when that e/h is equal to zero. This specimen (specimen AC2-100) is strengthened with two layers and the coverage length 100% of CFRP sheet. In contrast to the Type A columns, when the composite coverage percentage is less than 100%, the CFRP sheet is effective in the ultimate load in Type B columns (slender columns). In other words, the ultimate load of columns increased in both cases when the coverage percentage is less than 100% and equal 100%. For Type B columns, when the CFRP coverage is full, the rate of the increased ultimate load in columns increases with an increase in the ratio of eccentricity load. In these columns (Type B columns), the maximum percentage of increase of the ultimate load happened for the specimen BC2-100, when that e/h is one and half. Generally, in this study, the

Table 4 Analysis results for specimens of Type A

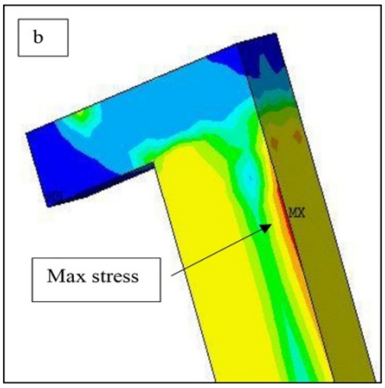
Designation of columns	Ultimate load (P (kN)), the ratio of eccentricity load (e/h) and % of increase in load				
AC0	e/h	0.00	0.50	1.00	1.50
	P (kN)	213.18	106.81	73.00	52.97
AC1-50	P (kN)	214.12	106.79	72.90	52.90
	% of increase in P	0.44	0.00	0.00	0.00
AC2-50	P (kN)	214.12	106.75	72.87	52.93
	% of increase in P	0.44	0.00	0.00	0.00
AC1-100	P (kN)	240.24	113.50	72.93	53.01
	% of increase in P	12.69	6.26	0.00	0.00
AC2-100	P (kN)	289.44	115.50	72.96	53.32
	% of increase in P	35.77	8.14	0.00	0.66

Table 5 Analysis results for specimens of Type B

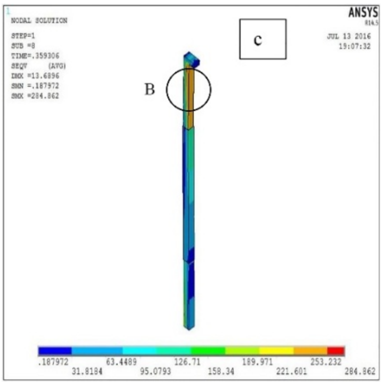
Designation of columns	Ultimate load (P (kN)), the ratio of eccentricity load (e/h) and % of increase in load				
BC0	e/h	0.00	0.50	1.00	1.50
	P (kN)	31.85	21.46	16.79	13.92
BC1-50	P (kN)	35.06	23.23	17.90	14.72
	% of increase in P	10.08	8.25	6.61	5.75
BC2-50	P (kN)	37.60	23.83	18.25	14.92
	% of increase in P	18.05	11.04	8.70	7.18
BC1-100	P (kN)	36.74	24.97	19.78	16.67
	% of increase in P	15.35	16.36	17.81	19.76
BC2-100	P (kN)	40.89	27.92	22.47	19.11
	% of increase in P	28.38	30.10	33.77	37.28



