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Effects of Vertical Deficiency Location on the Structural Behavior of Steel SHS Short Columns

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ABSTRACT: Structures that face damage require strengthening to reach the initial performance. Strengthening steel Square Hollow Section (SHS) short columns with initial deficiencies were not taken into account appropriately. In this paper, vertical deficiencies with the same dimensions were created at three locations (top, middle, and bottom) on the middle element and the middle of the corner element. Then, the effect of the location of such deficiencies on axial behavior of Carbon Fiber Reinforced Polymer (CFRP) strengthened steel tubular columns was investigated. To this end, a total of nine steel columns were experimentally tested and the same specimens were modeled using ABAQUS V.6.14. In the experimental work, a straight pressure test was performed. In the numerical simulation, three dimensional (3D) simulation method, static gradual loading, and non-linear static analysis were used. The specimens were: no deficiency (Control), four non-strengthened columns with deficiencies at different locations, and four CFRP strengthened specimens having deficiencies. The results showed that vertical deficiencies caused a significant decrease in load-bearing capacity and initial performance. As a result of axial loading, the area of vertical deficiencies experienced local buckling increase and lateral rupture. Local bucking at damaged locations caused the stress concentration, then the axial deformation increased. Vertical deficiencies at the bottom of the middle element caused the most critical conditions. Vertical deficiencies on the corner element led to greater destruction and bearing capacity decline compared to the middle element. Carbon Fiber played a key role in ductility and strength increase around the deficiency by covering it. Using CFRP layers the stress concentration overcame and the local buckling delayed due to high confining strength.

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1. INTRODUCTION

Today, there is a wide range of steel columns. Tubular sections are the most widely used ones. Because of their high strength to weight ratio, they are capable of absorbing energy in steel structures. These structures might not be able to meet the structural requirements due to different reasons including design and calculation errors, environmental factors, decay, and fire. Therefore, it is essential to strengthen and improve the element performance. CFRP strengthening is one of the most updated techniques in structures. FRP composites are the subject of interest due to different reasons such as high resistance and hardness, corrosion resistance, flexibility, and ease of use. In recent decades, using carbon fiber has not interested researchers as a constructional material for strengthening steel structures compared to concrete ones. The studies were mainly on the flexure and shear reinforcement of steel beams.

Teng and Hu investigated the performance increase of hollow steel tubes strengthened by Glass Fiber Reinforced Polymer (GFRP) on thin-walled elements under axial compression. In their study, four steel tubes (with and without GFRP) were analyzed. They found out that GFRP with transverse constraints increases flexibility [1]. Jiao and Zhao used CFRP to strengthen butt-welded steel tubes. They found out that the tensile strength increased by 25%-76% [2]. The study by Shaat and Fam showed that transverse CFRP layers were effective in limiting external local buckling of short columns. The layers increased the bearing capacity of short columns up to 18% and tall columns by 13%-23% [3]. Gao et al. strengthened steel hollow steel tubes with CFRP sheets. They found out that an increase was seen in strength and stiffness [4]. He et al. studied the behavior of recycled and conventional concrete-filled steel tubes strengthened by CFRP. A total of 10 CFRP-strengthened circular columns were experimentally tested. CFRP increased the ductility and bearing capacity. An increasing number of layers caused the bearing capacity to rise. Stiffness rises by complete wrapping. The study showed that using CFRP caused increasing compressive capacity and buckling load. Semi-wrapped CFRP had less axial compressive strain than the full wrapping [5]. Sundarraja and Prabhu experimentally studied the stress-strain behavior, ultimate bearing capacity, and failure modes of CFRP-strengthened CFST columns. They wrapped the carbon fiber strips around the column. They also considered some factors such as thickness and distance

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between strips. As the distance increased between CFRP strips, buckling occurs in parts without fiber. More layers had a better effect on controlling the axial deformation. Observing the proper distance between CFRP strips is essential to delay buckling, increase ultimate bearing capacity, and axial stress-strain behavior [6]. Dong et al. studied concrete-filled steel columns strengthened by CFRP. They studied 22 specimens. Some parameters such as strengthening method, type of concrete, and section were taken into account. They concluded that CFRP warping on hollow and filled circular columns displayed better results than square sections [7]. Feng et al. studied mortar-filled steel tubes strengthened by FRP. After strengthening, middle failure changed into local destruction and the resistance increased against buckling. Less thin specimens' local destruction occurred at the end of the element. Thinner specimens experienced buckling. Bearing capacity and ductility increased [8]. Prabiu and Sundarraja studied the effect of distance of CFRP strips on CFST strengthening. Out of 21 specimens, they strengthened 18 specimens with CFRP by considering some factors such as thickness, width, and distance of CFRP strips. They found out that CFRP strips prevent lateral deformation and delay the local buckling. The number of layers and the observation of proper distance control the lateral deformation and increase the bearing capacity. Failure more was seen up to 30 mm CFRP strips. Over 30 mm, the column experienced local buckling [9]. Bamabch and Elchalakani used steel SHS strengthened with CFRP under axial pressure and realized that CFRP increases the resistance and energy of the sections under pressure [10]. Bambach et al. strengthened the steel SHS strengthened with CFRP with welded edges. The specimens underwent axial pressure. They investigated a total of 20 strengthened specimens undergoing pressure theoretically and in the laboratory. They investigated the axial capacity of the sections and found out that using CFRP doubles the axial capacity and one-half times the resistance to weight ratio [11]. Bambach et al. conducted a lab study on the use of CFRP for strengthening steel-CFRP SHS tubes undergoing axial impact. They found out that CFRP increased the energy absorption and resistance [12]. Bambach et al. investigated the spot-welded thin-walled composite steel-CFRP tubes under static and dynamic axial crushing. They studied some steel tubes theoretically in the laboratory. They used axial crushing in the laboratory and compared the static and dynamic behavior. As a result, they found that using CFRP increased energy absorption [13]. Haedie and Zhao studied the effect of transverse and longitudinal CFRP strengthening of 10 short columns in the laboratory. They concluded that the transverse and longitudinal combination of CFRP increased the yield capacity. The greater amount of CFRP caused a delay in buckling [14]. Sivasankar et al. studied the failure modes, stress-strain behavior, and ultimate bearing capacity of CFRP jacketed HSS tubular members. Some 600mm steel columns were strengthened by two configurations of fiber in the laboratory. Attaching CFRP was found to be effective in increasing the bearing capacity and stiffness and delaying the buckling. Increasing the load caused the rupture of CFRP [15]. Kalavagunta et al. studied the cold-formed lipped channel strengthened with CFRP under axial pressure. In their experimental study, they investigated the channel column in two ways: attaching fiber to the whole columns and attaching to the web. They found out that the bearing capacity increased in fully reinforced specimens by up to 16.75% and web-reinforced specimens by up to 10.26%. Reduced capacity and sudden failure were observed due to delamination and CFRP detachment. Using CFRP increased the bearing capacity. It was also concluded that surface preparation and temperature were two important factors for obtaining proper adhesiveness between steel and fiber [16]. Sundarraja and Sivasankar strengthened 12 CFRP jacketed HSS tubular columns. They took the number of layers and CFRP strip distances into account in the laboratory. They concluded that CFRP increased the bearing capacity and delayed the lateral buckling. Transverse use of fiber increased the stiffness, bearing capacity, and axial deformation compared to the longitudinal use [17].

