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Experimental and Theoretical Analysis of Hollow Steel Columns Strengthening by CFRP

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Abstract: The need for strengthening and retrofitting is well known and extensive research is progressing in this field. The reasons for strengthening and retrofitting are numerous: increased loads, changes in use, deterioration, and so on. In recent years, the use of carbon fiber reinforced polymer (CFRP) for strengthening has shown to be a competitive method, both regarding structural performance, and economical aspects. Extensive research has been carried out in this field. However, most of the research has been undertaken on concrete structures and for confinement, flexural, and shear strengthening. Limited research has been carried out on steel structures strengthened with CFRP. This paper presents axially loaded steel columns strengthened for increased load. The topic is studied theoretically and through laboratory tests. The theory covers analytical methods. Carbon fiber reinforced polymers has been used to strengthen the columns. The tests have been undertaken on full scale specimens, non-strengthened for reference, partially strengthened and fully strengthened.

Keywords: CFRP; experimental; strengthened; steel column; theoretical analysis.

Introduction

In recent years, the use of CFRP for strengthening and retrofitting of steel structures has been considerably developed. A variety of strengthening or rehabilitation techniques such as section enlargement, external bonding of steel plates and fibers has been proposed to strengthen metallic structures. Though the external bonding of steel plate was successful in practice, it posed some problems such as adding of self-weight, requirement of heavy lifting equipment to place the plates in position, difficulty in shaping and fitting in complex profiles and complication in bonding/welding, besides added plates are susceptible to corrosion which leads to an increase in future maintenance costs. Fiber reinforced polymer composites represent a new and promising solution to the shortcomings of several traditional materials and upgrading techniques and has a great potential to integrate into the bridge infrastructure [1]. CFRP materials have high tensile strengths; most of them stretch to relatively high strain values before providing their full strength. CFRP also has a higher strength to weight ratios and impact resistance, offer greater design flexibility and better resistance to chemicals and corrosion [2].

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The other advantage of CFRP over the traditional method is its applicability and the capacity to cover areas in quick succession and therefore used in underwater applications [3]. No heavy instruments are necessitated for bonding CFRP over steel surface. Due to their low weight and good tailor ability, rapid execution can be achieved.

Zhao et al. [4] investigated the improved web crippling behaviors of rectangular hollow section (RHS) strengthened by CFRP, several types of strengthening were adopted, such as wrapping CFRP sheeting outside the RHS or applying CFRP plates outside or/and inside the RHS. It was found that the CFRP strengthening significantly increases the web crippling capacity especially for those with large web depth to thickness ratios. The design models are proposed to predict the increased capacity for CFRP strengthened RHS subjected to transverse end bearing force.

Silvestre et al. [5] carried out an experimental and numerical investigation on the nonlinear behavior and load carrying capacity of CFRP strengthened cold-formed steel lipped channel column. 19 short and long fixed ended lipped columns were strengthened with carbon fiber sheets (CFSs) bonded at different outer surface locations (web, flange or lips) and having the fibers oriented longitudinally or transversally, the results of the experiment showed that the presence of the single CFS may increase the load carrying capacity by up to 15% for the short column strengthened at column web and flanges with transverse CFS, and 20% for the long column strengthened over whole outer surface with transverse CFS.

Teng and Hu [6] investigated the performance enhancement of circular hollow steel tubes with FRP jacketing. Four steel tubes with or without glass fiber reinforced polymer (GFRP) jacket were tested. It was found that the use of FRP confinement enhanced the ductility of hollow steel tubes. In an investigation using CFRP for tubular steel sections [7], butt welded, very high strength (VHS) circular steel tubes reinforced with unidirectional CFRP sheets were tested under tensile load. The results showed that the strength increase varied from 25% to 76%, which proved CFRP wrapping as an effective method to strengthen VHS tubes.

Shaat and Fam [8] found that transverse CFRP layers are effective in confining the outward local buckling of short columns and that the load capacity increased by 18% for short columns and 13% to 23% for long columns.

Shaat and Fam [9] developed an analytical model for slender steel hollow section columns strengthened with CFRP sheets. A limiting strain of 0.13% was adopted in the model for the CFRP in compression. Further research is needed to examine the applicability of this value to other types of CFRP, or when CFRP is bonded to steel hollow sections of different sizes.

Zhao et al. [10] carried out tests on CFRP strengthened concrete filled steel hollow section short columns. The increase in load carrying capacity was found to be 5–22% and 20–44%, when one and two layers of CFRP were applied. The load capacity enhancement increased with increasing diameter to thickness ratio.

