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Effects of Horizontal Deficiency Location on the Structural Behaviors of Steel SHS Short Columns Strengthened using CFRP

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KEYWORDS

Horizontal defect
Steel short column
Strengthening
SHS
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ABSTRACT

Several deficient steel structural members require to be strengthened all over the world. In this article, horizontal defects were generated at three locations (top, middle, and bottom) on the middle element and the middle of the side element. Consequently, the effects of the location of such defects on axial behavior of Carbon Fiber Reinforced Polymer (CFRP) strengthened steel Square Hollow Section (SHS) tubular short columns were examined. To this end, a total of 13 steel columns were experimentally examined. The same specimens were simulated applying ABAQUS V.6.14. The samples were no defect (control), 6 non-strengthened columns with defects at different locations, and 6 strengthened specimens with defects. The results indicated that horizontal defects caused a significant decrease in load bearing capacity and initial performance. The damage located at the middle and the middle of the corner elements caused the most reductions on load bearing capacity by 16% and 17%, compared to the control, respectively. The defects on the side element led to greater destruction and bearing capacity decline compared to the middle defects. As a result of axial loading, the area of horizontal defects experienced local buckling, lateral rupture, and axial deformation boost. Carbon fiber played a key role in ductility and strength increase around the defect by covering it. Applying four CFRP layers declined the stress concentration, delaying the local buckling as a result of high confining strength. The fiber increased bearing capacity by 64% and 37% for the middle and the corner elements, compared to the control.

1. Introduction

Tubular sections are contemplated as the most widely used columns. These structures may not be capable of meeting the structural requirements for various factors such as design and calculation errors, environmental factors, decay, and fire. Thus, strengthening and improving the element performance is required. Fiber Reinforced Polymer (FRP) composites are the subject of interests because of various factors such as high strength, corrosion resistance, and ease of application. Recently, many researchers have inspected strengthening of steel tubular columns. Teng and Hu examined the performance of Glass Fiber Reinforced Polymer (GFRP)-reinforced hollow steel tubes on thin-walled elements under axial compression. They analyzed four steel tubes with and without GFRP and concluded that GFRP with transverse constraints caused flexibility increase [1]. Jiao and Zhao took advantage of CFRP to reinforce butt-welded steel tubes. They concluded that the tensile strength increased by 25%-76% [2]. Shaat and Fam discovered that the transverse Carbon Fiber Reinforced Polymer (CFRP) layers could be effective in restricting external local buckling of short columns. The layers caused a boost in the bearing capacity of short columns up to 18% and slender columns by 13%-23% [3]. Gao et al. applied CFRP sheets to reinforce steel hollow steel tubes. The results indicated an increase in strength and stiffness [4]. He et al. explored the behavior of CFRP-strengthened steel tube filled with recycled and conventional concrete. They examined 10 CFRP-strengthened circular