Another recent research investigated the effects of CFRP strengthening steel deficient short tubes [18-22]. They studied the behavior of steel tubular columns with deficiencies under axial loading in the lab and numerically. In their study, vertical and horizontal deficiencies in the middle of the steel column were strengthened by CFRP. They realized that CFRP sheets for strengthening tubular columns can significantly compensate for the lost strength due to the deficiencies. Note that they aimed to use CFRP for improving the performance of damaged members. As mentioned above, most studies in this regard focused on strengthening and restoring the tubular columns. Only a few studies focused on columns with primary deficiencies. As a result, few experimental results have been presented in this regard.

This article aimed to study the effect of the dimension and location of vertical deficiencies (top, middle, and bottom of middle member and middle of corner element) of Steel-Tube Short Columns strengthened with CFRP both experimentally and numerically using ABAQUS V6.14.2. The location of vertical deficiencies was considered in two modes (corner and middle of columns).

2. MATERIALS AND METHODS

2.1. Steel profiles

In this study, nine steel tube specimens (1 normal specimen, 4 specimens with a deficit, and 4 specimens with deficit strengthen by CFRP) were investigated. Fig.1 shows the specimens with vertical 20-200 mm deficits on the middle and corner elements at the top, middle, and bottom locations. NC was used to create vertical deficits. Table 1 lists the mechanical properties of steel specimens.

2.2. CFRP layers

To strengthen and improve the performance of steel tubes with deficiency, unidirectional SikaWrap®-230 C was used to reach the initial performance of the compressive element. The column was fully wrapped by CFRP. Therefore, two 220mm transverse CFRP layers (one transverse and one longitudinal

Table 1. Properties of steel specimens

Modulus of Elasticity (Gpa)	Yield Strength (Mpa)	Ultimate Stress (Mpa)	Ultimate Strain (%)
200	330	336	22

Table 2. CFRP specifications

Material	Thickness (mm)	Tensile Strength (Mpa)	Modulus of Elasticity (Gpa)	Ultimate Strain (%)
CFRP (SikaWrap®-230 C)	0.131	4300	238	1.8

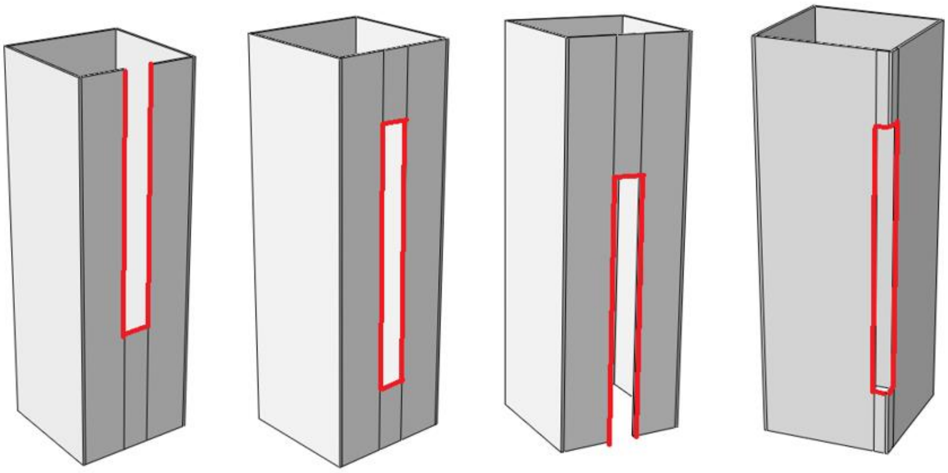


Fig. 1. Vertical deficiency of the steel columns.

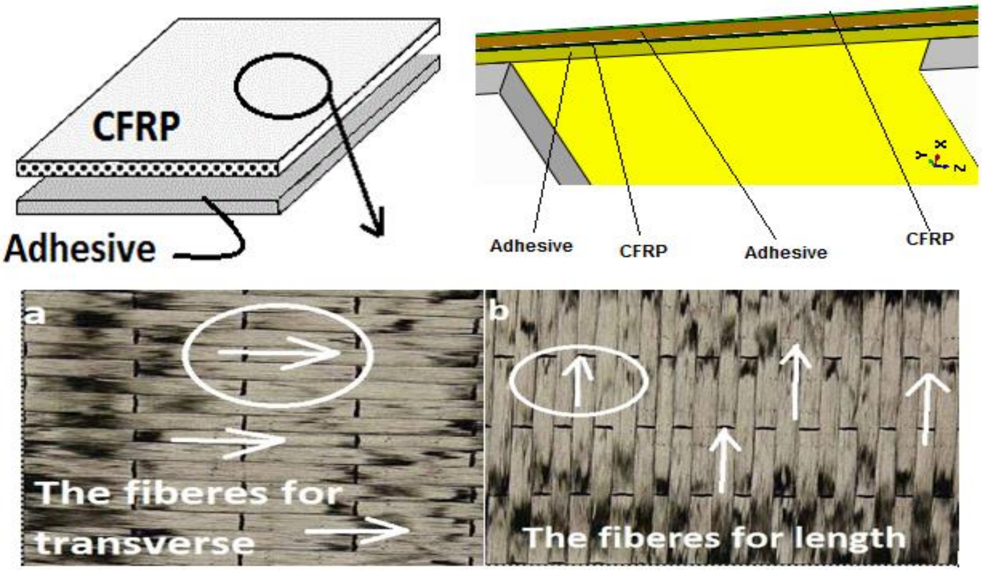


Fig. 2. CFRP sheets: transverse and longitudinal fibers.

layer) and four longitudinal 440mm (two transverse and two longitudinal layers) were used to cover the whole height. Note that a 20 mm overlap was used for each of the CFRP layers. Table 2 shows CFRP specifications. Fig.2 shows the position of CFRP on steel columns.