Tao et al. [11] carried out tests on concrete filled steel hollow section short columns strengthened by CFRP. Kinoshita [12] proposed a fiber model analysis method considering local buckling for improving the analytical response estimation of steel bridge columns. In this method, multi-fiber elements were used to model the local buckling length to simulate local buckling deformation. The proposed method shows good results not only for estimating peak strength, but also post-peak strength compared to previous experimental results.

Bambach et al. [13] studied the axial compression behavior of CFRP strengthened cold formed square hollow sections by conducting experiments. They showed that the application of CFRP delayed local buckling, and that the elastic buckling strength of slender sections is increased by up to 4 times. Gao et al. [14] strengthened hollow steel tubes with CFRP sheets. The results of their studies indicated that adding the number of layers can increase the strength and stiffness of the tubes.

Sundarraja et al. [15,16] retrofitted hollow steel short columns by wrapping CFRP sheets in the transverse and longitudinal. They observed that in the transverse method, increased the bearing capacity and axial stiffness of the columns. Additionally, their experiment indicated that axial deformations of the local buckling thrust were delayed.

From the past studies, one can observe that some studies have done with the use of CFRP as a strengthening material for square hollow section (SHS) steel members and also the presence of CFRP significantly enhance the behavior of SHS steel members. The main focus of the study is to experimentally and theoretically investigating the suitability of carbon fiber reinforced polymer for the strengthening of the SHS column with end condition, fixed-pinned. CFRP coverage is also one of the investigations.

Theory

For the theories, Young's modulus, E, and moment of inertia, I, of the involved material are needed. The Young's modulus for steel is well known. The composite the modulus is dependent on the fiber content. The moment of inertia is only dependent on geometry and for a square hollow section (SHS) with notations as in Fig. 1 it is calculated for the non-strengthen and strengthen in accordance to Equations 1 and 2 respectively;

$$I_s = \frac{D_s^4}{12} - \frac{d_s^4}{12} \tag{1}$$

$$I_{str} = \frac{(D_s + 2t_f)^4}{12} - \frac{D_s^4}{12} \tag{2}$$

For the strengthened members the modulus will vary over the cross-section and it is most convenient to calculate the product of Young's modulus and the moment of inertia, EI. Here we introduce the property $(EI)_{str}$ of the strengthened cross-section which may be calculated as in, Equations 3 to 5.

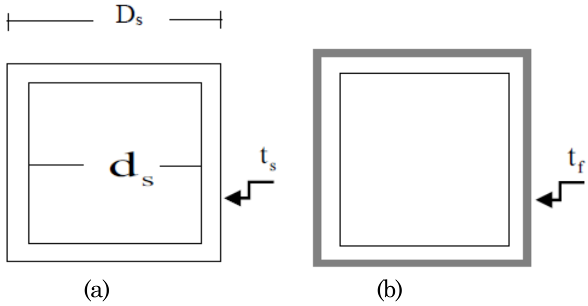

Figure 1. Cross-section of Non-strengthened (a) and Strengthened (b)

This is possible since the two materials have the same centre of gravity, as it is in this case, and is based upon that plane cross-sections remain plane.

$$(EI)_{str} = E_{cfrp}\left[\frac{(D_s + 2t_f)^4}{12} - \frac{D_s^4}{12}\right] + E_s\left[\frac{D_s^4}{12} - \frac{d_s^4}{12}\right] \quad (3)$$

d_s, may be written as:

$$d_s = D_s - 2t_s \quad (4)$$

$$(EI)_{str} = E_{cfrp}\left[\frac{(D_s + 2t_f)^4}{12} - \frac{D_s^4}{12}\right] + E_s\left[\frac{D_s^4}{12} - \frac{(D_s - 2t_s)^4}{12}\right] \quad (5)$$

By defining the Young's modulus for the CFRP as a function of Young's modulus for steel as:

$$E_{cfrp} = \alpha E_s \quad (6)$$

Equation 5 may be written as follows

$$(EI)_{str} = \alpha E_s\left[\frac{(D_s + 2t_f)^4}{12} - \frac{D_s^4}{12}\right] + E_s\left[\frac{D_s^4}{12} - \frac{(D_s - 2t_s)^4}{12}\right] \quad (7)$$

$$(EI)_{str} = \frac{E_s}{12}\left[\alpha(D_s + 2t_f)^4 + D_s^4(1-\alpha) - (D_s - 2t_s)^4\right] \quad (8)$$

