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AXIALLY-COMPRESSED BEHAVIOR OF DEFICIENT SHORT STEEL COLUMNS STRENGTHENED WITH CARBON-FRP

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ABSTRACT: Structural components surpassing their service life demand extensive repairs, constituting a significant share of the annual budget in advanced nations. This financial commitment arises from the vulnerability of these elements to diverse damages, and the considerable expense associated with reconstruction. Among these components, compression members, notably columns, are pivotal in supporting and transferring both vertical and lateral loads in a structure. Columns inevitably buckle under loads nearing their full capacity, leading to failure. Consequently, researchers are actively exploring retrofitting techniques to enhance column resistance through novel materials and methods. Compression members, often succumb to damage due to factors like aging, deterioration, and corrosion, leading to diminished durability. This study delves into the impact of dimensions and damage location on steel square members under axial loads. Primary damages are intentionally introduced both vertically and horizontally at the middle and corner positions, and retrofitting is performed using Carbon Fiber Reinforced Polymers (CFRP). Experimental testing and ABAQUS software modeling were conducted on eleven steel samples, revealing that compression members undergo local buckling and lateral rupture in damaged zones under axial loads. Notably, Corner damage located at mid-height of the column results in the most substantial loss of strength, reducing ultimate load by 17% compared to undamaged controls. Reinforcement using four layers of carbon fiber enhances load-bearing capacity by up to 18%. Full column wrapping increases stiffness and delays local buckling, improving resistance to axial failure.

Keywords: Steel columns, ABAQUS, Retrofitting, Lateral rupture, CFRP

1. INTRODUCTION

Carbon Fiber Reinforced Polymers (CFRP) have emerged as innovative solutions for reinforcing steel members, gaining prominence due to their advantageous properties, including high strength, low weight, and corrosion resistance. Despite previous research on thin-wall members, especially those reinforced with CFRP, the focus on damaged compression members with box-shaped sections remains limited. This study addresses this gap by exploring the effects of dimensions and damage location in box-shaped compression members retrofitted with CFRP.

Prior research has shown promising results for CFRP reinforcement of steel structures. Shaat and Fam found that horizontally applied CFRP layers are more effective in restricting external local buckling of short columns, increasing the load-carrying capacity of short members by up to 18% and tall members by 13% to 23% [1]. Bambach, Jama, and Elchalakani investigated the axial compression behavior of short steel box sections with welded edges retrofitted with CFRP. They studied 20 retrofitted steel sections under axial compression theoretically and experimentally, examining the axial capacity of the sections. The results showed that the use of CFRP doubles the axial capacity and increases the strength-to-weight ratio by one and a half times [2].

He, Dong, Wang, and Chen investigated the behavior of circular steel columns filled with ordinary and recycled concrete, retrofitted with CFRP under compression. Their study of 10 CFRP-reinforced columns showed an increase in ductility and load-carrying capacity, with the number of layers affecting cross-sectional load-bearing capacity, and complete wrapping significantly enhancing stiffness [3].

Gao, Balendra, and Koh reinforced hollow steel pipes with CFRP sheets, revealing that an increase in the number of layers enhances both strength and stiffness [4]. Prabhu and Sundarraja examined the impact of varying CFRP fiber spacings on the retrofitting of concrete-filled columns, finding that CFRP effectively mitigates lateral deformations, delays local buckling, and enhances load-carrying capacity. The study identified CFRP rupture as the failure mode at a 30-millimeter spacing between fibers, while greater distances led to local buckling [5]. Dong, Wang, and Guan also conducted research on the retrofitting of concrete-filled steel columns using CFRP. Among 22 samples, they examined parameters such as retrofitting methods, concrete type, and section shape. They concluded that full wrapping of CFRP fibers on circular and hollow steel columns has a more favorable effect compared to square-shaped sections [6].

Sundarraja and Prabhu conducted laboratory experiments on the stress-strain behavior, ultimate load capacity, and failure modes of steel sections filled with concrete and transversely reinforced with CFRP. They wrapped carbon fibers around the column in strips, considering factors such as thickness and spacing. The study emphasized the importance of an appropriate distance between CFRP strips to delay local buckling, increase ultimate load capacity, and control axial stress-strain behavior effectively [7].

Elkhabeery, Safar, and Mourad explored the application of CFRP to reinforce steel beams and discovered that CFRP sheets could achieve their maximum strength when sufficient bonding length was guaranteed [8]. Nobati and Ghanbari-Ghazijahani investigated utilizing CFRP to strengthen circular steel tubes with cutouts, revealing that strategic application of CFRP mitigates stress concentration and restores lost capacity [9].

Yousefi, Narmashiri, Hedayat, and Karbakhsh explored the effects of corrosion on slender steel columns by subjecting specimens to corrosive conditions and evaluating their performance under axial compressive loading. Employing CFRP retrofitting, the corroded columns demonstrate heightened load capacity, improved ductility, and controlled fractures, effectively alleviating the detrimental impact of corrosion on their structural integrity [10].