2.3 Adhesive

Resin epoxy (Sikadur®-330) was used to attach the CFRP

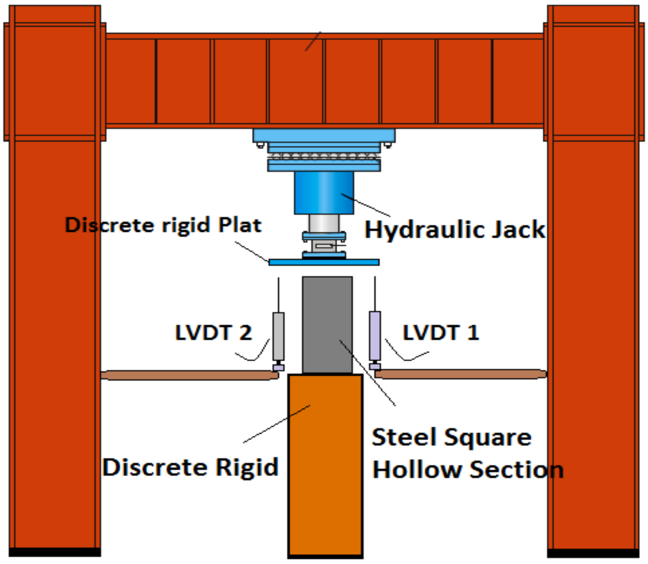


Fig. 3. Experimental test setup.

Table 3. Adhesive specifications

Material	Thickness (mm)	Tensile Strength (Mpa)	Modulus of Elasticity (Gpa)	Ultimate Strain (%)
Adhesive (*Sikadur*®-330)	0.869	30	4.5	0.9

Table 4. Specifications of the specimens

No	Specimen	Deficiency vertical (mm)			CFRP layers	Load-bearing Capacity (kN)		Increase/decrease (%)	
		Length	Width	Location		Experimental	Numerical	Experimental	Numerical
1	Control	N/A	N/A	N/A	N/A	241	235	-	-
2	MVTD	200	20	Middle-top	N/A	226	219	-7.46	-6.80
3	MVTD-2T2L	200	20	Middle-top	4	394	390	63.48	65.95
4	MVD	200	20	Middle-middle	N/A	225	219	-7.46	-6.80
5	MVD-2T2L	200	20	Middle-middle	4	391	385	62.24	63.82
6	MVBD	200	20	Middle-bottom	N/A	224	219	-7.05	-6.80
7	MVBD-2T2L	200	20	Middle-bottom	4	376	373	56.01	58.72
8	CVD	200	20	Corner-middle	N/A	210	206	-12.86	12.34
9	CVD-2T2L	200	20	Corner-middle	4	384	381	59.33	62.12

Table 5. Comparison between experimental and numerical results

No.	Dimension (mm)	Height (mm)	CFRP Layers	Experimental critical load (kN) Bambach and AlChalakany [10]	Numerical critical load (kN)	Diff. (%)
1	2*100*100	300	0	238.4	240	0.67
2	2*100*100	300	2	238	236	0.59
3	2*100*100	300	4	425	422.8	0.51

to the steel tube. Carbon layers were used to improve the performance of steel tubes. Note that the adhesive must be capable of enduring stress and adhesion resistance. Table 3 shows the adhesive properties.

3. SPECIFICATIONS OF SPECIMENS

In this study, nine specimens were investigated. As it can be seen in Fig.1, the deficiencies were created in the middle and corner elements at the top, middle, and bottom separately. According to Table, the abbreviation of specimens is tabulated. The locations are shown with C (Corner) and M (Middle). The vertical deficiency was shown by (H, D) and the last letter shows the location of deficiency. Note that the number and type of CFRP placement are shown with T, L, showing Transverse and Longitudinal layers, respectively. Experimental (EX) and Numerical (NU) specimens were investigated. Table 4 shows the specifications of steel columns. According to Table 4, the Control specimen has no deficiency and is not strengthened. MVTD specimens have a deficiency at the middle-top. MVD specimens have a deficiency at the middle-middle of the column. MVBD specimens have a deficiency at the middle-bottom of the column, and CVD specimens have a deficiency at the corner-middle of the column. The strengthened specimens using 4 CFRP layers (2 longitudinal and 2 transverse layers) for each specimen category is named 2T2L.

To experimentally investigate the performance of Steel-Tube Short Columns and study the effect of CFRP on axial load strengthening, the specimens were placed under the hydraulic jack. Force was axially imposed by the jack. In this case, the specimens were just subjected to static gradual axial load until failure. Displacement was measured by two LVDTs and saved in the software package. Fig.3 shows the experimental test setup.

4. NUMERICAL SIMULATION

To ensure the software accuracy of Steel-Tube Short Columns strengthened by CFRP layers, the experimental results of the study by Bambach and Al Chalakany (2007) were used for calibration [10]. In their study, a 100*100*2 steel tube (Height: 300 mm) was used. Table 5 shows the results. To investigate the effective parameters in steel column behavior, conducting experiments would be costly and time-taking. Therefore, simulation using Finite Element (FE) can provide a proper model for the test on a real scale. If the simulation is properly done, beneficial results would be expected. Finite Element is a numerical method for linear and non-linear engineering problems. The specimens were analyzed using ABAQUS V.6.14.2. Isotropic specimens (steel columns, adhesive, and CFRP) were selected using 3-D elements. Various meshes were selected. Non-linear static simulation was used. Table 5 show good agreement between numerical simulation and experimental.

5. RESULTS AND DISCUSSION

5.1 Load bearing capacity

A control specimen (non-strengthened steel columns without deficiency) was used to compare the results. Investigations were based on force-displacement graphs to study the effect of the location of deficiency of steel columns strengthened by CFRP. As it is evident from Table 4, the control specimen tolerated 241 KN as a result of axial load (Fig.4). Also, good agreement between numerical simulation and experimental results is shown in Fig.4.

This article aimed to determine the effect of the location of vertical deficiency of Steel-Tube Short Columns. Vertical deficiencies were studied at three locations (top, middle, and bottom) of the middle element and middle of the corner element. The dimension of vertical deficiency is 20*200 mm. The results showed that vertical deficiencies had a significant effect on axial deformation of the range of deficiency and reduction of stiffness and load-bearing capacity.

MVTD200-20 is the deficiency at the top of the middle element. As it is shown in Fig.5a, the load-bearing capacity of the damaged column declined by 7.46% compared to the control sample after imposing vertical deficiency. Displacement increased by 9.23% compared to the control sample. Using four longitudinal and transverse CFRP layers coupled with enclosed deficiency area increased the bearing capacity of damaged columns by almost 390 KN, which is 63.48% compared to the control specimen (Fig.5b).