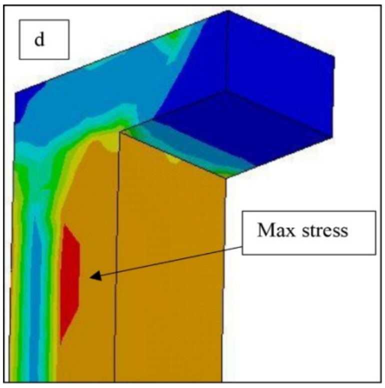
(a) The specimenAC0



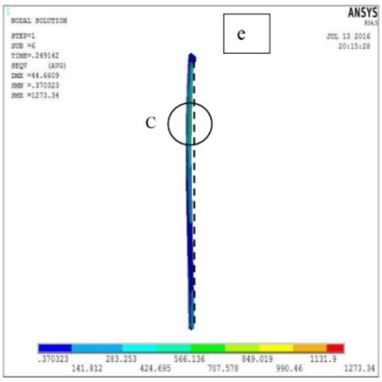
(b) Detail of A-section



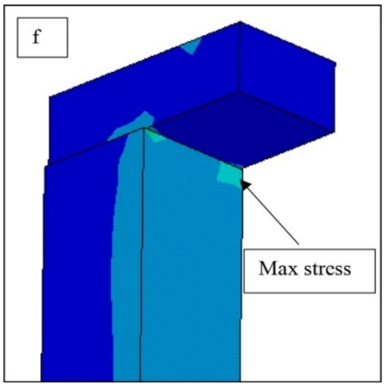
(c) The specimenAC2-50



(d) Detail of B-section



(e) The specimenAC2-100



(f) Detail of C-section

Fig. 5 Von Mises stress of columns of Type A in e/h = 1.00

maximum percentage of increase in the ultimate load happened for the specimen BC2-100 (37.28%).

