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Original Article

Effects of carbon fiber reinforced polymer wrapping strength on behavior of steel hollow short column under concentric axial force

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Abstract

In this study, behavior of steel hollow short columns fabricated from steel square section under axial load is investigated with and without CFRP strengthening, five specimens of SHSC without strengthening are tested by applying concentric axial force; and the obtained results are compared with fifteen SHSC strengthened with CFRP wrapping with different five percentage from the total length of the specimens as follows (20%, 40%, 60%, 80%, and 100%) and each strengthening length consist from three different layers (one, two and three) layers. The curves of load-displacement are plotted for the specimens with maximum strength load. The results show that the most effective type of CFRP wrap strengthening is the full length of the specimens and especially with two and three layers. The increase in the load carrying capacity is 34.5% from 126.37 kN for SHSC-C to 170.02 kN for SHSC-100-3L, and the increase for ductility index is 23.6 % from 1.39 for SHSC-C to 1.72 for SHSC-100-2L. The pattern of failure for the specimens; non strengthened or strengthened with less than full length is local buckling, while the failure is CFRP rupture with local buckling for specimens strengthened with full length specimen.

Keywords: *Steel Hollow Short Columns (SHSC), Carbon Fiber Reinforced Polymer (CFRP), Local Buckling, CFRP Rupture.*

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1. Introduction

Hollow structural sections (square, rectangular, or round) SHS are very variable sections for buildings, bridges, and other structures. These clean, neat-looking sections are easily fabricated and erected. They are often used as columns. Hollow structural sections are available with high yield strength with enhanced corrosion resistance [1]

Whereas, other researchers like: [2] is aimed to determine both: 1) the CFRP layer direction and 2) if (at the wrapping end there is a gap or not) on the compression strength of square hollow steel column.

Reference [3] investigate the CFRP strengthening on the deficient columns (aligned or perpendicular slots was carried out at the center or edge of the columns), two different types of layouts transverse and longitudinal of CFRP sheets bond. All the columns were tested under axial force. So, the layers' CFRP fiber bond can arise the ductility, when the CFRP number increase it can play considerable effect in restrict columns or the local buckling delaying, consequently, load capacity increase.

In study [4] the steel-frame structure flexural and compression members strengthen with CFRP sheets under flexural and compression their experiments gain a maximum increase of 11.3% because of CFRP sheets ply number and CFRP sheets length.

A short columns (SHS–Square Hollow Section and RHS-Rectangular Hollow Section) were tested by [5] using pure compression to study the local buckling behavior, by differentiation of results which show: significant react on CFRP strength when used full wrapping system then attain the ultimate (load and stiffness). Specimens which are bonding from outside by sheets of CFRP for full wrapping supplies an adequate confining action against local columns deformation, in addition to delay the elastic local buckling and then increase the axial capacity and stiffness.

Welded box-section stub columns tested by axial compression, studied by [6] the columns are made from four steel type grades, with three sizes of cross-sections, while are similar with slenderness ratio for each steel grade. The specimens are square cross section. All specimens were failed by local buckling mode for their plates and large ultimate bearing capacity. local buckling increased more quickly after failure, causing the welding to fracture rapidly.

Eight specimens of Square Hollow Section (SHS) tested by [7] to indicate the torsional strength of square hollow sections. All square hollow sections wrapped with an oriented angle 45o with respect to longitudinal axes of the specimens, also a simulation by using a finite element ANSYS to show the difference between experimental and numerical of modeling results.

Corrosion effects and techniques of strengthen on the columns behavior studied by [8], the strengthened columns were wrapped from external with CFRP sheets, compressive loading make the stress more intense in CFRP fibers due to shear rupture. So the ductility increase compared with unwrapped columns due to the CFRP fibers bond.

A comprehensive review provided by [9], and some of the conclusions can be listed such as: FRP materials with longitudinal oriented fiber are more efficient, FRP strengthen effectiveness for steel member prostrate to flexural buckling according to the quantity of fiber reinforcement, and the durability of structures strength with FRP depending on the adhesive properties.

Short columns of (CHS-Circular Hollow Section) with aligned and perpendicular defect were strengthened using CFRP layers by [10] to study the bearing load. So, using the CFRP lead to delay the local buckling and recover the maximum bearing capacity. Furthermore, a numerical simulation ABAQUS software used to model: the steel columns, CFRP sheets, and adhesive.

Nine columns' specimen were tested via [11] six of them composite columns, while others were bare steel columns, as well as subjected to compression force. Composite columns are consist of steel I-section and the voids between the flanges and web were brimmed with concrete then wrapped with FRP sheets. The FRP jackets increase the compressive strength of concrete to about 17%.

Forty stub columns were tested by [12], twenty of them circular tubular steel stub columns and the last twenty square steel tubular stub columns, all specimens exposed to high temperature: without CFRP and with CFRP strengthened specimens. After the columns cooled are wrapped with CFRP of different layers. The ductility of fire-exposed columns increase as the CFRP sheets are augmented.

The mechanical behavior of thin-walled steel box-section made from steel high strength; were studied by [13] using uniaxial compression tests. The specimens with thinner plate were failed by buckling while the specimens with thicker plate were failed by strength. FEM ANSYS program was used to simulate the tested curves to satisfy the validity of the numerical simulation methods.

The buckling behavior of slender steel columns strengthened by prestressed (PS) carbon fiber reinforced polymer strips made from (CFRP) examined via [14] under axial compression force, a novel strengthening method has been proposed for steel columns, strength method mechanism considered, the stiffness increase up (buckling load 150%) with a PS CFRP apply then buckling can be delayed.

A paper conducted by [15] presents the experimental in addition to the numerical investigation of stub columns of cold-formed (HSST) strengthen extremely using the (CFRP) wrap. Three variables were taken: thickness of CFRP, arrangement of CFRP were both (full, partial arrangement). Experimental results show that partial wrapping did not show any improvement in strength, while full wrapping was effective in improving the ultimate compression capacity.

Behavior of axial compressive and capacity of (HFRP) restrained short CHS steel columns consist of (CFRP) and (GFRP); were the experimental work by [16] consist of seven specimens used to assess the direction of wrapping of GFRP and CFRP on restraining capacity. Specimens suffered from early failure due to local buckling at the ends. Ductility and bearing capacity improve the CHS, HFRP composed of one layer CFRP as middle layer and two layers of transverse CFRP as middle and outer layers give good results than using two layers of transverse CFRP.

HSS steel columns were investigated by [17] under compression concentric loadings. The experimental fall in 3 sets control unstrengthened and the others 3 sets strengthened with CFRP plates (two CFRP strips were bonded on each of the two opposite sides of all the specimens), the advantages of CFRP system in increasing of the columns axial strength increase considerably as slenderness ratios become higher, CFRP failure may be due to deboning or crashing.

A research presented by [18] about the strengthen of thin-walled structures of steel using FRPs. Axial compressive strength of the composite steel-CFRP SHS (Square Hollow Section) was significantly greater than the sum of the capacities of individual components (the CFRP-only SHS strength plus the steel-only SHS strength).

A paper represents by [19] axial loaded steel columns strengthened for increasing load, with CFRPs and non-strengthened specimens for reference. Layers of CFRP were wrapped by using various coverage percentage around the hollow structural steel tubular columns to enhance the structural performance, the coverage of CFRP used has a direct effect on increasing minimum ultimate load, and for all SHS specimens, Best of CFRP coverage percentage is 100%.

This research is to investigate the strengthening steel hollow short column SHSC with CFRP wrap (Sika wrap 300 C) by using epoxy resin (Sikadur 330) to enhance the concentric load carrying capacity to resist local buckling from applied axial force also delay the presence of the local buckling from the upper parts of the short column to the parts beyond the strengthening region part with CFRP wrap; also to insure that the strengthening material CFRP wrap with epoxy resin for cooperation on the surface of the steel hollow column to confine the square section consequently inhibit local buckling formation in the strengthening part of the steel column with CFRP.

This research is exceptional supplement prior studies by considering the percentage length distance of the strengthening wrapping which are; 20%, 40%, 60%, 80%, and 100% of the total length of hollow steel columns, and the number of strengthening layers which are; 1,2, 3 layers.

