

Numerical and Experimental Study on Deficient Short Steel Tubes Strengthened with CFRP under Compression

Mohammad Reza Ghaemdoost^{1*}, Omid Yousefi¹, Kambiz Narmashiri¹, Masoumeh Karimian¹

¹ Department of Civil Engineering, Zahedan Branch,
Islamic Azad University, Zahedan, Iran

* Corresponding author, e-mail: mohammad.ghaemdoost@gmail.com

Received: 11 October 2018, Accepted: 15 July 2019, Published online: 09 September 2019

Abstract

In view of development and repair costs, support of structures is imperative. Several factors, for example, design and calculation errors, absence of appropriate installation, change of structures application, exhaustion, seismic tremor, fire and natural conditions diminish their strength. In such cases, structures have need of rehabilitation and restoration to achieve their original performance. One of the most up to date materials for retrofitting is carbon fiber reinforced polymer (CFRP) that can provide an amount of restriction to postpone buckling of thin steel walls. This paper provides a numerical and experimental investigation on CFRP strengthened short steel tubes with initial horizontal and vertical deficiency under compression. Ten square and circular specimens were tested to study effects of the following parameters: (1) position of deficiency, horizontal or vertical; (2) tube shape, square or circular; (3) CFRP strengthening. In the experiments, axial static loading was gradually applied and for the numerical study three-dimensional (3D) static nonlinear analysis method using ABAQUS software was performed. The results show that deficiency reduces load-bearing capacity of steel columns and the impact of horizontal deficiency is higher than the impact of vertical deficiency, in both square and circular tubes. Use of CFRP materials for strengthening of short steel columns with initial deficiency indicates that fibers play a considerable role on increasing load bearing capacity, reducing stress at the damage location, preventing deformation caused by deficiency and delaying local buckling. Both numerical and experimental outcomes are in good agreement, which underlines the accuracy of the models adopted.

Keywords

strengthening, short steel columns, deficiency, CFRP

1 Introduction

Hollow Structural Sections can be made of different types of metal and have various tubular shapes, namely circular (CHS) and square (SHS). Steel hollow structural sections have been used in the construction industry more and more due to their favorable characteristics in terms of good stability and high bearing capacity. Deterioration of steel structures arises from several factors but perhaps corrosion is the most important one. It may possibly arise non-uniformly according to its location concerning the source of corrosion. Several pillars of bridges put up of tubular columns are exposed to erosion due to rough environmental circumstances or gradual growth of fatigue cracks due to dynamic loading. Traditional strengthening techniques are section expansion and external bonding of steel plates. Despite the fact that these methods are effective in practice, they present some shortcomings such as increase of

self-weight, required heavy lifting equipment to install the plates in position, trouble in shaping and fitting in complex profiles and difficulty in bonding/welding. In contrast, rehabilitation using carbon fiber reinforced polymer (CFRP) composites do not show any of these problems [1–3].

Teng et al. [4] reviewed CFRP-reinforced steel structures. Their research provided a critical examination of CFRP reinforced steel structures, including the preparation of steel surfaces for adhesive bonding and selection of a suitable adhesive. By studying a number of compression members, Harries et al. [5] found that a small amount of FRP materials could improve buckling resistance, energy absorption and final ductility. Kalavagunta et al. [6] experimentally studied a CFRP bonded lipped channel column under axial load. It was understood that the load-bearing capacity in the fully reinforced section was increased by

16.75 % and in the web-reinforced member increased by 10.26 %. Due to the delamination and debonding of CFRP, a reduction in capacity and a sudden failure was noted. It was concluded that surface preparation and temperature are two important factors for achieving proper adhesion between steel and fiber.

Experimental study on 18 mortar-filled FRP tubes with different types of steel cores was conducted by Feng et al. [7]. After strengthening, the mid-height failure changed to local damage at the steel ends. End local damage in the steel was indicated for smaller non-dimensional slenderness specimens and global buckling occurred for greater ones. The ultimate load capacity and ductility improved by 44–215 % and up to 877 %, respectively. The use of CFRP increases the ductility and load-bearing capacity. The number of layers and bearing capacity are in direct relationship [8–10]. Investigations [11, 12] on CFRP jackets for retrofitting concrete-filled circular and box shaped short columns have shown that CFRP fibers have a significant effect on the increase of bearing capacity, but in rectangular columns this increase is small, in contrast to circular columns. In a study on moderate slenderness columns by Wang et al. [13], a total of 24 concrete-filled specimens were tested under axial loading. They concluded that failure was due to low cross-sectional strength for columns with small relative slenderness, and for columns with larger slenderness failure was due to instability of the columns.

Haedir and Zhao [14] evaluated the effect of retrofitting with CFRP transversally and longitudinally on short columns and concluded that the combined use of CFRP in the longitudinal and transverse directions increases the yield capacity, and also that a greater amount of CFRP plays more effective role on delaying local buckling. Shaat and Fam [15] investigated short SHS columns strengthened by CFRP and found out common failure modes which include delamination of transverse and longitudinal CFRP layers and rupture of the hoop CFRP near the corners. Bambach et al. [16–20] carried out extensive research on steel hollow short columns strengthened with CFRP. In numerical and experimental study, SHS columns were tested under static and dynamic axial impact and compression, examined the axial capacity of the sections, and compared the failure modes both in static and dynamic behavior. It has been shown that the crushing energy and strength of steel-CFRP columns depend on the type of steel and the ratio of the thickness of the CFRP to its width. Also, these studies revealed that usage of CFRP materials increases ultimate carrying capacity and specific energy absorption.

The specific energy absorption is described as the energy absorbed per crushed specimen weight, which is a significant factor regarding energy absorption capability. Several studies on CFRP strengthening showed that retrofitting scheme is a vital factor in increasing the load carrying capacity and delaying lateral buckling [21, 22]. Theoretical and experimental studies of thin cylindrical shells under axial compression were carried out by Teng and Hu [23]. They concluded that retrofitting with FRP jackets is an effective method for elephant's foot collapse failure mode and the use of FRP increases ductility, energy absorption and ultimate load bearing. The behavior of FRP-confined concrete cylinders under compression was investigated by Touhari and Mitiche-Kettab [24]. Two types of carbon and glass FRP sheets were used and parameters including number of FRP layers and strength of concrete were examined. The results illustrated that the use of CFRP wrapping leads to higher ultimate load bearing capacity in comparison to GFRP composites.