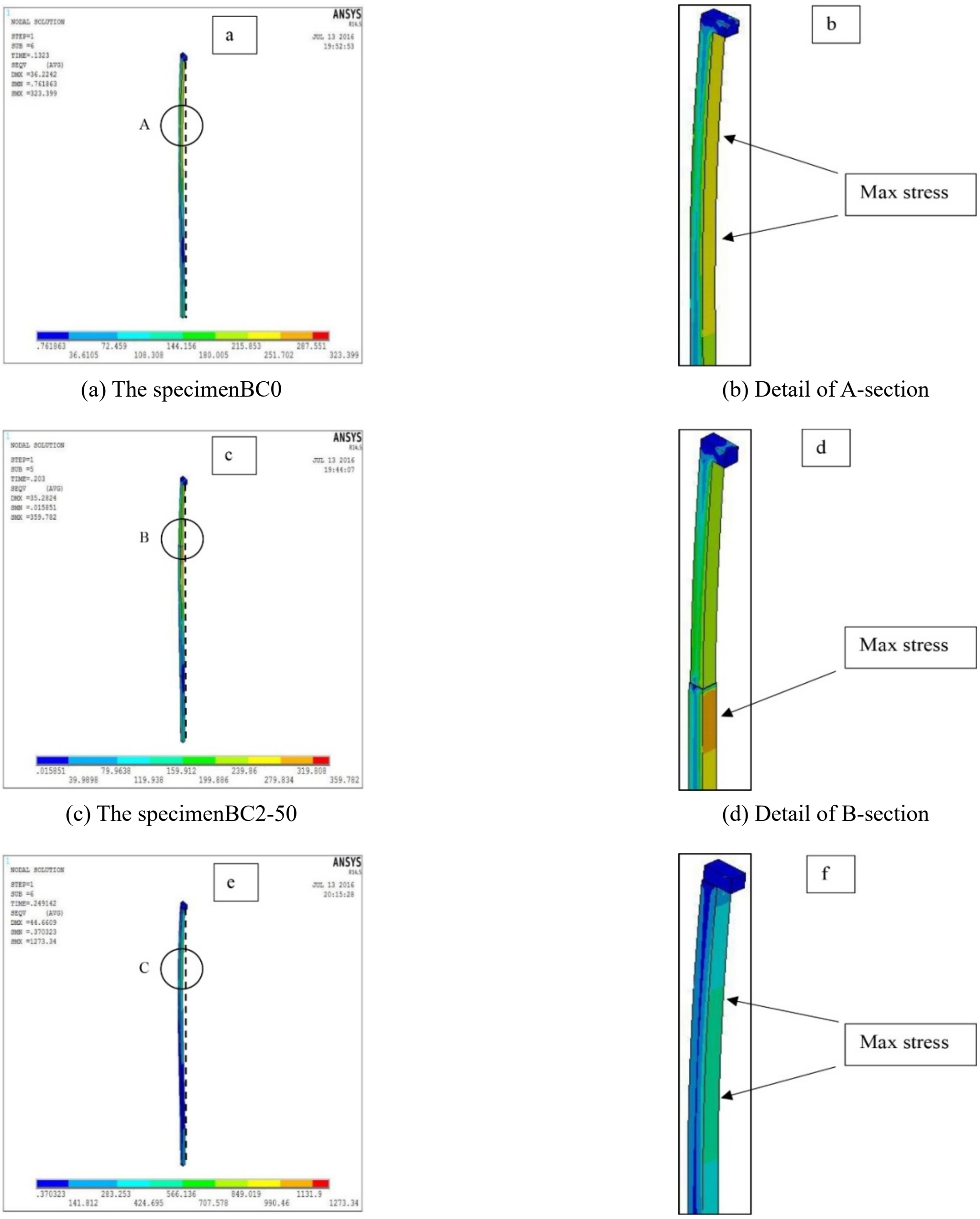
4.2 Failure modes

All specimens were subjected to a point load until failure. The P-load was applied on top of the columns as the compression load and eccentricity load. In Type A columns, when the composite coverage percentage is less than 100%, a local buckling was observed at non-strengthened location. For these columns, when the CFRP coverage was full, a local buckling was observed on top (in location of column joint to loading plate, see Fig. 5(c): Detail of C-section). For instance, the Von Mises stress of columns of Type A is shown in Figs. 5(a)-(f).

In Type B columns, the failure modes of all specimens are the same, and are the overall buckling. In these columns, in both cases, the composite coverage percentage less than 100% and equal 100% the overall buckling was observed at strengthened location. Therefore, in contrast to Type A columns, for these the columns, even when the composite coverage percentage is less than 100%, the CFRP sheet is effective in the ultimate load. For instance, Figs. 6(a)-(c) show the Von Mises stress of columns of Type B.

4.3 Curves of compression load - the ratio of eccentricity load

The test results such as the ultimate load carrying capacity and the rate of increased ultimate load of the SHS



(a) The specimenBC0

(b) Detail of A-section

(c) The specimenBC2-50

(d) Detail of B-section

(e) The specimenBC2-100

(f) Detail of C-section

Fig. 6 Von Mises stress of columns of Type B in e/h = 1.00

steel columns with respect to the reference columns were summarized in Tables 4-5. The results of the ultimate load carrying capacity for the Type A specimens is also presented in Fig. 7. In Type A specimens, when the CFRP coverage percent is less than 100%, the ultimate load carrying capacity are not increased with an increase in the number of CFRP layers (see Fig. 7 or Table 4). In other words, the CFRP composite is not effective in the ultimate load. The reason of no increase in the compression load in these specimens is that the failure modes of the specimens happened in location out of from the strengthened area (see Fig. 5). For Type A columns, when the CFRP coverage is full, CFRP is more effective in the ultimate load. The maximum percentage of the increase load of Type A columns happened for the specimen AC2-100 (35.77%) when that e/h was equal to zero. Note: as shown in Fig. 7, since some curves coincide together, they are not visible.

Fig. 8 and Table 5 show that, in Type B, when the composite coverage percentage is less than 100%, the CFRP sheet is effective in the ultimate load. In other words, the ultimate load of column increased in both cases and the composite coverage percentage is less than 100% and equal 100%. In the Type B columns, similar to Type A, with an increase of the ratio of eccentricity load, the ultimate load reduced. It is important, in contrast to Type A columns, when the CFRP coverage is full, the rate of the increased ultimate load in columns increased with an increase in the ratio of eccentricity load. In these columns (Type B columns), the maximum percentage of increase of the ultimate load happened for the specimen BC2-100 when