So the novel in this research is the percentage of the CFRP wrap strengthening to the total length of steel hollow short column, and the number of strengthening layers which are range from one to three layers. The parts that are strengthened with CFRP warp are not suffer from buckling and the failure is still happening by buckling in the parts that are not strengthened with CFRP wrap; until the short hollow columns strengthened with full length of the specimen then the failure changes to rupture of CFRP wrap.

2.Experiment Work:

Experimental work achieved to specify the concentric axial compression behavior and CFRP capacity used to strength SHSC short columns subject to local buckling. It consists of twenty short SHSC columns tests aimed to determine CFRP wrap layers effect number and the percentage of CFRP wrap length strengthening on the compression capacity. Below presents the experiment work.

2.1 Material Properties

2.1.1 Steel Hollow Short Column

In this study steel hollow square column (SHSC) with a dimension 100 × 100 mm and thickness 1.6 mm with length 600 mm is used, this section is lightweight, high energy absorption capacity, versatility and prone to local buckling. Dimensions of tested steel columns and test arrangements shown in Fig. 1.

The mechanical properties of steel column are listed in Table 1. Based on the American Society for Testing Materials (ASTM: E8/E8M-22) [20].

The tensile steel samples are designed as shown in Fig. 2, also the tensile samples were tested on the WDW-200E universal testing machine, the details are illustrated in Fig.3. The specimens average modulus of elasticity obtained from material property test was 198,700 MPa. The ultimate tensile strength was approximately 399.4 MPa, as Grade 55 according to

(ASTM:A322-91) [21] More test data are illustrated in Table 1 and Fig. 4.

The length of the short columns was chosen 600 mm, to provide a slenderness ratio (kL/r) of 14.8 less than 40 so that the specimens could be classified as short columns according to [22, 23,24, 25] .

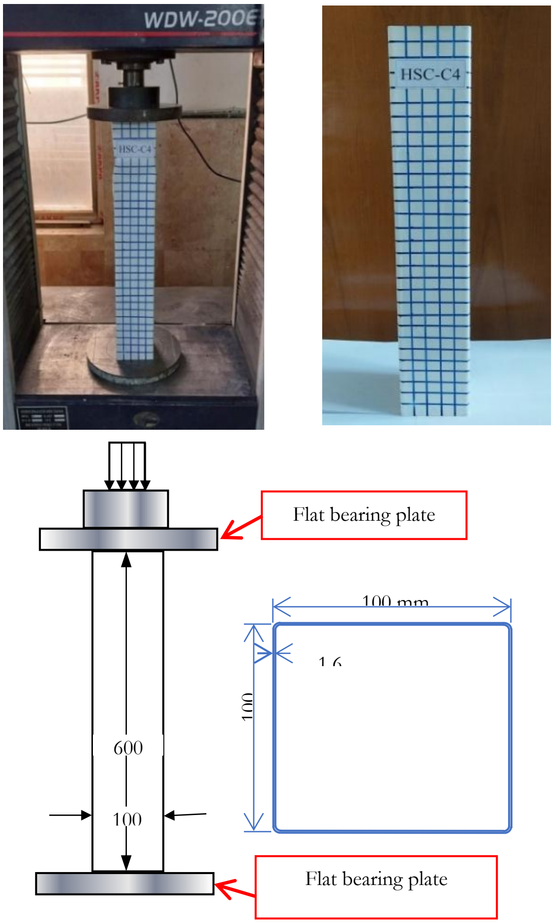


Figure 1. Experimental test up of hollow steel columns.

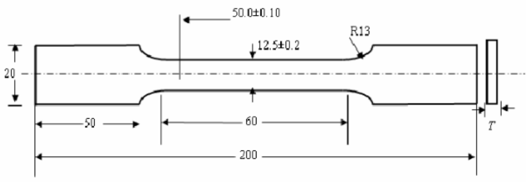
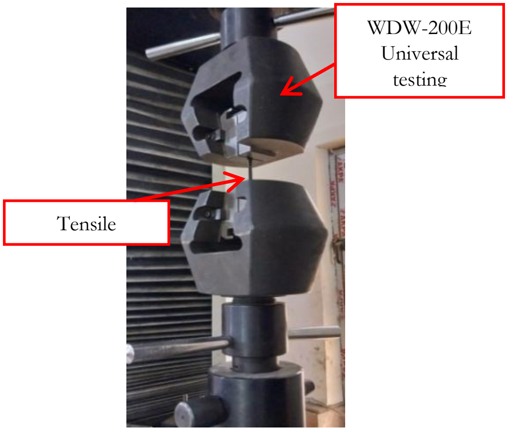


Figure 2. Tensile coupon dimensions.



(a) Test setup.

(b) Tensile coupons

Figure 3. Material tests

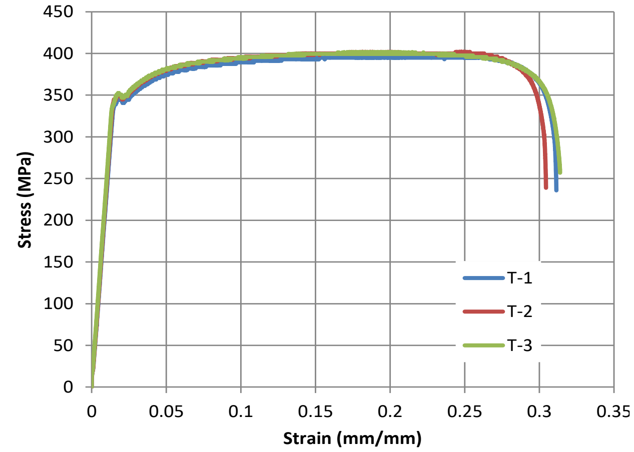


Figure 4. Stress-strain curves of tensile coupons.

2.1.2 CFRP Wrap

In this paper the CFRP wrap (Sikawrap-300C) was used as shown in Fig. 5, Modulus of elasticity of CFRP fibers is 230,000 MPa, tensile strength is 4000 MPa and the thickness of the fiber 0.167 mm. The specifications of the fiber are listed in Table 2. [26]

Table 1. Material properties

Coupons	*Fy* MPa	*Fu* MPa	$E \times 10^5$ MPa	δ %
	Test results Mean results	Test results Mean results	Test results Mean results	Test results Mean results
T-1	346.1	396.7	1.87	21.2
T-2	349.1	399.9	2.03	19.7
T-3	350.7	401.8	2.06	19.5
Avg.	348.6	399.4	1.987	20.1

Table 2. CFRP specifications* [26]

Thickness (mm)	Density (gm/cm^3)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Ultimate strain (%)
0.167	1.82	4000	230,000	1.7

2.1.3 Adhesive

Adhesive must be strong and supplies the force transmission between the steel section surface and the composite materials to cause the identical performance of composite and columns. In this study (Sikadur-330) as shown in Fig. 6 was used. It is two part epoxy resin, compound of a resin and a hardened with the 4:1 mixing ratio. Table 3 shows the adhesive specifications. [27]

Table 3. Resin epoxy specifications* [27]

Density (kg/l)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Ultimate strain (%)
1.3	30	4500	0.9

2.1.4 Steel - CFRP Coupon:

To study the behavior of bond force between steel column material and CFRP wrap through the epoxy resin, a rectangular coupon is fabricated with dimension 25 mm width and 250 mm length from the same section of hollow steel column while the CFRP wrap are cut to fit the same dimensions of the steel rectangular coupon. In addition to that, rectangular steel plate with dimensions 25 × 56 mm made from the same hollow steel column bonded to the end of both sides of the specimens to work to catch the specimen and as a gauge length from the both sides. The steel plate and CFRP wrap (Sikawrap-300C) are bonded together with epoxy resin (Sikadur-330) as shown in Fig.7. The numbers of the coupons are 9 which are strengthened with one, two and three layers; for each number of layers strengthening there are three specimens.

The tests were done by using a testing machine WDW-200E universal, the details of the test shown in Fig. 8.