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columns. CFRP increased the ductility and bearing capacity. A boost in the number layers increased bearing capacity. The stiffness increased by full wrapping. Semi-wrapped CFRP had less axial compressive strain than the full wrapping [5]. Sundarraja and Prabhu conducted experimental research on the stress-strain behavior, ultimate bearing capacity, and failure modes of Concrete Filled Steel Tubes (CFST) columns strengthened with CFRP. They wrapped the carbon fiber strips around the columns with a focus on thickness and distance between strips. Increasing the gap between CFRP strips revealed buckling in parts without fiber. Greater number of layers had better influence on axial deformation control [6]. Dong et al. investigated CFRP-strengthened concrete-filled steel columns. They studied 22 samples. They found out that CFRP warping on hollow and filled circular columns had better results than square sections [7]. Feng et al. examined steel tubes filled with mortar and strengthened applying FRP. The resistance increased against buckling [8]. Prabhu and Sundarraja explored the effect of CFRP strip distance on strengthening CFST. They strengthened 18 samples with CFRP out of 21 samples. Some factors were considered: thickness, width, and distance of CFRP strips. They realized that CFRP strips prevent the lateral deformation and delay the local buckling [9]. Bamabch and Elchalakani investigated the steel SHS strengthened with CFRP under axial pressure. They discovered that CFRP causes an increase in the resistance and energy of the sections undergoing the pressure [10]. Bambach et al. inquired the CFRP-strengthened steel SHS strengthened with welded edges. They surveyed 20 strengthened samples undergoing axial pressures theoretically and in the laboratory. They concluded that applying CFRP doubles the axial capacity and one half times the resistance to weight ratio [11]. Bambach et al. found out that using CFRP for strengthening steel-CFRP SHS tubes undergoing axial impact 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. Moreover, they compared the static and dynamic behavior and found that CFRP increased energy absorption, appropriately [13]. The study by Haedir and Zhao on the effect of transverse and longitudinal CFRP strengthening of 10 short columns in the laboratory displayed that transverse and longitudinal combination of CFRP increased the yield capacity [14]. Sivasankar et al. inspected the failure modes, stress-strain behavior, and ultimate bearing capacity of CFRP jacketed Steel Hallow Section (SHS) tubular members, 600 mm columns, were strengthened by two arrangements of fiber in the laboratory. Bonding CFRP was effective in increasing the bearing capacity and stiffness. Furthermore, it delayed the buckling [15]. Kalavagunta et al. inquired the cold formed lipped channel strengthened with CFRP under axial pressure. They surveyed the channel column in two ways in laboratory (bonding of fiber to the whole columns and bonding to the web). Their study revealed that the bearing capacity enhanced in fully reinforced samples by up to 16.75% and web-reinforced samples by up to 10.26%. They observed the reduced capacity and sudden failure as a result of delamination and CFRP debonding, as well. Surface preparation and temperature were found two important factors for obtaining proper adhesiveness between steel and fiber [16]. Sundarraja and Sivasankar strengthened 12 CFRP jacketed HSS tubular column deliberated the number of layers and distance between CFRP strips in the laboratory. They concluded that CFRP caused an increase in the bearing capacity. Moreover, it delayed the lateral buckling. Transverse application of fiber caused an increase in the stiffness, bearing capacity, and axial deformation compared to the longitudinal application [17].

Recently, researches have been operated on strengthening deficient steel tubes under axial compression. Ghaemdoust et al. inspected the behavior of defected steel tubular columns under axial loading in the laboratory and numerically. The vertical and horizontal defects in the middle of the steel column were strengthened by CFRP. The study revealed that CFRP sheets could significantly compensate the lost strength caused by the defects. It is noteworthy to mention that they attempted to apply CFRP in order to enhance the performance of damaged members. However, they did not contemplate the effect of dimensions and location of defects [18]. Karimian et al. inspected 8 steel Circular Hollow Section (CHS) short columns with similar dimensions and cross sections in the laboratory and software. The results indicates that deficiency decreased the bearing capacity. The effect of the horizontal defect was greater than the vertical one. Using CFRP for strengthening the steel CHS short columns with deficiency displayed an appropriate effect in increasing the bearing capacity, decreasing stress at defect zone, and preventing local deformations caused by deficiency [19]. Shahabi and Narmashiri investigated the effects of deficiency location on the structural behaviors of CFRP strengthening Circular Hollow Section (CHS) short columns, numerically and experimentally. The deficiencies were located vertically or horizontally at the middle or bottom of the columns. The horizontal deficiency at the middle and vertical deficiency at the bottom of the steel columns was discovered as the most critical [20]. Shabani Ammari and Narmashiri explored the effects of vertical deficiency location on the CFRP strengthening of SHS short columns in numerical and experimental studies. Vertical deficiencies at the bottom of middle element caused the most critical conditions [21].

As discussed above, most of the studies in this field have been focused on strengthening and restoring the tubular columns. Few studies focused on columns with primary defects. This research aimed to study the effect of location of horizontal defects of steel SHS short columns strengthened using CFRP experimentally and numerically. Two locations of horizontal defects were considered: side and middle (Top, Middle, and Bottom).

2. Materials and Methods

2.1. Steel Profiles

In this study, the steel SHS columns with the dimensions of 90×90 mm (thickness: 2 mm and height: 300 mm) were applied. Thirteen specimens were investigated: one control specimen, six deficient specimens without strengthening, and six deficient and CFRP-strengthened specimens. Fig. 1a displays the horizontal deficiencies on the side and middle elements on top, middle, and bottom of the elements (20*60 mm). The CNC machine was employed to create deficiencies. Table 1 presents the mechanical properties of the steel columns.