According to experimental studies [25], it was determined that corrosion results in decrease in steel thickness, mechanical strength, and weight. It also was established that corrosion plays an important role for overall capacity reduction. Application of CFRP to rehabilitate damaged steel welded beams [26] has shown that the average growth in strength was 47 % and 83 % for single and dual wrapping, respectively. Yousefi et al. [27] carried out research on defects in the tensile flanges of steel beams. The two-side deficient specimens showed the greatest reduction in load capacity, while the one-side deficient specimens had more lateral buckling. In order to prevent and control this buckling, the web, in addition to the flange, was strengthened.

Ghaemdoust et al. [28] examined the position and effect of defects in the structural performance of the compression members and the corresponding failure modes. They found that horizontal defects were more critical than vertical defects, observed elephant's foot failure in the control column and CFRP delamination at the ends of the strengthened columns. Huang et al. [29] repaired damaged CHS sections with CFRP or grout to study compressive behavior of steel columns. They understood that both techniques are effective for rehabilitation. Chen et al. [30] found out that CFRP sheets improve the ultimate strength of specimens and postpone local buckling. By analyzing the effects of static and dynamic loading on hot rolled steel SHS deficient columns, Hamood et al. [31] pointed out that the defects locations and dimensions have important impacts on column strength and performance. Shahabi

and Narmashiri [32] conducted a research on the effects of defect at the middle or bottom of the columns. They concluded that the deficiencies are responsible for resistance and stiffness decline of these members and the middle-vertical deficiency at the bottom of the steel columns is the most serious. It was also revealed that application of CFRP sheets significantly increases the resistance and limits failure around the deficiency zone. Study on CFRP strengthened deficient columns under combined tensile, torsional, and lateral loadings by Keykha [33] concluded that deficiencies reduce ultimate capacity and the transverse deficiency has higher impact than the longitudinal one.

According to previous studies, the application of CFRP fibers has proven to be a successful way of enhancing structural performance of short steel columns. However, more research is needed to develop the use of CFRP in rehabilitation of damaged columns. Therefore, the purpose of this research is to compare different effects of deficiencies on CHS and SHS short columns and investigate the feasibility of using CFRP materials to repair damaged columns.

2 Materials and methods

Specimens consist of ten tubular columns where five of them are SHS and the rest are CHS. In order for examining the CFRP laminate effects and strengthening performance, two control columns and eight deficient columns were considered, six of them bonded by using CFRP sheets.

2.1 Steel tubes

Two types of SHS and CHS steel nonslender sections according to AISC section classification for members [34] subjected to axial load were prepared to conduct this research. SHS tubes with section of 90 × 90 mm² and length of 270 mm were used. In addition, for CHS short columns, steel tubes with radius 82.5 mm and length of 240 mm were considered. All columns had wall thickness of 3 mm. The dimensions of the selected steel sections are shown in Fig. 1. With the aim of making deficiency, a horizontal or vertical notch was created by CNC machine at the mid-height of the sections (Fig. 2), resulting in the deficiency patterns shown in Fig. 3. The mechanical properties of the steel tubes, which were predicted by tensile test as shown in Fig. 4, are presented in Table 1.

2.2 CFRP

Due to their high tensile strength and ease of application, CFRP materials have been comprehensively used for retrofitting of structural steel components. CFRP that was

used in this research is a unidirectional woven carbon fiber named SikaWrap®-230 C. It is a mid-strength carbon fiber with modulus of elasticity of 238 kN/mm² and tensile strength of 4300 N/mm². The nominal thickness of the fiber is 0.131 mm. CFRP sheet properties are given in Table 2.

2.3 Adhesive

Using a two-component, high-strength and high-modulus epoxy adhesive (Sikadur®-330), the CFRP materials were bonded to the steel columns. The adhesive is a 2-part epoxy impregnation resin, containing a resin and a hardener with mixing ratio of 4:1, with a nominal Young's modulus of 4500 N/mm² and a tensile strength of 30 N/mm². The mechanical properties of the adhesive are presented in Table 2.

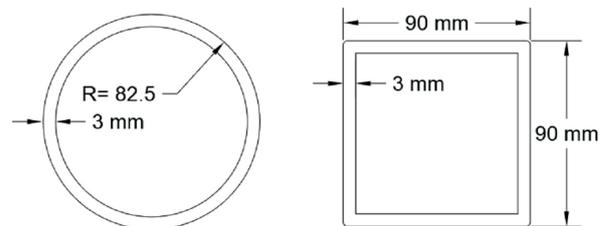


Fig. 1 Dimensions of steel sections



Fig. 2 Making initial deficiency by CNC machine

Table 1 Mechanical properties of steel specimens

Tube section	Modulus of elasticity (GPa)	Yield strength (MPa)	Width-to-thickness ratio	Section designation [34]
SHS	200	190	27	Nonslender
CHS	200	315	55	Nonslender

Table 2 CFRP and adhesive properties

Material	Thickness (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain (%)
CFRP (SikaWrap®-230 C)	0.131	4300	238	1.8
Adhesive (Sikadur®-330)	0.869	30	4.5	0.9