Style of failure in the Steel–CFRP coupons was occurred first by rupture of the CFRP wrap then the steel plate yielding and failed by necking as shown in Fig. 8.

Load–displacement curves are shown in Fig. 9 and Table-4 for the nine CFRP-Steel coupon specimens it can be notice that displacement decrease with the CFRP wrap number layers increase and this obvious through specimen CFRP-Steel 2L-1 which its displacement is 26.267 mm, while for specimen Steel-1 coupon which it without strengthen its deformation is 42.94 mm and from this result it can concluded, the increase in the number of layers enhance the tensile strength and the resistance to the stretch that occurs because of tensile load.

Figure 5. Carbon fiber

Figure 6. Epoxy resin

fabric (Sika-wrap -300C). (Sikadur-330).

Figure 7. Steel-CFRP strengthening coupons: 1 layer, 2 layers and 3 layers.

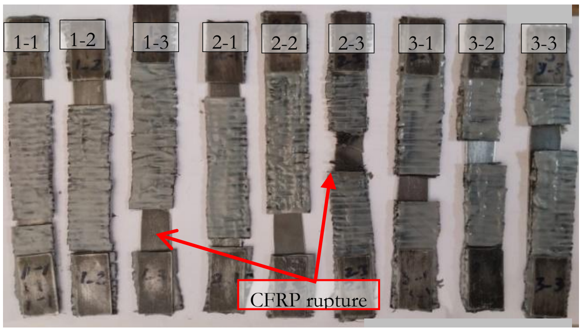


Figure 8. Steel-CFRP tests.

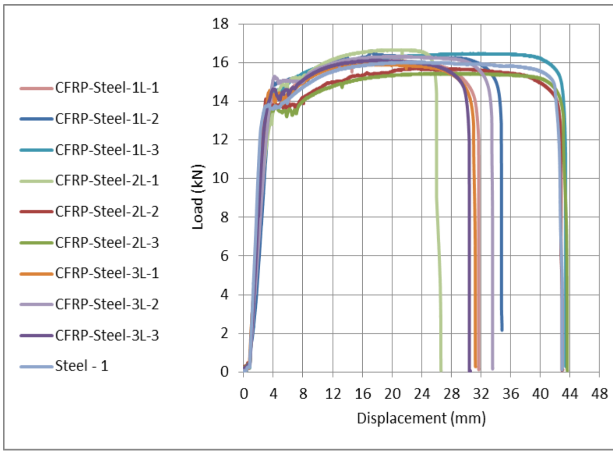


Figure 9. Load-Displacement curve for the CFRP-Steel coupons tensile test.

Table 4. Percentage of deformation decrease for CFRP–Steel specimens.

Specimen	Displacement (mm)	Displacement % decrease
Steel	42.940	0
CFRP-Steel 1-1	31.722	26.12
CFRP-Steel 1-2	34.827	18.89
CFRP-Steel 1-3	43.460	-1.210
CFRP-Steel 2-1	26.627	37.99
CFRP-Steel 2-2	43.020	-0.186
CFRP-Steel 2-3	43.637	-1.623
CFRP-Steel 3-1	31.291	27.12
CFRP-Steel 3-2	33.583	21.79
CFRP-Steel 3-3	30.565	28.82

2.2 Test Specimens

The test specimens (square hollow short column SHSC) were fabricated from 6 meter steel hollow section boxes through cutting them to about 600 mm length and their ends were arranged on the bed of a milling machine to make them flat end surfaces. The number of the specimens were twenty, five of them were control as shown in Fig. 10 and the others were strengthened with CFRP wraps with one, two, and three layers and 20%, 40%, 60%, 80%, and 100% percentage of the total length of the specimens as shown in Fig. 11, in addition Table 5 provides the details of the test specimens.

The specimens which strengthened with CFRP wrap their surfaces were brushed and cleaned to obtain a good bind between the steel and CFRP, however these surfaces were sand blasted to remove all external infects and make them clean and rough to produce a high force surface which has the ability to contact materials (CFRP and adhesive) to the subtract surface (steel). As well as the CFRP-wraps were cut to the required dimensions (20%, 40%, 60%, 80% and 100%) of the short column length. After that an adhesive which was a two-part epoxy was mixed then external surfaces of steel columns covered with an adhesive. Finally, CFRP wraps are bonded to the square steel columns with one, two or three layers, whereas; the remain part of the specimen which not strengthened with CFRP wrap were painted with white color and marked with mesh of blue color lines to indicate the occurred buckling place under the test axial force. All columns cured for a minimum of 7 days at room temperature according to the epoxy resin manufacturer's instructions.

Table 5. Test specimens CFRP wrap strength details.

No	Specimen	CFRP % specimen length	CFRP no. layers
1	SHSC-C1	N/A	N/A
2	SHSC-C2	N/A	N/A
3	SHSC-C3	N/A	N/A
4	SHSC-C4	N/A	N/A
5	SHSC-C5	N/A	N/A
6	SHSC-20-1L	20	1
7	SHSC-20-2L	20	2
8	SHSC-20-3L	20	3
9	SHSC-40-1L	40	1
10	SHSC-40-2L	40	2
11	SHSC-40-3L	40	3
12	SHSC-60-1L	60	1
13	SHSC-60-2L	60	2
14	SHSC-60-3L	60	3
15	SHSC-80-1L	80	1
16	SHSC-80-2L	80	2
17	SHSC-80-3L	80	3
18	SHSC-100-1L	100	1
19	SHSC-100-2L	100	2
20	SHSC-100-3L	100	3

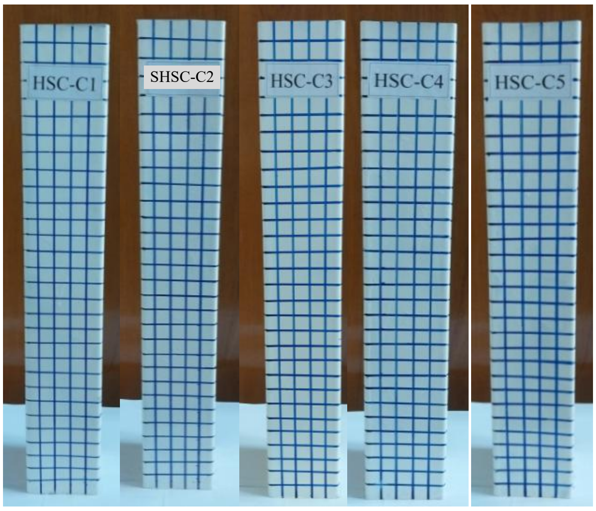
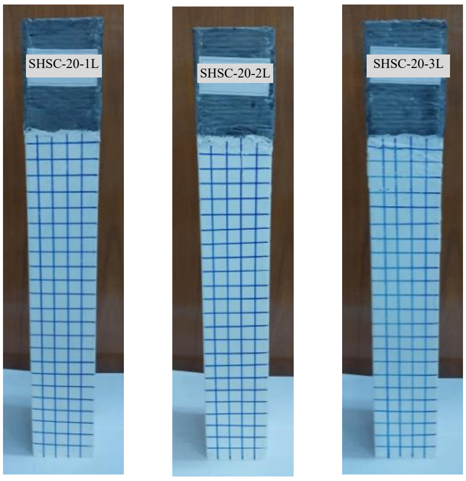
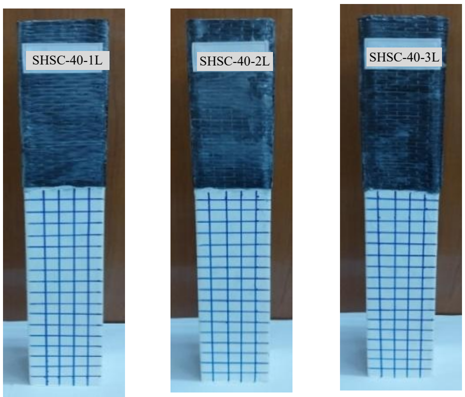


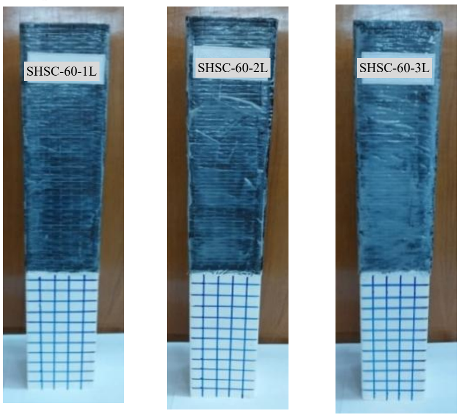
Figure 10. Control hollow steel columns : SHSC-C1, SHSC-C2, SHSC-C3, SHSC-C4, and SHSC-C5.



