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Experimental Investigation on the Behaviour of CHS Short Columns Strengthened Using FRP Composites under Compression

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Abstract: The use of hollow steel structures is increasing rapidly around the world due to the many advances in construction technologies. Developments of mega structures demand hollow sections that possess high-strength, light-weight and sufficient ductility. However, the behavior of these sections is characterized by a range of buckling modes (local and overall buckling). These buckling problems lead to strength reduction and they can be eliminated or delayed by discovering new technologies. Existing methods of retrofitting utilize steel plates that are bolted or welded to the structure. However, some drawbacks are allied with those methods. As an alternative, composite system has emerged as an attractive strengthening technique for steel structures. The advanced properties of FRP materials make them well promising for strengthening of steel structures. The main objective of this investigation is to assess the feasibility of strengthening circular hollow steel (CHS) tubular sections with FRP and to develop or predict the suitable wrapping scheme of FRP to enhance the structural behavior of it. It is proposed to use mild steel tubes and carbon fiber used as external material. Experiments will be undertaken until failure to fully understand the influence of FRP characteristics on the compressive behavior of CHS tubes.

Keywords - *Axial Compression, Circular Hollow Sections, FRP, Local Buckling, Strengthening*

I. Introduction:

Recent architecture is dominated by tubular structures, specifically rectangular hollow sections (RHS), square hollow sections (SHS), and circular hollow sections (CHS) are used for their artistic fascination. Several well-known bridges constructed during the nineteenth century made use of tube shaped members. Among the different shapes, circular hollow sections have the advantage of being equally rigid in all directions and are usually very economical. In the last decades, hollow steel sections have got increasing recognition in buildings, bridges and other structural applications, since they possess several advantages regarding earthquake resistance (e.g. high strength, high ductility and large energy absorption). Indeed, a considerable quantity of aging civil infrastructure has been reported with hollow steel structures. Some of these members have been degraded due to corrosion whereas others due to overloading. In addition, it is a renowned reality that the failure modes influenced by local buckling is obvious in the behaviour of thin tubular columns. A variety of procedures have been in use to renovate the original carrying capacity or enlarge it to deal with higher load demands [1].

Recently the use of fibre reinforced polymers as construction materials has been developed rapidly. Their high tensile strength to weight ratio, ability to be molded into different shapes, resistance to environmental conditions and other advantages they possess over other traditional materials make FRP composites a superior substitute for inventive construction. Their application in construction includes both strengthening existing structures and building new ones [2]. Over the past decade, carbon fibre reinforced polymer (CFRP) has gained increasing acceptance as a structural material, typically applied to concrete structures, however, more recently also to steel structures.

There have been more studies presented regarding the performance of FRP composites as a confining material to sections under compression, steel joints, sections in bending; combined bending and compression, load bearing members, hollow steel beams and tension members. Modern research on the strengthening of circular hollow sections (CHS) with FRP by Teng and Hu [3] and Hong et al. [4] in axial compression, Haedir et al. [5] in bending, Doi et al. [6] in bending and compression, Jiao and Zhao [7] in tension and Zhao et al. [8] in very high strength steel tubes (VHS) and Xiao et al. [9] on concrete filled CHS has shown significant benefits in strength and stiffness of steel members with externally bonded CFRP. Research on the strengthening of SHS with CFRP is limited to a set of experiments by Shaat and Fam [10]. An extensive review of research in the general field of steel structures strengthened with CFRP is given by Wardenier [11]. The investigations on steel hollow sections were all performed on compact sections. In this paper SHS having geometries within each of the slenderness categories of compact, non-compact and slender [12] are tested under large deformation axial compression, in order to investigate the effect of section slenderness on the strengthening and energy absorption capacity of the high-strength CFRP.

Whist research regarding the application of FRP to strengthen compression members, specifically on short CHS columns is limited. Furthermore, the available research in this area has not concentrated on the performance of CFRP strengthened circular hollow sections in connection with the different fibre lay-outs and the effect of D/t ratio [13].

II. Material Properties:

A. *Carbon fibre:*

The CFRP used in this study is a low modulus carbon fibre in the MBrace family, MBrace CF240, with an elastic modulus of 240 GPa and an ultimate tensile strength of 3800 GPa. The fibre is unidirectional with thickness and width of the fibre as 0.234 mm and 500mm respectively. It is fabric type and can be tailored into any desired shape.

B. *Resin Matrix:*

The MBrace saturant supplied by BASF India Inc was used in this study to get the good bonding between steel tube and carbon fibre. It is a two part systems, a resin base and a hardener and the mixing ratio was 100:40 (B: H).