2.2. CFRP Layers

For strengthening and ameliorating the steel tube performance with deficiency, unidirectional SikaWrap®-230 C was employed in order to reach the initial performance of compressive elements. The column was completely wrapped, applying CFRP. Consequently, two 220mm transverse CFRP layers (one transverse and one longitudinal layer) and four longitudinal 440mm (two transverse and two longitudinal layers) were employed for covering the height. Note that a 20mm overlap was employed for each of the CFRP layers. Fig. 1b indicates the bonding configuration of CFRP on steel columns. Table 2 presents the CFRP layers specifications.

2.3. Adhesive

Resin epoxy (Sikadur®-330) was applied to bond the CFRP sheets to the steel tubes. Note that the adhesive must be capable of enduring the stress and adhesion resistance. Table 3 depicted the adhesive properties.

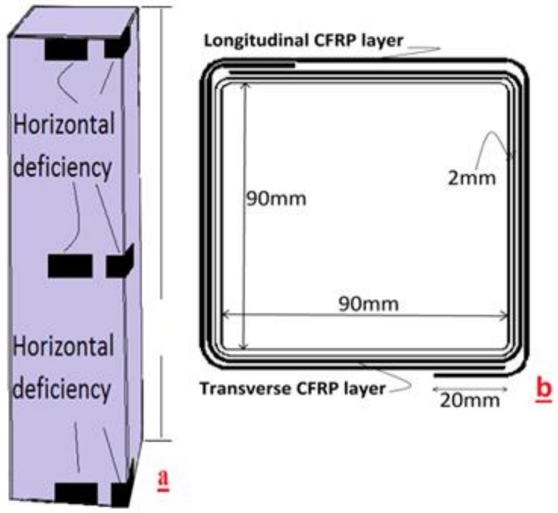


Fig. 1. Steel Short Column (a) Location of horizontal deficiency, (b) Wrapping of CFRP in the laboratory

Table 1. Steel material property

Modulus of Elasticity (GPa)	Yield Strength (MPa)	Ultimate Stress (MPa)	Ultimate Strain (%)
200	330	336	22

Table 2. CFRP material property (SikaWrap®-230 C)

Thickness (mm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Strain (%)
0.131	4300	238	1.8

Table 3. Adhesive material property (Sikadur®-330)

Thickness (mm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Strain (%)
0.869	30	4.5	0.9

3. Specimens' Specifications

In this research thirteen specimens were investigated. As can be observed in Fig. 1a, the deficiencies were generated in the middle and corner elements at the top, middle, and bottom, separately. Table 4 indicates the naming abbreviation of the specimens. The locations are illustrated by C (Corner) and M (Middle). Horizontal deficiency is indicated by H and D, respectively. The last letter indicates the deficiency position. It is noteworthy to mention that the number and type of CFRP placement are illustrated by T, L, displaying Transverse and Longitudinal layers, respectively. Table 4 illustrates the specifications of the steel columns. In order to investigate the steel short columns performance experimentally, and inspect the effect of CFRP strengthening, the specimens were placed under the hydraulic jack. Force was axially imposed by the jack. Displacement was measured by two LVDTs and saved in the software package.

Table 4. Specifications of Specimens

No	Specimen	Deficiency dimensions (mm) and locations		Number of CFRP layers	Axial Load-bearing Capacity (kN)		Increase/ decrease (%)	
					Exp.	Num.	Exp.	Num.
1	Control	N/A		N/A	241	235	-	-
2	MHTD	60*20	Middle @ Top	N/A	209	202	-13.27	-14.04
3	MHTD-2T2L	60*20	Middle @ Top	4	328	317	36.10	34.89
4	MHD	60*20	Middle @ Middle	N/A	202	195	-16.18	-17.02
5	MHD-2T2L	60*20	Middle @ Middle	4	397	388	64.73	65.11
6	MHBD	60*20	Middle @ Bottom	N/A	211	202	-12.44	-14.04
7	MHBD-2T2L	60*20	Middle @ Bottom	4	338	327	40.24	39.14
8	CHTD	60*20	Corner @ Top	N/A	205	199	-14.93	-15.31
9	CHTD-2T2L	60*20	Corner @ Top	4	387	385	60.58	63.82
10	CHD	60*20	Corner @ Middle	N/A	200	195	-17.01	-17.02
11	CHD-2T2L	60*20	Corner @ Middle	4	332	329	37.76	40.00
12	CHBD	60*20	Corner @ Bottom	N/A	206	200	-14.52	-14.89
13	CHBD-2T2L	60*20	Corner @ Bottom	4	378	373	56.85	58.79