From Equation 8, a fictitious moment of inertia, I^*_{str}, for the strengthened cross section corresponding to a cross-section with Young's modulus for steel can be identified as

$$I^*_{str} = \frac{1}{12}\left[\alpha(D_s + 2t_f)^4 + D_s^4(1-\alpha) - (D_s - 2t_s)^4\right] \quad (9)$$

Analysis

Shown in Fig. 2b and c are the diagrams of a pinned-fixed column and the free body of a short segment of the same column cut at a distance, x, from the pinned support. Note that for moment equilibrium, a shear force of M_F/L must be present at both ends of the column to balance the fixed end moment M_F, which is induced in the built in end as the column buckles.

The equilibrium equation for the column segment shown in Fig. 2c is [17]:

$$-M_{int} = Py - \frac{M_F}{L}x = 0 \quad (10)$$

and since

$$M_{int} = -EIy'' \quad (11)$$

Equation (10) can be rewritten as

$$y'' + k^2 y - \frac{M_F}{EIL}x = 0 \quad (12)$$

where $k^2 = P/EI$

The general solution is

$$y = A\sin kx + B\cos kx + \frac{M_F}{PL}x \quad (13)$$

The boundary conditions are

$$y(0) = 0 \quad (14)$$

$$y(L) = 0 \quad (15)$$

$$y'(L) = 0 \quad (16)$$

Using the first two boundary conditions,

$$B = 0 \quad (17)$$

$$A = -\frac{M_F}{P\,sin\,KL} \quad (18)$$

and the deflection (13) becomes

$$y = \frac{M_B}{P}\left(\frac{x}{L} - \frac{\text{Sin }Kx}{\text{Sin }KL}\right) \quad (19)$$

Using the third boundary condition in Eq. (19) gives,

$$\text{Tan }KL = KL \quad (20)$$

From which KL can be solved by trial and error or by graphical means. The lowest value that satisfies Eq. (20) is

$$KL = 4.4934 \quad (21)$$

The deflected shaped of the column at buckling is

$$y = \frac{M_F}{P}\left[\frac{x}{L} + 1.0245\sin\left(4.4934\frac{x}{L}\right)\right] \quad (22)$$

However, an examination of the bending moment diagram for a buckled column indicates that a uniform cross section along the length is not the most economical form for strengthening to increase the critical load. The greater part or the strengthening material should be applied in the midsection of the column. The buckling mode of the column with higher moment of inertia in the near midsection, shown in Fig. 2a, is presented in Fig. 2b.

By using an energy approach, the critical load for the column, may be analytically determined. The internal work to deform the column may be expressed as

$$\Delta U = \int_0^L \frac{M^2}{2EI}dx \quad (23)$$

By combining Eq. (22), and (23) and with notation as in Fig. 2, the internal work becomes:

$$\Delta U = \int_0^L \frac{EI}{2}\left(\frac{d^2y}{dx^2}\right)^2 dx \quad (24)$$

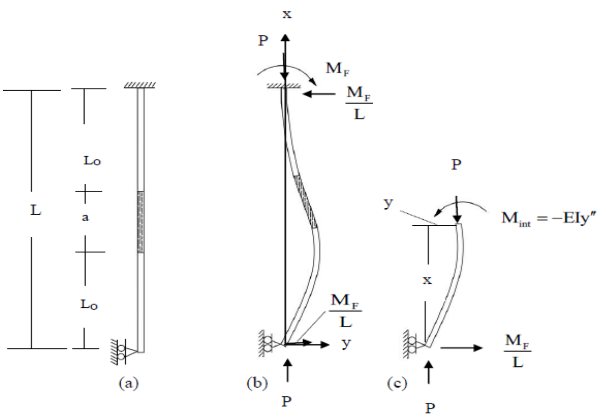

Figure 2. Pinned-fixed Column with Partially Strengthened

The vertical deformation, δ, is described as,

$$\delta = \frac{1}{2}\int_0^L \left(\frac{dy}{dx}\right)^2 dx \qquad (25)$$

and the external work to move the end of the column a distance δ becomes

$$\Delta T = \frac{1}{2} P\delta \qquad (26)$$

For energy equilibrium the internal and external work must be equal

$$\Delta U = \Delta T \qquad (27)$$

and the critical load for the column may be written as

$$P_{cr} = \frac{\int_0^{L_0} E_s I_s \left(\frac{d^2y}{dx^2}\right)^2 dx + \int_{L_0}^{L_{0+a}} (EI)_{str} \left(\frac{d^2y}{dx^2}\right)^2 dx + \int_{L_{0+a}}^{L} E_s I_s \left(\frac{d^2y}{dx^2}\right)^2 dx}{\int_0^L \left(\frac{dy}{dx}\right)^2 dx} \qquad (28)$$