Saad, Tay, and Shukor conducted a comprehensive investigation into reinforced concrete beams strengthened with different CFRP configurations, exploring various application methods and their impact on beam strength, stiffness, and ductility. This research provides valuable insights into optimizing CFRP layouts for efficient beam strengthening [11]. Addressing the challenge of maintaining structural integrity in beams with openings, Rashid, Osman, and Mohd Sam focused on the flexural behavior of CFRP-strengthened reinforced concrete beams with openings. Their work demonstrates how CFRP can effectively mitigate the weakening effects of these openings, offering solutions for retrofitting existing structures and designing more flexible new ones [12].

Expanding to column strengthening, Alrasyid, Suluch, Tavio, and Mingdong conducted a comparative study on reinforced concrete columns strengthened with CFRP and Glass Fiber Reinforced Polymer (GFRP) sheets. This research aids in understanding the relative merits of CFRP and GFRP, guiding material selection based on performance and cost-effectiveness [13].

Hadi, Zhao, and Alhussainy examined CFRP-confined concrete-filled steel tubular columns, investigating how CFRP confinement affects load-bearing capacity, ductility, and failure modes. This study bridges the gap between concrete and steel applications of CFRP, offering insights into its use in hybrid structural systems [14]. Complementing research on concrete structures, Narmashiri, Sulong, and Jumaat analyzed failure mechanisms in steel I-beams strengthened with CFRP plates. Their study identified critical failure modes and their relation to overall structural behavior, contributing to the development of design guidelines for CFRP-strengthened steel members [15].

Yousefi studied the influence of CFRP retrofitting on lengthy steel columns with inherent defects, uncovering a notable 52% reduction in load-bearing capacity due to damages. The application of CFRP significantly fortifies the columns, resulting in a remarkable 51% increase in load capacity, delayed buckling, and the mitigation of stresses in damaged zones [16]. Li, Wang, Fang, Li, and Zhou conducted research on strengthening CFST members with I-shaped CFRP under impact loads, revealing that the improvement in impact resistance from the inner CFRP profile was notably more pronounced at higher impact energies [17].

This current study builds upon these foundations, focusing specifically on box-shaped compression members. The deliberate introduction of damages at strategic locations and the subsequent retrofitting with carbon fibers serve to enhance the structural integrity of these members. Through a combination of experimental testing and numerical simulations, the study aims to provide comprehensive insights into the performance improvements achieved through CFRP reinforcement.

This paper is structured as follows: Section 2 discusses the research significance of this study. Section 3 details the materials and specifications of the steel columns, CFRP, and adhesive used in the investigation. Section 4 describes the sample specifications and experimental setup. Section 5 outlines the numerical modeling approach using ABAQUS software. Section 6 presents the results and discussion, focusing on the effects of dimensions and damage location on load-bearing capacity, failure modes of samples, and the enhanced performance achieved through carbon fiber reinforcement. Finally, Section 7 provides the conclusions drawn from this comprehensive investigation into the axially-compressed behavior of deficient short steel columns strengthened with CFRP.

2. RESEARCH SIGNIFICANCE

This study combines laboratory testing and finite element modeling to enable a thorough analysis and validation of the results. By introducing intentional damage at strategic locations, both at the middle and corners, and in vertical and horizontal orientations, this research offers a comprehensive understanding of how the location and type of damage affect column performance. The study provides precise measurements of load capacity reduction across various damage scenarios and highlights the improvements achieved through CFRP reinforcement. Additionally, the research evaluates a full-wrapping CFRP reinforcement method that is practical for field application, thereby enhancing its relevance for real-world structural rehabilitation.

3. MATERIALS AND SAMPLES SPECIFICATIONS

3.1 Steel Columns

A comprehensive examination involved 11 box-shaped steel members, comprising one intact member and 10 samples with distinct damages under investigation. Five of these samples underwent reinforcement with carbon fibers. In (Fig. 1), the support conditions and dimensions of the studied column are illustrated. (Fig. 2) provides a visual representation of the horizontal and vertical damages strategically introduced at the center and corners of the member. These damages were meticulously applied to laboratory samples using a CNC machine. The mechanical properties of the steel sheet were determined through a tensile test conducted with a pneumatic automatic jaw of 150 kN capacity. The resulting tensile behavior was recorded and presented through stress-strain curves in (Fig. 3). (Table 1) provides the mechanical properties of the steel sheet.