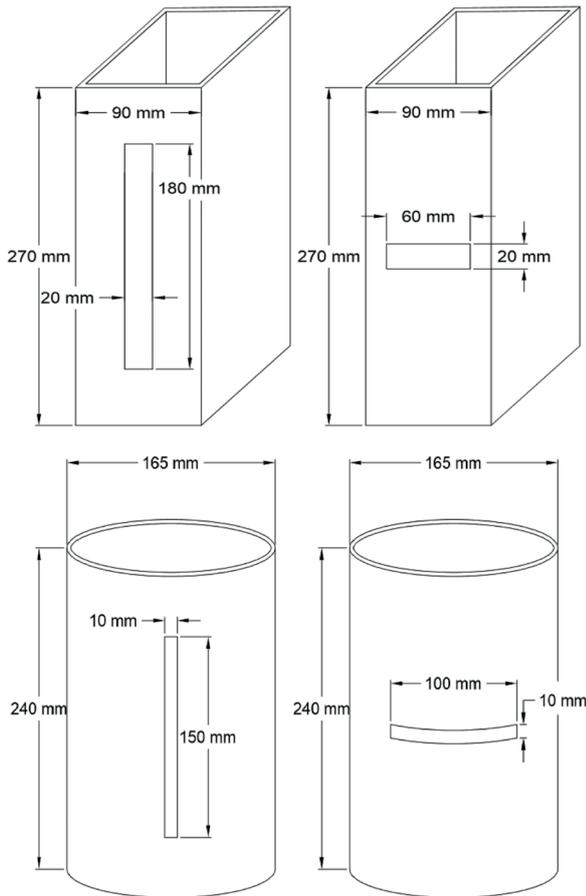


Fig. 3 Deficiency patterns

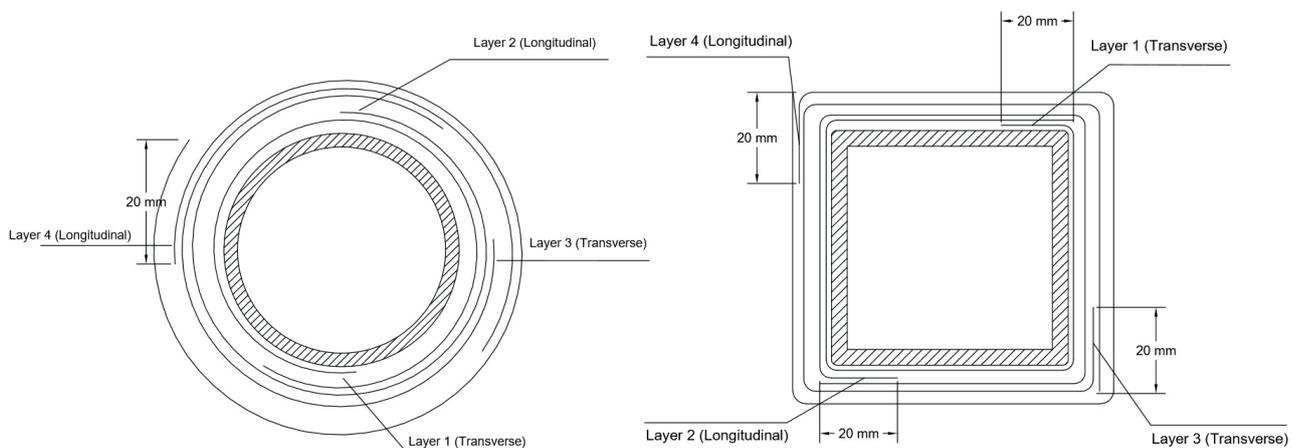


Fig. 5 Scheme of CFRP arrangement for experimental tests

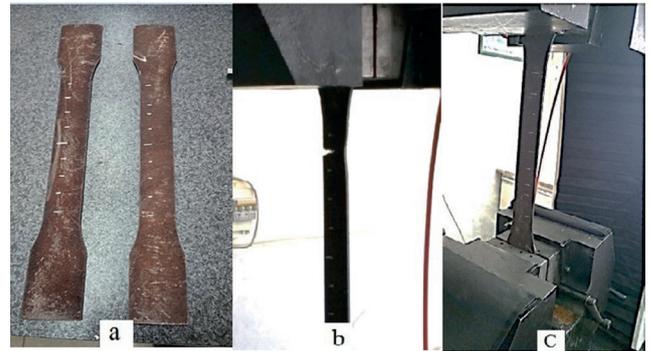


Fig. 4 Tensile testing: (a) tensile specimens; (b) fracture of specimen; (c) universal testing machine

3 Specifications of specimens

In this research, ten columns with square and circular sections were studied. Two columns are non-deficient and the remaining have defects horizontally and vertically. For identification, non-deficient members were called control (control SHS and control CHS) and the other specimens were named according to the shape of the section, direction and dimensions of deficiency, and CFRP layers. For example, specimen S-H 60×20 is a square column notched horizontally within $60 \times 20 \text{ mm}^2$. Specimen C-V-2T2L is a circular column with vertical deficiency, strengthened by two transverse (around the tube perpendicular to the direction of axial load) and two longitudinal (in the direction of axial load) CFRP layers. It is noteworthy that the strengthening method is the same for all specimens (full-length wrapping of the tubes). The CFRP sheets, as shown in Fig. 5, were overlapped by 20 mm to avoid premature failure and obtain good bonding behavior. Table 3 presents the specimens labels, section types, deficiency details, and ultimate loads obtained.

Table 3 Specifications, deficiency details and ultimate loads of the specimens

No	Specimen Label	Shape	Deficiency			CFRP Layers	CFRP Layers Direction	Load Bearing Capacity			
			Length (mm)	Width (mm)	Direction			Experimental		Numerical	
								Load (kN)	Increase/Decrease (%)	Load (kN)	Increase/Decrease (%)
1	Control SHS	Square	N/A	N/A	N/A	N/A	N/A	249	N/A	258	N/A
2	S-H-45×10	Square	45	10	Horizontal	N/A	N/A	N/A	N/A	186	27.90-
3	S-H-45×20	Square	45	20	Horizontal	N/A	N/A	N/A	N/A	186	27.90-
4	S-H-60×10	Square	60	10	Horizontal	N/A	N/A	N/A	N/A	176	-31.78
5	S-H-60×20	Square	60	20	Horizontal	N/A	N/A	161	-35.34	175	-32.17
6	S-H-2T2L	Square	60	20	Horizontal	4	2T-2L	237	-4.81	270	4.65
7	S-V-180×20	Square	180	20	Vertical	N/A	N/A	173	-30.52	184	-28.68
8	S-V-2T2L	Square	180	20	Vertical	4	2T-2L	252	1.20	268	3.87
9	Control CHS	Circular	N/A	N/A	N/A	N/A	N/A	412	N/A	459	N/A
10	C-H-100×10	Circular	100	10	Horizontal	N/A	N/A	333	-19.17	371	-19.17
11	C-H-2T2L	Circular	100	10	Horizontal	4	2T-2L	446	8.25	462	0.65
12	C-V-150×10	Circular	150	10	Vertical	N/A	N/A	354	-14.07	374	-18.51
13	C-V-2T2L	Circular	150	10	Vertical	4	2T-2L	438	6.31	460	0.21