Material

The dimensions and material properties of SHS steel used in this study are given in Table 1. The yield strength found by coupon tests is 280 N/mm2 and the ultimate tensile strength is 340 N/mm2.The properties of carbon fiber reinforced polymerused in this research SikaWraps-230C reinforced with unidirectional carbon fiber. Properties of carbon fiber reinforced polymer sheets are shown in Table 2. The properties of epoxy used in this study are shown in Table 3.

Table 1. Dimensions and material properties of SHS steel

Dimensions	Length	Modulus of Elasticity	Stress (N/mm2)	
(h × b × t) (mm)	L (mm)	(N/mm2)	Yielding (F_y)	Ultimate (F_u)
40 × 40 × 2	3000	200000	280	340

Table 2. Properties of fiber

SikaWraps-230C				
Fabric design Thickness (mm)	Modulus of Elasticity (N/mm2)	Ultimate Tensile Strength (N/mm2)	Ultimate Tensile elongation (%)	Thickness (Impregnated with Sikadurs-330) (mm)
0.131	238000	4300	1.8	1

Table 3. Properties of adhesive

Sikadurs-330			
Tensile strength (N/mm2)	Modulus of elasticity (N/mm2)		Elongation at break (%)
	Tensile	Flexural	
30	4500	3800	0.9

Experimental Study and Specimen Fabrication

The 3000 mm length SHS steel cut from 6 m SHS steel. To get the flat surface, both ends of the SHS steel were surfaced by the surface grinding machine. Surface preparation of the metal substrate is very important to achieve good bonding between SHS steel and CFRP fabrics. The strength of the adhesive bond is directly proportional to the quality of the surfaces to which it is bonded. So the exposed surface of the SHS steel specimen was blasted by the coarse sand to remove the rust and also to make the surface rough one. The SHS steel specimens before and after sand blasting are shown in Figure 3. The entire sand blasted surface was cleaned by using acetone to remove all contaminant materials before retrofitting with the fibers. Finally, the carbon fibers were bonded to the exterior surface of the SHS steel members. During the wrapping of fiber fabrics, the resin and hardener are correctly proportioned and thoroughly mixed together and the excess epoxy and the air were removed using a ribbed roller moving in the direction of the fiber. The specimens bonded with CFRP fabrics are shown in Fig. 4.

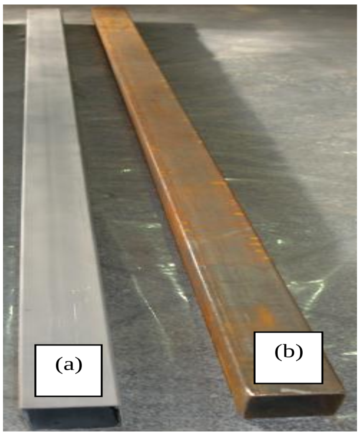

Figure 3. Specimens after (a) and before (b) Sand Blasting

Figure 4. Specimens before and after Wrapped with CFRP

Description of specimens

The tested columns include two control specimens and five specimens strengthened with two layers of CFRP applied on all four sides of the column. The CFRP fiber fabric was wrapped around the five SHS steel with the required number of plies and remaining two specimens are control specimens without wrapping. To identify the specimen easily, the columns were designated by the names such as C2-20, C2-30, C2-40, C2-50, and C2-100. For example, the specimen C2-100 indicates that it was strengthened by two layers of CFRP fabrics fully wrapped around the column, in the longitudinal direction, while specimen C2-20 specifies that it was the column strengthened by two layers 20% CFRP fabrics in the longitudinal direction. The control column specimen is designated as C0.

Test results

The ultimate load carrying capacity and the percentage of increase in all specimens are summarized in Table 4. From the test results, it can be observed that CFRP plays a vital role in increasing the load carrying capacity of SHS steel columns. In addition, there is more gain in load carrying capacity when the coverage of CFRP is increased.

Failure modes

All SHS steel column specimens were tested to failure. Failure of the SHS steel column without CFRP confinement (C0) is generally marked by the overall buckling as shown in Figure 5. In all cases of strengthened, the overall buckling occurs at near the middle of the span and failure mode are presented in Figures 6-8. From the above test results, it can be observed that the columns fully wrapped around with two layers of CFRP show great resistance against overall buckling and an increase in load carrying capacity to that of other confined columns.