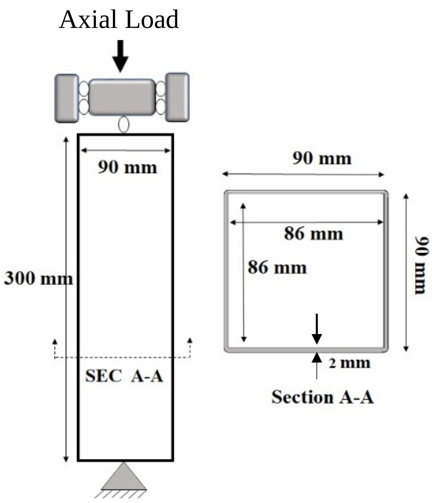

Fig.1 Specifications of the column dimensions and support conditions

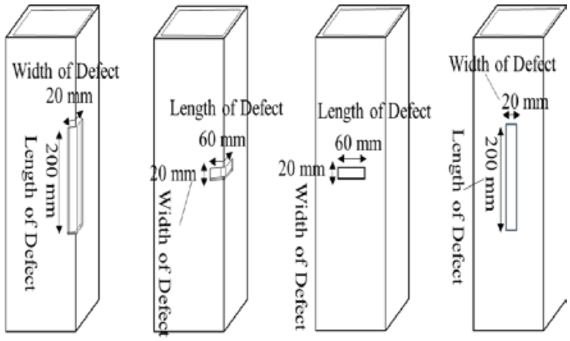

Fig.2 Damages applied to the corner and middle of the columns

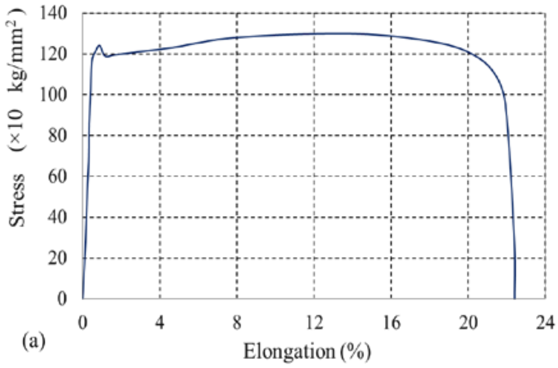

Fig.3 Tensile test

Table 1. Material specifications

Material	Thickness (mm)	Ultimate Stress (MPa)	Modulus of Elasticity (GPa)	Ultimate Strain (%)
Steel Square Hollow Section	2	336	200	22
CFRP(SikaWrap®-230 C)	0.131	4300	238	1.8
Adhesive (Sikadur®-330)	0.869	30	4.5	0.9

3.2 CFRP

In this study SikaWrap®-230 C carbon fibers were employed. It designed for installation using the dry or wet application process. Suitable for use in hot and tropical climatic conditions. Carbon fiber materials have the advantages of low density, high strength, corrosion resistance, fatigue resistance, and low thermal expansion coefficient [18]. Possessing unidirectional properties, these carbon fibers were helically wrapped in a complete pattern, covering the entire height of the member. The reinforcement included one layer in the transverse direction and one layer in the longitudinal direction, applied alternately, with a consistent 20-millimeter overlap for all CFRP-reinforced specimens. Specifications of the carbon fibers are detailed in (Table 1), and (Fig. 4) illustrates the arrangement of carbon fibers for reinforcement.

3.3 Adhesive

Sikadur®-330 adhesive was selected for bonding carbon fibers to the steel member. This adhesive exhibited reliable performance during loading, ensuring a robust bond between the steel member and carbon fiber-reinforced polymer (CFRP) layers. The specifications of the adhesive are presented in Table 1.

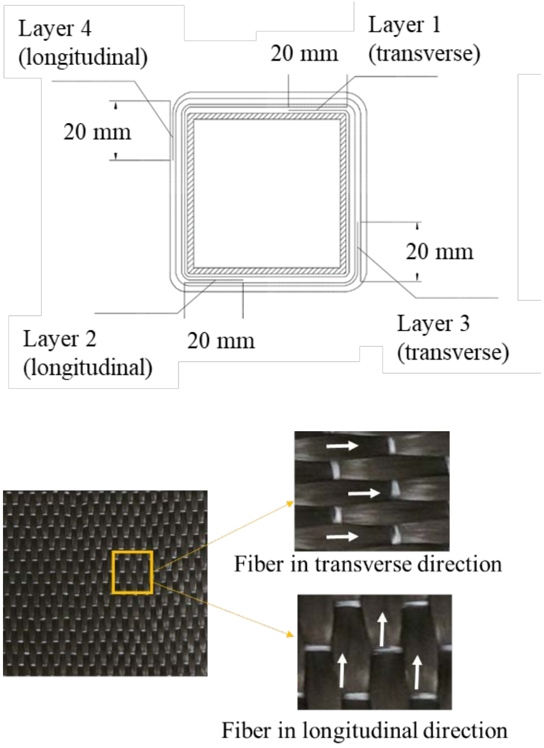

Fig.4 CFRP strengthening method

4. SAMPLE SPECIFICATIONS

The study concentrated on the examination and assessment of 11 square-shaped compressive members through a combination of experimental testing and modeling. Deliberately induced damages were located at the center and corners of these members. To designate these specimens, abbreviations were utilized, with parameters indicating the location of damage denoted by the letters M and C for center and corner, respectively. Horizontal damage was represented by H, while vertical damage was denoted by V. The number and arrangement of carbon fibers were indicated by T and L, signifying longitudinal and transverse layers, respectively. For example, the specimen MH-60-20-2T2L is a compressive member with horizontal damage at the center, measuring 20×60 mm^2. It was reinforced with 4 layers of carbon fibers (2 transverse and 2 longitudinal layers).

