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MAJOR PARAMETERS GOVERNING THE STRENGTH OF HOLLOW STEEL SECTIONS STRENGTHENED BY CFRP

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ABSTRACT

This paper aims at investigating the parameters that affect strengthening of Steel Square Hollow Sections (SHS) and Rectangular Hollow Sections (RHS) against local buckling failure using CFRP sheets and strips. Two main parameters that affect the percentage of strength enhancement provided by CFRP strengthening schemes have been studied. The first parameter is the individual plate slenderness for full strengthening technique, and the second is the distance between strips for partial strengthening technique. The effect of the two parameters has been studied for both square and rectangular sections using finite element non-linear analysis (FENLA) modeling after being verified with previous experimental work. The enhancement percentage provided by either full wrapping or partially wrapping techniques increases by increasing the plate slenderness of SHS and RHS. The enhancement in axial capacity of fully wrapped SHS columns ranges between 25.9 % and 95.4 while, fully wrapped RHS columns have an enhancement in axial capacity ranges between 7 % and 36%. The enhancement in axial capacity of partially strengthening SHS and RHS increases by decreasing the spacing between fiber strips however, it is still lower than the enhancement provided by full wrapping. The conducted study reveals that; strengthening using CFRP wrapping is more efficient in case of SHS than the case of RHS.

KEYWORDS: Square Hollow Sections (SHS), Rectangular Hollow Sections (RHS), strengthening, CFRP, FENLA.

1. INTRODUCTION

Advanced technologies in fabrication and erection of steel structures have been rapidly developed in the past decades, and new innovative products have been introduced into the steel construction industry. Fiber Reinforced Polymer (FRP) materials have recently been demonstrated to enhance the stability of steel members [7]. The linear material behavior, remarkable confinement action and high stiffness of the utilized unidirectional FRP help them to improve the buckling and post-buckling behavior of steel components.

Many of researches have been conducted on Carbon Fiber Reinforced Polymers (CFRP) strengthened steel members; dealing with different strength parameters. CFRP played a good role in enhancement of strength of rafters of steel bridges by applying carbon sheets to tension flanges [11]. CFRP also used to overcome fatigue problems at steel members [10]. Zerbo et al. [19] has presented a review on research works covering the efficiency of FRP strengthening systems on steel structures.

The hollow steel sections (HSS) are widely used due to their high strength to weight ratio and having large energy absorption [15]. They are of high sectional resistance against compression, tension, torsion and bending due to their relatively large radius of gyration comparing to opened sections. A reasoned review has been conducted by Zhao and Zhang [20] on research works about strengthening HSS, fatigue crack propagation in the FRP–Steel system and bond between steel and FRP.

Most of researches performed in the field of applying fiber to HSS concerned with studying overall buckling behavior only. Some recent studies discussed the strengthening of opened and closed thin-walled sections against local buckling using Fiber Reinforced Polymer (FRP) fabrics.

Shaat and Fam [12], retrofitted short and long HSS columns with CFRP and GFRP sheets. Effects of number of layers and fiber orientations were investigated for two types of CFRP sheets and one type of GFRP. Maximum enhancement of about 18% and 23% in load carrying capacity was achieved for short and long columns respectively. The utmost gain was achieved for specimens with three layers applied on four sides.

Bambach et al. [3], experimentally studied 20 short axially compressed cold formed Square Hollow Section (SHS) steel columns strengthened by CFRP. The plate width to thickness ratio of studied sections ranged between 42 and 120. Two CFRP strengthening techniques were investigated. The first, is wrapping steel columns by one transverse and one longitudinal CFRP laminates. The second, is using two transverse and two longitudinal CFRP laminates for wrapping. studied columns. It is shown that the application of CFRP to slender sections delays local buckling leading to increasing in elastic buckling stress, axial capacity and strength-to-weight ratio of the studied axially compressed specimens. They revealed that; the axial capacity increases by increasing the plate slenderness ratio of strengthened columns.

Haedir and Zhao [6], proposed a design and an experimental evaluation of external strengthening of CHS short columns with high-strength CFRP sheets. The tested columns were subjected to axial compression. They found that; applying a combination of transverse and longitudinal CFRP on a slender tube caused an enhancement in yielding capacity of the bare tube. The experimental results showed well conformation with AS/NZS 4600, AS 4100 and Eurocode 3 provisions. Moreover, they provided strength curves for CFRP-reinforced steel columns with varying yield strength tubes based on the available design guidelines. The strength of tubes was found to be increased with higher amount of CFRP.

Kalavagunta et al. [8], proposed a design method to predict the allowable load carrying capacity of cold formed steel channel section strengthened by carbon fiber reinforced polymer composites applied to the web of the channel. The presented design method was verified by comparing with the experimental test results. Also, steel columns with and without reinforced by high-strength CFRP sheets were tested under compression load to investigate the pure axial behavior and strength of the columns. They found that the capacity of the columns strengthened with CFRP was 10% higher than the plain ones. The experimental results well confirmed with the presented BS5950-5 provisions [4].

Sundarraja et al. [16], experimentally and numerically investigated the behavior of axially compressed SHS columns strengthened by CFRP strips. The CFRP strips were used with various parameters such as the number of layers and spacing of strips. The ultimate strength was enhanced with the application of -three layer-CFRP strips with percentage reached to 44.32% more than that of bare steel tube. The external strengthening of SHS using CFRP effectively delayed the local buckling of steel tube. The bonding of CFRP provided a confinement against lateral deformations leading to increasing in axial stiffness of HSS columns. The results showed that; increasing the number of layers turned into failure mode of inward buckling rather than outward buckling.

Sundarraja and Shanmugavalli [17], presented an analytical investigation to assess the possibility of strengthening axially compressed CHS tubular sections using CFRP composites This investigation was performed based on recommendations of various standards and codes to predict the axial compressive capacity of CHS strengthened by CFRP. The presented study also aimed to predict the suitable CFRP wrapping scheme to enhance the structural behavior of studied specimens. They found that, the full wrapping of CFRP around CHS effectively enhanced the axial capacity of studied CHS specimens. It was noticed that, the enhancement amount at strengthened columns was significantly affected by plate slenderness of the studied sections. The lower plate slenderness, the greater increase in strength was achieved.

Ghaemdoust et al. [5], utilized experimental test and numerical simulation studies for evaluating the achievability of strengthening box-shaped axially compressed members with initial deficiency by unidirectional CFRP sheets to gain load-bearing capacity. Two schemes of strengthening were carried out, and unidirectional CFRP orientation in both the longitudinal and transverse directions assisted the procedure. Using CFRP sheets increased ultimate load-bearing capacity up to 55.49%. The number of CFRP layers played a significant role in confining columns or delaying the local buckling, and subsequently, load carrying capacity increased.