4 Experimental setup

Experimental specimens were cut at the factory and the initial horizontal and vertical defects were created by CNC machine. The columns were sandblasted in the factory in order to create a clean, rough and rust free surface for better adhesion between the fibers and steel. It is noteworthy that the time between sandblasting and CFRP sticking was less than 24 hours. Then, the specimens were cleaned by acetone to prepare CFRP bonding. Finally, four layers of CFRP fibers were utilized, transversely and longitudinally in the columns. The samples were cured at room temperature for at least 7 days, according to Sikadur instructions [35]. All columns were tested until complete failure under axial load. It is worth noting that a preload was slowly introduced in the column to prevent slipping of the column and fix it. After ensuring the stability of the column, loading was applied. Displacement obtained from two LVDTs and load capacity were recorded. The test setup and equipment are given in Fig. 6. Fig. 7 indicates the overall experiment system of the short columns and the position of LVDTs.

5 Numerical simulation

In this research, the samples were modeled three-dimensionally using ABAQUS software. All samples were meshed by 3D stress 20-node quadratic brick elements (C3D20R) with reduced integration, which generally acquire good results. According to conducted convergence



Fig. 6 Test setup and equipment

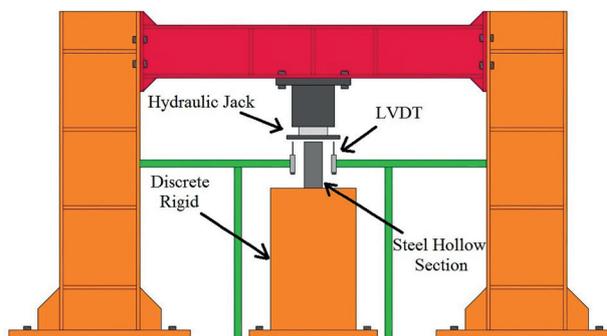


Fig. 7 columns under hydraulic jack and installation of LVDTs

tests, a mesh size of 5 mm was found to be appropriate to comply with experiments. The properties of steel and adhesive were assumed as non-linear and CFRP fibers were defined as orthotropic and linear since CFRP materials have unidirectional properties [36]. To define CFRP

material in ABAQUS, laminar behavior was considered, with negligible magnitude for shear modulus since in-plane shear strength is considerably lower than the normal tensile strength. Although there might be a negligible slip in bonds in experiments, interaction between CFRP, adhesive, and steel was characterized by tie contact. Since all steel tubes are non-slender and short, no imperfection was applied in the FE model. Nonlinear effects of large deformations were taken into account. In order to verify the software, square sections from Bambach and Elchalakani [17] and circular sections from Teng and Hu [23] were used. In Fig. 8, the force-displacement curves of specimens $75 \times 75 \times 2$ (Bambach and Elchalakani) and F0, F1 (Teng and Hu) are shown. These curves are similar to the responses obtained through software modeling, which illustrates acceptable accuracy of the analysis.

6 Results and discussions

In order to investigate the effect of CFRP fibers on the axial capacity and study the failure modes of CFRP strengthened short columns, both numerical and experimental methods have been carried out. The results display that the usage of CFRP fibers is very promising for restoring short compression members to their primary resistance and decrease stress intensity around the damaged zone. For the reason that circular tubular members

show different buckling behavior compared to square elements, short columns were discussed by cross-section. All results related to the failure modes, load-bearing capacity, and deficiencies' effects are discussed in the following sections.

6.1 Failure modes

All steel columns were subjected to axial compression; the load was gradually applied to the column until failure. Short steel columns generally failed by local buckling, while for control columns elephant's foot collapse occurred for both square and circular sections, as shown in Fig. 9. Regarding horizontally deficient columns, by increasing loading the amount of stresses around the deficiency increased, which caused local buckling around the defect. For the square specimens, outward local buckling occurred on the flange next to the deficiency followed by overall buckling of the column and local buckling at the load location (top of the column). In the circular columns, buckling was symmetrical, so collapse at the edges of the defect and outward buckling on both sides of the defect occurred. Fig. 10 indicates the failure mode of horizontally notched columns. The circular columns show better structural performance than the square ones, which exhibited overall buckling.

In square specimens with vertical defect, the deficient flanges showed inward local buckling because of stress concentration; subsequently, flanges on both sides of the defect showed tendency to outward buckling. For circular samples with vertical defect, the dimensions of the defect increased in size with increasing stresses, which resulted in a considerable opening, and outward buckling appeared on both sides of the deficiency (Fig. 11). This opening caused the structural function of the column to become more critical. It should be noted that for the square samples the opening of the defect did not happen.