To evaluate the laboratory performance of the steel columns, axial loads were applied to these specimens, considering the location of the steel plate axis. Loading was executed using a hydraulic jack, and the displacement of the specimens was measured by two LVDTs, recorded by a data logger.

5. NUMERICAL MODELING

To study the effective parameters in the behavior of steel specimens without the constraints of laboratory experiments, finite element analysis through ABAQUS software was employed. Steel columns, adhesive, and carbon fibers were modeled using three-dimensional elements with a mesh size of 10 mm and a twenty-node element type (C3D20R). The analysis method in modeling was considered as non-linear static, and loading was applied by a rigid plate subjected to compressive loading. Supports were considered as hinged, similar to laboratory specimens, and 'Tie' constraints were used for the connection of adhesive and carbon fibers.

Initially, for the validation of the reference specimen, three different mesh sizes were used, and the 10 mm mesh size showed the least difference in load-bearing capacity compared to the laboratory specimen. (Fig. 5) displays the load-bearing capacity of the reference specimen (Control) experimentally performed and simulated using software with three mesh sizes of 10, 12, and 14 mm. In (Fig. 6), the failure mode of the control specimen is observable.

6. RESULTS AND DISCUSSION

6.1 Effects of Dimensions and Damage Location on Load-Bearing Capacity

To scrutinize and compare the results, the reference sample (undamaged steel member without reinforcement) served as the basis. The analysis focused on comparing force-displacement patterns, aiming to discern the impact of dimensions, conditions, and damage location on the behavior of the compressive member and its reinforcement with carbon fibers. Horizontal and vertical damages at the middle, corner, and center of the steel member were studied, with the dimensions of horizontal damage set at 20×60 mm^2. The control sample withstood a load of 241 kN under axial load.

Table 2. Specifications of Laboratory Samples and Modeling

No.	Cases	Specification of damages			CFRP layers	Load bearing capacity (kN)		Increase/ Decrease (%)	
		Length (mm)	Width (mm)	Location		Experimental	Numerical	Experimental	Numerical
1	Control	N/A	N/A	N/A	-	241	235	-	-
2	MV-200-20	200	20	Middle	-	225	219	-6.64	-6.81
3	MV-200-20-2T2L	200	20	Middle	4	256	251	+6.22	+6.8
4	CV-200-20	200	20	Corner	-	210	206	-12.9	-12.3
5	CV-200-20-2T2L	200	20	Corner	4	249	244	+3.32	+3.83
6	CV-60-20	60	20	Corner	-	-	211	-	-10.2
7	MH-60-20	60	20	Middle	-	202	195	-16.2	-17
8	MH-60-20-2T2L	60	20	Middle	4	244	239	+1.245	+1.7
9	MH-60-20-1T1L	60	20	Middle	2	-	221	-	-5.96
10	CH-60-20	60	20	Corner	-	200	195	-17	-17.2
11	CH-60-20-2T2L	60	20	Corner	4	239	234	-0.83	-0.43

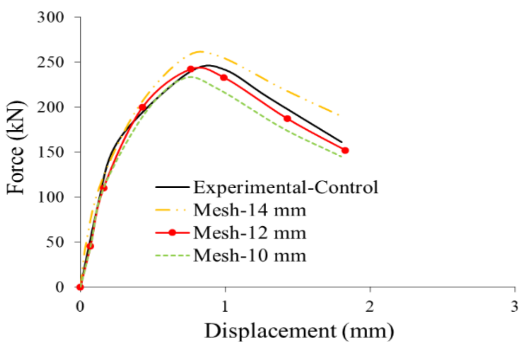

Fig.5 Sensitivity Diagram of Mesh Size for the Control Sample

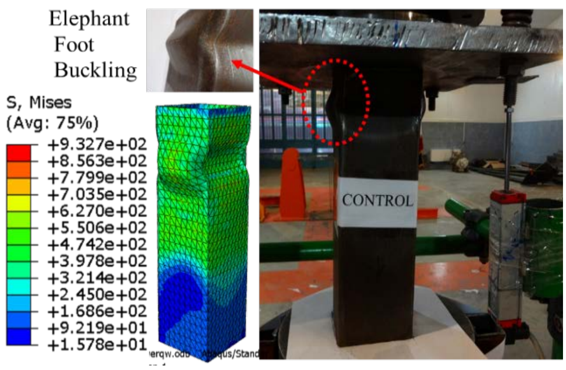

Fig.6 The failure mode of the control specimen

The undamaged control sample likely exhibited a sudden post-peak decline in load capacity, characteristic of ductile steel behavior. In (Fig. 7), the force-displacement diagram for the horizontally damaged specimen at the center indicates a 16.2% reduction in load-bearing capacity compared to the undamaged control case. Notably, the damaged member experienced a sudden fracture after reaching the yield point, demonstrating some degree of re-hardening following the initial deformation. Subsequently, the damaged member experienced a gradual load drop due to the re-hardening effects. The post-peak behavior likely involved a gradual load drop due to localized buckling at the damage site.