C. *Circular Steel Tubes:*

The circular hollow steel tubes confirming to IS 1239: 1983 were used in this study. The steel tubes were classified into two categories according to their wall thickness; (i) compact section (nominal 4.5 mm wall thickness denoted by HS (4.5) and (ii) non-compact section (nominal 4.8 mm wall thickness denoted by HS (4.8). All CHS sections were nominally 139.7 mm in diameter and 600 mm in height. The average yield strength obtained from tensile coupon tests was 303.15 MPa.

III. Experimental Investigation:

To investigate the behaviour of CFRP strengthened CHS columns under pure axial compression, a series of tests were executed to consider the influence of D/t ratio on the axial compressive strength of HSS columns. The ratios of diameter to thickness (D/t) of the steel cross section considered in this study were 29.01 and 31.04. Fibre wrapping was done as full wrapping along the length of the column and with 30mm wide CFRP strips by varying the spacing between the strips. The effects of varying the number of CFRP layers were also examined. The experimental series consisted of testing eighteen CHS specimens under pure axial compression.

A. *Specimen Preparation:*

The 600mm long circular hollow tubular specimens were cut from 6m long hollow steel tubes. The surfaces of the steel specimens were roughened by sand blasting. Then the surfaces of the steel specimens were scrubbed by a sand paper to remove the corroded particles in steel and to get better bonding between steel specimen and carbon fibre. Afterwards the sand blasted surface of the specimen was cleaned by acetone to eradicate all contaminations before wrapped with the fibres. Prior to the specimens strengthened by carbon fibre, a thin layer of glass fibre fabric was introduced between the steel surface and CFRP composites to eliminate the galvanic corrosion. Finally, the carbon fibres were wrapped to the external surface of the hollow steel members with the different wrapping schemes. During wrapping of fibre fabrics, the resin and hardener are correctly proportioned and thoroughly mixed together and the excess epoxy and air gap were removed using a ribbed roller moving in the direction of the fibre.

B. *Instrumentation:*

The hollow steel columns were tested in compression testing machine of capacity 2000 kN. The experimental set up is shown in Fig.1. Earlier to apply loading, the specimens were positioned on the support and also centered to make sure that the two supporting ends were parallel to each other and at right angles to the loading axis. The load was applied to the column by hydraulic jack and monitored by using 1000 kN capacity load cell. Axial deformation of the column was measured using linear voltage displacement transducer (LVDT) which was kept at top of the jack. The load cell and LVDT were connected with the 16- Channel Data Acquisition System to store the respective data. The load was applied slowly and the column was tested to failure by applying the concentric compressive load in small increments and the observations such as axial deformation and ultimate load were carefully recorded. The load at which the column starts rupturing and the nature of failure were also noted for each column.

Fig.1 Experimental Set-up

C. Details of the test Specimens:

Totally eighteen specimens consisting of nine 4.5mm thick tubes and nine 4.8mm thick tubes were used. The overall outer diameter and length were nominally 139.7mm and 600mm respectively for all the specimens. The tube dimensions were chosen so that the effect of D/t ratio on the compressive behaviour of CHS columns can be investigated for the same diameter.

The strengthened specimens were nominated as HS(4.5)-FWT1, HS(4.5)-FWT2, HS(4.5)-30-20-T1, HS(4.5)-30-20-T2, HS(4.5)-30-40-T1, HS(4.5)-30-40-T2, HS(4.5)-30-60-T1, HS(4.5)-30-60-T2, HS(4.8)-FWT1, HS(4.8)-FWT2, HS(4.8)-30-20-T1, HS(4.8)-30-20-T2, HS(4.8)-30-40-T1, HS(4.8)-30-40-T2, HS(4.8)-30-60-T1 and HS(4.8)-30-60-T2. The number in the parenthesis represents the thickness of the steel tube. The numbers followed by the thickness represent the width of CFRP strips and spacing between the strips respectively. At the end, T1 and T2 represent transversely wrapped one and two layers of CFRP respectively. FW implies for the full wrapping scheme. The control specimens were designated as HS (4.5)-CC and HS (4.8)-CC.

IV. Results and Discussion:

A. Failure Modes:

The columns were symmetrically loaded until failure so that the influence of CFRP on the compressive behaviour of CHS can be analyzed. Furthermore the columns were still loaded after failure to understand the failure pattern.

