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Analytical Investigation on the Compressive Behaviour of CHS Tubular Columns Strengthened Using FRP Composites

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Abstract

There are increasing research efforts concerning the application of fibre reinforced polymer (FRP) to steel structures with very promising results. One particular researched area is the application of composite materials to hollow structural steel (HSS) tubular sections and their resulting behaviour, and the application of FRP composites to circular steel hollow section (CHS) is the focus of this study. The main objective of this investigation is to assess the feasibility of strengthening circular hollow steel tubular sections subjected to compression and to develop or predict the suitable wrapping scheme of FRP to enhance the structural behaviour of it. For this study, mild steel tubes by varying D/t ratio are considered with the main variable being FRP characteristics. Carbon fibre reinforced polymer (CFRP) was considered and used as continuous sheets with several other parameters such as the number of layers and wrapping scheme. Analytical investigation has been done in this paper to predict the axial compressive strength of circular hollow steel tubes strengthened with CFRP as per the recommendations of various codes and standards. Evaluation of the results will lead to optimum FRP jacketing/wrapping arrangements for the steel tubes considered here.

Keywords: CHS tubes, CFRP fabrics, strengthening, compression, externally bonded.

1. Introduction

Steel concentrated structures are popular almost all over the world. Circular hollow steel (CHS) tubes are progressively more used both in building and bridge structures due to their well-organized geometry. During their service life, these members are subjected to loading of various types such as axial loading, bending and torsion. Rehabilitation of such structures is frequently required owing to loss of cross-section from corrosion and/or changes of the demand or use of a structure.

Current techniques for strengthening steel structures have some negative aspects including requiring heavy equipment for installation, their fatigue performance, in addition to the need for continuing maintenance due to persistent corrosion attack. Hence inventive and cost effective methods are necessary for the strengthening and rehabilitation of steel structures that are deficient due to the demand to increase the specified load and/or deterioration as a result of corrosion.

External bonding of advanced composite materials is one such method to strengthen steel structures efficiently. The most common material used is Carbon fibre fabric or laminate. Numerous design specifications have been made in an attempt to predict bond failure, fatigue and strength of CFRP strengthened steel members which take into account the CFRP stiffening. The strength improvement is found to be depending on factors such as cross-sectional shape, slenderness ratio, diameter to thickness ratio or thickness of steel tube and local buckling behaviour of steel tube. To ensure perfect composite action, it is important to provide sufficient bond between the steel and CFRP.

Extensive research has been conducted on the bond behavior which includes studies like dynamic bond strength [1], fatigue loading [2–4], bond characteristics due to impact tensile loads [5,6] and bond strength [7]. The recent studies were undertaken by Haedir et al. [8–10] analyzed and proposed design equations for CFRP-strengthened steel CHS beams, Narmashir et al. [11] for flexural strength for CFRP strengthened steel-beams, Silvestre et al. [12–14] proposed design methods for channel column section, Elachalakani et al. [15] proposed design equations for CHS stub columns, Shaat and Fam [16, 17] for short and long hollow columns, Haedir et al. [18] proposed design equations for tubular column sections, and Bambach et al. [19] proposed design equations for square hollow sections.

This study analytically investigates the behaviour of CHS columns strengthened with CFRP under pure axial compression as per various codes and recommendations. Primarily the variable considered here is D/t ratio of the steel tubes and number of fibre layers.

2. Materials

2.1 Carbon fibre

The unidirectional carbon fibre called MBrace 240, fabricated by BASF India Inc was used in this study. It is a low modulus CFRP fibre having modulus of elasticity 240 kN/mm^2 and the tensile strength was 3800 N/mm^2. The thickness and width of the fibre were 0.234mm and 500mm respectively. It is fabric type and can be tailored into any desired shape.

2.2 Adhesive

The MBrace saturant supplied by BASF India Inc was used in this study. It is a two part systems, a resin base and a hardener and the mixing ratio was 100:40 (B: H).

2.3 Steel Tube

The circular hollow steel tubes confirming to IS 1161-1998 with different cross sections were used in this study. The length of the circular hollow steel tube was considered to be 600 mm. The yield strength of the steel tubes was considered as 300N/mm^2.

3. Analytical Studies

3.1 Australian/ New Zealand Standard AS/NZS 4600

Plate slenderness ratio for circular hollow steel tubular sections (λ) is given by equation (1). The elastic buckling coefficient (*k*) is taken as 4.0 for stiffened elements. The elastic buckling stress (f_{cr}) is given by the equation (2). The equations (1) and (2) are applicable only to plain steel columns and they are used to predict the ultimate load carrying capacity of plain steel columns.

$$\lambda_s = \sqrt{\frac{f_y}{f_{crs}}} \tag{1}$$

$$f_{crs} = \frac{k\pi^2 E_s}{12(1-\nu^2)}\left(\frac{t_s}{d_i}\right)^2 \tag{2}$$

By knowing the values of elastic buckling stress and plate slenderness ratio, the ultimate load carrying capacity of the plain steel section (P_{us}) can be predicted through the following equations (3) and (4).