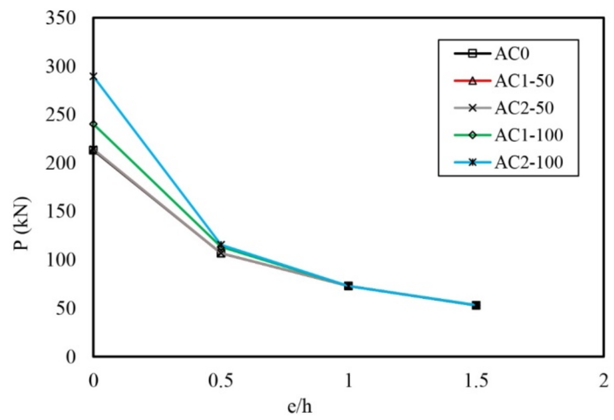


Fig. 7 The Curves of compression load-the ratio of eccentricity load of Type A columns

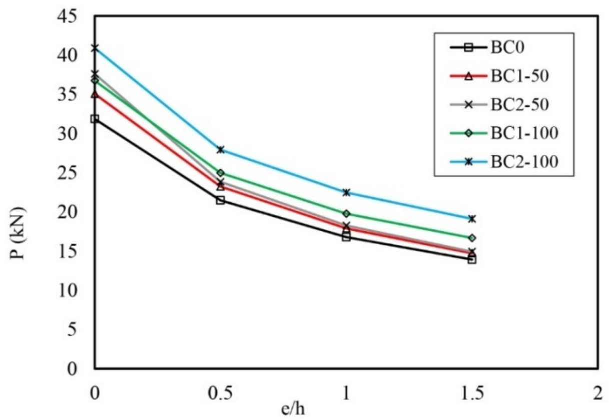


Fig. 8 The Curves of compression load-the ratio of eccentricity load of Type B columns

that e/h is one and half (see Table 5). In this study, the maximum percentage of increase in the ultimate load happened for the specimen BC2-100 (see Fig. 8 or Table 5).

5. Conclusions

In this paper, the CFRP layers with different in lengths were wrapped around the stocky (Type A columns) and the slender (Type B columns) SHS steel columns. The failure modes, the ultimate load carrying capacity, the percentage of the ultimate load increase and the CFRP wrapping position on the SHS steel columns were discussed. Based on ten analyzed specimens, eight specimens were strengthened with the different coverage lengths and with one and two CFRP layers, the following conclusions can be drawn:

- In stocky columns, when the composite coverage percentage is less than 100% CFRP, it is not effective in the ultimate load. The reason of no increase in the the ultimate load in these columns is that the failure modes of the specimens happened in location out of from the strengthened area (see Figs. 5(a)-(f)).
- With an increase in the ratio of eccentricity load of the columns, the rate of the ultimate load increase of the Type A columns decreased. For these columns, when the ratio of eccentricity load is more than a half, the ultimate load all columns is almost equal (see Table 4).
- For Type A columns, when the CFRP coverage is full, CFRP is more effective in the ultimate load. Also, when the ratio of eccentricity load is equal to zero, the amount of the ultimate load increase rate is 12.69 and 35.77 kN for the specimens of strengthened with one and two CFRP layers, and full wrapped, respectively.
- In Type B columns, when the composite coverage percentage is less than 100%, the CFRP sheet is effective in the ultimate load. In other words, the ultimate load of columns increased in both cases when the composite coverage percentage is less than 100% and equal 100%. In Type B columns, similar to Type A, with an increase in the ratio of eccentricity load, the ultimate load decreased. It is important, in contrast to Type A columns, when the CFRP coverage is full, with an increase in the ratio of eccentricity load, the rate of the increased ultimate load in columns increased. In these columns (Type B columns), the maximum percentage of increase of the ultimate load happened for the specimen BC2-100 when that e/h is one and half. In this study, the maximum percentage of increase in the ultimate load happened for the specimen BC2-100 (37.28%).
- Generally, from comparing Type A and Type B specimens showed that when the ratio of eccentricity load increased, the CFRP sheet is more effective in the rate of the increased ultimate load of Type B columns.