Shahraki et al.[14] studied the effect of strengthening of axially loaded deficient SHS columns using CFRP and steel plates. They performed experimental and numerical investigations on fourteen specimens of different parameters. The carrying capacity and failure pattern were improved at strengthened specimens compared to control specimens. It was founded that; utilizing CFRP sheets is more effective than welding steel plates to retrofit deficient SHS columns.

Karimian et al. [9] and Shahabi and Narmashiri [13] studied the effect of retrofitting deficient CHS columns of various deficient locations using CFRP. They concluded that; utilizing CFRP sheets compensates the reduction in capacity of deficient columns and control the local deformation around the deficiency zone.

An experimental study had been presented by, Tang et al. [18] to predict the effect of externally bonding CFRP strips for strengthening cold-formed channel sections in transverse direction. The experimental testing was applied upon eccentrically loaded seven short and axially loaded seven long columns of lengths 750 mm and 1400 mm respectively. The results demonstrated that; the ultimate axial capacity was increased for each strengthened specimens in different extent. The utmost increase in axial capacity with value 9.13% and 12.1% for long and short columns respectively was achieved for specimens strengthened with two layers and 50 mm spacing between strips. For short columns, the mode of failure was noticed to be changed from global buckling to local buckling when strengthened by two layers of CFRP strips at spacing of 50 mm and 100 mm

Amoush and Ghanem [2], carried out an experimental program for studying the behavior and capacities of strengthened cold-formed lipped channel columns using CFRP. They tested twelve cold-formed columns specimens under axial compression. Different parametric variables such as flange width - thickness, web depth-thickness ratios were studied for un-strengthened, partially, and fully strengthened columns. The experimental results for un-strengthened specimens revealed that; the higher the depth- thickness ratio, the larger obtained axial shortening for the column. The results also showed that the axial shortening deformation was inversely proportional to the column stiffness. The results for the partially and the fully strengthened columns showed an improvement in behavior and capacities of steel columns.

The current study aims at investigating the effect of various parameters on the efficiency of different CFRP strengthening techniques of slender SHS and RHS columns under pure compression. This study is based on the experimental and numerical investigations performed by Badawy Abu-Sena et al [1] to monitor the strength and structural behavior of SHS and RHS strengthened with CFRP utilizing different strengthening techniques. The parametric study is performed with verified finite element non-linear analysis (FENLA) models with the experimental results revealed by reference [1].

2. NUMERICAL MODEL AND VERIFICATION

NLFEA model is performed using ANSYS.15.0 to be verified against the results obtained from the experimental work performed by reference [1]. SHS column of section (100x100x1.5) with length of 700mm is chosen to be modeled for verification. The NLFEA will be performed on the chosen SHS for both full strengthening technique and partial strengthening technique.

2.1. Modeling Procedure

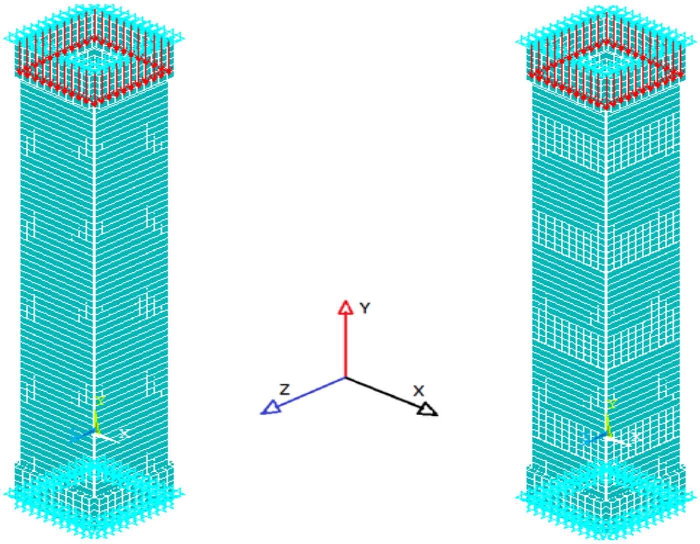
The generated solid model using Bottom-up modeling approach represents the centerline- dimensions of cross section of studied specimens. For partially strengthened specimens, the CFRP strips of 100 mm width are arranged with spacing 50mm similar to reference [1]. The material of steel is simulated using bilinear stress-strain curve [1]. **Table (1)** shows the geometrical and mechanical properties of the steel columns that is adopted as a verification specimen from reference [1]. The Poisson's ratio of steel is taken equal to 0.3. CFRP is modeled as orthotropic unidirectional material of 1mm thickness. The CFRP laminate including the carbon fiber and the resin is defined by linear stress–strain curve. The mechanical properties are; Fy =3200 MPa and E= 220 GPa, [1]. The Poisson's ratio of CFRP is taken equal to 0.22 as assumed by Sundarraja, et al. [16].

Table (1) Geometrical and material properties of steel tubes [1]

Specimen	Sectional dimensions (mm)			Modulus of Elasticity (GPa)	Yield strength (MPa)	Ultimate strength (MPa)
	Width (b)	Depth (d)	Thickness (t)			
SHS	100	100	1.5	178.0	303.0	364.0

Thin shell element (SHELL181) which is suitable for analyzing thin to moderately-thick shell structures is used to simulate steel columns. However, structural solid element SOLID185 is used to represent the applied CFRP as modeled by Sundarraja, et al [16]. The contact element (CONTA174) is utilized to simulate the contact between steel section and carbon fiber sheets or strips.

The specimens are restrained laterally at both upper and lower end nodes; thus, the specimen is prevented from rotation and lateral translation at the two ends. To prevent failure at stress concentration zone (Web crippling Failure); the stiffness of first and last 5 cm of columns has been increased. Axial load is applied to the top nodes of column while axial restraints in direction opposing to loading are assigned to the bottom nodes of column. **Figure (1)** shows the finite element mesh, the boundary conditions and the arrangement of CFRP layers for partially and fully wrapped columns. Geometrical imperfection and arc length analysis method are applied to the model to perform the non-linear analysis as recommended by reference [1]