For horizontal damage at the corner (Fig. 8), the reduction in load-bearing capacity was even higher, reaching up to 17%, emphasizing the critical nature of this type of damage. The corner-damaged sample (CH-60-20) may have experienced a steeper post-peak decline compared to the middle-damaged sample (MH-60-20) due to more severe stress concentration.

Vertical damages, particularly corner damages, exerted a more substantial impact on ultimate load, as seen in (Fig. 9-10). The CV-60-20 sample, with vertical damage of 20×60 mm^2, experienced a roughly 10% reduction in load-bearing capacity. When the dimensions increased to 20×200 mm^2, the final load-bearing capacity decreased by about 12%.

While vertical damages, especially at corners, had a more critical effect on ultimate load, the reduction for smaller dimensions was significantly less compared to horizontal damages. The results underscore the substantial role of damages in increasing axial deformations within the damage range, consequently diminishing hardness and load-bearing capacity. Additionally, damaged compressive members exhibited significant deformation at the location of damage under axial loading.

For vertically damaged samples (MV-200-20 and CV-200-20): Less severe reduction in load capacity (6.64% for middle, 12.9% for corner) was observed. Post-peak behavior probably involved more gradual load decline compared to horizontally damaged samples. The corner-damaged sample (CV-200-20) likely showed a steeper post-peak drop than the middle-damaged sample (MV-200-20).

Generally, strengthened samples exhibited improved post-peak behavior compared to their unreinforced counterparts. The post-peak response likely involved a more gradual decline in load capacity due to the confinement effect of the CFRP.

Effect of damage location on CFRP-reinforced samples: Corner-damaged reinforced samples (e.g., CH-60-20-2T2L) might show a slightly steeper post-peak decline compared to middle-damaged reinforced samples (e.g., MH-60-20-2T2L) due to stress concentration effects.

Vertical vs. Horizontal damage in CFRP-reinforced samples: Vertically damaged reinforced samples (e.g., CV-200-20-2T2L) might exhibit a more gradual post-peak response compared to horizontally damaged reinforced samples (e.g., CH-60-20-2T2L) due to the alignment of CFRP fibers with the primary load direction.

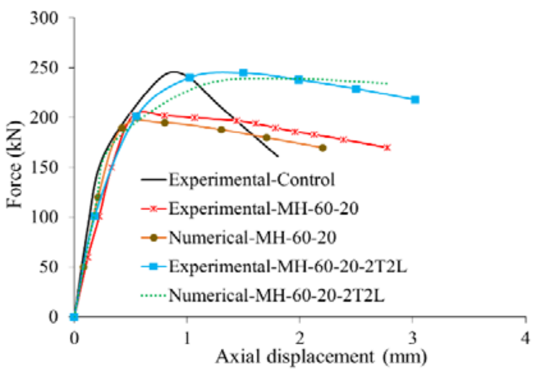

Fig.7 Force-Displacement Diagram for the columns with Horizontal Damage of 20×60 mm^2 at the Center

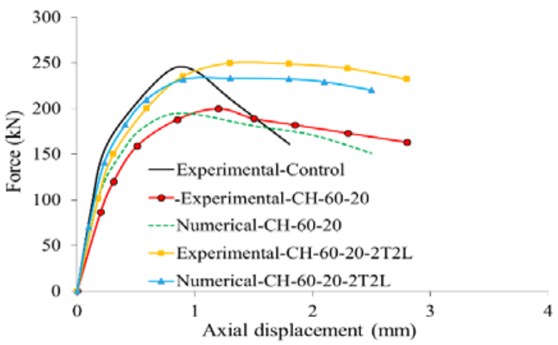

Fig.8 Force-Displacement Diagram for the columns with Horizontal Damage of 20×60 mm^2 at the Corner

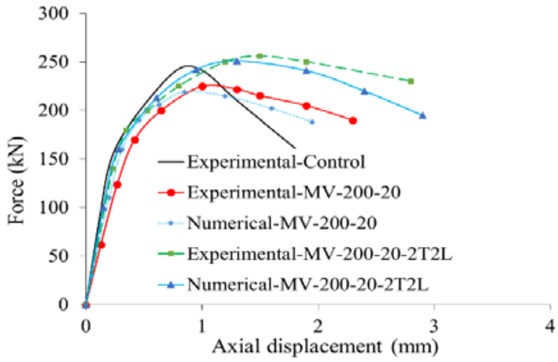

Fig.9 Force-Displacement Diagram for the columns with Vertical Damage of 20×60 mm^2 at the Center

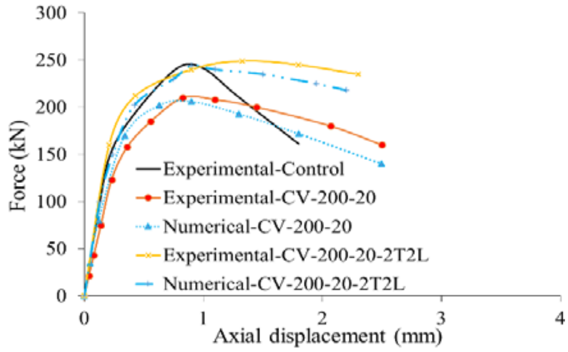

Fig.10 Force-Displacement Diagram for the columns with Vertical Damage of 20×60 mm^2 at the Corner