4. Numerical Model

In order to explore the effective parameters in steel column behavior, conducting experiments would be costly and time-taking. Therefore, Simulation applying Finite Element (FE) can provide a proper model for the test on a real scale. If 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 modelled applyig ABAQUS V.6.14.2. Fig. 2a indicates a simulated specimen. The steel columns were simulated using three dimensional (3D) Isotropic solid elements. The adhesive and CFRP sheets were simulated applying shell elements. The CFRP layers were modelled using orthotropic property regarding the direction of the fibers. All rotational degrees of freedom (DoF) at the bottom and top of the columns were free (simple supports). The displacements DoF of the bottom was fixed, and just an axial displacement at the top of the columns was free. The degree of freedom is illustrated in Fig. 2a. The automatic map meshing method was selected. Since the loading state in experimental test was static gradual type (Fig. 2b), consequently in numerical simulation, the same loading type and non-linear analysis methods were utilized. Failures of dissimilar elements including steel columns, adhesive, and CFRP, such as local fracture, debonding, delamination, and splitting, were monitored applying maximum strain defined as the material property of each element. In order to ensure the software accuracy of Steel-Tube Short Columns strengthened by CFRP layers, the experimental results of the research by Bambach and Al-Chalakany (2007) were applied for calibration [10]. In their examination, a 100*100 mm steel tube (thickness: 2 mm and height: 300 mm) was used. Three of the investigated specimens in their research were chosen for calibration of the software. Table 5 displays the specimens' specifications and simulation results. The percentages of error indicate the accuracy of the simulation.

5. Results and Discussions

5.1. Load Bearing Capacity

Control specimen (non-strengthened steel columns without deficiency) was applied to compare the results. Investigations were pursuant to force-displacement graphs in order to study the effect of the location of deficiency of steel columns strengthened by CFRP. As it is evident from Table 4, control specimen tolerated 241 kN as a result of axial load (Fig. 3).

This article aims to compute the effect of the location of horizontal deficiency of Steel-Tube Short Columns. Horizontal deficiencies were investigated at three locations (top, middle, and bottom) middle of corner element. The dimension of horizontal deficiency is 20*60 mm.

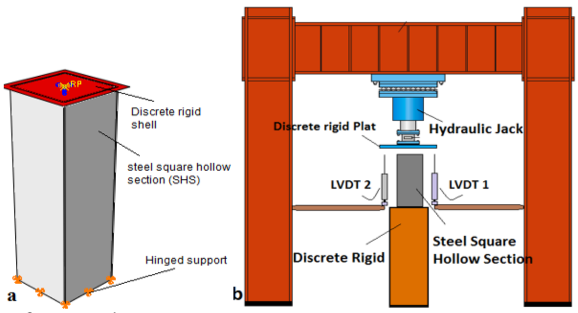


Fig. 2. Schematic of the steel columns (a) ABAQUS model, (b) Experimental test setup

Table 5. Comparison of results between experimental and numerical specimens

No.	Dimensions (mm)	Number of CFRP Layers	Critical Load (kN) Experimental [10]	Critical Load (kN) Numerical	Percentage of error
1	100*100*2	0	238.4	240	0.67
2	100*100*2	2	238	236	0.59
3	100*100*2	4	425	422.8	0.51