References

Abdollahi Chakand, N., Zamin Jumaat, M., Ramli Sulong, N.H., Zhao, X.L. and Mohammadizadeh, M.R. (2013), "Experimental and theoretical investigation on torsional behavior CFRP strengthened square hollow steel section", *Thin-Wall. Struct.*, **68**, 135-140.

ACI Committee 440 (2002), Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures; ACI440.2R-02, American Institute, Farmington Hills, MI, USA.

Al Zand, A.W., Badaruzzaman, W.H.W., Mutalib, A.A. and Qahtan, A.H. (2015), "Finite element analysis of square CFST beam strengthened by CFRP composite material", *Thin-Wall. Struct.*, **96**, 348-358.

Al-Zubaidy, H., Al-Mahaidi, R. and Zhao, X.L. (2013), "Finite element modelling of CFRP/steel double strap joints subjected to dynamic tensile loadings", *Compos. Struct.*, **99**, 48-61.

Bambach, M.R., Jama, H.H. and Elchalakani, M. (2009), "Axial capacity and design of thin-walled steel SHS strengthened with CFRP", *Thin-Wall. Struct.*, **47**(10), 1112-1121.

Bhuvaneshwari, P. and Vishruth, J. (2016), "Axial and eccentric compression of GFRP jacketed steel tubes", *Asian J. Civil Eng. (BHRC)*, **17**(5), 625-634.

Deng, J., Lee, M.M.K. and Moy, S.S.J. (2004), "Stress analysis of steel beams reinforced with a bonded CFRP plate", *Compos. Struct.*, **65**(2), 205-215.

Fanggi, B.A.L. and Ozbakkaloglu, T. (2015), "Square FRP–HSC–steel composite columns: Behavior under axial compression", *Eng. Struct.*, **92**, 156-171.

Haedir, J. and Zhao, X.L. (2011), "Design of short CFRP-reinforced steel tubular columns", *J. Construct. Steel Res.*, **67**(3), 497-509.

Islam, S.M.Z. and Young, B. (2013), "Strengthening of ferritic stainless steel tubular structural members using FRP subjected to Two-Flange-Loading", *Thin-Wall. Struct.*, **62**, 179-190.

Keykha, A.H., Nekooei, M. and Rahgozar, R. (2015), "Experimental and theoretical analysis of hollow steel columns strengthening by CFRP", *Civil Eng. Dimension*, **17**(2), 101-107.

Keykha, A.H., Nekooei, M. and Rahgozar, R. (2016b), "Numerical and experimental investigation of hollow steel columns strengthened with carbon fiber reinforced polymer", *J. Struct. Construct. Eng.*, **3**(1), 49-58.

Keykha, A.H., Nekooei, M. and Rahgozar, R. (2016a), "Analysis and strengthening of SHS steel columsn using CFRP composite materials", *Compos.: Mech. Computat. Appl., Int. J.*, **7**(4), 275-290.

Kim, Y.J. and Harries, K.A. (2011), "Behavior of tee-section bracing members retrofitted with CFRP strips subjected to axial compression", *Compos. Part B: Eng.*, **42**(4), 789-800.

Park, J.W. and Yoo, J.H. (2013), "Axial loading tests and load capacity prediction of slender SHS stub columns strengthened with carbon fiber reinforced polymers", *Steel Compos. Struct., Int. J.*, **15**(2), 131-150.

Teng, J.G. and Hu, Y.M. (2007), "Behavior of FRP jacketed circular steel tubes and cylindrical shells under compression", *Int. J. Construct. Build. Mater.*, **21**(4), 827-838.

Youssef, M.A. (2006), "Analytical prediction of the linear and nonlinear behaviour of steel beams rehabilitated using FRP sheets", *Eng. Struct.*, **28**(6), 903-911.

CC