The use of CFRP fibers with regard to the confinement of the column is a suitable method for retrofitting, which delays local buckling of the column. Concerning specimens with CFRP fibers, no delamination was observed before reaching the ultimate load state, which indicated good adhesive behavior between steel and fibers. Due to the increasing stresses surrounding the defect that were transmitted to the adhesive and CFRP during loading, rupture and delamination were observed around the defect for both square and circular sections with horizontal and vertical deficiency (Figs. 12 and 13). As a result of the symmetrical deformation of circular columns with horizontal

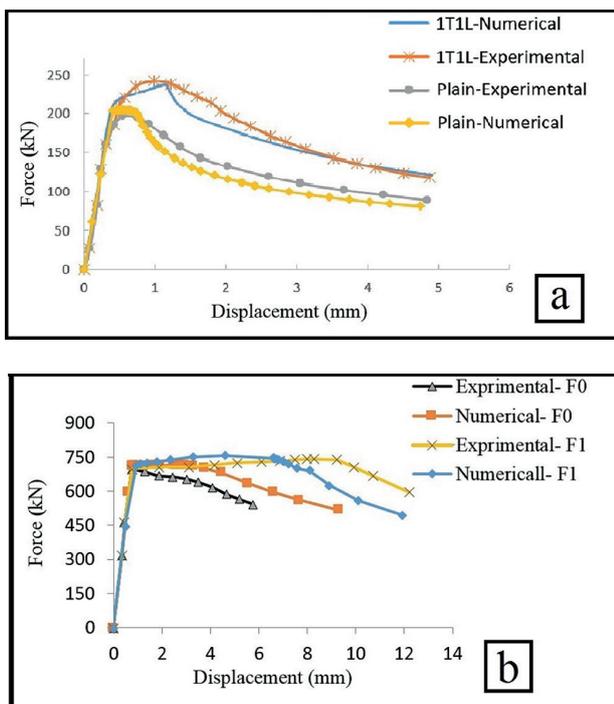


Fig. 8 Force-Displacement validation of specimens: (a) $75 \times 75 \times 2$ from Bambach and Elchalakani [17], (b) F0 and F1 from Teng and Hu [23]

deficiency, there is a negligible amount of debonding and delamination at the top of the column. In contrast, square columns exhibited overall buckling because of local buckling at the flange nearby the deficiency, which was followed by the rise of stresses between steel, adhesive and CFRP on the upper edge, that caused a significant amount of debonding, delamination and sometimes rupture. Fig. 14 shows the failure modes at the top of square columns.



Fig. 9 Experimental and numerical elephant's foot collapse of control columns

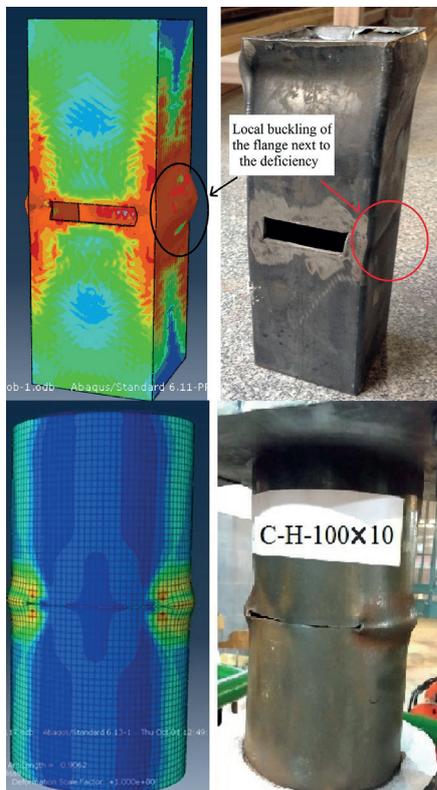


Fig. 10 Experimental and numerical failure mode of specimens with horizontal deficiency

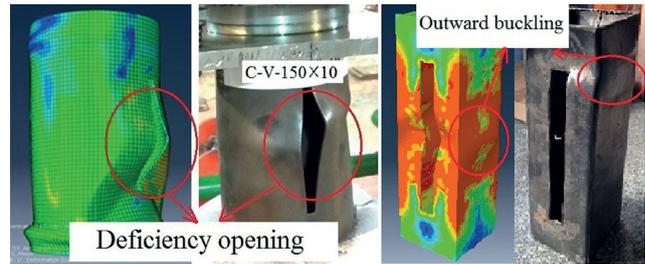


Fig. 11 Failure modes of tested columns with vertical deficiency

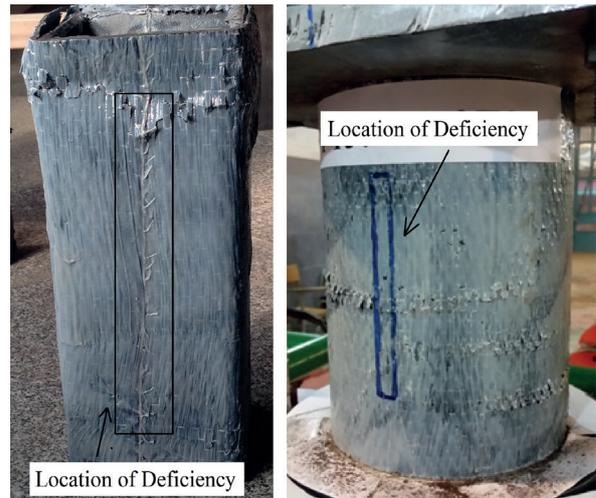


Fig. 12 CFRP rupture and delamination at defect zone for strengthened columns with horizontal deficiency

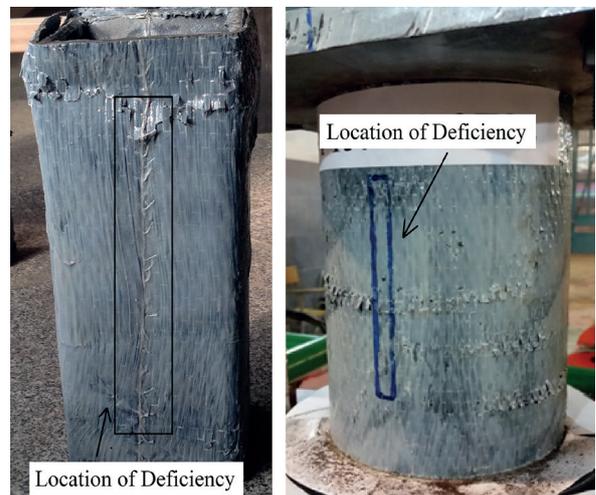


Fig. 13 CFRP rupture and delamination at defect zone for strengthened columns with vertical deficiency