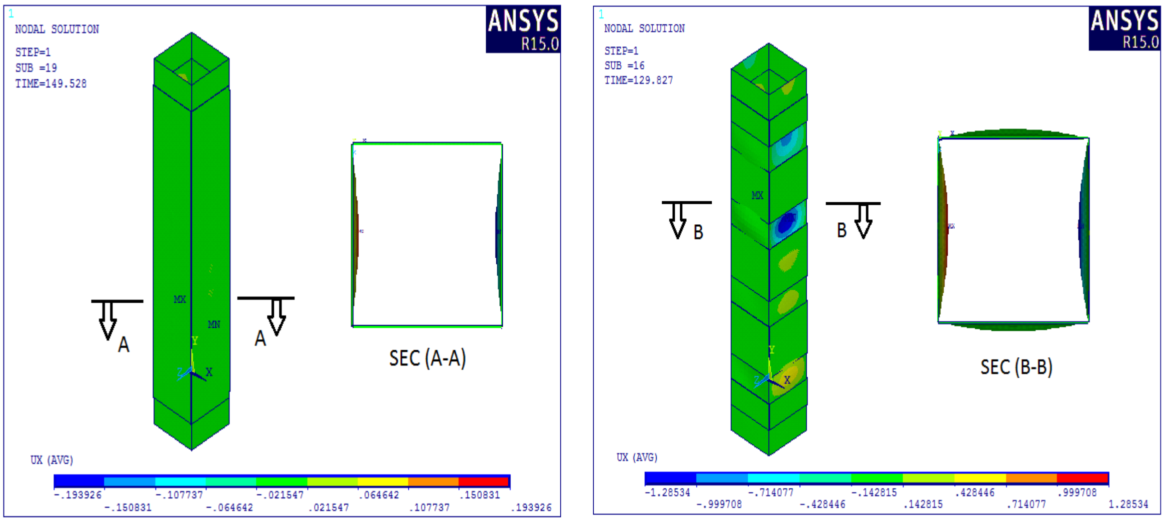


(a) Fully Wrapped Specimen (b) Partially Wrapped Specimen

Figure (1) Created models for fully and partially strengthened specimens

2.2. Model Verification

The results of the adopted numerical model has been verified with the test results of the experimental work conducted by reference [1]. The observed mode of failure of fully wrapped specimen is the inward buckling of steel section while the partially wrapped specimen failed under local buckling at the non-strengthened zone between fiber strips that well agreed with the experimental test failure modes noticed by reference [1]. **Figure (2)** shows the failure modes of both fully and partially wrapped specimens. A comparison between the results of the developed numerical model and reference [1] test results in the form of load-shortening curves is shown in **Figure (3)**.



(a)Fully Wrapped Specimen

(b)Partially Wrapped Specimen

Figure (2) Failure modes for fully and partially strengthened specimens

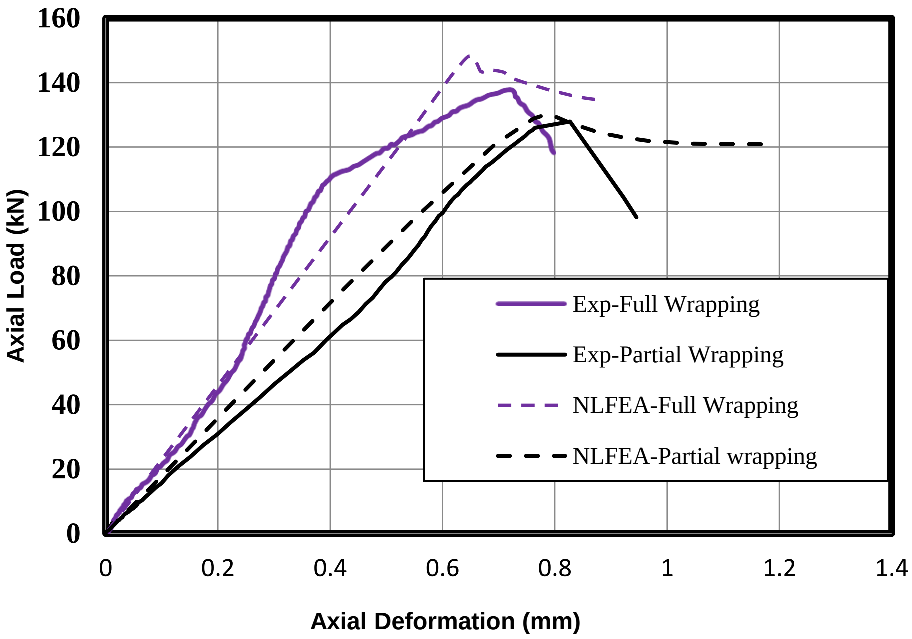


Figure (3) Axial load-deformation curves for fully and partially strengthened SHS (100x100x1.5)

3. PARAMETRIC STUDY

After the developed NLFEA modeled has been validated with experimental results, the parametric study is performed on slender SHS and Rectangular Hollow section (RHS) where the local buckling is the govern in-stability mode. The study is conducted for two main parameters. The first is the plate slenderness ratio of steel section for fully wrapped specimens (B/t or D/t) and the second is the spacing (S) between carbon fiber strips for partially wrapped specimens. To perform the investigation; Young's modulus and yielding strength of steel are considered to be 200 GPa and 350 MPa respectively for all specimens. The mechanical properties of CFRP have been taken as stated in section 2.1.

3.1 Full Wrapping Technique

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Axially compressed square hollow columns with section of (100 mm x 100mm) and thicknesses range between 0.5 mm to 2 mm have been studied. These sections represent a plate slenderness ratio range between 50 to 200. The non-linear buckling analysis has been performed using the verified ANSYS model for control (Un-strengthened) and fully wrapped specimens. The ultimate capacities of control and strengthened SHS is presented in **Table (2).**

Table (2). Axial capacity for studied control specimens and corresponding fully wrapped specimens

Specimen-section	Plate-slenderness (B/t)	Failure Load for control specimen (kN)	Failure Load for fully wrapped specimen (kN)	Yielding load (kN)	capacity enhancement %
S-100x100x0.5	200	19.3	37.3	70	95.4
S-100x100x0.65	154	30.1	57.5	91	91.3
S-100x100x0.8	125	42.6	79.3	112	86.1
S-100x100x1	100	62.3	113.1	140	81.4
S-100x100x1.2	83	84.5	145.9	168	72.5
S-100x100x1.5	67	125.9	197.9	210	57.2
S-100xx100x1.8	56	180.1	251.2	252	39.5
S-100x100x2	50	224.4	282.5	280	25.9

The CFRP full wrapping technique provides large enhancement in axial capacity of steel columns **Figure (4)** shows the enhancement in axial capacity by provided CFRP full wrapping technique.