MVD200-20 was the deficiency in the middle of the middle element. Load-bearing capacity and deformation are 12% and 7.46% compared to the control specimen. CFRP strengthening of this specimen increased ductility and bearing capacity by almost 385 KN, which is 62.24% compared to the control specimen. Deficiencies at the bottom of the middle element (MVBD200-20) reduced bearing capacity by almost 219 KN, which is 7.05% compared to the control specimen. Vertical deficiency at this location caused the most critical mode in the middle element. Longitudinal and transverse CFRP strengthening increased bearing capacity by almost

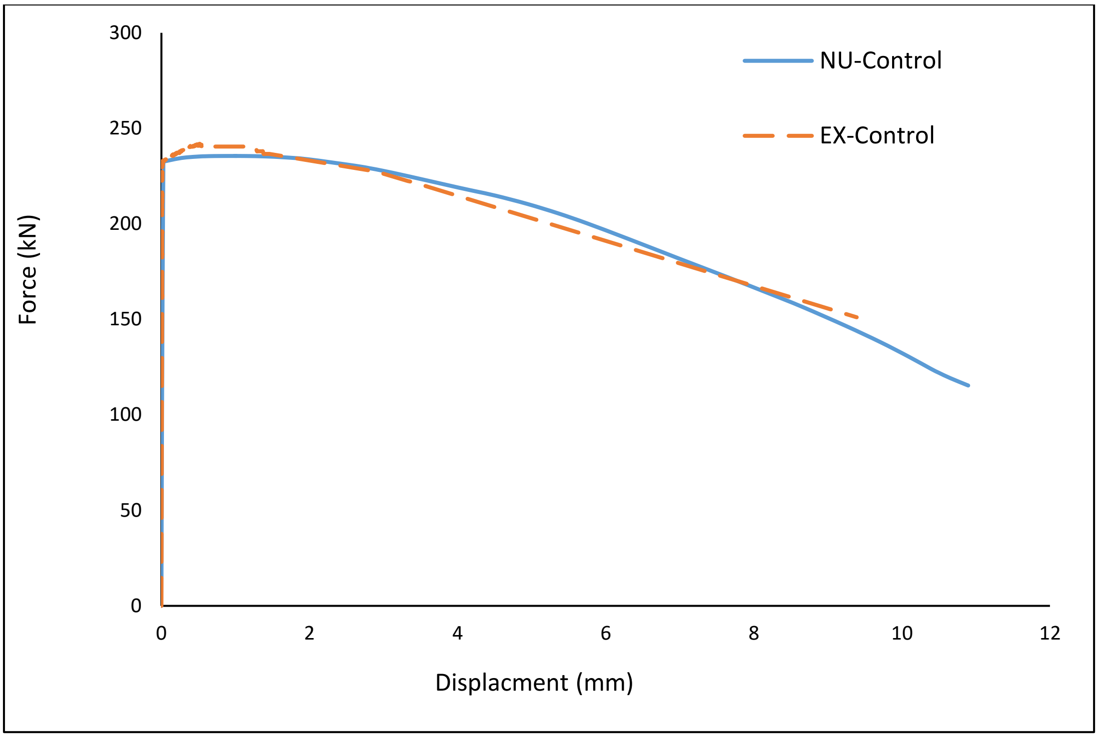
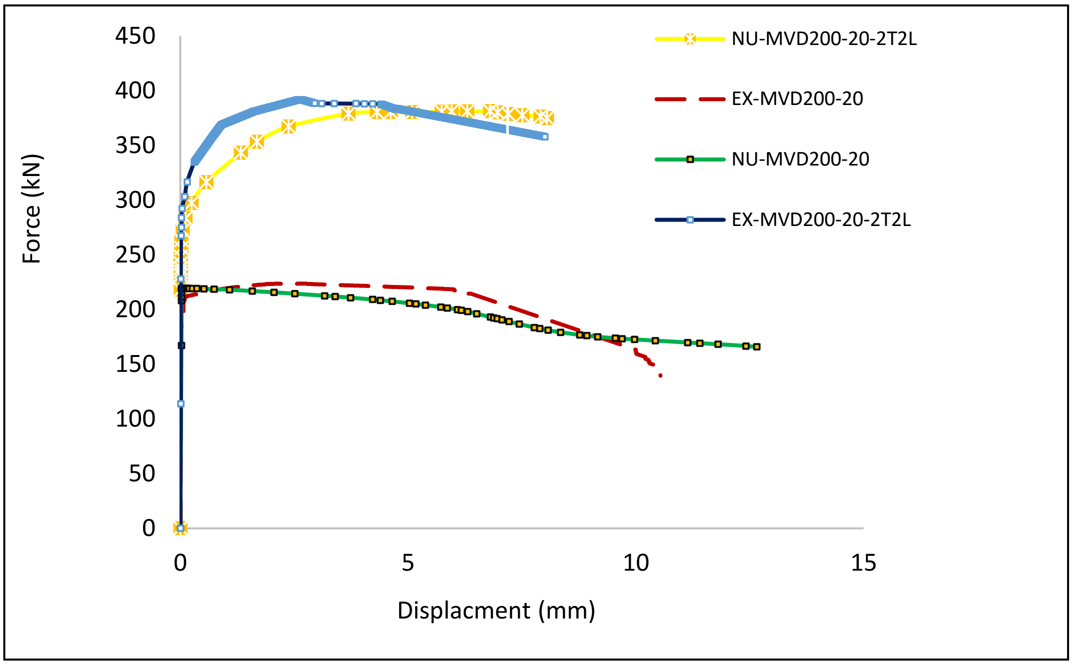
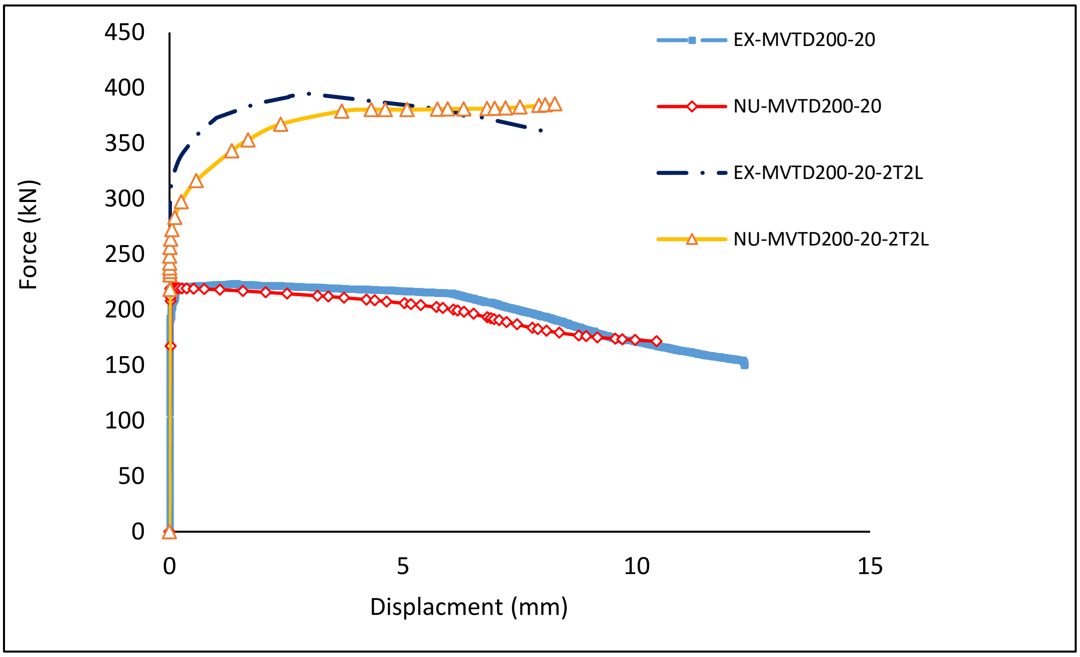