Table 4. Specimen details and test results

S. No	Designation of Columns	CFRP coverage (%)	Ultimate load (KN)	% of increase in load
1	C0	0	31.80	-------
2	C2-20	20	35.00	10.06
3	C2-30	30	35.55	11.80
4	C2-40	40	36.10	13.52
5	C2-50	50	37.80	18.87
6	C2-100	100	43.80	37.74

Theoretical analysis results

Table 5 shows the theoretical analysis resultsfor samples with two layers of CFRP. The length of column and number of CFRP layers for all samples are the same. The percent coverage varies based on the length of the columns, and the center CFRP wrapping position is at the center column. The maximum rate critical load of columns happened in coverage is 100%.

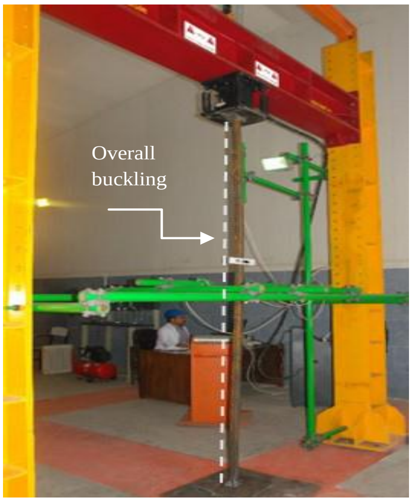

Figure 5. Failure Mode of C0

Figure 6. Failure Mode of C2-20

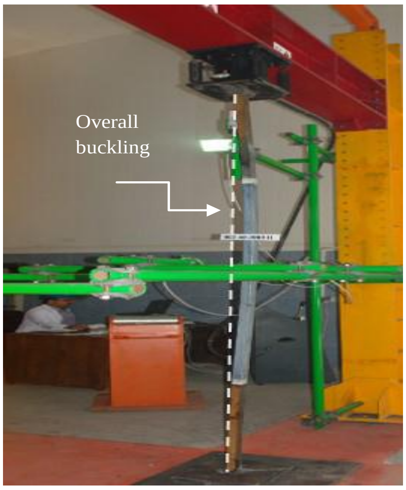

Figure 7. Failure Mode of C2-50

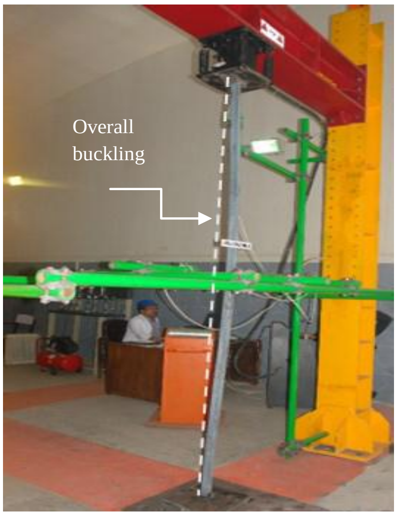

Figure 8. Failure Mode of C2-100

Table 5. Ultimate Loads of Columns (theoretical)

S. No	Designation of Columns	CFRP coverage (%)	Ultimate load (KN)	% of increase in load
1	C0	0	32.86	-------
2	C2-20	20	34.67	5.51
3	C2-30	30	35.49	8.00
4	C2-40	40	36.15	10.01
5	C2-50	50	37.23	13.30
6	C2-100	100	39.79	21.09

Conclusion

In this study, CFRP layers were wrapped with different coverage percentage around the hollow structural steel tubular columns to enhance the structural performance. Based on the obtained results, the failure modes, ultimate load carrying capacity and CFRP wrapping position on hollow steel columns were discussed. Based on the analysis on five specimens wrapped with CFRP sheet with different coverage percentage, the following conclusions can be made:

- The analysis results showed that fiber composites can be used for strengthening of axially loaded SHS steel columns.
- The research showed that, the theoretical analysis and experimental results are close together.
- The coverage of CFRP used has a direct effect on increasing the maximum ultimate load.
- For all SHS steel column specimens, the best coverage percentage of CFRP is 100%.
- Failure modes for all SHS steel column specimens are overall buckling.

The results showed that in most strengthened specimens, ultimate loadla boratory is more than ultimate load theory. Slight increase of the ultimate load of the columns in laboratory method probably were caused by changes in the thickness of the adhesive.

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