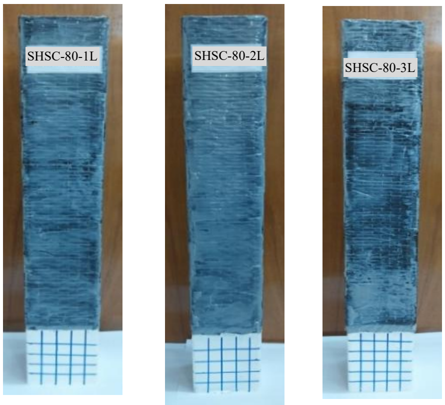
(a) Hollow steel columns strengthened with CFRP-wrap: SHSC-20-1L, SHSC-20-2L, and SHSC-20-3L.



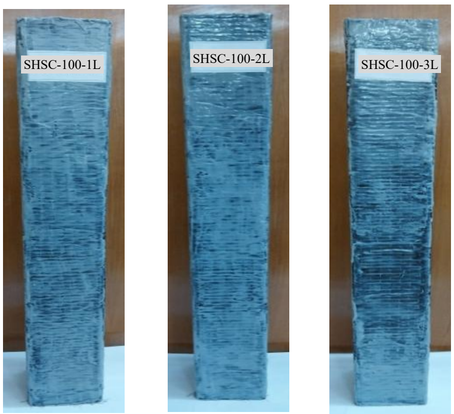
(b) Hollow steel columns strengthened with CFRP-wrap: SHSC-40-1L, SHSC-40-2L, and SHSC-40-3L.



(c) Hollow steel columns strengthened with CFRP-wrap: SHSC-60-1L, SHSC-60-2L, and SHSC-60-3L.



(d) Hollow steel columns strengthened with CFRP-wrap: SHSC-80-1L, SHSC-80-2L, and SHSC-80-3L.



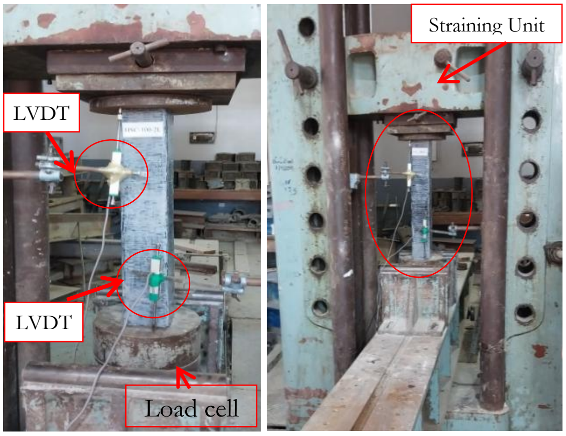
(e) Hollow steel columns strengthened with CFRP-wrap: SHSC-100-1L, SHSC-100-2L, and SHSC-100-3L

Figure 11. Hollow steel columns strengthened with CFRP wrap.

2.3 Experimental Setup

The hollow steel control columns; from SHSC-C1, to SHSC-C5, and hollow steel columns strengthened with CFRP wrap: SHSC-20-1L to SHSC-80-1L, SHSC-20-2L to SHSC-80-3L, and SHSC-20-3L to SHSC-80-3L which were their failure at low loads, they are tested using a 160 kN capacity, WDW-200E universal test machine as shown in Fig. 1, this test machine measures the load and axial-displacement using a Software through a computer this machine supply with it which provide high accuracy of the output curves date. While the specimens SHSC-100-1L to HSC-100-3L which are likely to fail at higher loads were tested using an "AVERY" machine, it comprise of two units-the straining unit for applying the load, and the indicating unit for measuring the load and for the accommodation of pumps and control gear as shown in Fig. 12. The specimen was placed in the testing machine between two flat bearing plate, these plates are thick to ensure a load uniform distribution along the specimen.

Axial displacement was measured using two 100 mm linear voltage displacement transducer (LVDTs) placed at top and bottom of specimens, load cell in addition to LVDTs were connected with data logger to save the data.



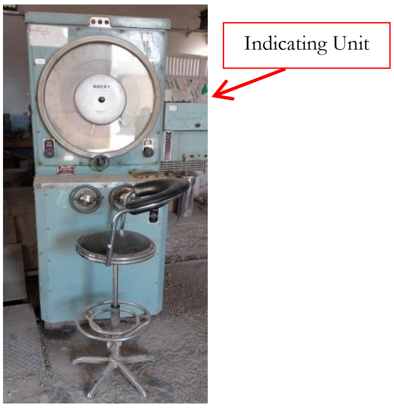


Figure 12. Test set up "AVERY" test machine.

2.4 Results and Discussions

The manner of the tested columns can be studied from applied axial load against displacement relationships. Fig. 13 shows the axial load against axial displacement curves for the tested columns. The behavior of the strengthened hollow square columns as versus to the control hollow square columns; the improvement is noticed in terms of the increasing in compressive strength force. For the hollow steel columns strengthened with 20% of specimen length; with 1 , 2, and 3 layers (SHSC-20-1L, SHSC-20-2L and SHSC-20-3L) there no increase in strength with respect to the control column SHSC-C as shown in Fig. 14 and Table-6 and this enhancement increase slightly for specimens strengthened with 40% CFRP of the columns length with 1.16% for SHSC-40-1L, 2.84% for SHSC-40-2L, and 3.6% for SHSC-40-3L as shown in Fig.15 and this increase be bigger for specimens strengthened by ratio with 60%, 80%, and 100% as shown in Figs. 16, 17, and 18, and that particular improvement developed higher than the others as well for specimen SHSC-100-3L exhibited gain in strength 34.5%.

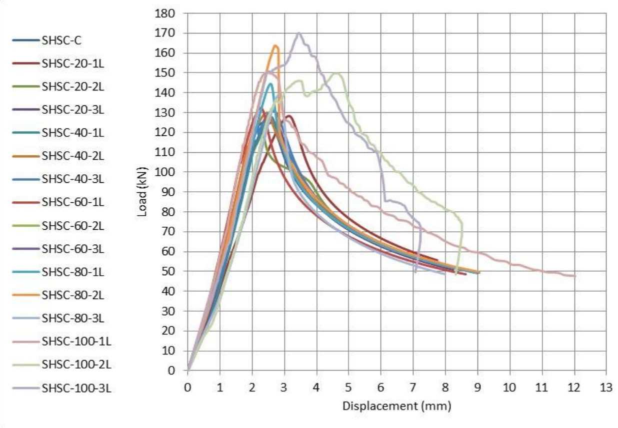


Figure 13. Load versus axial displacement curves for the tested specimens.

This value so close to which obtained from the tensile test in (section 2.1.4) of the specimen CFRP-Steel 2-1 coupon (37.99 %) which represent the decrease in the deformation as shown in table 4 .

The modes of failure for the Control Hollow Steel Columns: from SHSC-C1 to SHSC-C5 are presented in Fig. 19, all five columns are failed in local buckling when opposite two sides their buckling outward and the two other sides their buckling inward (local buckling Eigen mode), the member capacity is reached yielding when a section plates reached to yield strength and fail in buckling which was reflected in the load versus displacement curves when the axial stiffness starts to reduce; in addition, the load versus displacement curves show a rapidly increase in lateral displacement when local buckling occurred. This buckling case failure are move from the top to the middle height of the hollow steel column depending on the accuracy of the experimental test setup (applied axial load) and the test specimen fabrication (imperfection), in other words when the test more exact the buckling move downward then the load bearing capacity increase.