All unstrengthened control specimens exhibited a distinctive buckling failure (i.e. elephant's foot buckling) which is proved to be the common failure mode in hollow steel tubes in the past researches. Ring buckles were developed along the circumference of the control columns which is shown in Fig.2

Fig. 2 Failure modes of Control Columns

The failure modes of HS (4.5)-FWT1 and HS (4.8)-FWT1 specimens implicated outward local buckling deformations near the ends. In these columns the FRP ruptures due to circumferential tension. This implies that there is perfect bond between the steel and CFRP. Columns which are strengthened with two layers of CFRP (FWT2) the same failure pattern was observed and outward buckling near the column ends causes the rupture of FRP. But the buckling was delayed significantly in these columns and some amount of inward buckling also was observed which is illustrated in Fig.3. This inward buckling was caused due to the resistance offered by the CFRP against outward buckling.

Fig. 3 Failure modes of Full wrapped specimens

In the HS (4.5)-30-20-T1 and HS (4.8)-30-60-T1 specimens, a noticeable elephant's foot buckling fold at the bottom end was observed and crushing of CFRP was occurred at the loads of 920 kN and 1030 kN respectively. The columns HS (4.5)-30-40-T1, HS (4.5)-30-60-T1, HS (4.8)-30-20-T1 and HS (4.8)-30-40-T1, the buckling fold was determined fairly near the mid-height of the specimen and the crevice of the fibre was heard at the loads of 880 kN, 860 kN, 1090 kN and 1050 kN respectively. In those columns the buckling of the steel tube was predominant at the space between the CFRP strips, which is the unconfined portion of the column which is shown in Fig.4. Further increase in load leads to the rupture of fibre and the crushing of fibre occurs afterwards. There was no observation of delamination of fibres in any of the single layer wrapped specimens and the reason is attributed to good bond between the steel and fibre.

Fig. 4 Failure modes of Strip wrapped T1 columns

Even though the columns wrapped with two layers of CFRP exhibit the same trend of failure mode as that of the single layer wrapped specimens, the behaviour is dominated only by the steel yielding. The crushing of fibre was identified in columns with 20mm spacing and there was no rupture of fibre occurred in columns with 40mm and 60mm spacing as shown in Fig.5. The reason is endorsed to the increase in unwrapped area when increasing the spacing between the strips. In the space between two consecutive CFRP strips the confining pressure offered by the CFRP is absent and those areas were subjected to additional strain compared to the confined area and hence in these areas the steel buckles by reaching its ultimate strain. Owing to the nonexistence of the CFRP confinement, the unconfined area (space between the strips) is subjected to excessive strain when compared to the wrapped area, and hence in this portion steel buckles by reaching its ultimate strain.

Fig.5 Failure modes of Strip wrapped T2 columns

The HS (4.5)-30-20-T2 and HS (4.8)-30-20-T2 were failed by the buckling of the steel tube only and a small amount of fibre rupture was also noticed at the loads of 1000 kN and 1100 kN respectively. Since the confinement effect of CFRP is more in these columns when compared with one layer wrapped specimens the steel yields first before the fibre starts crushing. With further increase in load, the fibre also starts rupturing and the failure was dominated mainly by the buckling of the steel only. The buckling fold was observed at the space between the strips and almost near the mid-height of the columns and is exemplified in Fig.5. The HS (4.5)-30-40-T2 and HS (4.8)-30-40-T2 specimens exhibited a ring like buckling near the bottom end of the column at the loads of 900kN and 1080kN respectively and there were no observations of fibre rupture in those columns. The reason is attributed to increase in space between the strips. But with a further increase in load, the resin lies in between the fibre strips starts crushing and a small amount of fibre rupture was also observed. In case of the columns HS (4.5)-30-60-T2 and HS (4.8)-30-60-T2, the failure was influenced primarily by steel yielding and there was no observation of fibre rupture. The confinement effect provided by the fibres in those columns was not significant and hence the failure involves only yielding of steel. Even though there is an increase in number of CFRP layers, the confinement effect is not increased since the spacing between the strips was large.

B. Axial stress -strain behavior:

The axial stress -strain behaviour of unwrapped and CFRP wrapped column specimens under axial compression is shown in Fig.6. From the stress -strain curves of all columns, it was observed that, there exists linearity in the graph until the failure load and thereafter the graph shows non-linearity and the reason is that resin starts crushing at the failure load. When the fibre started rupturing, there was a sudden return in load transfer.

Until the load of 700kN is reached, there exists a consistency in the stress-strain behaviour of all columns. Afterwards the inconsistency observed is attributed to increase in number of layers and increase in spacing between the CFRP strips.