6.2 Failure Modes of Samples

6.2.1 Undamaged Compressive Member (Control Sample)

The behavior and failure of a sample depend on factors such as load-bearing capacity, deformability, and yielding under axial load. To comprehend the results of damaged box-shaped members, it is crucial to first examine the behavior and yielding of an undamaged column under axial load. (Fig. 11) corresponds to the control case. Upon axial loading of the box-shaped steel member, outward buckling occurred at the top, known as "Foot Elephant" buckling. This type of buckling results from the dominance of forces on the internal surface within the elastic range of the member. (Fig. 11) illustrates the stress distribution in the inner and outer walls under the influence of "Foot Elephant" buckling caused by axial loading on the box-shaped compressive member.

As axial displacement increases in an undamaged column, compressive stresses can lead to Elephant Foot buckling, causing a sudden loss of load-carrying capacity and a sharp drop in force response. Damaged columns, however, do not exhibit this sudden drop. Instead, they experience gradual and distributed buckling, resulting in a more gradual reduction in load-bearing capacity. Even after reaching the peak load, damaged columns can still carry a load, though at a reduced capacity as the damage progresses.

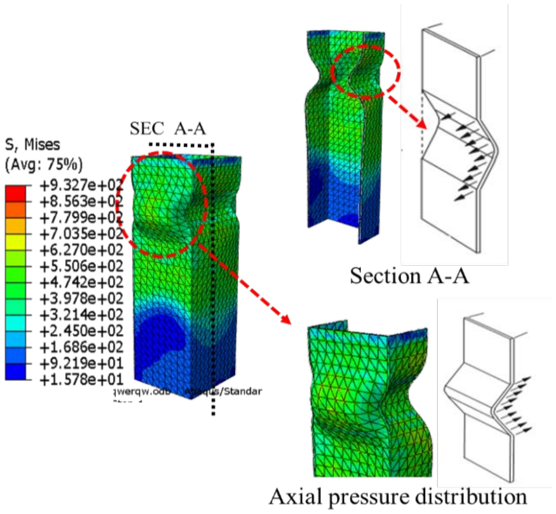

Fig.11 Stress distribution in the inner and outer walls of a short steel column under axial load

6.2.2 Effects of Horizontal Damages

MH60-20 Sample: This member, with horizontal damage at the center of the middle edge, exhibited compression, reduction in the width of the damage, and local buckling around the outer surface. Yielding initiated at approximately 58 kN, and axial deformations continued up to 202 kN (Fig. 12a).

Corner Damage**:** The member with horizontal damage at the corner showed an increase in axial yielding and compression within the damage range. Fractures and failures started at a load of 51 kN and continued up to 200 kN (Fig. 12b). Comparing the final deformations of the box-shaped steel sections revealed that, due to horizontal damage at the center, stress concentration and local buckling in the outer walls increased. The failure mode was characterized by a decrease in the width of the damage.

6.2.3 Effects of Vertical Damages in the Compressive Member

For case CV200-20, with vertical damage at the corner, experienced widening of the damage zone under axial loading. Failures began at 83 kN, and axial resistance continued up to 210 kN (Fig. 13a). Axial loading resulted in the widening of the damaged area, an increase in stress distribution, and concentration in the outer walls of the member.

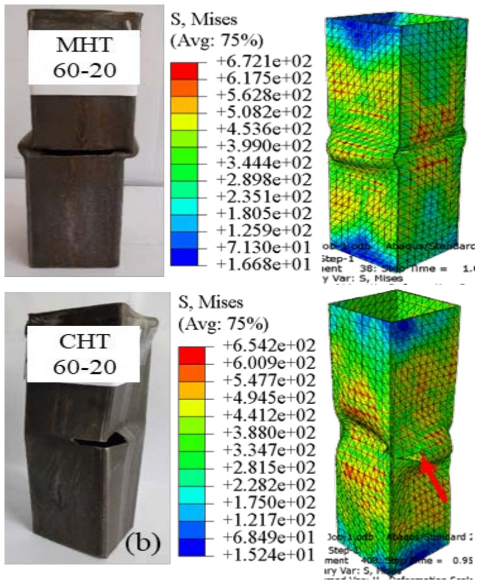

Fig.12 Comparison of Final Deformations for the horizontal Damage: a) at the center, b) at the corner

The MV200-20 sample has vertical damage in the middle of the edge. As depicted in (Fig. 13b), this sample exhibited less deformation in the damaged area compared to the vertically damaged sample created at the corner. Yielding in this sample commenced at a load of 95 kN and continued up to a load of 225 kN. The results indicate that localized buckling in the outer edge led to a reduction in hardness and an increase in stress concentration in the damaged area.