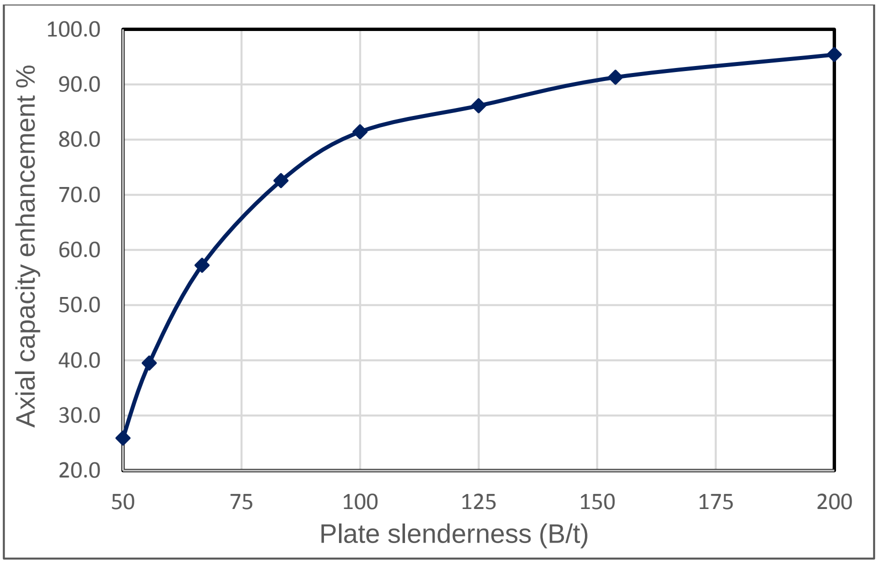

Figure (4) Axial capacity enhancement provided by full wrapping of SHS

Figure (4) shows that; the percentage of enhancement in axial capacity provided by CFRP full wrapping increases by increasing the slenderness of steel plates. Failure in low slenderness sections may occur due to yielding so, wrapping process will not significantly affect the failure load. As the slenderness ratio increases, the local buckling begins to be the dominate failure mode, that describes the changes in slope of curve. **Figure (5)** shows a comparison of failure loads of control and wrapped specimens with yielding load. A limited enhancement value in axial capacity is observed for low plate-slenderness specimens, where the yielding is the dominate failure for wrapped specimens

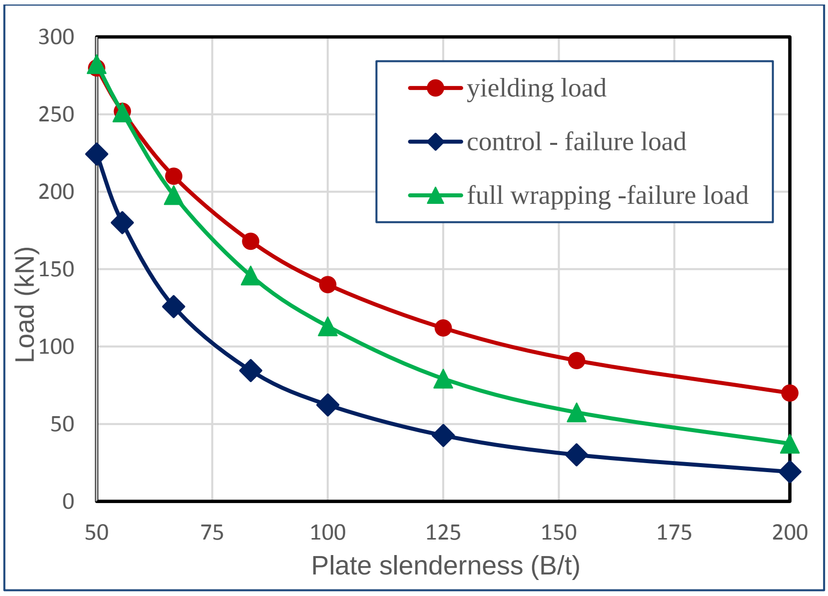

Figure (5) Failure loads of control and wrapped specimens of SHS

The effectiveness of CFRP full wrapping of axially compressed Columns of rectangular section (40 mm x 100mm) and thicknesses range between 0.5 mm to 2 mm have been studied. The enhancement value is studied with changing in larger rectangle plate slenderness (D/t). The study has been conducted on a plate slenderness ratio (D/t) ranges between 50 to 200. The non-linear buckling analysis has been performed using the verified ANSYS model.

As the inward buckling failure of rectangle larger plates provides a more conservative enhancement values as concluded by reference [1]., the geometrical imperfection is taken from the in-ward buckling of larger plates. **Table (3)** shows the obtained ultimate axial capacity for studied control and full wrapped specimens. **Figure (6)** shows a comparison between failure loads of control and wrapped RHS specimens, and yielding load. **Figure (7)** shows the variation of enhancement in axial capacity with the plate slenderness ratio of larger plate of RHS, with full wrapping strengthening using CFRP

Table (3) Axial capacity for studied RHS control specimens and corresponding fully wrapped specimens.

Specimen-section	**Plate-slenderness (D/t)**	**Failure Load for control specimen (kN)**	**Failure Load for fully wrapped specimen (kN)**	**Yielding load (kN)**	**Axial capacity enhancement %**
R-40x100x0.5	200	18.9	25.775	49	36
R-40x100x0.65	154	30.3	40.56	63.7	34
R-40x100x0.8	125	43.0	56.133	78.4	31
R-40x100x1	100	60.2	76.489	98	27
R-40x100x1.2	83	79.2	97.492	117.6	23
R-40x100x1.5	67	112.3	133.07	147	19
R-40x100x1.8	56	153.2	172.37	176.4	13
R-40x100x2.0	50	183.0	194.95	196	7

At low plate slenderness ratio; the yielding is considered the dominate failure mode. Therefore; the enhancement provided by CFRP wrapping is relatively low. By increasing the plate slenderness ratio; the failure mode changes to local buckling failure and enhancement in axial capacity also increases.

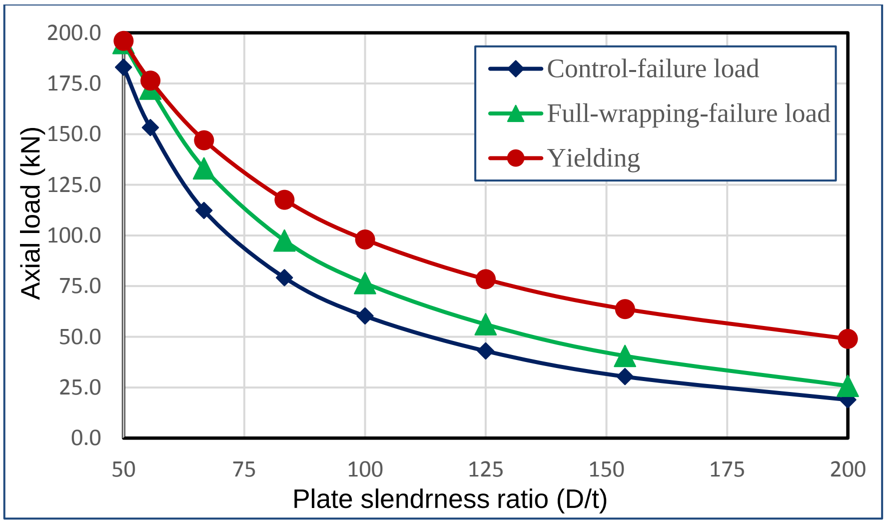

Figure (6) Failure loads of control and fully wrapped studied RHS specimens in comparison with yielding load