C. Load carrying capacity:

From the graph it was evident that all the specimens wrapped with CFRP showed a considerable increase in ultimate load carrying capacity over bare steel tube specimens. This increase in load carrying capacity of the specimens increases with the increase in number of layers and it decreases with the increase in space between the fibre strips. The confinement provided by the fibre is more in case of two layers wrapped specimens when compared to one layer wrapped specimens of all cases. But the same is less when the spacing between the strips is increased.

The ultimate load comparison is illustrated in the Fig.7 and the experimental observations are tabulated in Table 1. From the chart it can be seen that the increase percentage of axial load carrying capacity of fully wrapped columns over bare steel columns were in the range of 22% - 35% for HS (4.5) specimens. The similar pattern is observed in the case of HS (4.8) specimens also. Compared to HS (4.8)-CC the enhancement in ultimate axial load carrying capacity of HS (4.8)-FWT1 and HS (4.8)-FWT2 were 34.92% and 39.46% respectively.

For partially wrapped columns with 20mm spacing the increase in load carrying capacity is 12%-22% in HS (4.5) specimens and the same is in the range of 24%-25% in HS (4.8) specimens. For 40mm spacing the axial capacity increase is in the range of 7%-10% for HS (4.5) specimens and 19%-23% for HS (4.8) specimens. When the spacing between the strips in fixed to 60mm the axial capacity shows only 5%-7% for HS (4.5) specimens. But the same is increased in the range of 17%-19% for HS (4.8) which is considerable when compared to HS (4.5) specimens.

D. Deformation Control:

The control of deformation is clearly observed in strengthened columns when compared with control columns as shown in Fig 8. The CFRP as a strengthening material efficiently delays the buckling and hence significantly controls the deformation of steel tubes. From the observed experimental results it has been evident that the deformation control is much greater in case of HS (4.8) specimens when compared to HS (4.5) specimens. This means that the D/t ratio significantly influences the deformation control of strengthened specimens especially in fully wrapped specimens. Here is also the same pattern of decreasing the deformation control with the increase in spacing between the strips was observed. The reason is attributed to the reduction in CFRP confined area in those cases.

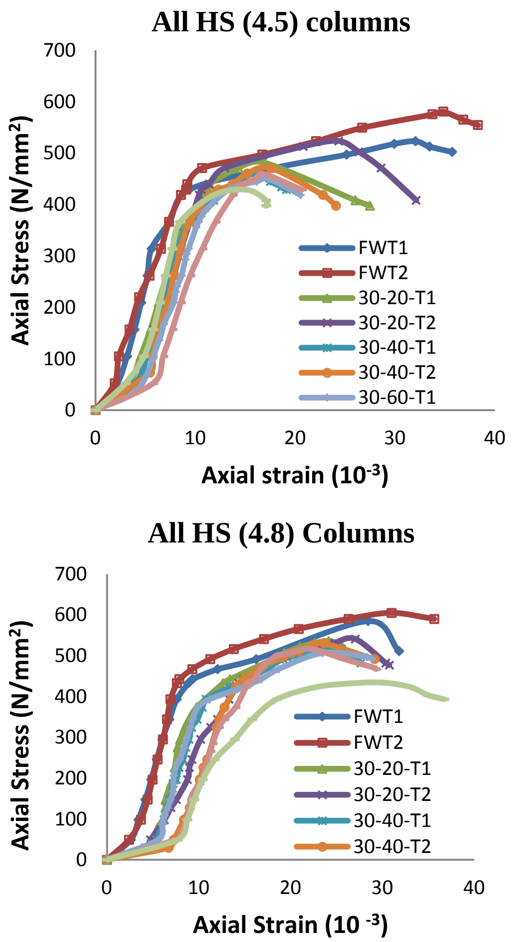

Fig.6 Axial stress -strain behaviour- comparison

V. Parametric Study

A. Effect of Distribution of CFRP layers:

When the number of CFRP layers increases, the strengthened specimens showed enhancement in their load carrying capacity and deformation control. CFRP gives good lateral confinement to the steel tubes in the aspect of increasing the axial capacity. For the fully wrapped specimens the trend follows an ascending order with the increase in number of layers. But for the partially wrapped specimens the enhancement in load carrying capacity and deformation control decrease with the increase in the spacing between the CFRP strips since the confinement provided by the fibre decreases.

