STRENGTHENING OF SQUARE HOLLOW STRUCTURAL STEEL (HSS) TUBULAR SECTIONS USING CFRP STRIPS

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ABSTRACT

Hollow structural steel (HSS) tubular sections are the most versatile and efficient form of construction industry. The long term behavior of HSS tubular sections gets suspended due to the deterioration on aging and by corrosion on exposing to the environmental conditions. The suspended behavior of HSS tubular members can be brought back to it by strengthening. The strengthening technique with carbon fibre reinforced polymer (CFRP) in the steel structures is more advanced than the traditional approaches of strengthening. The only disadvantage of CFRP is the cost. By so, the full wrapping of section with CFRP will become expensive. Hence the applicability of CFRP in the form of narrow strip wrapped around the section with uniform spacing between them leads to the economical solution. In this study, an analytical model is formulated for the square HSS sections wrapped with CFRP strips to predict the lateral confinement strength exerted by the strips. The various factors such as number of CFRP layers, effect of buckling mode and confinement effectiveness influencing the predicted model are studied. Based on the predicted model, the load carrying capacity of the confined HSS sections is estimated. Also, evaluation of the proposed model is carried out with the experimental results of past researches so as to evaluate the validity and accuracy of the proposed model. The proposed model exists well satisfactory with the experimental results in this study.

Keywords: Axial Compression, CFRP strips, Lateral confinement strength, Strengthening, Square Hollow sections.

I. INTRODUCTION

Many of the strongest and most impressive structures in the world today would not have been possible without hollow structural steel (HSS) tubular sections. The tubular form section is inherently strong and efficient. It gives a better strength to-weight ratio than the conventional steel, concrete or timber products. They also have a wide and diverse application in the current trend of construction practices since they possess excellent structural and earthquake resisting properties because of its ductile properties. Hence they gain popularity in buildings, bridges and other structural applications such as onshore and offshore structures. In addition to that, the HSS tubular members are having a diversity of strength, formability, toughness which are susceptible to deterioration and corrosion on exposing to severe environmental conditions or leading to the gradual growth of fatigue cracks due to dynamic loading. Most of them are usually replaced due to the lack of knowledge about the techniques of repair. The most common method of traditional approaches of strengthening the steel structures involves welding of steel plates externally and section enlargement that will directly impose excess self-weight to the structures and in addition to that, the requirement of heavy machineries to lift the steel plates, difficulty while assessing steel structures with complex profiles. Besides that, external steel plates provided might have a chance to expose in the corrosive environment and get corroded under severe condition that indeed requires periodic maintenance for being durable.

In recent years, fibre reinforced polymer (FRP) fabrics have been used as structural materials in the modern repair techniques, which enhance the structures properties by external strengthening. They inhibit drawbacks exhibited in the traditional methods of strengthening steel structures. The carbon fibre reinforced polymer (CFRP) external strengthening is significantly enhancing the ductility and strength of the steel structure. The property of ductility is more important than the strength when the structure performing under seismic condition. They possess many advantages like high tensile strength to weight ratio, ease of applicability and handling, quick process of bonding to the steel structure and durability [1]. However, the evaluation of long term behavior of CFRP is difficult. Additionally, fatigue behavior of carbon fibre reinforced polymer causes damages against the ultraviolet radiation, and also, high price of CFRP fabrics are another reason for limiting the usage in repair methods.

The HSS tubular members strengthened externally with CFRP which arrest the outward buckling of steel and thereby enhancing the load carrying capacity and sustain deformation [2]. There have been researches on CFRP as confining material to the concrete, steel etc. in flexural, shear and compression. Researches related to the performance of CFRP wrapped hollow structural steel columns under axial compression have been conducted through experimental investigations. However, the analytical and numerical models to assess the strengthened hollow steel are still limited due to its failure behavior under compression. Lam and Teng [3] proposed a simplified strength model to predict the lateral confinement pressure exerted by FRP composites on confining short concrete column. The model was created with the consideration of effect of various factors such as size and type of fibre, length to diameter ratio, unconfined compressive strength of concrete etc., Shaat and Fam [4] studied the behavior of short and long hollow steel columns confined with different orientation of CFRP fibres i.e., transverse and longitudinal direction. The study implied that the transversely oriented fibre confined the steel section effectively than the longitudinal fibre do. The experimental results obtained that the maximum load carrying capacity of the section achieved was 18% for short columns with 2 layers of transverse CFRP and 13-23% for long columns with three layers of longitudinal CFRP on all four sides. Seica and Packer [5] experimentally studied the flexural behavior of CFRP strengthened circular hollow steel sections for underwater applications. The strengthened hollow sections showed increased flexural capacity of 16% and 8-21% under curing conditions in air and seawater respectively, over the bare steel specimen achieved. J.Haedir et.al [6] conducted experimental and analytical investigation on cold form short steel tubular circular column sections strengthened externally with CFRP fibres by full wrapping. The experimental results revealed that the combined use of both hoop and longitudinal CFRP fibres increased the attainment level of yield capacity of the steel sections with higher slenderness value. The analytical investigation was carried out by the standard approach followed in codal provisions AS/NZS 4600, AS4100 and Eurocode 3. The analytical results were deviated up to