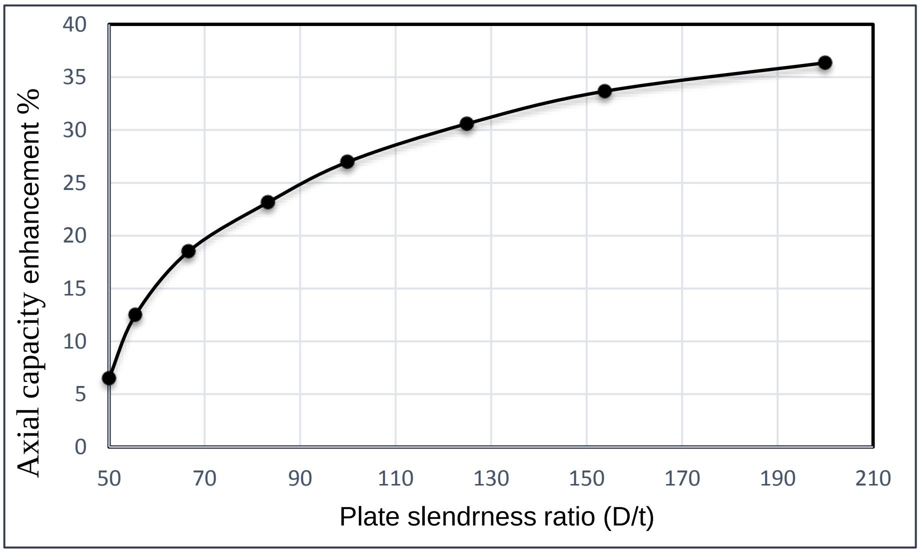

Figure (7) Variation of enhancement percentage for fully wrapped RHS with larger plate slenderness ratio (D/t)

3.2 Partial Wrapping Technique

The impact of spacing between fiber strips on partially strengthening of SHS has been studied. SHS (100 mm x 100mm) with critical half wave length (ℓ_{cr}) equals 100 mm has been studied with various thicknesses. The enhancement in axial capacity provided by fiber strips of various spacing has been monitored compared to the control specimen. The width of fiber strips equals to 100 mm and spacing between them ranges between 15 mm to 200 mm. The local buckling failure has been occurred at the non-strengthened zones between fiber strips **Table (4)** shows the enhancement value corresponding to each spacing between fiber strips.

Table (4) Enhancement in axial capacity for partially strengthened SHS (100x100) using CFRP strips of various spacing.

section	**Strips-Spacing S (mm)**	**Critical half wave length ℓcr (mm)**	**Failure Load for control specimen (kN)**	**Failure Load for partially strengthened specimen (kN)**	**Axial capacity enhancement %**
S-100x100 x0.5	15	100	18.9	29.7	57.0
	25			27.8	46.8
	50			24.5	29.3
	75			22.9	21.0
	100			22.3	17.7
	150			20.0	5.7
	200			19.8	4.5
S-100x100x1	15	100	62.4	97.6	56.4
	25			91.3	46.4
	50			78.6	25.9
	75			71.8	15.0
	100			71.4	14.4
	150			65.7	5.3
	200			64.7	3.6
S-100x100x1.5	15	100	125.9	188.6	49.9
	25			182.5	45.0
	50			156.3	24.2
	75			144.5	14.8
	100			143.8	14.2
	150			131.5	4.5
	200			129.5	2.9
S-100x100x2	15	100	224.4	280.6	25.0
	25			280.1	24.8
	50			268.9	19.8
	75			250.0	11.4
	100			248.7	10.8
	150			234.1	4.3
	200			230.5	2.7

The results show that; the axial capacity of partially wrapped SHS increases with decreasing the spacing between fiber strips. The axial capacity of partially strengthened specimens ranges between the capacities of control and full wrapped specimens as shown in **Figures (8 to.11**) Maximum enhancement corresponds to minimum strips spacing, however it still smaller than the full wrapping enhancement. A limited enhancement is achieved when spacing between strips increases than the critical half wave length. The strips setup should be carefully chosen to obtain the optimum strips arrangement that provides the required enhancement with lowest cost. **Figure (12)** shows the enhancement value corresponding to each strips setup for SHS 100x100 of various thicknesses.

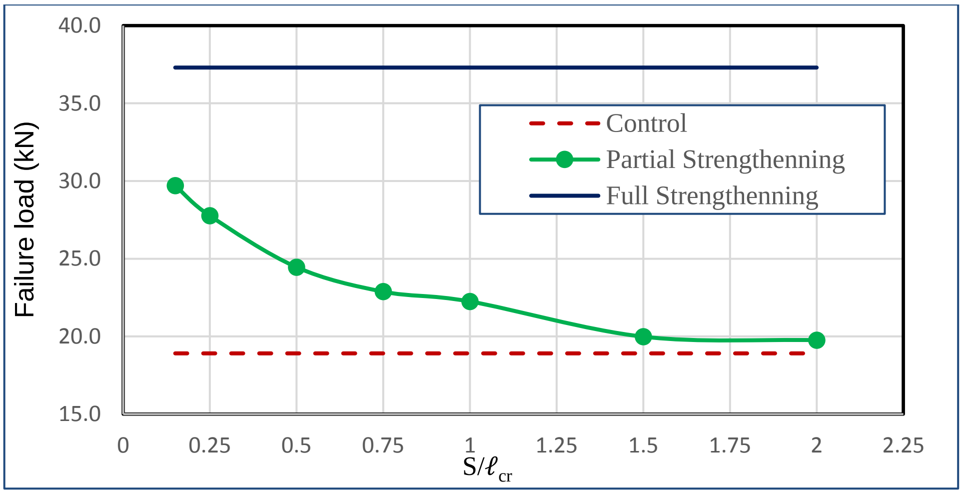

Figure (8) Axial capacity of control, full wrapped and partially wrapped specimens of SHS-100x100x0.5 (ℓ_{cr} =100mm)

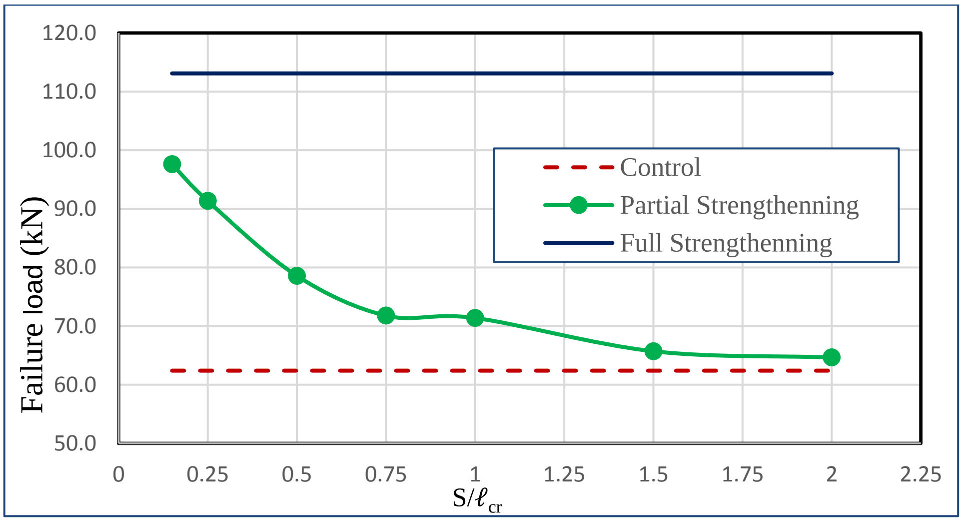

Figure (9) Axial capacity of control, full wrapped and partially wrapped specimens of SHS-100x100x1 (ℓ_{cr}=100mm)