Fig. 14 Delamination, debonding, and rupture at the top of square columns

6.2 Load-bearing capacity

The main factors investigated in this paper are the effect of deficiencies, the influence of CFRP fibers on the ultimate carrying capacity of steel columns. Table 3 shows the axial capacity of all tested columns, along with the corresponding variation of the load capacity relative to the control columns in percentage. The results indicate that the maximum reduction in bearing capacity occurs in the S-H-60 × 20 specimen with a decrease of 35.34 %. This specimen presented the highest reduction in cross-section (perpendicular to the axial load) which led to smaller area of section. This decline in area of section caused a higher level of stress distributed around deficiency which consequently induced a decrease of strength. Nevertheless, the column behavior is significantly improved by using four CFRP layers, which compensate completely the weakness due to defects. From the comparison of the results, it can be seen that horizontal defects create a more critical state than vertical defects for both circular and square sections. It was also noticeable that for specimens S-H-45 × 10, S-H-45 × 20, S-H-60 × 10, and S-H-60 × 20, by increasing the dimension of deficiency perpendicular to the axial load, the ultimate load reduces more; however, this was not seen for the dimension parallel to the axial load since the increase of stresses nearby defects brings about yielding. In the column S-H-60 × 10 with horizontal defect, the ratio between the defect length and the perimeter of the cross-section is 16.67 %, and for the column C-H-100 × 10, this ratio is 19.29 %. According to Table 3, although this ratio is higher in the circular column, the decrease of bearing capacity for the square column is more considerable, while both sections have the same thickness. This indicates better structural performance of the deficient circular columns in comparison with the square ones. Carbon composites used to reinforce the columns increased the carrying capacity by 23.7 to 47.2 %. From Figs. 15–18, by comparing axial force-displacement curves obtained by experiments, it can be seen that the use of CFRP fibers postpones local buckling and gains load bearing capacity which consequently leads to structural improvement of the short columns.

6.3 Effect of artificial deficiencies

Table 3 shows that deficiencies created in steel columns significantly reduce the resistance of square tubes and circular ones up to 35.34 % and 19.17 %, respectively. In addition to ten specimens, three more numerical cases (S-H-45 × 10, S-H-45 × 20, S-H-60 × 10) were examined to assess the

effect of deficiency width. By comparing the orientations of deficiency, it can be observed that the reduction of resistance is much more critical for specimens with horizontal defects than for those with vertical defects.

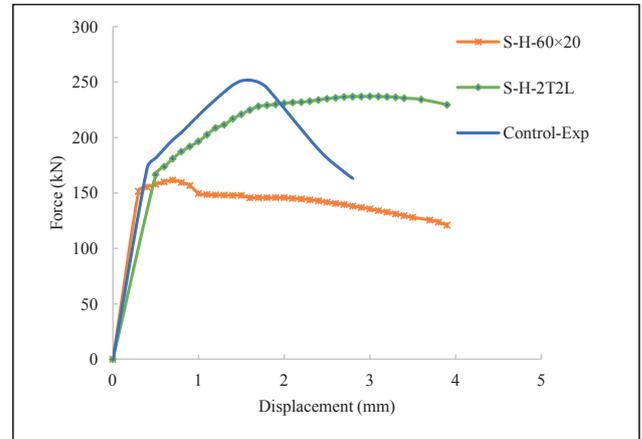


Fig. 15 Experimental force-displacement curves for square specimens with horizontal deficiency

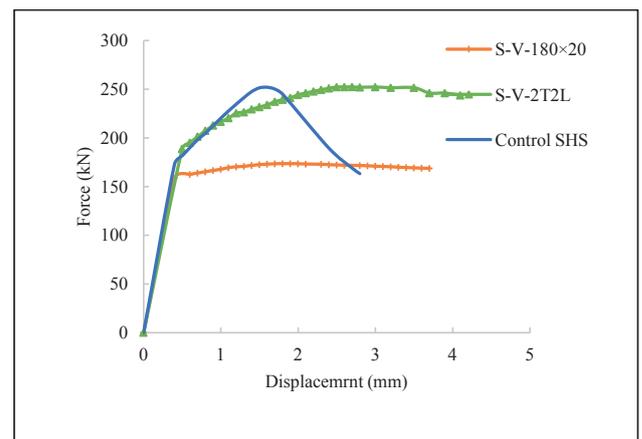


Fig. 16 Experimental force-displacement curves for square specimens with vertical deficiency

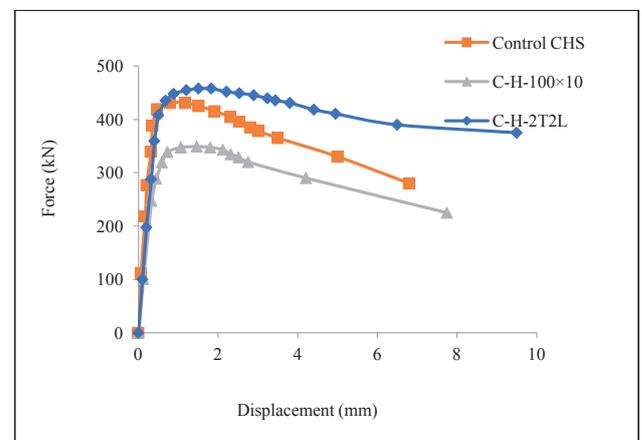


Fig. 17 Experimental force-displacement curves for circular specimens with horizontal deficiency

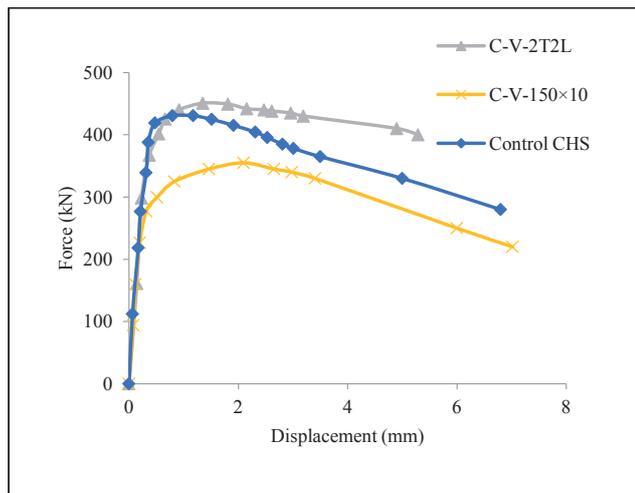


Fig. 18 Experimental force-displacement curves for circular specimens with vertical deficiency