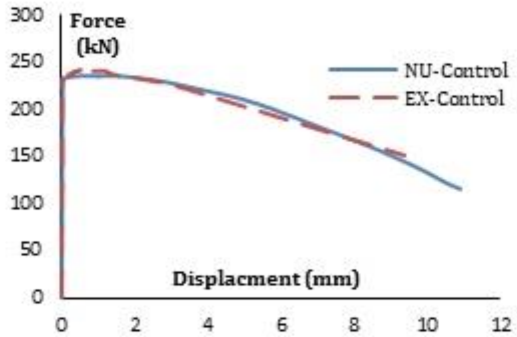


Fig. 3. Force-Displacement Diagram of Steel Column without Deficiency

The results revealed that horizontal deficiencies had a significant effect on reduction of stiffness and load-bearing capacity. The elements undergoing axial loading experienced a dramatic deformation at the location of deficiency. Fig. 4a portrays displacement-force of MHTD60-20 at upper location of steel column. This specimen experienced 13.27% bearing capacity reduction compared to the control. Axial deformation and displacement increased by 10% compared to the control. Horizontal deficiency in the center of steel column reduced the bearing capacity and displacement by 16.18% and almost 15% compared to the control, respectively. Fig. 4b displays force-displacement at the most critical situation (the greatest displacement and lowest bearing capacity) among the middle elements (MHD 60-20). MHBD60-20 is related to the horizontal deficiency at the bottom of the middle element of the steel column. Bearing capacity reduction and axial deformations were 12.44% and 13% compared to the control (Fig. 4C).

Fig. 5a indicates a force-displacement diagram of specimens with horizontal deficiency of corner element. Investigating CHTD 60-20 manifested that the bearing capacity reduction and displacement were 14.93% and 13% compared to the control, respectively. CHD 60-20 is related to the horizontal deficiency of the corner element. The results revealed that this specimen was the most critical mode among the lab experiments. The maximum bearing capacity reduction was 17.01%. Axial deformation was reported almost 17% compared to the control (Fig. 5 b). CHBD 60-20 correlated to the horizontal deficiency at the bottom of the corner element. Bearing capacity reduction and axial deformations was 14.52% and 15%, respectively (Fig. 5C).

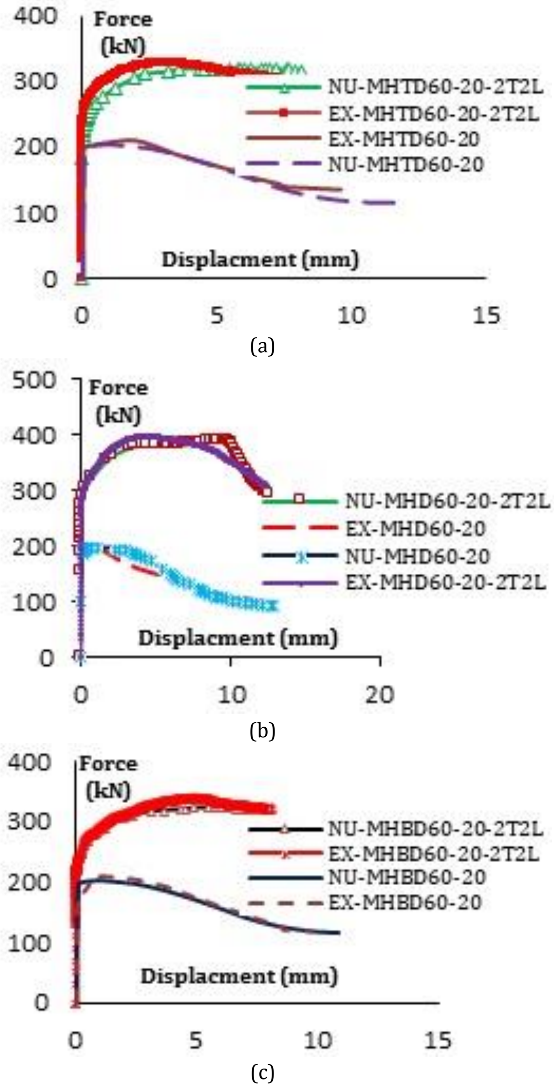
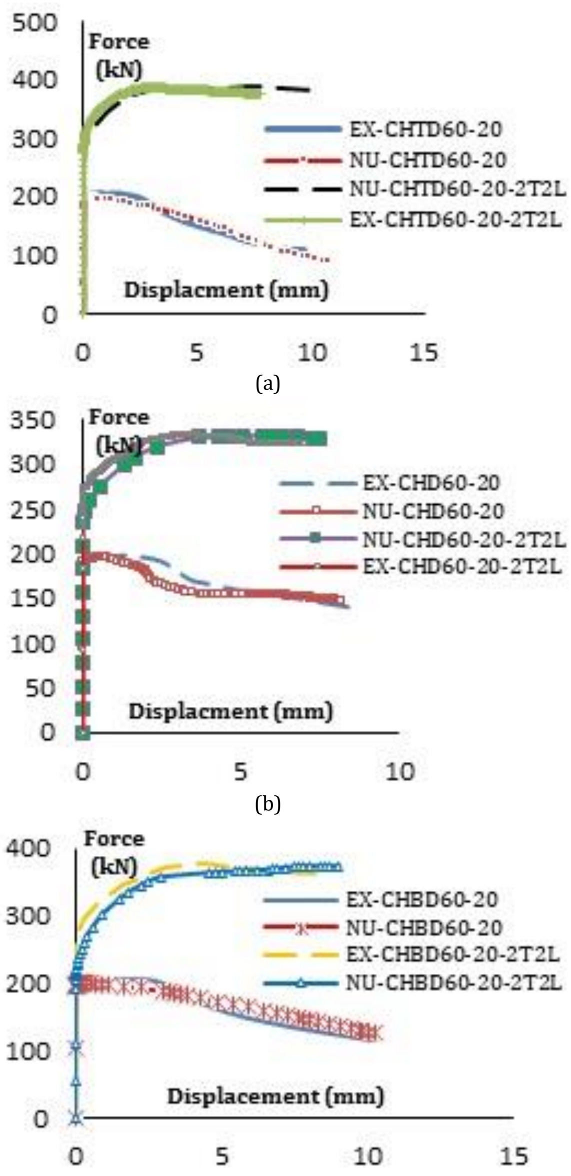