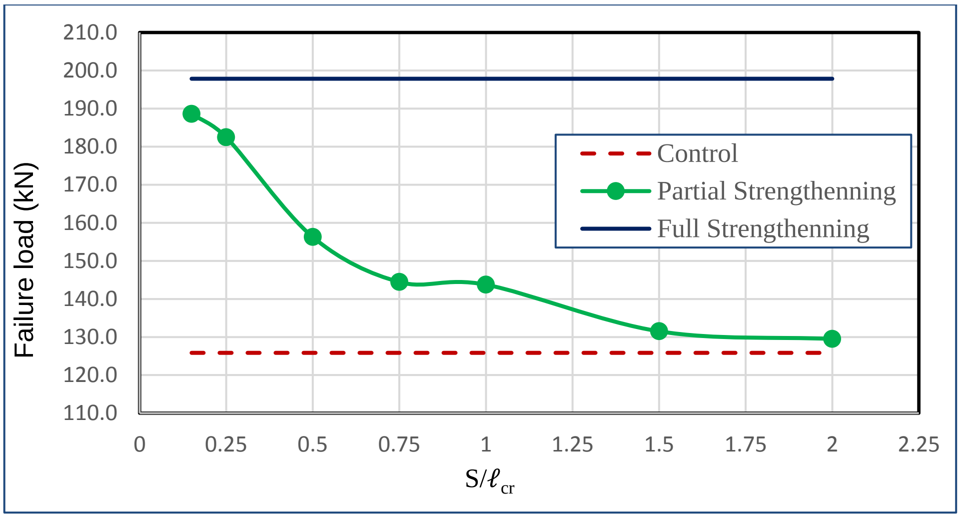

Figure (10) Axial capacity of control, full wrapped and partially wrapped specimens of SHS-100x100x1.5 (ℓ_{cr}=100mm)

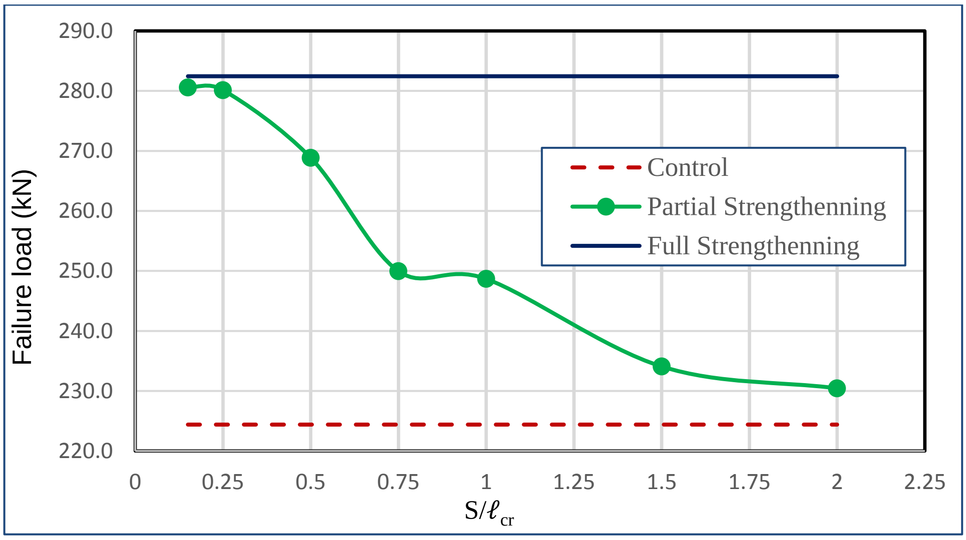

Figure (11) Axial capacity of control, full wrapped and partially wrapped specimens of SHS-100x100x2 (ℓ_{cr}=100mm)

For SHS of low plate slenderness ratio, the partially strengthening of the sections may provide enhancement close to the enhancement provided by fully wrapping technique while the yielding failure is the dominate failure mode for both strengthening techniques as shown in Figure (11). For the same strips setup; the enhancement percentage in axial capacity increases by increasing the plate slenderness of SHS as shown in Figure (12).

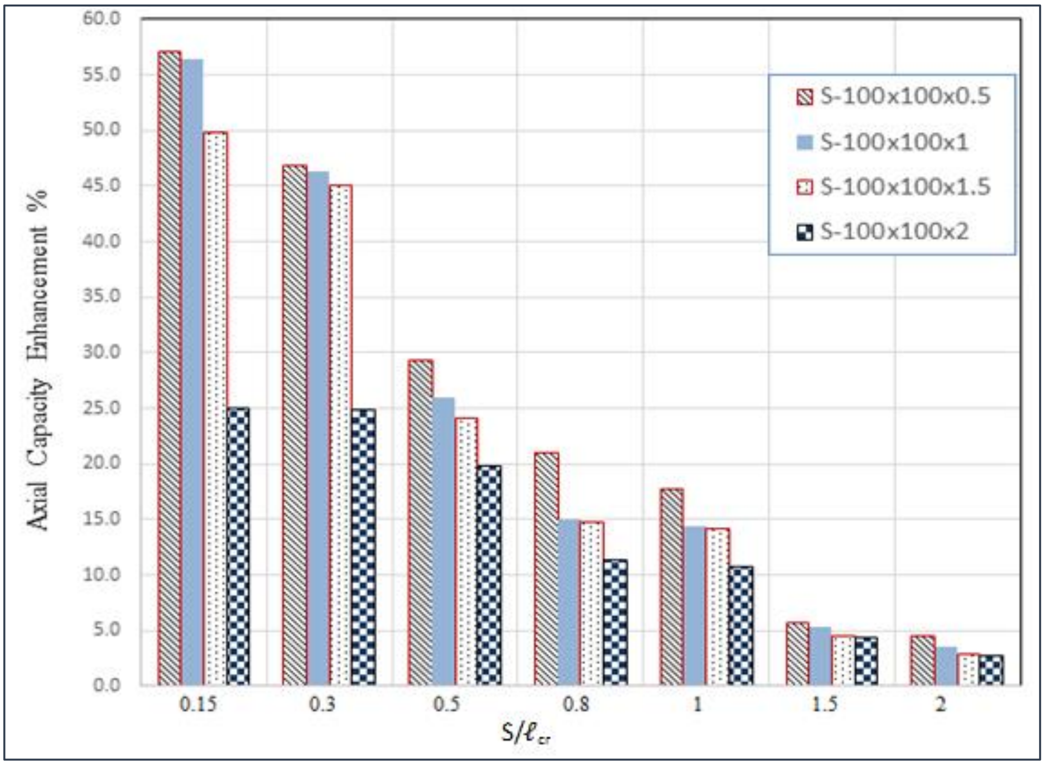

Figure (12) *Enhancement percentage for partially strengthened SHS (100x100) of various thicknesses with respect to strips spacing (ℓ$_{cr}$=100 mm)*