18% from the experimental results. Ganesh Prabhu and Sundarraja [7, 8, 9] investigated the behavior of concrete filled steel tubular (CFST) square sections strengthened by CFRP composites experimentally and analytically under compression. The CFRP strips are wrapped with uniform vertical spacing between them. The experimental results showed increased section capacity of up to 30% and deformation control of up to 66% on decreasing the spacing between strips. The postponed action of steel tube local buckling by CFRP strips under axial compression was also observed. The local outward buckling failure occurred on the unconfined region. Deviation of $\pm$5% was observed from the analytical results obtained. In another investigation, Sriram, Sundarraja and Ganesh Prabhu [10] carried out a feasibility study on CFRP in axial strengthening of square hollow sections by experimentally. In this research, the specimens wrapped with narrow transverse strips of 50mm by varying the vertical spacing between the strips were tested against compression. The experimental results revealed that the strength and stiffness of the section increased with increasing the number of layers and decreasing the vertical spacing between the strips. Moreover, the axial deformation of column increased with increasing the spacing due to more unwrapped region lead to reduction in restraint against axial deformation. Sivasankar and Sundarraja [2, 11] carried out experimental investigation of square hollow steel sections confined by strip wrapping and full wrapping scheme of CFRP fibres. The confined hollow sections exhibited more stiffness and increased the load carrying capacity over the control specimens. The transverse fibres used in strengthening the sections contributed more strength than the combination of two directionally oriented fibres. Touanji et.al [12] studied the behavior of large scale rectangular RC column confined with FRP composite. This study explained the confinement effect of round corners and reentrant corners of the non-circular section while strengthening, where the stress concentration and non-homogeneous strain occurs in the fibre and tends to fail the fibre at the corners. This study preferred the round corner approach and increased the confinement pressure exerted by the FRP.

From the review of past researches, it was found out that there have been investigations on using CFRP as a strengthening material for the steel columns and also in external wrapping of CFRP fabrics, which significantly enhanced the strength and stiffness of the steel tubular columns. More experimental researches are necessary to develop the applications of CFRP in the form of narrow strips for strengthening of hollow sections under axial compression. The aim of this research is to propose analytical model for predicting the lateral confinement strength exhibited by CFRP strips in the hollow sections under compression. By use of predicted model, the ultimate axial capacity of the strengthened hollow sections will be obtained and validated the results of theoretical modeling with the experimental results.

II. ANALYTICAL STUDY

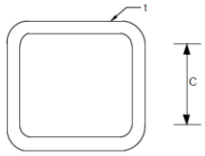
2.1. Prediction of Axial Load Capacity of Square Hollow Sections

In EC3 **[13]**, Steel sections are classified into four classes such as Class1, 2, 3 and 4. For square and rectangular hollow sections, the classes are categorized with different limiting C/t ratios are given in the Table 1. Where D = Nominal diameter of circular hollow sections (CHS), C = Flat width of element under compression and t = Thickness of the section. The sections, which fail to satisfy the limits for Class 3, should be taken as Class 4, which is designed as per EC 1993-1-6. The design resistance of cross section for uniform compression for class 1, 2 and 3 sections can be determined by:

$$N_u = A_s f_y \quad (1)$$

Where A_S = Cross sectional of steel, f_y = Yield strength of the steel.