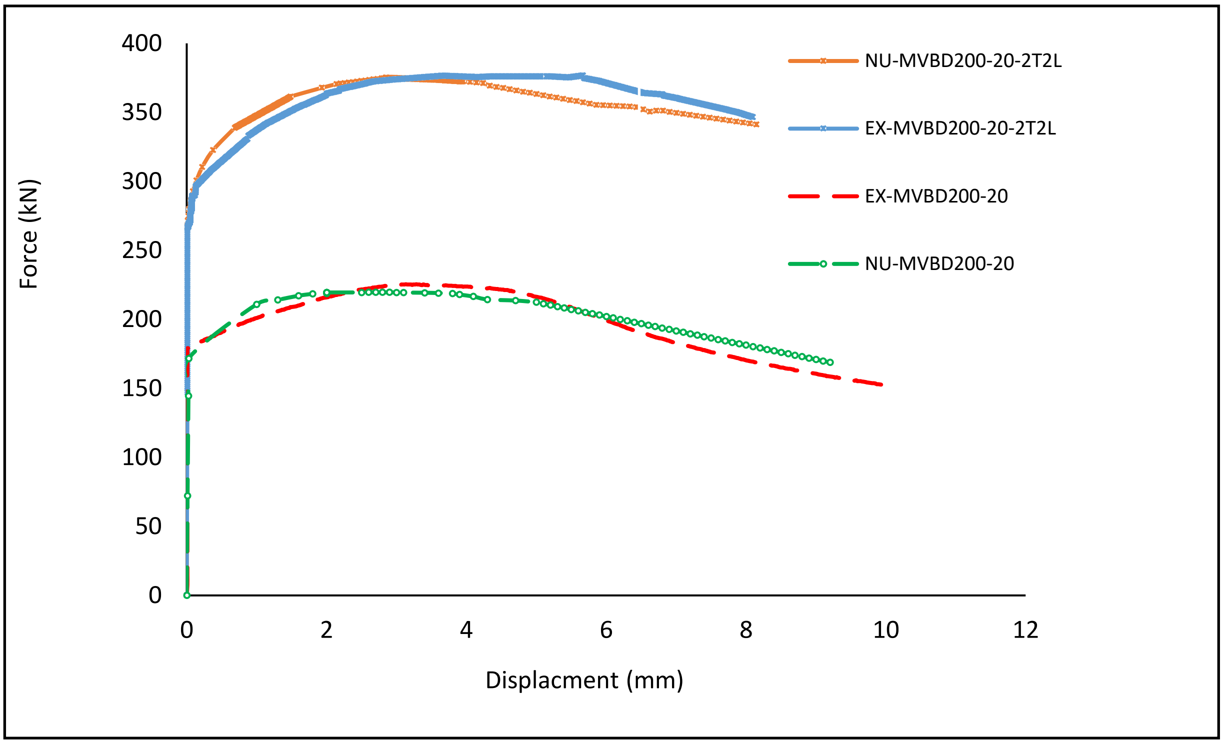
Fig. 4. Force-displacement diagram of steel column with no deficiency



(a)



(b)



(c)

Fig. 5. Force-displacement diagram of the columns with vertical deficiency of middle element (a) top, (b) middle, and (c) bottom

373 KN, which is 56.01% compared to the control specimen (Fig.5C).

CVD200-20 shows the vertical deficiency in the middle of the corner element. Vertical deficiency caused a reduction of bearing capacity by 210 KN, which is 12.86% compared to the control specimen. Deficiency in this mode caused the most critical situation among all specimens (Fig.6).

5.2 Failure Modes

The behavior and rupture depend on the load-bearing capacity, ductility, and rupture of elements undergoing axial loads. Buckling in the deficiency region is one of the important

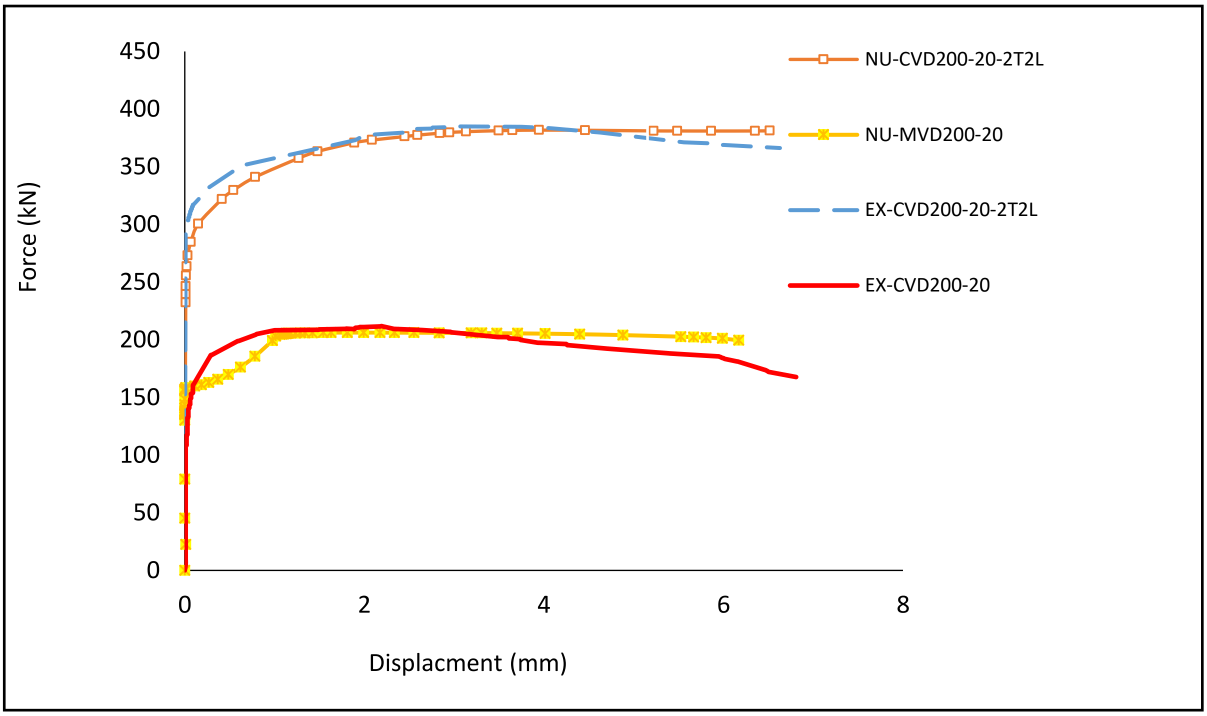


Fig. 6. Force-displacement diagram of the columns with vertical deficiency of corner element.

factors to study the behavior and failure of damaged columns. Firstly, the behavior and rupture of the specimen with no deficiency are studied. Fig.7 shows the control column before and after failure. Elephant Foot Buckling was observed after completing the test, which is mainly associated with prevailing the force over internal elements in the elastic area of the element.