For specimens strengthened with CFRP wrap with 20% of specimen length; with 1 , 2, and 3 layers (SHSC-20-1L, SHSC-20-2L and SHSC-20-3L) are displayed in Fig. 20 (a, b, and c) are failed in local buckling which is similar to the buckling in the Control Hollow Steel Sections in shape, and this reflect on the bearing capacity increase of the specimens strength with about 1.5 % as illustrated in table-6.

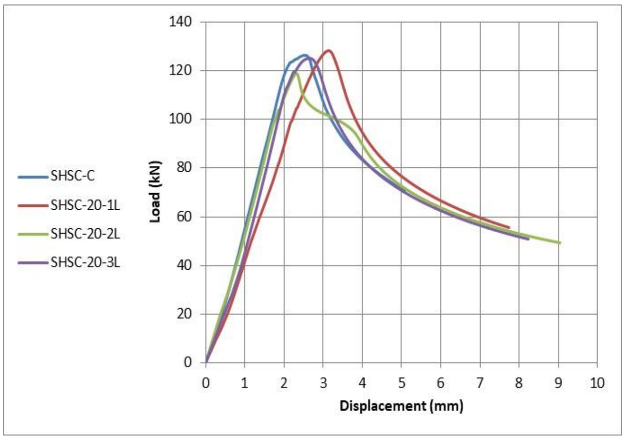


Figure 14. Load versus axial displacement curves for: SHSC-20-1L, SHSC-20-2L, and SHSC-20-3L.

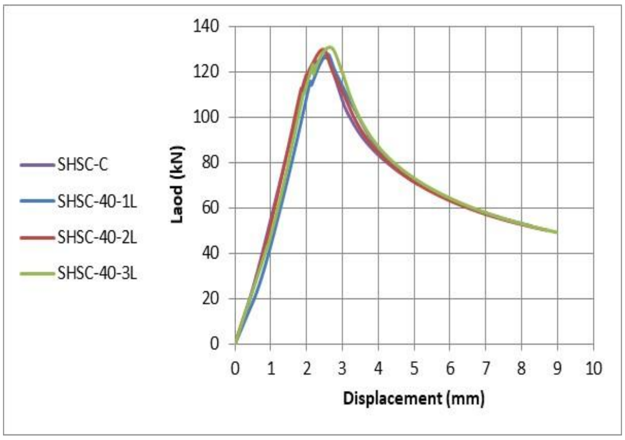


Figure 15. Load versus axial displacement curves for: SHSC-40-1L, SHSC-40-2L, and SHSC-40-3L.

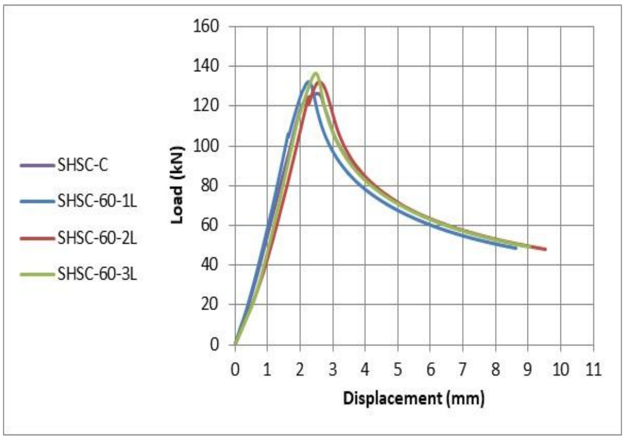


Figure 16. Load versus axial displacement curves for: SHSC-60-1L, SHSC-60-2L, and SHSC-60-3L.

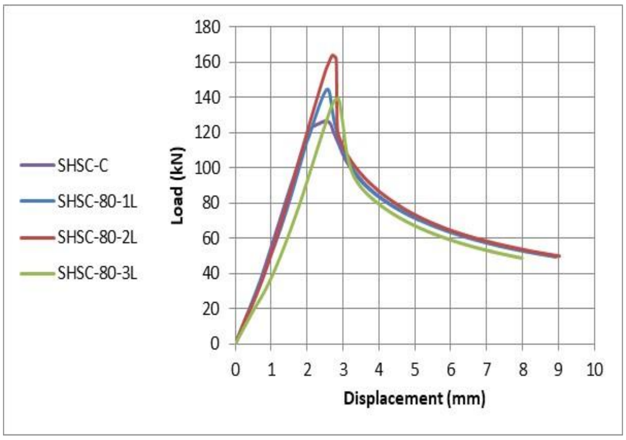


Figure 17. Load versus axial displacement curves for: SHSC-80-1L, SHSC-80-2L, and SHSC-80-3L.

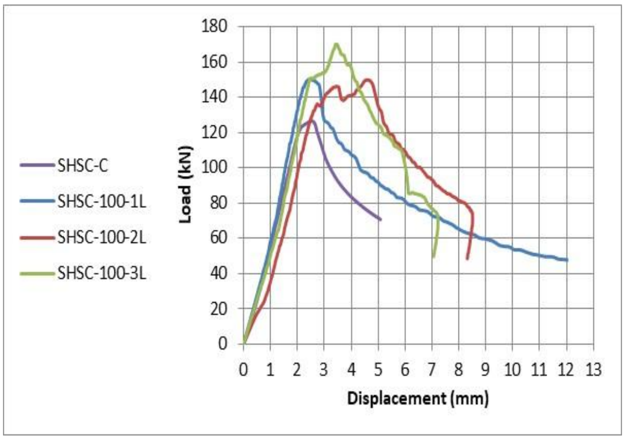
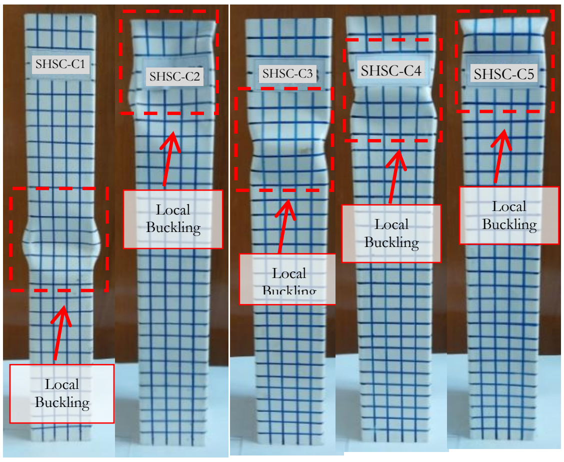
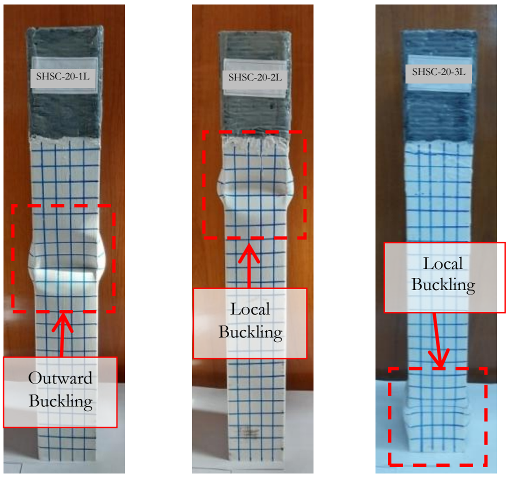


Figure 18. Load versus axial displacement curves for: SHSC-100-1L, SHSC-100-2L, and SHSC-100-3L.

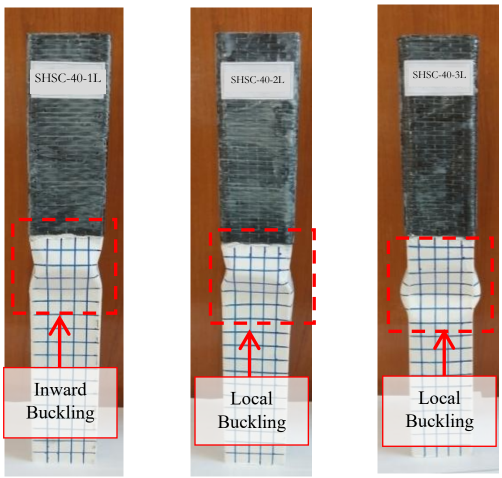


(a)SHSC-C1(b)SHSC-C2 (c)SHSC-C3 (d)SHSC-C4 (e) SHSC-C5

Figure 19. Failure modes of Control Hollow Steel Columns: SHSC-C1, SHSC-C2, SHSC-C3, SHSC-C4, and SHSC-C5.