Table 1 Maximum C/ t ratio of box type section for Compression

Cross-section of Box type hollow section	Class	Maximum C/t ratio
	1	33ε
	2	38ε
	3	42ε

2.2. Existing Confinement Models

When a FRP confined concrete column is subjected to axial compression, the concrete core expands laterally and this lateral expansion is resisted by FRP, which is subjected to tension in lateral direction. **L.** Lam and J.G. Teng [3] related lateral confining pressure (f_l) to the amount and strength of FRP by:

$$f_l = \frac{2 f_{frp} t_{frp}}{d} \quad (2)$$

Where f_{frp} = Tensile strength of the FRP in the hoop direction, t_{frp} = Total thickness of the FRP and d = Diameter of the confined concrete. G. Ganesh Prabhu and M.C. Sundarraja [7,8] proposed the analytical model for predicting the lateral confining pressure (f_{lcon}) exerted by CFRP strips provided at uniform spacing, on confining CFST sections by relating f_{lcon} similar to Lam and Teng [3]. In addition to that, they also related the number of layers, participation of successive additional layer to the confinement and vertical spacing between strips. They predicted analytical models individually for square sections with above said considerations and are given as follows.

For square CFST sections:

$$f_{lcon} = \frac{3 f_{cfrp} t_{cfrp} n \,[1+0.16(n-1)]}{\gamma_{cfrp} D} \quad (3)$$

$$f_{lcon} = \frac{4 f_{cfrp} \rho_{cfrp} [1+0.23(n-1)]}{5 \gamma_{cfrp}} \quad (4)$$

Where f_{frp} = Tensile strength of the FRP in the hoop direction, t_{frp} = Thickness of the FRP, n = the number of FRP layers, γ_{frp} = Static design safety factor for FRP:

$$\rho_{cfrp} = \frac{A_{cfrp}}{A_{Gross}} \quad (5)$$

Where A_{cfrp} and A_{Gross} is Cross sectional area of the CFRP and CFST column member.

2.3. Proposed Model

Based on the existing model of Lam and Teng, a new simple analytical model is proposed to predict the lateral confinement pressure exerted by CFRP strips on confining hollow sections with the consideration of various factors such as number of layers, effect of buckling and confinement effectiveness coefficient, influencing it:

$$f_{lcon} = \frac{2 f_{cfrp} t_{cfrp}}{D} \quad (6)$$

Direct application of values in the above model shows very less confinement pressure value due to the ratio ($\frac{t_{cfrp}}{D}$). This ratio only defines the lateral confinement pressure that varies with various cross sections. In order to achieve accurate lateral confinement pressure exerted by CFRP, the volumetric ratio concept is introduced and replacing $\frac{2\,t_{cfrp}}{D}$ with ρ_{cfrp_v} in the above model.

$$\rho_{cfrp_v} = \frac{A_{cfrp}}{A_s} X \frac{l_{cfrp}}{l_s} \quad (7)$$

Where ρ_{cfrp_v} = volumetric ratio between CFRP and steel, A_{cfrp} = cross section area of the CFRP, A_s and l_s = cross sectional area and total length of the hollow steel section respectively.

$l_{cfrp} = Number\ of\ CFRP\ strips\ X\ Breadth\ of\ one\ strip$

Where l_{cfrp} is the total length of CFRP measured in longitudinal direction of the steel section. The proposed model for predicting the lateral confinement pressure exerted by CFRP strips is given as follows:

$$f_{lcon} = f_{cfrp}\,\rho_{cfrp} \quad (8)$$

Above model can be expressed in terms of hoop tension:

$$f_{lcon_h} = 2 f_{cfrp}\,\rho_{cfrp}\,l_{cfrp}\,t_{cfrp} \quad (9)$$

The above model has to be modified by considering the following factors which affects the lateral confinement hoop tension.

2.3.1 NUMBER OF LAYERS

When the number of CFRP layer increases, the lateral confinement hoop tension exerted by successive additional layer will be lesser than lateral confinement exerted by one layer. This is because of integral action of confining by additional successive layer with primary layer, reduces the attainment of strain in those layers thus consequently implies reduction in lateral confinement hoop tension exerted by two or more layers on individually considering. Based on Ganesh Prabhu's model, the effective participation of successive additional layer to the first layer is taken as 23% for square hollow sections.