Fig.8 shows the vertical deficiency at the top of the middle element (non-strengthened and CFRP strengthened specimens). For non-strengthened specimen, damage caused deformation and increased local buckling as a result of axial loading. For strengthened columns using four CFRP layers, a significant, optimal effect on increased ductility and rupture control was observed. Rupture and failure of carbon fiber occurred at the support outside of deficiency was occurred. Wrapping the deficiency with CFRP caused separation and local buckling at column foot.

The vertical deficiency in the middle of the middle element showed that axial loading increased the stress and rupture in the exterior of the steel column. This increasing stress distribution causes axial deformation and local buckling. As it is evident in Fig.9, steel column strengthening is effective for improving the buckling property performance of the section. CFRP arrangement plays a key role in increased stiffness and ultimate strength of the damaged column. CFRP also reduced the stress distribution by enclosing the deficiency area.

Fig.10 shows the vertical deficiency at the bottom of the middle element. As it is clear, the deficiency caused local buckling along with the deficiency and energy absorption limitation. Increasing local buckling along the vertical deficiency caused the maximum stress and strain distribution. This specimen experienced the most critical situation among the specimens with vertical deficiency. Using four longitudinal and transverse CFRP layers had a significant effect on the strengthening and stiffness of the damaged specimen. As Figure 10 showed, VFRP layers minimized the deformation by wrapping the location of deficiency. On the other hand, increasing vertical loading caused the rupture and CFRP separation exterior to the deficiency. CFRP separation at the top location of the element happened due to increasing local stress and strain distribution.

We also studied the behavior of steel columns at the corner element. As it is clear in Fig.11, the vertical deficiency in the middle of the corner element caused the deficiency opening, increased axial deformation, and local buckling at the exterior of the column. This specimen experienced maximum bearing capacity, displacement, and axial deformation. This is the most critical specimen among all specimens. The experimental results of strengthening showed that carbon fiber had a significant effect on increasing ductility, absorbing energy, and reducing the stress distribution of steel columns. Failure and separation of carbon fiber at the end of vertical deficiency are due to increased bearing capacity, energy absorption capability, and local buckling at the foot of the steel column.

As it is seen in Fig.12b, software-based specimens

Fig. 7. Failure modes of Control specimen

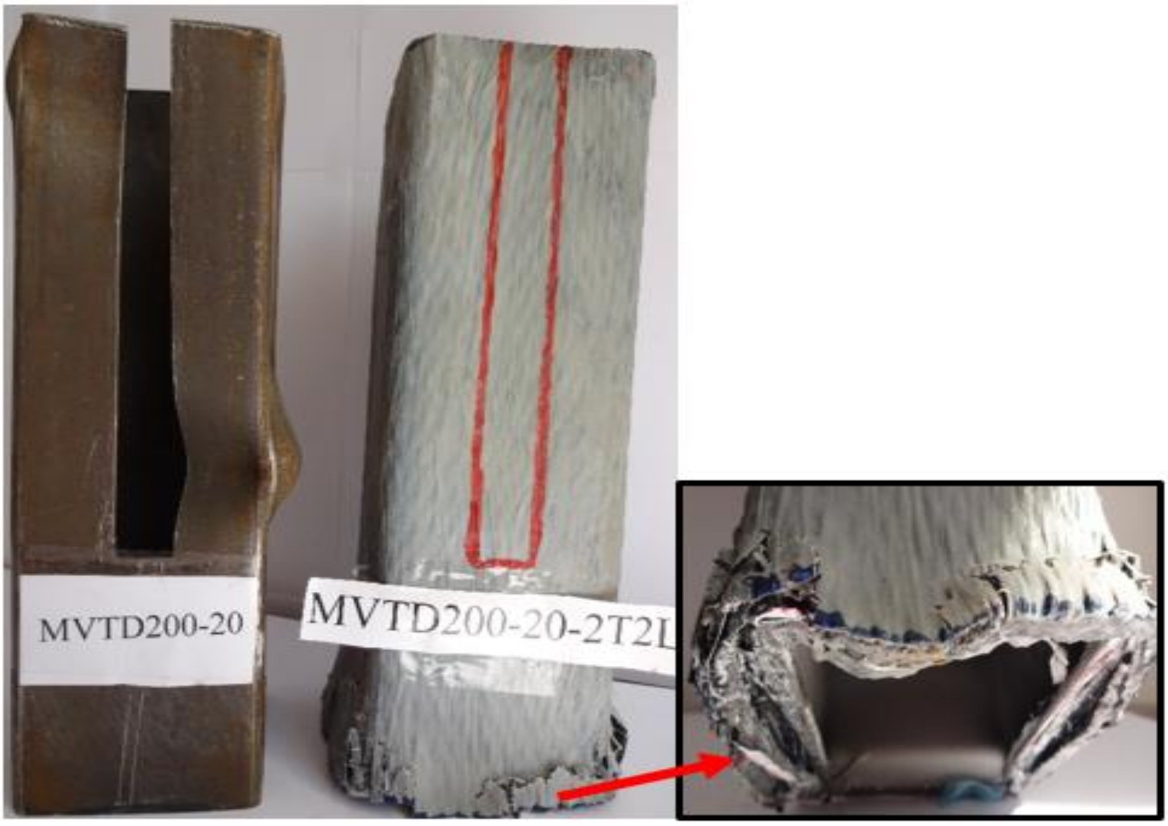


Fig. 8. Failure modes of the specimens with middle-top deficiency: non-strengthened and strengthened.