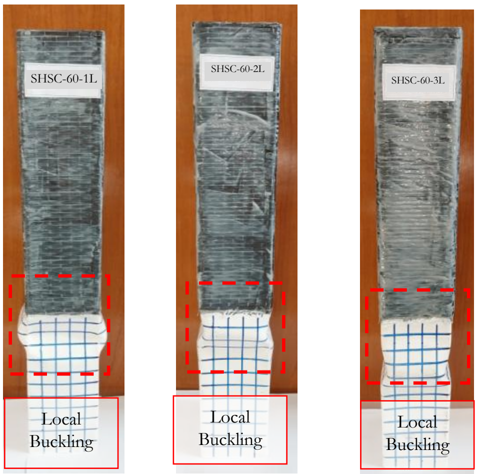


(a) SHSC-20-1L (b) SHSC-20-2L (c) SHSC-20-3L

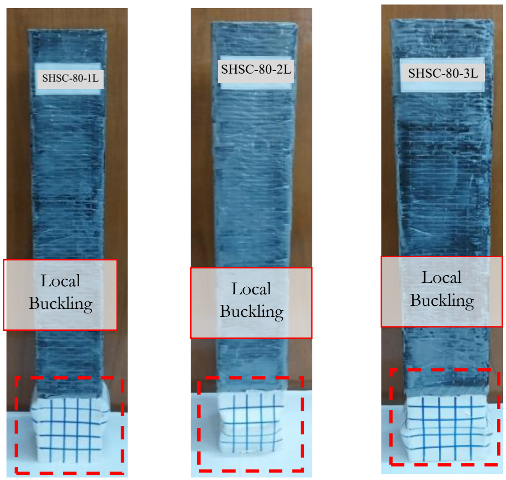


(d) SHSC-40-1L (e) SHSC-40-3L (f) SHSC-40-3L

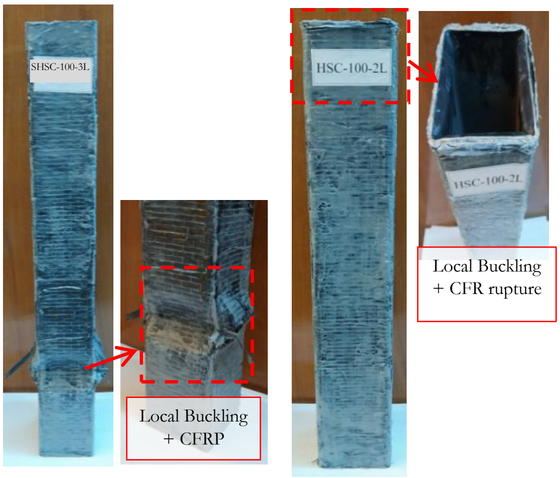
Figure 20. Failure modes of Hollow Steel Columns Strengthened with CFRP wrap:SHSC-20-L1, SHSC-20-L2. SHSC-20-L3, SHSC-40-L1, SHSC-40-L2, SHSC-40-L3.



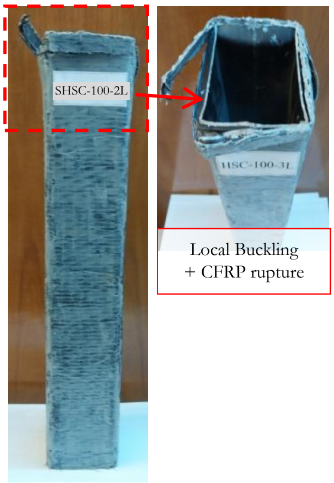
(a) SHSC-60-1L (b) SHSC-60-2L (c) SHSC-60-3L



(d) SHSC-80-1L (e) SHSC-80-3L (f) SHSC-80-3L



(g) SHSC-100-1L (h) SHSC-100-2L

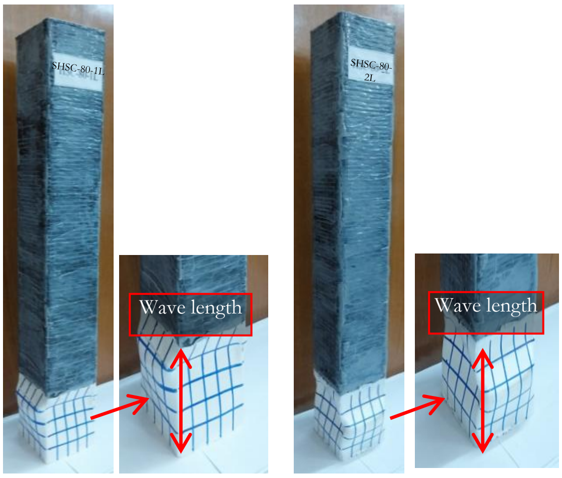


(i) SHSC-100-3L

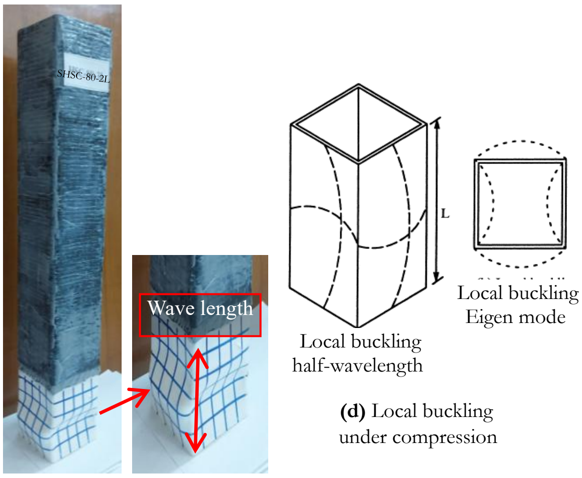
Figure 21. Failure modes of Hollow Steel Columns Strengthened with CFRP wrap: SHSC-60-L1, SHSC-60-L2. SHSC-60-L3, SHSC-80-L1, SHSC-80-L2, SHSC-80-L3, SHSC-100-1L, SHSC-100-2L. and SHSC-100-3L.

For specimens strengthened with CFRP wrap with 40% to 60% of the specimen length with 1, 2, and 3 layers (from SHSC-40-1L to SHSC-60-3L) are presented in Fig. 20 (d, e and f) and Fig. 21 (a, b, and c) are failed in local buckling which their buckling are similar to the previous specimens in shape, and even this buckling near to the CFRP wrapping and did not reach bottom edge of specimens. For specimens strengthened by CFRP wrapping with 80% of the specimens length with 1,2, and 3 layers (SHSC-80-1L, SHSC-80-8L and SHSC-80-3L) are expressed in Fig. 21 (d, e and f) are collapse in local buckling which is also their buckling shape are similar to the previous specimens but the length of the buckling wave shorter because the left distance between CFRP wrapping edge and bottom edge of specimen is not enough distance to make the complete half wave which it is like (sine or cosine half equation) shown in Fig. 22 (a ,b ,c, and d).

Specimens strengthened with 100% of specimens with 1, 2 and 3 layers (SHSC-100-1L, SHSC-100-2L and SHSC-100-3L) are presented in Fig. 21 (g, h and i) are failed in local buckling with CFRP wrap rupture for specimens (SHSC-100-1L, SHSC-100-2L, and SHSC-100-3L).



(a) SHSC-80-1L (b) SHSC-80-3L



(c) SHSC-80-3L

(d) Local buckling under compression

Figure (22) Local buckling of Hollow Steel Columns Strengthened with CFRP wrap: SHSC-80-1L, SHSC-80-2L, and SHSC-80-3L.

From the above the wrap strengthening specimens restrict failures from local buckling and admit the specimens to fail by yielding, which it is show the influence of CFRP wrap strengthening in vanish local buckling failures.