2.3.2 EFFECT OF BUCKLING

Normally, hollow sections fail by local buckling i-e inward or outward buckling. When the steel reaches its ultimate strain, it tends to buckle. The outward buckling of steel can be resisted by external CFRP confinement and sometimes outward buckling may accompany inward buckling that lead to sudden reduction in the axial load carrying capacity. Inward buckling may also occur due to section capacity failure or over confinement provided by CFRP strips. The risk of inward buckling increases as the number of layers used for confinement increases. In that case, the strength exhibited by CFRP on confining will be much lower than the proposed model value. So, based on the buckling effect consideration, some approximate percentage of reduction in lateral confinement hoop tension exerted with successive additional layer is to be done to achieve some degree of accuracy in the proposed model.

2.3.3 CONFINEMENT EFFECTIVENESS COEFFICIENT (K_s)

Several researchers proposed K value for full wrapped CFRP confinement, based on lateral confining pressure exerted and it lies between 3-1. As early stated, Ganesh Prabhu proposed the confinement effectiveness coefficient value K value which is 3 for 20mm spacing between strips and reduced by 0.5 as the spacing between the strips increased. Similar to that, the confinement effectiveness coefficient values are proposed for uniformly varying of vertical spacings between the strips from 20mm to100mm and are listed in the following Table 2.

Table 2 Proposed confinement coefficient (K_ε) value for various spacing between the strips

Vertical spacing between the strips	Proposed K_ε value
20mm	3.00
30mm	2.75
40mm	2.50
50mm	2.25
60mm	2.00
70mm	1.75
80mm	1.50
90mm	1.25
100mm	1.00

K should be taken as 1 when the spacing between the strips greater than or equal to 100mm. In that case, the lateral confinement tension will be quite less because of local buckling was predominant in the unwrapped zone rather than effective confinement provided by the CFRP strips.

2.4. MODIFIED PROPOSED MODEL

Based on the influence of various factors affecting the lateral confinement tension exerted by CFRP strips on confining hollow sections, the proposed model is to be modified to nullify those effects in it. The lateral confinement tension exerted by CFRP strips corresponding to number of layers n≤ 3, can be calculated by following modified model.

For hollow sections confined by one layer:

$$f_{lcon\ 1\ layer} = 2 f_{cfrp}\, \rho_{cfrp}\ l_{cfrp} t_{cfrp} \quad (10)$$

For hollow sections confined by two layers:

$$f_{lcon\ 2\ layer} = 1.3 f_{cfrp} \rho_{cfrp}\ l_{cfrp} t_{cfrp} [1 + C(n-1)] \quad (11)$$

For hollow sections confined by three layers:

$$f_{lcon\ 3\ layer} = f_{cfrp}\, \rho_{cfrp}\ l_{cfrp} t_{cfrp} [1 + C(n-1)] \quad (12)$$

Where $f_{lcon\ 1\ layer}$, $f_{lcon\ 2\ layers}$ and $f_{lcon\ 3\ layers}$ are the lateral confinement tension exerted by one layer, two layers and three layers of CFRP strips respectively, C is the participation value of successive additional layer to the first layer of CFRP strip on confining hollow sections and n is the numbers of layers of CFRP strip wrapped around the section. C value is taken as 0.23 for square and rectangular sections. From the above models, the ultimate axial load carrying capacity of strengthened hollow sections with CFRP strips can be predicted by following expression which is similar to Ganesh Prabhu's [8, 9] expression:

$$f'_{ccon_H} = [1 + K_\varepsilon \frac{f_{lcon_h}}{f_{uncon_H}}]\, f_{uncon_H} \quad (13)$$

$$f_{uncon_H} = A_s f_y \quad (14)$$

Where f'_{ccon_H} & f_{uncon_H} = confined and unconfined compression capacity of hollow steel column respectively, K_s= confinement effectiveness coefficient, f_y = Yield strength of the steel and A_s= Cross sectional area of hollow steel section.

Table 3 Specifications of the materials used in Sivasankar's investigation

Specifications of materials used	Details
Steel section	
Type of hollow section	Square
Dimension of Section	91.5 mm X 91.5 mm
Thickness of the section	3.6 mm
Height of the section	600mm
Yield strength of steel	250 N/mm^2
Young's modulus of steel	200 Gpa
CFRP	
Type of CFRP	MBrace 240 (Unidirectional)
Young's modulus of CFRP	240 Gpa
Ultimate tensile strength of CFRP	3800 Mpa
Thickness of CFRP	0.234

III. EVALUATION OF MODIFIED PROPOSED MODEL

The past experimental data on square hollow sections confined with CFRP strips done by Sivasankar [2] and Sriram[10] are taken for the evaluation of the model and the comparison study is presented in Table 4. The material specifications of both experimental researches are same and are given in the Table 3. The area calculation of the square hollow section with round corners is done as per IS 4923: 1997[14].