$$\rho_s = \frac{1-\frac{0.22}{\lambda_s}}{\lambda_s} \tag{3}$$

$$P_{us} = \rho_s A_s f_y \tag{4}$$

The concept of modular ratio is applied for modifying the above four equations to calculate the axial capacity of CFRP strengthened steel tubular short columns. The thickness of each carbon layer was assumed to be uniform and the bond between the CFRP and the steel to be adequate. The equivalent elastic modulus of CFRP can be determined by equation (6), where the nominal values of carbon fibre modulus (E_{cf}) and the adhesive modulus (E_a) of 240 GPa and 1.9 GPa, respectively are used. To calculate the elastic buckling stress for CFRP strengthened section, the transformed flexural rigidity (D_t) was used. With the above transformations the equations (1) to (4) can be modified for the case of strengthened steel columns as follows,

$$f_{crc} = \frac{k\pi^2}{t_t {d_i}^2} D_t \tag{5}$$

$$\lambda_c = \sqrt{\frac{f_y}{f_{crc}}} \tag{6}$$

$$\rho_c = \frac{1-\frac{0.22}{\lambda_c}}{\lambda_c} \tag{7}$$

$$P_{uc} = \rho_c A_s f_y \tag{8}$$

3.2. European Standard EN 1993 – 1-1 (2005) Eurocode 3

This standard classifies steel sections as class1, 2, 3 and 4. Cross sections with $\left(\frac{d_s}{t_s}\right) \leq 90\varepsilon^{2,}$ where $\varepsilon = \sqrt{235/\sigma_y^s}$, are classified as class 1, 2 and 3. In this study both the sections considered fall under this category. The design compression resistance of the strengthened steel CHS can be calculated by,

$$N_u = N_{sd} = A_{es}\sigma_y^s \tag{9}$$

$$\text{where } A_{es} = \pi(t^s + t_{es}^{cs})^2 \left(\frac{\frac{d^s}{t^s} + 2\frac{t_{es}^{cs}}{t^s}}{1+\frac{t_{es}^{cs}}{t^s}} - 1\right) \tag{10}$$

3.3 Australian Standard AS 4100

The normalized cross section slenderness parameter $\lambdabar_s$ for circular hollow sections is usually expressed in the form

$$\lambdabar_s = \frac{d^s}{t^s}\frac{\sigma_y^s}{250} \tag{11}$$

Accounting for the equivalent cross section the slenderness parameter $\lambdabar_{es}$ is now written in the form

$$\lambdabar_{es} = \frac{d^{es}}{t^{es}}\frac{\sigma_y^s}{250} \tag{12}$$

Total thickness $t_t = t_s + {t_{es}}^{cs}$ (13)

Equivalent diameter $d_{es} = d_s + 2\,{t_{es}}^{cs}$ (14)

$$\text{For } \frac{d_{es}}{t_{es}} \leq \left(\frac{250}{\sigma_y^s}\right)82 \tag{15}$$

Area of the equivalent steel section $A_{es} = A_s\,(1 + {t_{es}}^{cs}/t^s)$ (16)

The section capacity of the CFRP reinforced circular hollow steel column under axial compression is determined as

$$N_u = A_{es}\sigma_y^s \tag{17}$$

All of the above codal recommendations have been analyzed and the axial compressive strengths of CHS columns with different cross sections have been calculated. The results are tabulated in Table 1.

4. Conclusion

The wrapping schemes such as full wrapping with one layer, two layers and three layers were analyzed. These wrapping schemes are proposed for further improvement of load carrying capacity of the hollow steel columns. Based on the analytical study performed for all types of wrapping, the following conclusions can be made:

- As expected, external bonding of CFRP significantly enhances the axial compressive strength of the CFRP wrapped columns compared to the control columns.
- A good agreement was observed among the three different codes considered to predict the axial strength of the columns.
- The columns with lower plate slenderness exhibit a greater strength increase when compared to those with higher plate slenderness. Hence it can be concluded that the plate slenderness plays a significant role in strength increase of wrapped columns.
- The axial capacity increases with the increase in number of CFRP layers.
- There exists a strength reduction in case of very thick tubes strengthened with CFRP when compared to bare steel tubes. Hence it can be concluded that in very thick tubes, the contribution of CFRP does not play for strength increase.

Table 1: Axial Load Carrying Capacity – Comparison of Three Codes.

Diameter of Steel Tube (mm)	**Thickness of Steel Tube (mm)**	**D/t Ratio**	**Plate Slenderness λ**	**No. of CFRP Layers**	**Axial Load Carrying Capacity (kN)**		
					AS/NZS 4600	**EC 3**	**AS 4100**
114.3	3.6	31.75	38.1	0	402	392	379
	3.6			1	411	442	425
	3.6			2	418	482	461
	3.6			3	424	521	496
	4.5	25.4	30.5	0	533	489	471
	4.5			1	535	541	516
	4.5			2	534	581	551
	4.5			3	532	621	586
	5.4	21.17	25.4	0	622	588	560
	5.4			1	613	639	605
	5.4			2	603	680	639
	5.4			3	509	721	674
127	4.5	28.22	33.9	0	581	544	525
	4.5			1	588	601	576
	4.5			2	592	645	615
	4.5			3	595	689	654
	4.8	26.46	31.8	0	628	580	559

	4.8			1	632	637	609
	4.8			2	634	681	648
	4.8			3	635	726	687
	5.4	23.52	28.2	0	710	653	625
	5.4			1	708	710	676
	5.4			2	704	755	714
	5.4			3	698	799	753
139.7	4.5	31.04	37.3	0	619	598	579
	4.5			1	629	660	635
	4.5			2	638	708	678
	4.5			3	645	757	721
	4.8	29.10	34.9	0	676	638	617
	4.8			1	684	700	672
	4.8			2	690	749	715
	4.8			3	695	797	758
	5.4	25.87	31	0	780	718	691
	5.4			1	783	781	746
	5.4			2	784	829	789
	5.4			3	785	878	832

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