7 Conclusions

The effects of CFRP retrofitting on steel circular and square short deficient columns were studied. In the modeling of the columns by using the ABAQUS finite element software, nonlinear analysis was used to determine the failure mode and observe post-buckling failure. The columns were examined with initial vertical and horizontal defects, and strengthened with four layers of CFRP fibers. In column samples, the effect of the horizontal defect was very significant compared to the vertical one, meaning that further increase in the defect dimension perpendicular to

the load will decrease sharply the ultimate load capacity. The declines observed were 35.34 % for square columns and 19.17 % for circular columns. At the beginning of the loading, due to the fact that, for horizontal defect, a large part of the deficient cross-section is perpendicular to the loading, the axial load-resistance level has been reduced and the intensity of stresses around the defect has increased, resulting in shrinkage of the defect edges. In order to compensate the reduced load capacity, four CFRP layers were used transversally and longitudinally. Use of CFRP materials increased the ultimate bearing capacity up to 47.2 %. The results showed that the fibers not only compensated the reduced bearing capacity, but also had a significant effect on reducing the stress around the defect and preventing the expansion of defects, and in general, these fibers had a direct effect on the increase of ductility and delaying local buckling. For strengthened columns, the failure modes included rupture, delamination and debonding at the ends of the columns.

Acknowledgement

Islamic Azad University, Zahedan Branch, Zahedan, Iran, and Iranian Construction Engineering Organization, Sistan and Baluchestan Province, Zahedan, Iran, financially supported the study presented here. The authors would like to record their appreciation for the supports.

References

- [1] Bakis, C. E., Bank, L. C., Brown, V. L., Cosenza, E. "Fiber-Reinforced Polymer Composites for Construction – State-of-the-Art Review", *Journal of Composites for Construction*, 6(2), pp. 73–87, 2002. [https://doi.org/10.1061/\(ASCE\)1090-0268\(2002\)6:2\(73\)](https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(73))
- [2] Hollaway, L. C., Head, P. R. "Advanced Polymer Composites and Polymers in the Civil Infrastructure", 1st ed., Elsevier Science, Oxford, UK, 2001. <https://doi.org/10.1016/B978-0-08-043661-6.X5000-1>
- [3] Tumialan, G., Nanni, A., Ibell, T., Fukuyama, H. "FRP composites for strengthening civil infrastructure around the world", *Sample Journal* 38(5), pp. 9–15, 2002.
- [4] Teng, J. G., Yu, T., Fernando, D. "Strengthening of steel structures with fiber-reinforced polymer composites", *Journal of Constructional Steel Research*, 78, pp. 131–143, 2012. <https://doi.org/10.1016/j.jcsr.2012.06.011>
- [5] Harries, K. A., Abraham, E. J., Peck, A. "FRP-Stabilised steel compression members", In: *Asia-Pacific Conference on FRP in Structures (APFIS 2007)*, Hong Kong, China, 2007, pp. 987–992.
- [6] Kalavagunta, S., Naganathan, S., Bin Mustapha, K. N. "Proposal for design rules of axially loaded CFRP strengthened cold formed lipped channel steel sections", *Thin-Walled Structures*, 72, pp. 14–19, 2013. <https://doi.org/10.1016/j.tws.2013.06.006>
- [7] Feng, P., Zhang, Y., Bai, Y., Ye, L. "Strengthening of steel columns in compression by mortar-filled FRP tubes", *Thin-Walled Structures*, 64, pp. 1–12, 2013. <https://doi.org/10.1016/j.tws.2012.11.001>
- [8] Sundararaja, M. C., Prabhu, G. G. "Experimental study on CFST columns strengthened by CFRP composites under compression", *Journal of Constructional Steel Research*, 72, pp. 75–83, 2012. <https://doi.org/10.1016/j.jcsr.2011.10.014>
- [9] Prabhu, G. G., Sundararaja, M. C. "Behaviour of concrete filled steel tubular (CFST) short columns externally reinforced using CFRP strips composite", *Construction and Building Materials*, 47, pp. 1362–1371, 2013. <https://doi.org/10.1016/j.conbuildmat.2013.06.038>
- [10] He, D., Dong, J., Wang, Q., Chen, X. "Mechanical behaviour of recycled concrete filled steel tube columns strengthened by CFRP", In: *The 2nd International Conference on Multimedia Technology*, Hangzhou, China, 2011, pp. 1110–1113. <https://doi.org/10.1109/ICMT.2011.6002838>
- [11] Tao, Z., Han, L.-H., Zhuang, J.-P. "Using CFRP to strengthen concrete-filled steel tubular columns: Stub column tests", In: *Proceedings of the Fourth International Conference on Advances in Steel Structures*, Shanghai, China, 2005, pp. 701–706. <https://doi.org/10.1016/B978-008044637-0/50103-7>