6-3 Enhanced Performance with Carbon Fiber Reinforcement

6.3.1 Reinforcement of Horizontal Damage

The effectiveness of carbon fiber reinforcement in mitigating the impact of horizontal damage is evident in the laboratory results. For the MH-60-20-1T1L sample, reinforced with two layers (one transverse and one longitudinal), the load-bearing capacity did not fully compensate for the damage-induced reduction. Subsequently, all other samples were reinforced with 4 layers.

a) Sample with Damage at the Center: In the case of horizontal damage at the center, (Fig. 14a) demonstrates the localized buckling in the transverse direction. CFRP cracking initiated at 192 kN, with final resistance up to 244 kN.

b) Specimen with Damage at the Corner: For the member with horizontal damage at the corner (Fig. 14b), the compressive load led to localized fiber yielding. CFRP failure occurred due to the reduction in section width, with increased stress concentration causing rupture in the damaged region.

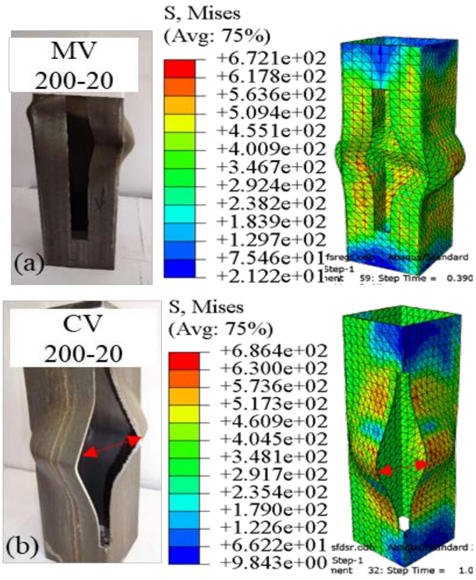

Fig.13 Comparison of Final Deformations for the Vertical Damage: a) at the center, b) at the corner

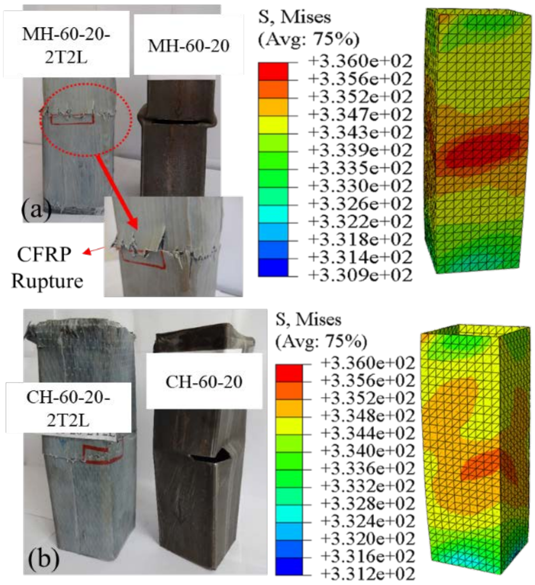

Fig.14 Comparison of strengthened columns with horizontal damage: a) damage at the center, b) damage at the corner

6.3.2 Reinforcement of Vertical Damage

For samples with vertical damage, the reinforcement with carbon fibers significantly contributed to axial performance and reduced localized buckling.

a) Specimen with Damage at the Center: In the case of vertical damage at the center (Fig. 15), full section coverage with 4 layers effectively confined and compensated for the damage. This resulted in strengthened axial performance and reduced localized buckling.

b) Case with Damage at the Corner: (Fig. 16) illustrates the failure mode of the sample with vertical damage at the corner. Carbon fiber reinforcement enhanced ductility and reduced localized buckling, as indicated by fiber rupture and failure at the end of the vertical damage.

Fig.15 Strengthened columns with vertical damage (200×20 mm^2) at the center

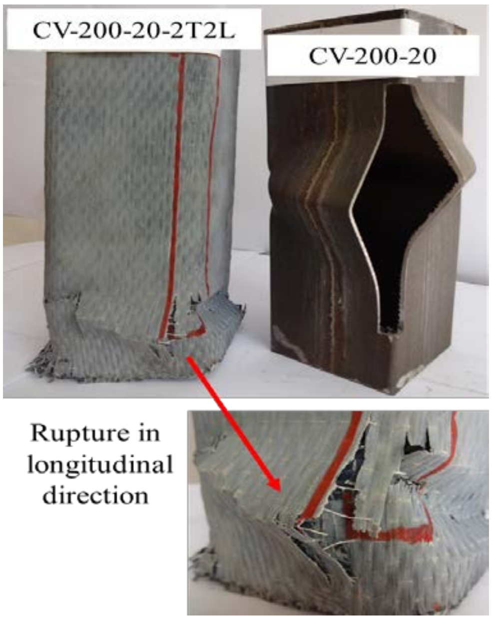

Fig.16 Strengthened columns with vertical damage (200×20 mm^2) at the corner

The application of CFRP to steel columns significantly alters their structural behavior and failure mechanisms compared to unreinforced specimens. CFRP reinforcement enhances the overall stiffness of the column, resulting in a more linear force-displacement response and delaying the onset of yielding and local buckling in the steel. This reinforcement creates a confinement effect, restraining outward local buckling and maintaining the column's cross-sectional integrity under higher loads.