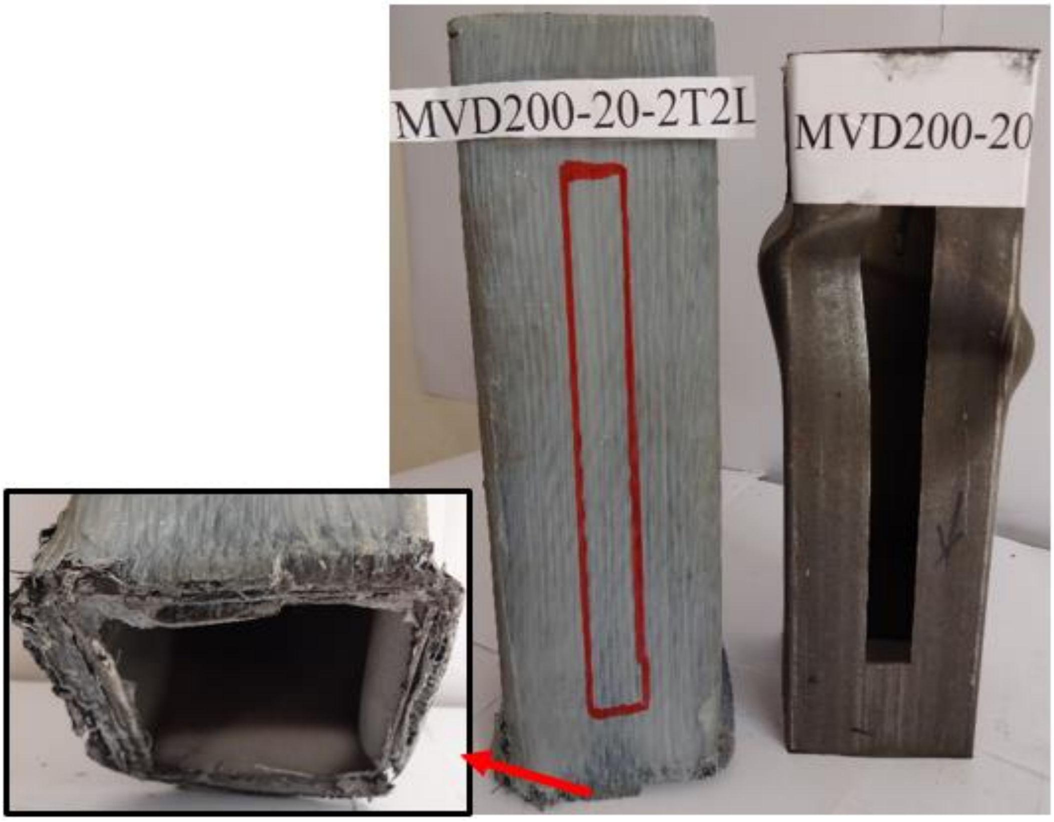


Fig. 9. Failure modes of the specimens with middle deficiency: non-strengthened and strengthened

Fig. 10. Failure modes of the specimens with middle-bottom deficiency: non-strengthened and strengthened

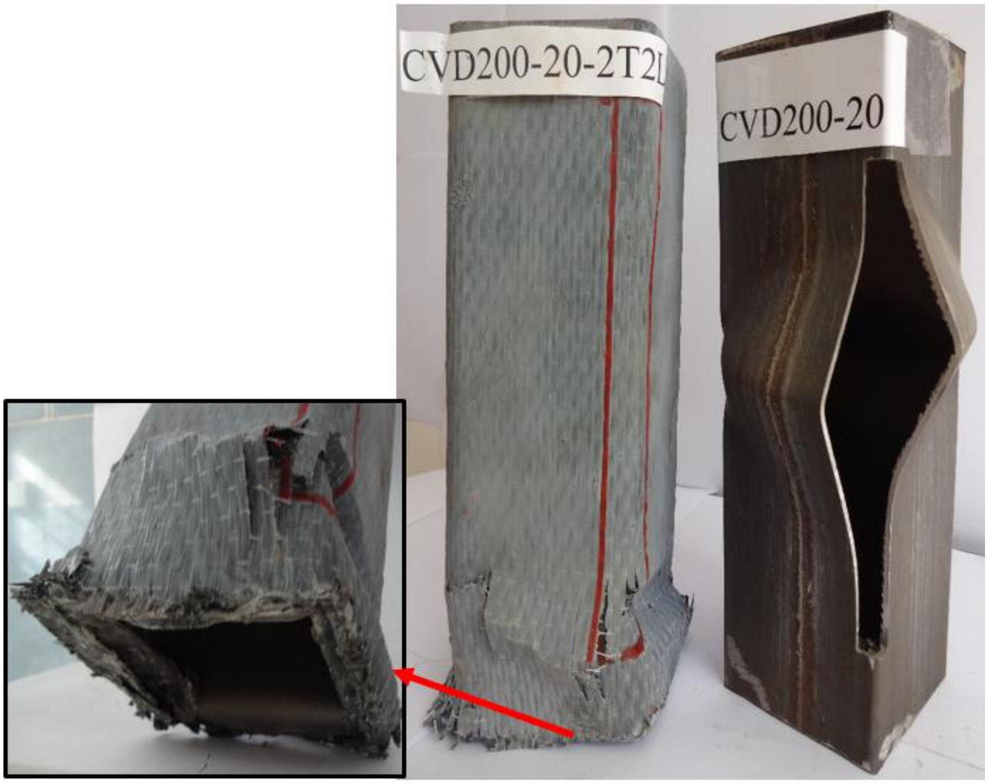


Fig. 11. Failure modes of the specimens with corner deficiency: non-strengthened and strengthened

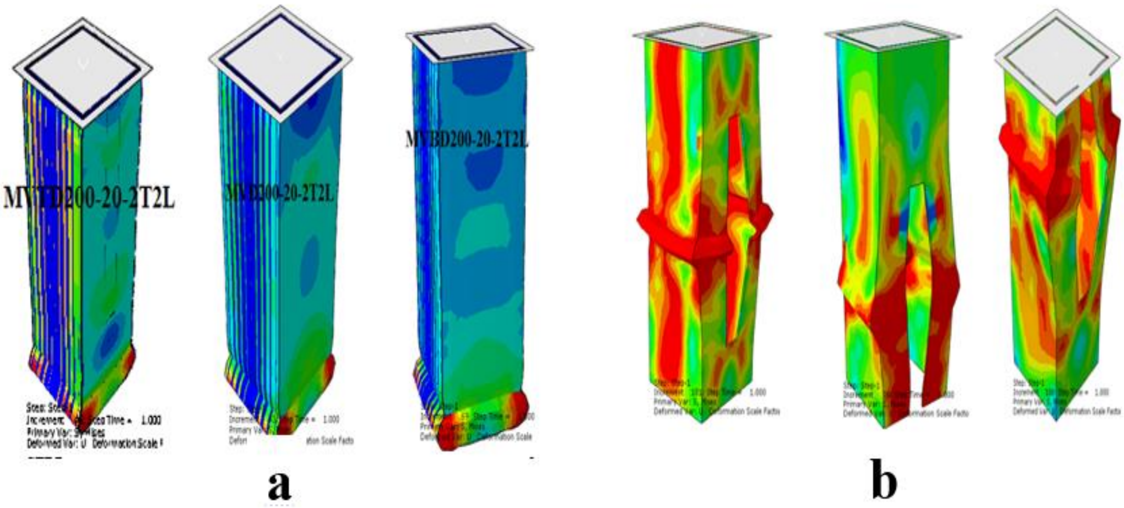


Fig. 12. Deformation of Vertical Deficiency at the Middle Element of Steel Columns (Simulation): (a) strengthened, (b) non-strengthened.

are similar to the experimental ones. It shows the vertical deficiency on the corner and middle elements in 3-D ABAQUS. The vertical deficiency at various locations, rupture (local buckling), and Mises stress distribution caused reduced bearing capacity and strengthening. Fig.12a shows the damaged specimen strengthened by four CFRP layers. As it is clear, separation and rupture of strengthened specimens are close to experimental ones.