Fig. 4. Force-Displacement of Columns with Horizontal Deficiency of Middle Element (a) deficiency at the top, (b) deficiency at middle, and (c) deficiency at the bottom of the heigh

Figures 4 and 5 indicate that the damage located at the middle and the middle of the corner elements caused the most reductions on load bearing capacity compared to the control. The defects on the side element led to a greater reduction in load bearing capacity compared to the middle defects. The application of CFRP enhanced the strength and stiffness of the specimens with horizontal deficiency significantly.

Figure 4 illustrates the strengthened specimens with a horizontal deficiency in the middle element. Applying four CFRP layers in MHTD60-20-2T2L, MHD60-20-2T2L, and MHBD-

60-20 2T2L increased the bearing capacity by 36.10%, 64.73%, and 40.24% compared to the control specimen, respectively. Axial displacement of strengthened columns reduced by 26%, 31%, and 29% compared to the damaged specimens, respectively. Fig. 5 indicates the specimens with horizontal deficiency of corner element. Wrapping the columns with deficiency by CFRP for CHTD60-202T2L, CHD60-20-2T2L, and CHDB60-20-2T2L increased the strength and energy absorption by almost 60.58%, 37.76%, and 56.85% compared to the control, respectively. Displacement was reported almost 25%, 29%, and 28% compared to the damaged columns, respectively.



(a)

(b)

(c)

Fig. 5. Force-Displacement of Columns with Horizontal Deficiency in the Middle of Corner Element (a) deficiency at the top, (b) deficiency at middle, and (c) deficiency at the bottom of the heigh

5.2. Failure Modes

Failure modes are one of the essential issues for engineers while designing structures. Monitoring rupture and destruction helps engineers take essential measures to prevent and ameliorate the performance of elements [22]. Here, rupture and destruction of elements undergoing axial loading are inspected. Firstly, the behavior and rupture of the Control column undergoing axial loading are studied. Consequently, the failure, and deformation of deficient specimens are investigated. Lastly, the failure modes of deficient and CFRP strengthened specimens are studied.

When short thin-walled structures undergo compressive loading, the inner walls experience deformation. Increasing load causes column buckling in the elastic area. For short columns, normally local buckling takes place. This brings about Elephant Foot Buckling in kind of steel columns. Fig. 6a indicates Control column without deficiency. Elephant Foot Buckling was observed after completing axial loading on Steel-Tube Short Columns, associated with prevailing force on the inner surface of member.