2.4.1 (Ductility – Energy) Dissipation Capacity

To determine the amount of ductility for the tested columns, the ductility index explained by [8, 11, 28] was used, as is given:

$$DI = \frac{\varepsilon_{0.85}}{\varepsilon_y} \quad (1)$$

ε_(85%) = positive axial strain corresponding to 85% of the compressive strength.

The yield strain ε_y= is taken as ε_(75%) divided by 0.75.

ε_(75%) = the axial strain prior to failure, corresponding to 75% of the ultimate load, as illustrated in Fig 23.

The ability of the hollow steel columns to dissipate energy is:

$$E_d = \frac{1}{2} N_u \, \varepsilon_y + N_u \left(\varepsilon_u - \varepsilon_y\right) \quad (2)$$

Where: N_u= maximum load

ε_u = ultimate strain.

The strengthening ratio defined as the percentage increase in the ultimate load:

$$SEI = (N_{eS} - N_{eU}) \,/\, N_{eU} \quad (3)$$

Where: N_eS and N_eU are maximum loads for wrapped and unwrapped specimens.

The values of SEI are shown in Table 6.

It can be seen that ductility generally increase with increase of length CFRP wrap and layer numbers and the energy dissipation increase with increase of CFRP wrap (number and length) layers also.

Fig. 24 shows the chart in which the x-axis represent the rate of variation of ultimate strength for Square Hollow Steel Columns strengthened with CFRP wrap to the Control Square Hollow Steel Columns and in the y-axis is the CFRP % strengthening of the specimens, it can be concluded that the maximum strength enhanced for columns strengthened with 3 CFRP wrap layers and with 100% of the total length of the specimen.

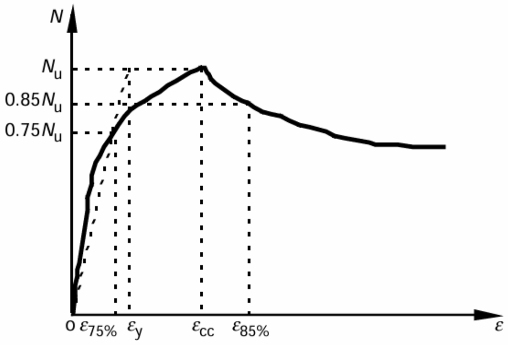


Figure 23. Definition of the ductility index [28].

While, Fig. 25 shows the bar chart comparison between the ultimate axial load carrying capacity obtained from experimental work of the Hollow steel columns control and strengthened with CFRP wrap with the length percentage and number of layers. The maximum values of the bars in the chart are for the specimens SHSC-80-2L with load 163.78 kN and SHSC-100-3L with load 170 kN, this indicates that CFRP wrap SHSC load carrying capacity improvement is not considerable until the specimens are strengthening done of these specimens with two and three layers, while the ductility index and energy dissipation in table 6 are significant increase especially for specimens SHSC-100-1L and SHSC-100-3L which fail by steel section yielding except the specimen SHSC-100-3L has value greater the other last two mentioned before because this specimen fail by rupture of CFRP and yielding of steel section material.

So it can compare the local buckling for the control specimen experimental results with local buckling load theoretical results according to AISC (American Institute Steel Construction) [22] Code specifications, the limit load–carrying capacity:

$$P_n = F_{cr} \, A_g \quad (4)$$

Where P_nis the nominal compressive strength, F_cris the critical stress and can be determined as follows:

(a) when $\frac{L_c}{r} \le 4.71 \sqrt{\frac{E}{F_y}}$ (or $\frac{F_y}{F_e} \le 2.25$)

$$F_{cr} = \left(0.658^{\frac{F_y}{F_e}}\right) F_y \quad (5)$$

(b) when $\frac{L_c}{r} > 4.71 \sqrt{\frac{E}{F_y}}$ (or $\frac{F_y}{F_e} > 2.25$)

$$F_{cr} = 0.877 \, F_e \quad (6)$$

Where:

A_g= gross cross-sectional area of member mm2

E = modulus of elasticity of steel, MPa

K = effective length factor

L_c = KL = effective length of member, mm

L = laterally unbraced of the member, mm

r = radius of gyration ,mm

F_e= (π^2 E)/(L_c/r)^2

F_e= elastic buckling stress MPa,

F_y = specified minimum yield stress of the type of steel being used, MPa

The calculated load-bearing capacity from the above equations is 134.57 kN while the experimental values is 126.37 kN so the difference is 6.4%.

3. Conclusion

This study has described the behavior of short hollow steel column without CFRP wrap strengthening under concentric compression force and compare this behavior with specimens strengthened with CFRP wrap based on investigation experimental program. The column strengthened with full length of CFRP and three layers revealed up to 1.35 axial compression capacity enhancement. It is clearly perceived that strengthened with external CFRP wrap bond exposed to axial load can rise the ductility compared with the non-strengthened columns; and number of CFRP layers increase have important function in columns confining or local buckling delay so therefore the ability to resist the applied axial load increase. The modes of failure; for short columns that non strengthened and strengthened with up to 20% of the total length of specimen with CFRP wrap is suffered from out ward and inward local buckling and the buckling move from the top of the specimen to the middle, while for short columns partially strengthened with CFRP (from 40% to 80%) of the total length of the specimen it is failed outward and inward buckling and confined directly after the CFRP wrapping and for specimens strengthened with full length of CFRP wrap failed with CFRP rupture then local buckling. The ductility index increase with the increase of the CFRP layers and length with about 23.6%, so the energy dissipation increase with the increase of the CFRP layers and length with about 1.485.

Table 6.: Specifications, load bearing capacities, of the specimens.

Specimen	*Experimental* *Nu* (kN)	*SEI* (%) Increase/decrease	*Ductility Index DI*	E_d *(kN)*
SHSC-Control	126.37	-	1.39	0.313
SHSC-20-1L	128.28	1.5	1.27	0.363
SHSC-20-2L	118.88	- 5.92	1.538	0.244
SHSC-20-3L	125.16	0.00	1.36	0.306
SHSC-40-1L	127.84	1.16	1.294	0.289
SHSC-40-2L	129.96	2.84	1.379	0.294
SHSC-40-3L	130.92	3.60	1.36	0.322
SHSC-60-1L	132.28	4.67	1.249	0.268
SHSC-60-2L	132.16	4.58	1.224	0.296
SHSC-60-3L	136.52	8.03	1.172	0.291
SHSC-80-1L	144.44	14.29	1.09	0.310
SHSC-80-2L	163.78	29.60	1.036	0.745
SHSC-80-3L	139.24	10.18	1.028	0.319
SHSC-100-1L	150.17	18.83	1..289	0.336
SHSC-100-2L	149.69	18.45	1.719	0.778
SHSC-100-3L	170.02	34.54	1.489	0.56

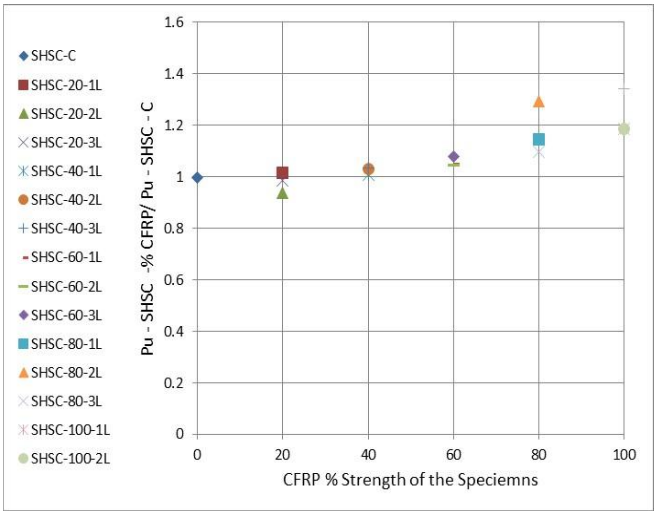


Figure 24. Variation of P_u(SHSC-CFRP) / P_u(SHSC-Control) versus CFRP % strength of the specimens.