- [12] Dong, J. F., Wang, Q. Y., Guan, Z. W. "Structural behaviour of recycled aggregate concrete filled steel tube columns strengthened by CFRP", *Engineering Structures*, 48, pp. 532–542, 2013.
<https://doi.org/10.1016/j.engstruct.2012.11.006>
- [13] Wang, Q.-L., Zhao, Z., Shao, Y.-B., Li, Q.-L. "Static behavior of axially compressed square concrete filled CFRP-steel tubular (S-CF-CFRP-ST) columns with moderate slenderness", *Thin-Walled Structures*, 110, pp. 106–122, 2017.
<https://doi.org/10.1016/j.tws.2016.10.019>
- [14] Haedir, J., Zhao, X.-L. "Design of short CFRP-reinforced steel tubular columns", *Journal of Constructional Steel Research*, 67(3), pp. 497–509, 2011.
<https://doi.org/10.1016/j.jcsr.2010.09.005>
- [15] Shaat, A., Fam, A. "Axial loading tests on CFRP-retrofitted short and long HSS steel columns", *Canadian Journal of Civil Engineering*, 33(4), pp. 458–470, 2006.
<https://doi.org/10.1139/105-042>
- [16] Bambach, M. R. "Axial capacity and crushing behavior of metal-fiber square tubes – Steel, stainless steel and aluminum with CFRP", *Composites Part B: Engineering*, 41(7), pp. 550–559, 2010.
<https://doi.org/10.1016/j.compositesb.2010.06.002>
- [17] Bambach, M. R., Elchalakani, M. "Plastic mechanism analysis of steel SHS strengthened with CFRP under large axial deformation", *Thin-Walled Structures*, 45(2), pp. 159–170, 2007.
<https://doi.org/10.1016/j.tws.2007.02.004>
- [18] Bambach, M. R., Elchalakani, M., Zhao, X. L. "Composite steel-CFRP SHS tubes under axial impact", *Composite Structures*, 87(3), pp. 282–292, 2009.
<https://doi.org/10.1016/j.compstruct.2008.02.008>
- [19] Bambach, M. R., Jama, H. H., Elchalakani, M. "Axial capacity and design of thin-walled steel SHS strengthened with CFRP", *Thin-Walled Structures*, 47(10), pp. 1112–1121, 2009.
<https://doi.org/10.1016/j.tws.2008.10.006>
- [20] Bambach, M. R., Jama, H. H., Elchalakani, M. "Static and dynamic axial crushing of spot-welded thin-walled composite steel-CFRP square tubes", *International Journal of Impact Engineering*, 36(9), pp. 1083–1094, 2009.
<https://doi.org/10.1016/j.ijimpeng.2009.03.002>
- [21] Sivasankar, S., Thilakranjith, T., Sundararaja, M. C. "Axial behavior of CFRP jacketed HSS tubular members an experimental investigation", *International Journal of Earth Sciences and Engineering*, 5(6), pp. 1729–1737, 2012.
- [22] Sundararaja, M. C., Sivasankar, S. "Behaviour of CFRP jacketed HSS tubular columns under compression an experimental investigation", *Journal of Structural Engineering*, 39(5), pp. 574–582, 2013.
- [23] Teng, J. G., Hu, Y. M. "Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression", *Construction and Building Materials*, 21(4), pp. 827–838, 2007.
<https://doi.org/10.1016/j.conbuildmat.2006.06.016>
- [24] Touhari, M., Mitiche-Kettab, R. "Behaviour of FRP Confined Concrete Cylinders: Experimental Investigation and Strength Model", *Periodica Polytechnica Civil Engineering*, 60(4), pp. 647–660, 2016.
<https://doi.org/10.3311/PPci.8759>
- [25] Cinitha, A., Umesha, P. K., Iyer, N. R. "An overview of corrosion and experimental studies on corroded mild steel compression members", *KSCE Journal of Civil Engineering*, 18(6), pp. 1735–1744, 2014.
<https://doi.org/10.1007/s12205-014-0362-0>
- [26] Elchalakani, M. "CFRP strengthening and rehabilitation of degraded steel welded RHS beams under combined bending and bearing", *Thin-Walled Structures*, 77, pp. 86–108, 2014.
<https://doi.org/10.1016/j.tws.2013.12.002>
- [27] Yousefi, O., Narmashiri, K., Ghaemdoust, M. R. "Structural behaviors of notched steel beams strengthened using CFRP strips", *Steel and Composite Structures*, 25(1), pp. 35–43, 2017.
<https://doi.org/10.12989/scs.2017.25.1.035>
- [28] Ghaemdoust, M. R., Narmashiri, K., Yousefi, O. "Structural behaviors of deficient steel SHS short columns strengthened using CFRP", *Construction and Building Materials*, 126, pp. 1002–1011, 2016.
<https://doi.org/10.1016/j.conbuildmat.2016.09.099>
- [29] Huang, C., Chen, T., Wang, X. "Compressive characteristics of damaged circular hollow section (CHS) steel columns repaired by CFRP or grout jacketing", *Thin-Walled Structures*, 119, pp. 635–645, 2017.
<https://doi.org/10.1016/j.tws.2017.07.008>
- [30] Chen, Y., Wan, J., He, K. "Experimental investigation on axial compressive strength of lateral impact damaged short steel columns repaired with CFRP sheets", *Thin-Walled Structures*, 131, pp. 531–546, 2018.
<https://doi.org/10.1016/j.tws.2018.07.026>
- [31] Hamood, M. J., Ghaddar, M. G., Husain, Z. A. A. "Performance of deficient steel hollow square section short column strengthened with CFRP", *ARNP Journal of Engineering and Applied Sciences*, 13(19), pp. 8032–8043, 2018. [online] Available at: http://www.arpn-journals.org/jeas/research_papers/rp_2018/jeas_1018_7301.pdf [Accessed: 10 July 2019]
- [32] Shahabi, R., Narmashiri, K. "Effects of deficiency location on CFRP strengthening of steel CHS short columns", *Steel and Composite Structures*, 28(3), pp. 267–278, 2018.
<https://doi.org/10.12989/scs.2018.28.3.267>
- [33] Keykha, A. H. "Structural performance evaluation of deficient steel members strengthened using CFRP under combined tensile, torsional and lateral loading", *Journal of Building Engineering*, 24, Article ID: 100746, 2019.
<https://doi.org/10.1016/j.job.2019.100746>
- [34] AISC "AISC 360-16 Specification for Structural Steel Buildings", American Institute of Steel Construction, Chicago, IL, USA.
- [35] Sika, Sikadur®-330 Product Data Sheet [computer program] Available at: https://irn.sika.com/en/solutions_products/construction-markets/sika-structural-strengthening-solutions/02a013/02a013sa09.html [Accessed: 10 July 2019]
- [36] Linghoff, D., Haghani, R., Al-Emrani, M. "Carbon-fibre composites for strengthening steel structures", *Thin-Walled Structures*, 47(10), pp. 1048–1058, 2009.
<https://doi.org/10.1016/j.tws.2008.10.019>