Fig. 7a portrays the failures of horizontal deficiency of middle element. As it can be observed, the deficiencies at various places caused great local deformation, reduced strength and stiffness, increased local buckling, stress distribution around the deficiency, and limitation of energy absorption. MHTD 60-20 indicates horizontal deficiency on top of the element. The damaged area experienced rupture and local buckling as a result of axial loading. MHD 60-20 implies the horizontal deficiency of the center of the middle element. Reduced deficiency width and local buckling were observed around the corner surface of steel column as a result of deficiency in the center of compressive element (Fig. 7a). MHBD60-20 correlated to the deficiency around the support (bottom). Axial loading caused local buckling and rupture around the external surface (Fig. 7 a).

Fig. 8a indicates CFRP strengthened specimens having a deficiency at middle element. Axial loading of CFRP strengthened columns minimized steel columns deformation as a result of high strength and stiffness. Pursuant to the strengthened specimens, the origin of the first failure was in the horizontal deficiency area. The loading did not cause local buckling of strengthened columns as non-strengthened ones. Carbon fiber inhibited the damaged elements.

After loading, damaged area experienced maximum stress. Consequently, with the distribution of stress in horizontal area, steel columns experienced local buckling. Increasing axial loading caused maximum yield and then fiber rupture in the horizontal area. Carbon fiber failure was associated with the local buckling in external surface of the steel columns. Carbon fiber separation and failure were observed prior to the final load in all strengthened specimens.

As Fig. 8a indicates, MHTD 60-20 2T2L is associated with the horizontal deficiency at the top of middle element, strengthened by four CFRP layers. Four transverse and longitudinal CFRP layers caused an increase in strength and local buckling control. Carbon fiber failure separation (debonding) occurred at the top of compressive element.

MHBD60-20 2T2L correlated to the horizontal deficiency at the bottom. In agreement with the results indicated in applying CFRP in damaged areas caused increased ductility and energy absorption of steel columns. As Fig. 8billustrates, stress distribution of steel column in damaged area resulted in CFRP debonding and failure (Fig. 8a).

Fig. 6. Failure Mode in Control Column undergoing Axial Loading

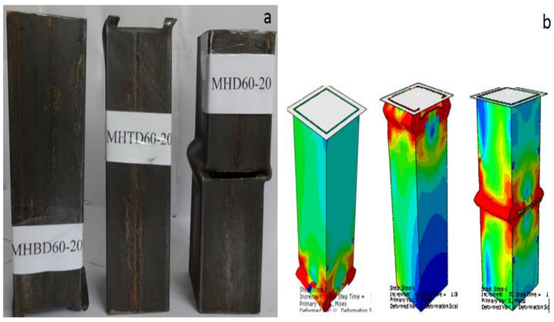


Fig. 7. Failure Modes of Non-Strengthened Specimen with Horizontal Deficiency at Middle Element of (a) Experimental Test, (b) Numerical Model

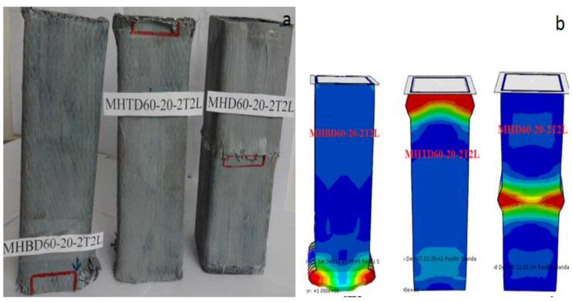


Fig. 8. Failure Modes of CFRP Strengthened Specimen with Horizontal Deficiency at Middle Element of (a) Experimental Test, (b) Numerical Model

The location of horizontal deficiency is one of the most effective parameters in tubular column behaviors. To this end, the effects of the location of horizontal deficiencies at top, middle, and bottom of the corner element were inspected. CHTD 60-20 is related to the horizontal deficiency at the top of corner element. The horizontal deficiency reduced final strength and load. As Fig. 9a indicates top of horizontal deficiency experienced local buckling and rupture inside the steel column as a result of axial loading. CHD 60-20 correlated to the horizontal deficiency in the middle of corner element. The damage caused the greatest reduction in bearing capacity. CHBD 60-20 is related to the horizontal deficiency on the bottom of corner element. As Fig. 9a, b displays, the deficiency caused rupture of column foot because of axial loading.