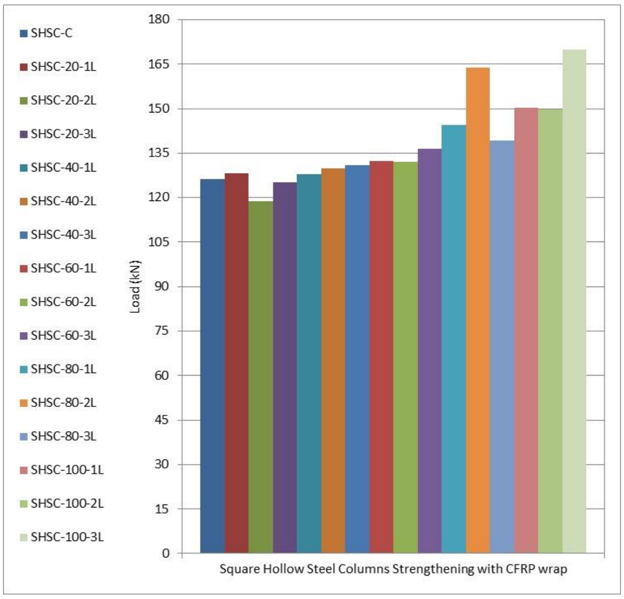


Figure 25. Comparison load carrying capacity of Square Hollow Steel Column Specimens.

4. References:

[1] J. C. McCormac and S. F. Csernak, Structural Steel Design. India: Pearson, 2013.

[2] M. Imran, M. Mahendran, and P. Keerthan, "Experimental and numerical investigations of CFRP strengthened short SHS steel columns," Eng. Struct., vol. 175, pp. 879-894, 2018. https://doi.org/10.1016/j.engstruct.2018.08.042

[3] M. R. Ghaemdoust, K. Narmashiri, and O. Yousefi, "Structural behavior of deficient steel SHS short columns strengthened using CFRP," Constr. Build. Mater., vol. 126, pp. 1002-1011, 2016. https://doi.org/10.1016/j.conbuildmat.2016.09.099

[4] J. Park and J. Yoo, "Flexural and compression behavior for steel structures strengthened with carbon fiber reinforced polymers (CFRPs) sheet," Steel Compos. Struct., vol. 19, no. 2, pp. 441-465, 2015. https://doi.org/10.12989/scs.2015.19.2.441

[5] A. B. B. Abu-Sena, M. Said, M. A. Zaki, and M. Dokmak, "Behavior of hollow steel sections strengthened with CFRP," Constr. Build. Mater., vol. 205, pp. 306-320, 2019. https://doi.org/10.1016/j.conbuildmat.2019.01.237

[6] J. Wang, J. Di, Q. Zhang, F. Qin, and P. Men, "Local buckling analysis of axially compressed welded box-section stub columns using Q429-Q960 steel," J. Constr. Steel Res., vol. 210, pp. 1-13, 2023. https://doi.org/10.1016/j.jcsr.2023.108100

[7] I. R. M. Mohamed and S. S. Safar, "Experimental and numerical investigation on torsion strength of high gauge SHS strengthened with CFRP wraps," Struct., vol. 34, pp. 2818-2839, 2021. https://doi.org/10.1016/j.istruc.2021.08.109

[8] O. Yousefi, K. Narmashiri, A. A. Hedayat, and A. Karbakhsh, "Strengthening of corroded steel columns under axial compressive loads using CFRP," J. Constr. Steel Res., vol. 178, pp. 1-11, 2021. https://doi.org/10.1016/j.jcsr.2020.106496

[9] T. Tafsirojjaman, A. U. R. Dogar, Y. Liu, A. Manalo, and D. P. Thambiratnam, "Performance and design of steel structures reinforced with FRP composites: A state-of-the-art review," Eng. Fail. Anal., vol. 138, pp. 1-25, 2022. https://doi.org/10.1016/j.engfailanal.2022.106371

[10] M. Karimian, K. Narmashiri, M. Shahraki, and O. Yousefi, "Structural behavior of deficient steel CHS short columns strengthened," J. Constr. Steel Res., vol. 138, pp. 555-564, 2017. https://doi.org/10.1016/j.jcsr.2017.07.021

[11] K. Karimi, W. W. El-Dakhakhni, and M. J. Talit, "Behavior of slender steel-concrete composite columns wrapped with FRP jackets," J. Perform. Constr. Facil., vol. 26, no. 5, pp. 590-599, 2012. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000280

[12] K. He and Y. Chen, "Experimental investigation of fire-exposed steel tubular stub columns wrapped with CFRP sheets," Compos. Struct., vol. 253, pp. 1-16, 2020. https://doi.org/10.1016/j.compstruct.2020.112807

[13] L. Gao, H. Sun, F. Jin, and H. Fan, "Load-carrying capacity of high-strength box-sections I: Stub columns," J. Constr. Steel Res., vol. 65, pp. 918-924, 2009. https://doi.org/10.1016/j.jcsr.2008.07.002

[14] P. Feng and L. Hi, "Steel columns strengthened/reinforced by prestressed CFRP strips: Concepts and behaviors under axial compressive loads," Compos. Struct., vol. 217, pp. 150-174, 2019. https://doi.org/10.1016/j.compstruct.2019.03.038

[15] G. M. Al-Mekhlafi, M. A. Al-Osta, and A. M. Sharif, "Experimental and numerical investigations of stainless steel tubular columns strengthened by CFRP composites," Thin-Walled Struct., vol. 157, pp. 1-14, 2020. https://doi.org/10.1016/j.tws.2020.107080

[16] C. Liu, J. Xiao, K. Ma, Z. Liu, H. Zhang, and Y. Qiu, "Experimental and numerical investigation on short CHS steel columns restrained with HFRP under axial compressive loading," Constr. Build. Mater., vol. 438, pp. 1-19, 2024. https://doi.org/10.1016/j.conbuildmat.2024.136715

[17] A. Shaat and A. Z. Fam, "Slender steel columns strengthening using high-modulus CFRP plates for buckling control," J. Compos. Constr., vol. 1, no. 1, pp. 2-12, 2009. https://doi.org/10.1061/(ASCE)1090-0268(2009)13:1(2)

[18] M. R. Bambach, "Strengthening of thin-walled (hollow) steel sections using fiber-reinforced polymer (FRP) composites," in Rehabilitation of Metallic Civil Infrastructure Using Fiber-Reinforced Polymer (FRP) Composites, V. M. Karbhari, Ed. Cambridge, UK: Woodhead, 2014, pp. 140-163. https://doi.org/10.1533/9780857096654.2.140

[19] A. H. Keykha, N. Nekooei, and R. Rahgozar, "Experimental and theoretical analysis of hollow steel columns strengthening by CFRP," Civil Eng. Dimens., vol. 17, no. 2, pp. 101-107, 2015. https://doi.org/10.9744/ced.17.2.101-107

[20] American Society for Testing Materials (ASTM), Annual Book of ASTM Standards E8/E8M-22. PA, USA, 2022.

[21] American Society for Testing Materials (ASTM), Annual Book of ASTM Standards A322-91. PA, USA, 2014.

[22] Steel Construction Manual. American Institute of Steel Construction, 15th ed., USA, 2017.

[23] C. G. Salmon, J. E. Johnson, and F. A. Malhas, Steel Structures Design and Behavior. 5th ed., USA: Pearson, 2009.

[24] L. F. Geschwindner, Unified Design of Steel Structures. USA: John Wiley & Sons Inc., 2008.

[25] G. L. Kulak and G. Y. Grondin, Limit States Design in Structural Steel. 7th ed., Canada: Canadian Institute of Steel Construction, 2002.

[26] Product Data Sheet, Sika Wrap-300 C, Carbon Fiber Fabric for Structural Strengthening. Sika Construction Chemicals, Switzerland, 2020.

[27] Product Data Sheet, Sika dur-330, Epoxy Laminating Resin for the Sika-Wrap Structural Strengthening System. 2018.

[28] Z. Tao, L. Han, and J. Zhuang, "Axial loading behavior of CFRP strengthened concrete-filled steel tubular stub columns," Adv. Struct. Eng., vol. 10, no. 1, pp. 37-46, 2007. https://doi.org/10.1260/136943307780150814