6. CONCLUSIONS

This article aimed to study the effect of dimensions and location of vertical deficiency (top, middle, and bottom) of middle and corner elements. The experimental results showed that the vertical deficiency at various locations increased the speed of failure, resistance drop, and axial behavior of the damaged column in the plastic range. Applying axial load in steel columns caused increasing stress and rupture of vertical deficiency in the exterior surface of a steel column. Concentration and increased stress in affected areas caused an increase in local buckling and axial deformation. The vertical deficiency in the middle of the corner element created the most critical mode. The deficiency in the middle of corner element and bottom of middle element-MVBD200-20 and CVD200-20) decreased bearing capacity by almost 7.05% and 12.86% compared to the control specimen, respectively. Vertical deficiency on the corner element caused more destruction and bearing capacity compared to the middle element. Deficiency length and width play a key role in the reduced ultimate bearing of axial elements. Using CFRP increased ductility and strength of affected columns. Longitudinal and transverse CFRP arrangement had a significant effect on increased bearing capacity and reduced maximum axial stress. Fully enclosing of the exterior surface by CFRP layers controlled the rupture and delayed combined stress, lateral strain, and local buckling. Carbon fiber is an efficient and proper method for strengthening the damaged and affected columns.

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REFERENCES

[1] J. Teng, Y. Hu, Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression, Construction and Building Materials, 21(4) (2007) 827-838.

[2] H. Jiao, X.L. Zhao, CFRP strengthened butt-welded very high strength (VHS) circular steel tubes, Thin-Walled Structures, 42(7) (2004) 963-978.

[3] A. Shaat, A. Fam, Axial loading tests on short and long hollow structural steel columns retrofitted using carbon fibre reinforced polymers, 33(4) (2006) 458-470.

[4] X.Y. Gao, T. Balendra, C.G. Koh, Buckling strength of slender circular tubular steel braces strengthened by CFRP, Engineering Structures, 46 (2013) 547-556.

[5] D. He, J. Dong, Q. Wang, X. Chen, Mechanical behaviour of recycled concrete filled steel tube conlumns strengthened by CFRP, in: 2011 International Conference on Multimedia Technology, IEEE, 2011, pp. 1110-1113.

[6] M.C. Sundarraja, G.G. Prabhu, Experimental study on CFST members strengthened by CFRP composites under compression, Journal of Constructional Steel Research, 72 (2012) 75-83.

[7] J.F. Dong, Q.Y. Wang, Z.W. Guan, Structural behaviour of recycled aggregate concrete filled steel tube columns strengthened by CFRP, Engineering Structures, 48 (2013) 532-542.

[8] P. Feng, Y. Zhang, Y. Bai, L. Ye, Strengthening of steel members in compression by mortar-filled FRP tubes, Thin-Walled Structures, 64 (2013) 1-12.

[9] G.G. Prabhu, M. Sundarraja, Behaviour of concrete filled steel tubular (CFST) short columns externally reinforced using CFRP strips composite, Construction and Building Materials, 47 (2013) 1362-1371.

[10] M.R. Bambach, M. Elchalakani, Plastic mechanism analysis of steel SHS strengthened with CFRP under large axial deformation, Thin-walled structures, 45(2) (2007) 159-170.

[11] M.R. Bambach, H.H. Jama, M. Elchalakani, Axial capacity and design of thin-walled steel SHS strengthened with CFRP, Thin-Walled Structures, 47(10) (2009) 1112-1121.

[12] M.R. Bambach, M. Elchalakani, X.L. Zhao, Composite steel–CFRP SHS tubes under axial impact, Composite Structures, 87(3) (2009) 282-292.

[13] M.R. Bambach, H.H. Jama, M. Elchalakani, Static and dynamic axial crushing of spot-welded thin-walled composite steel–CFRP square tubes, International Journal of Impact Engineering, 36(9) (2009) 1083-1094.

[14] J. Haedir, X.-L. Zhao, Design of short CFRP-reinforced steel tubular columns, Journal of Constructional Steel Research, 67(3) (2011) 497-509.

[15] S. Sivasankar, T. Thilakranjith, M. Sundarraja, Axial Behavior of CFRP Jacketed HSS Tubular Members-An Experimental Investigation, International Journal of Earth Sciences and Engineering, 61(413) (2012) 1729-1737.

[16] S. Kalavagunta, S. Naganathan, K.N.B. Mustapha, Proposal for design rules of axially loaded CFRP strengthened cold formed lipped channel steel sections, Thin-Walled Structures, 72 (2013) 14-19.

[17] M. Sundarraja, S. Sivasankar, Behaviour of CFRP jacketed HSS tubular columns under compression an experimental investigation, Journal of Structural Engineering, 39(5) (2013) 574-582.

[18] M.R. Ghaemdoust, K. Narmashiri, O. Yousefi, Structural behaviors of deficient steel SHS short columns strengthened using CFRP, Construction and Building Materials, 126 (2016) 1002-1011.

[19] M. Karimian, K. Narmashiri, M. Shahraki, O. Yousefi, Structural behaviors of deficient steel CHS short columns strengthened using CFRP, Journal of Constructional Steel Research, 138 (2017) 555-564.

[20] M. Shahraki, M.R. Sohrabi, G.R. Azizyan, K. Narmashiri, Experimental and numerical investigation of strengthened deficient steel SHS columns under axial compressive loads, Structural Engineering and Mechanics, 67(2) (2018) 207-217.

[21] R. Shahabi, K. Narmashiri, Effects of deficiency location

on CFRP strengthening of steel CHS short columns, Steel and Composite Structures, 28(3) (2018) 267-278.

[22] I. Badih Damghani, K. Narmashiri, Strengthening of Deficient Mortar Filled Steel Tubes using Carbon Fiber Reinforced Polymers %J Amirkabir Journal of Civil Engineering, 52(2) (2018) 17-17.

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