The parameter of strips spacing has been studied for partially strengthened RHS. RHS (100 mm x 40mm) with 80 mm critical half wave length (ℓ$_{cr}$) for different thicknesses has been chosen. The enhancement in axial capacity provided by fiber strips of various spacing has been monitored comparing to the control and fully wrapped specimens. The width of fiber strips equals to 100 mm and spacing between them ranges between 15 mm to 200 mm. Table (5) shows the enhancement value provided by each partially strengthened RHS specimen.

In a similar manner; decreasing the spacing between fiber strips results in increasing the axial capacity of partially wrapped RHS. The max capacity of partially wrapped specimen with fiber spacing equals 20 mm is still lower than the capacity provided by full wrapping. When fiber strips are arranged at spacing more than the critical half wave length of the column (ℓ$_{cr}$), the capacity enhancement is insignificant. **Figures (13 to 16)** shows the axial capacity of partially strengthened specimens comparing to control and full wrapped counterparts.

Table (5). Enhancement in axial capacity for partially strengthened RHS (100x40) using CFRP strips of various spacing.

Section	**Strips-Spacing S (mm)**	**Critical half wave length ℓ_{cr} (mm)**	**Failure Load for control specimen (kN)**	**Failure Load for partially strengthened specimen (kN)**	**Axial capacity enhancement %**
R-100x40x0.5	20	80	18.9	25.3	33.7
	40			21.5	13.8
	80			20.8	10.2
	100			19.7	4.1
	140			19.4	2.5
	200			19.3	2.3
R-100x40x1	20	80	60.23	75.6	25.5
	40			67.3	11.8
	80			63.7	5.8
	100			62.5	3.8
	140			62.0	2.9
	200			61.6	2.3
R-100x40x1.5	20	80	112.3	132.5	18.0
	40			125.1	11.4
	80			118.3	5.3
	100			116.0	3.3
	140			115.7	3.0
	200			114.7	2.1
S-100x40x2	20	80	183.02	193.5	5.7
	40			193.1	5.5
	80			191.0	4.4
	100			188.7	3.1
	140			187.8	2.6
	200			186.3	1.9

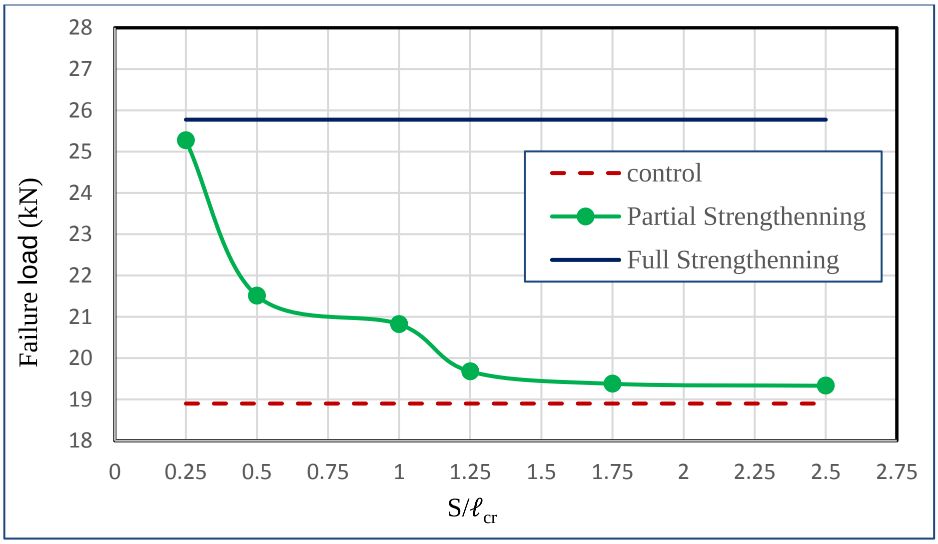

Figure (13) Axial capacity of control, full wrapped and partially wrapped specimens of RHS -100x40x0.5 (ℓ_{cr}=80mm)

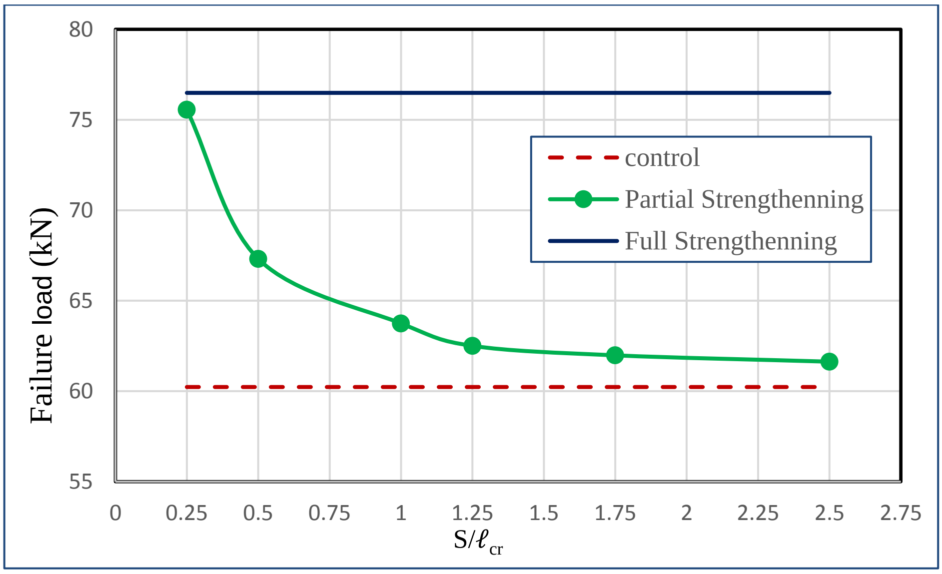

Figure (14) Axial capacity of control, full wrapped and partially wrapped specimens of RHS -100x40x1(ℓ_{cr}=80mm)

It can be noticed that; no great increase in enhancement when spacing is larger than the critical half wave length (ℓ_{cr}). When strips are utilized with very small spacing such as 0.25 of critical half wave length, a relatively large enhancement is achieved. **Figure (17)** shows the enhancement provided for each studied RHS when partially wrapped.