CHTD 60-20 2T2L was correlated to the strengthening of horizontal deficiency at the top of steel column. As Fig. 10a displays, applying four CFRP layers compensated the damage. Carbon fiber rupture occurred at the column foot because of axial loading. Consequently, the deficiency should be strengthened. CHD 60-20 2T2L is related to the horizontal deficiency in the middle of middle element. As Fig. 10 a displays, carbon fiber has a significant effect on ductility and strength of the damaged column. Rupture and local buckling occurred on the external surface of the steel column after completing the test. This caused carbon fiber separation (debonding) and rupture. CHBD 60-20 2T2L is related to the strengthening of horizontal deficiency at bottom. As Fig. 10b portrays, acceptable integration of carbon fiber with steel column delayed, and limited buckling. Applying two transverse and longitudinal carbon fiber layers strengthened steel column against the axial loading, appropriately.

As Figs. 7, 8, 9 and 10 manifests, the results of the simulation of the specimens were highly similar to the experimental ones. Figs. 7b and 9b indicate the 3D horizontal deficiency of middle and corner elements using ABAQUS. Local buckling caused high Mises stress concentration resulted in reduction in bearing capacity and strength.

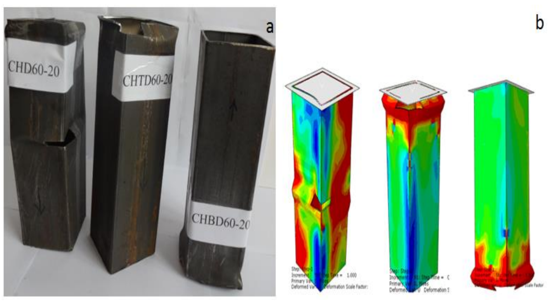


Fig. 9. Failure Modes of Non-Strengthened Specimen with Horizontal Deficiency at Corner Element of (a) Experimental Test, (b) Numerical Model

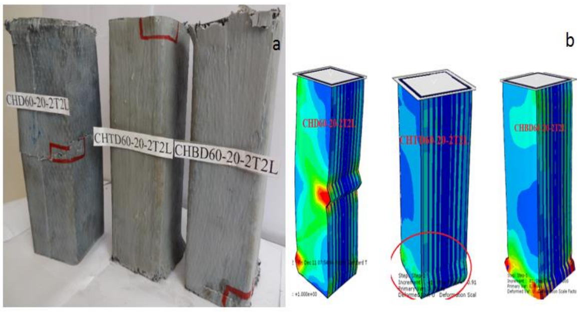


Fig. 10. Failure Modes of CFRP Strengthened Specimen with Horizontal Deficiency at Corner Element of (a) Experimental Test, (b) Numerical Model

Figures 8b and 10b illustrate the results of strengthened specimens using four CFRP layers simulated applying ABAQUS. As it is evident, the simulated rupture was highly similar to the experimental ones. Note the failures of elements simulated using final strain definitions.

6. Conclusions

Horizontal deficiency in steel columns indicated significant local buckling. Local buckling caused stress concentration at damaged areas resulted in the reduction of ultimate load bearing capacity. Pursuant to the results of experimental and numerical studies, horizontal deficiency in the middle of columns caused the most critical of middle and corner elements. The damage in the middle of corner and middle elements (MHD 60-20 and CHD 60-20) decreased bearing capacity by 16% and 17% compared to the control, respectively. Horizontal deficiency of corner element caused greater destruction and reduced bearing capacity compared to the middle element. Applying four transverse and longitudinal CFRP layers were inspected in terms of strength and bearing capacity improvement. Carbon fiber strengthening, delayed rupture, and reduced local buckling. Carbon fiber had a significant effect on lateral deformation and local buckling by covering the deficiency and increasing the strength. The fiber enhanced bearing capacity by 64% and 37% for middle and corner elements for the most critical columns. CFRP is an efficient and appropriate method for strengthening the damaged columns.

Acknowledgements

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