3.1 COMPARATIVE STUDY

Specimen details are designated as 30-40-T1, 50-30-T3 in which first notation represents the breadth of the strip, the second notation represents the vertical spacing between the strips and the third notation represents the number of layers provided for the confinement.

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Table 4 Comparative study between (Sivasankar's and Sriram's) experimental results and the model results

Specimen details	Experimental ultimate load f'_{ccon} kN	Theoretical ultimate load f'_{ccon} kN	% of ± of Theoretical f'_{ccon} from experimental f'_{ccon}	Specimen details	Experimental ultimate load f'_{ccon} kN	Theoretical ultimate load f'_{ccon} kN	% of ± of Theoretical f'_{ccon} from experimental f'_{ccon}
Sivasankar (2012)				**Sriram (2014)**			
30-20-T1	654	647.36	-1.01	50-20-T1	709	672	-5.50
	642		+0.80		692		-2.97
30-20-T2	672	700.58	+4.07		697		-3.72
	679		+3.08	50-20-T2	764	743.5	-2.75
30-20-T3	686	753.10	+8.90		747		-0.04
	701		+6.90		753		-1.27
30-40-T1	581	598.70	+2.95	50-20-T3	814	813	-0.01
	578		+3.04		803		+1.23
30-40-T2	586	622.78	+5.90		793		+2.46
	598		+3.90	50-30-T1	690	639	-7.98
30-40-T3	624	646.54	+3.48		682		-6.72
	612		+5.30		691		-8.14
30-60-T1	574	582.13	+1.30	50-30-T2	749	691	-8.14
	575		+1.20		741		-7.23
30-60-T2	578	596.28	+3.00		739		-6.94
	581		+2.50	50-30-T3	770	740	-4.05
30-60-T3	588	610.25	+3.60		764		-3.24
	584		+4.79		761		-2.84

3.2. Results and Discussion

From the comparison of results, it was found that the model exhibits conservative results for square hollow sections, which belong to class 1 category. When the spacing between the strips increased, the lateral confinement strength goes on decreasing, because of, local buckling which is predominant in the unwrapped zone. As the strips length increased, the lateral confinement hoop tension increased with the same spacing in both the cases of experimental and theoretical analysis. It is because of increased strip which assessing more surfaces as confined than the smaller one. The variation of experimental results over theoretical results is negative in case of Sivasankar's research works and positive in case of Sriram's research. The variation of 4-8.9% of theoretical results was observed in the sections confined with two and three layers of CFRP strips of

30mm. The modified model exhibited satisfactory results for both the experimental results in all the cases of confinement. The maximum percentage of variation between the experimental and the theoretical results of square hollow section, which is -8.9% and +8.14% in case of Sivasankar's and Sriram's experimental results respectively. The obtained variation percentage is within ±20 % for Class 1 sections. The model modified for the various factors shows good agreement with the experimental results. It implies that the factors considered for the model creation is right in case of square hollow sections.

IV. CONCLUSIONS

The hollow sections possess greater aesthetic importance in the modern construction industry. Because of its high strength to weight ratio, lightweight and increased resistance for compression, bending and torsion in both directions, hollow sections have wide and diverse applications. These hollow sections may deteriorate or corrode while aging or exposing to the severe environment thereby need of strengthening technique to bring those sections to its service state condition. The strengthening technique of confining the sections under compression with transverse narrow CFRP strips quite be emerging one. An analytical investigation of hollow steel sections strengthened with CFRP strips is made in this study. Comparison between the experimental results of the past researches and the theoretical results obtained was carried out to validate the models accuracy. From the comparison results, the following conclusions can be made.

1. There was a greater confinement pressure in the case of specimens with increased width of CFRP strip. However, the variation between the experimental and theoretical results of 30mm and 50mm strip widths having same spacing's showed slight deviation only.
2. The model showed conservative results for class 1 sections and maximum variation of -8.9 % and +8.14% for square hollow sections were observed.
3. The obtained variations between the experimental and theoretical results are within ±20 %.
4. The model applicability is limited to the sections strengthened with maximum of 3 layers.
5. The various factors considered for the modification of the model is right that observed from the comparative study.

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