The composite action between the bonded CFRP and steel substrate leads to a distinct force-displacement response, differing from the behavior of pure steel yielding. As the steel begins to yield locally, stresses are redistributed to the CFRP, a mechanism absent in unreinforced specimens. This stress transfer contributes to a different post-yield behavior and often results in higher residual strength for CFRP-reinforced columns after initial yielding.

However, it's important to note that while steel exhibits ductile yielding, CFRP is a brittle material. When the CFRP reaches its ultimate strain, it fails suddenly through fiber rupture or debonding, introducing a more abrupt drop in load capacity compared to the gradual yielding of unreinforced steel. This characteristic shift in failure mode from local buckling and steel yielding to CFRP rupture or debonding is a key distinction between reinforced and unreinforced specimens.

7. CONCLUSION

This comprehensive study examined the effects of damage dimensions and location on tubular compressive members reinforced with carbon fibers. The research employed both experimental testing and numerical modeling through ABAQUS software, with horizontal and vertical damages intentionally applied to the center and corners of the specimens.

Key findings from the investigation include:

- Induced damages exacerbated failure modes, reduced strength, and increased axial deformation in the plastic range of affected members.
- Damaged areas exhibited stress concentration, leading to increased local buckling and axial deformation.
- Horizontal damages had a more significant impact on reducing compressive load-bearing capacity compared to vertical damages.
- Corner damage proved to be the most critical condition, characterized by localized buckling and intensified stress concentration, resulting in the greatest reduction in axial resistance among the samples.
- Reinforcement with multiple layers of carbon fibers, wrapped completely around the members, substantially improved axial performance by delaying buckling and localized bending in damaged areas.

The results strongly support the use of carbon fiber reinforcement as an effective method for enhancing axial performance and strengthening damaged column sections. This approach shows considerable promise for improving the structural integrity and longevity of steel compression members across various applications in civil engineering and construction.

8. REFERENCES

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

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

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

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

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

[6] Dong J, Wang Q, Guan Z, Structural behaviour of recycled aggregate concrete filled steel tube columns strengthened by CFRP. Engineering structures, Vol. 48, 2013, pp. 532-542.

[7] Sundarraja M C, Prabhu G G, Experimental study on CFST members strengthened by CFRP composites under compression. Journal of Constructional Steel Research, Vol. 72, 2015, pp. 75-83.

[8] Elkhabeery O H, Safar S S, Mourad S A, Flexural strength of steel I-beams reinforced with CFRP sheets at tension flange. Journal of Constructional Steel Research, Vol. 148, 2018, pp. 572-588.

[9] Nobati J A, Ghanbari-Ghazijahani T, CFRP-reinforced circular steel tubes with cutout under axial loading. Journal of Constructional Steel Research, Vol. 164, 2020, pp. 105775.

[10] Yousefi O. Narmashiri K. Hedayat A.A. Karbakhsh A. Strengthening of corroded steel CHS columns under axial compressive loads using CFRP. Journal of Constructional Steel Research, Vol. 178, 2021, pp. 1835-1856.

[11] Saad M A, Tay K L, Shukor N A, Structural Performance of Reinforced Concrete Beams

Strengthened with Different CFRP Configurations. International Journal of GEOMATE, Vol. 20, Issue 82, 2021, pp. 126-133.
[12] Rashid R S M, Osman M H, Mohd Sam A R, Flexural Behaviour of Reinforced Concrete Beams with Openings Strengthened Using CFRP. International Journal of GEOMATE, Vol. 20, Issue 79, 2021, pp. 105-112.
[13] Alrasyid H, Suluch M, Tavio T, Mingdong Y, Strengthening of Reinforced Concrete Columns Using CFRP and GFRP Sheets: A Comparative Study. International Journal of GEOMATE, Vol. 21, Issue 85, 2021, pp. 1-8.
[14] Hadi M N S, Zhao T, Alhussainy F, Behavior of CFRP-Confined Concrete-Filled Steel Tubular Columns. International Journal of GEOMATE, Vol. 22, Issue 89, 2022, pp. 84-91.
[15] Narmashiri K, Sulong N H R, Jumaat M Z, Failure Analysis of Steel I-Beams Strengthened with CFRP Plates. International Journal of GEOMATE, Vol. 22, Issue 91, 2022, pp. 102-109.
[16] Yousefi O., Numerical Investigation on Structural Behaviors of Deficient Steel CHS Long Columns Strengthened Using CFRP %J. AUT Journal of Civil Engineering, Vol. 6, Issue 4, 2022, pp. 509-520.
[17] Li G, Wang J, Fang C, Li X, Zhou Y, Performance of CFST members internally strengthened with I-shaped CFRP under impact load. Journal of Constructional Steel Research, Vol. 211, 2023, pp. 108132.
[18] Product Data Sheet. SikaWrap®-230 C. June 2017, Version 01.01