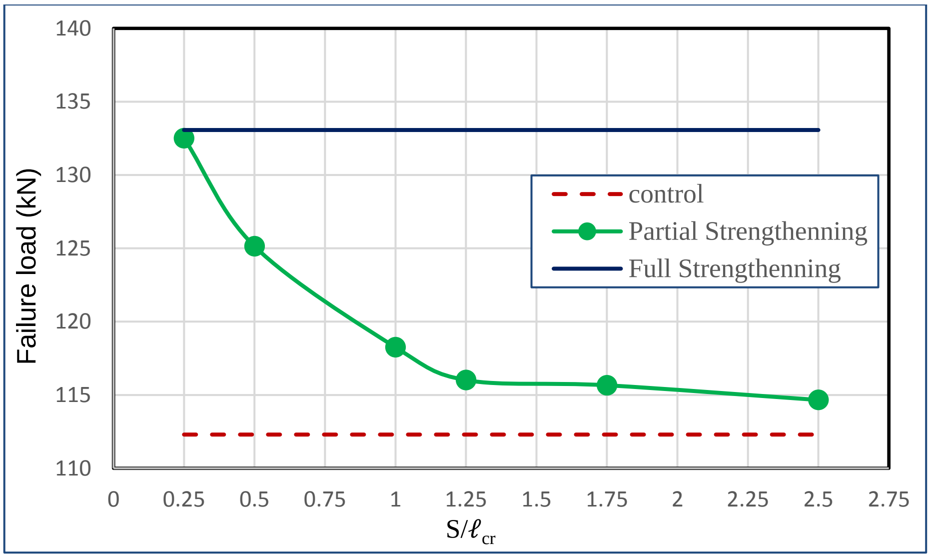

Figure (15) Axial capacity of control, full wrapped and partially wrapped specimens of RHS -100x40x1.5 (ℓ_{cr}=80mm)

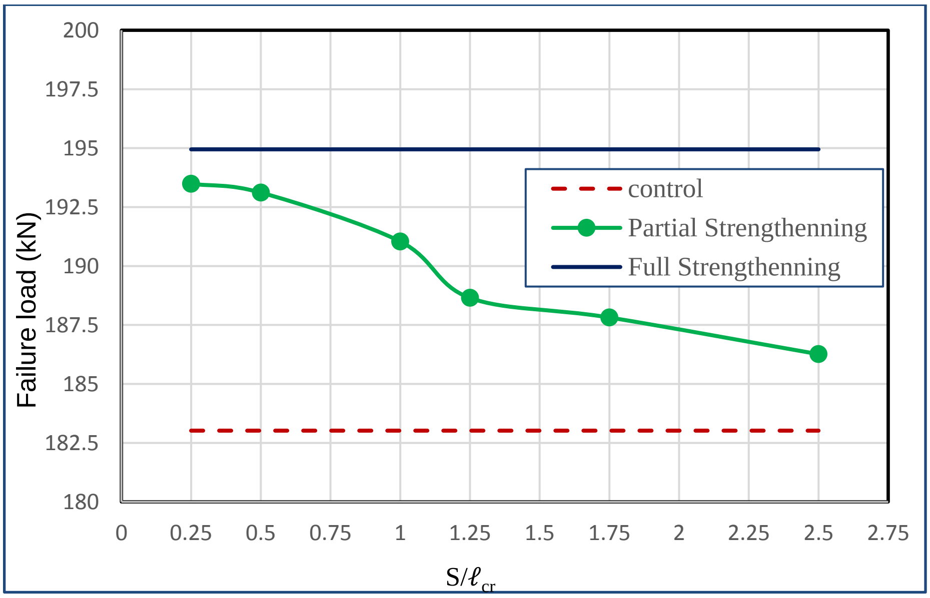

Figure (16) Axial capacity of control, full wrapped and partially wrapped specimens of RHS -100x40x2(ℓ_{cr}=80mm)

At low strips spacing, the provided enhancement may be almost equal to fully wrapped enhancement while the yielding failure is the dominate failure mode for both strengthening techniques as shown in Figures 13 to Figures 16.The enhancement percentage in axial capacity increases by increasing the plate slenderness of RHS for the same strips arrangement as shown in Figure 17.

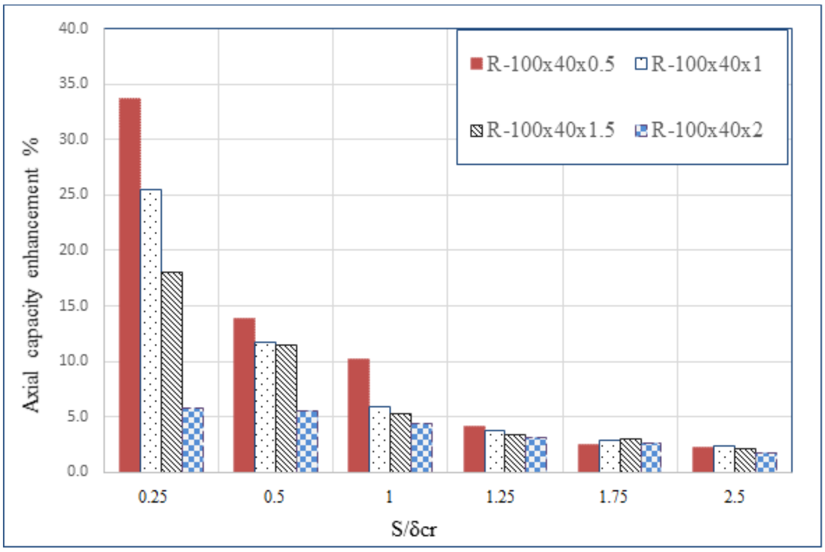

Figure (17). Enhancement percentage for partially strengthened RHS-100x40 of various thicknesses with respect to strips spacing (ℓ_{cr}=80mm)

4. CONCLUSION

The parametric study is performed on SHS and RHS of plate slenderness ratio ranges between 50 to 200. The enhancement percentage provided by either full wrapping or partially wrapping techniques increases by increasing the plate slenderness of SHS and RHS. The enhancement in axial capacity of fully wrapped SHS columns ranges between 25.9 % and 95.4 while, fully wrapped RHS columns have an enhancement in axial capacity ranges between 7 % and 36%. The conducted study showed that; strengthening using CFRP wrapping is more efficient in case of SHS than the case of RHS. The enhancement in axial capacity of partially strengthening SHS and RHS increases by decreasing the spacing between fiber strips however, it is still lower than the enhancement provided by full wrapping. To obtain a reasonable increase in axial capacity the fiber strips should be applied at intervals less than the critical half wave length of the strengthened specimens.

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