B. Effect of D/t Ratio

Both HS (4.5) and HS (4.8) specimens showed a similar behaviour regarding load carrying capacity and deformation control. But increase in load carrying capacity is considerably large in case of HS (4.8) specimens when compared to HS (4.5) specimens. Hence it is evident that D/t ratio plays a significant role in increasing the load carrying capacity. The similar pattern is observed in deformation control also that the specimens with larger D/t ratio were outperformed in the aspect of deformation control irrespective to the other factors such as number of layers of CFRP and spacing between the strips.

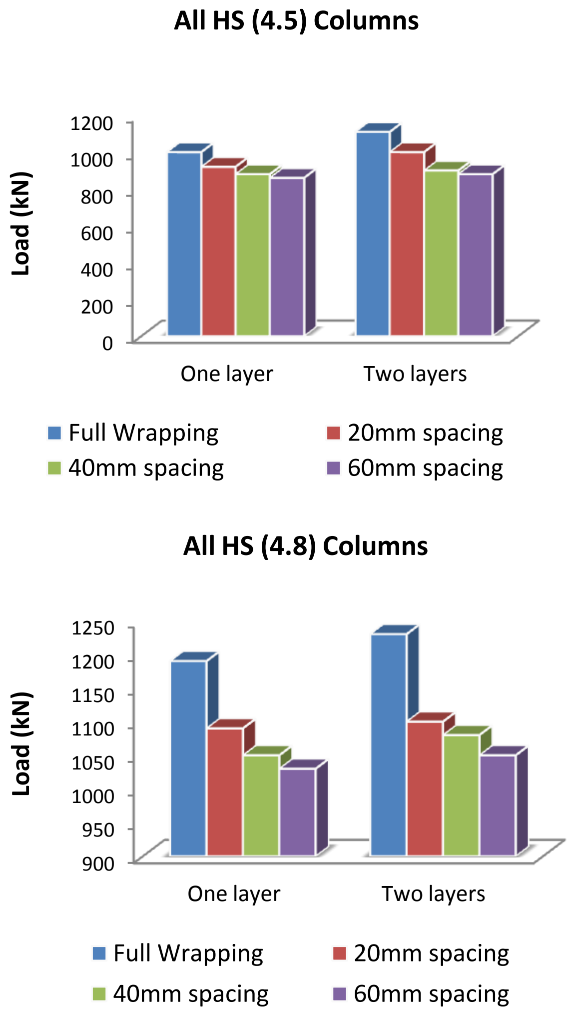

Fig.7 Ultimate load of all columns –Comparison

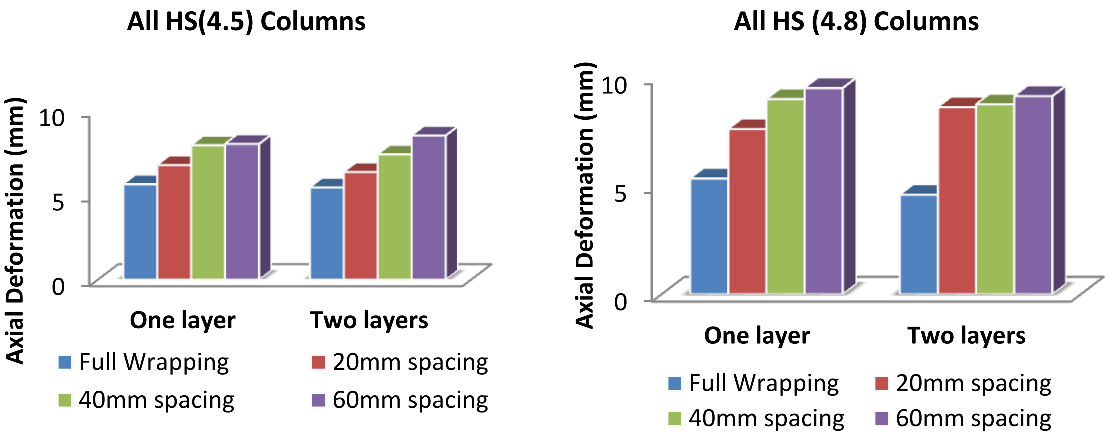

Fig. 8 Deformation Control of All columns – Comparison

Table I Experimental Observations

Specimen Designation	Ultimate Load (kN)	Axial Deformation* (mm)	Increase in axial load ** (%)	Reduction in axial deformation** (%)
HS(4.5)-CC	820	9.1	-	-
HS(4.5)-FWT1	1000	5.63	21.95	38.13
HS(4.5)-FWT2	1110	5.44	35.37	40.22
HS(4.5)-30-20-T1	920	6.76	12.20	25.71
HS(4.5)-30-20-T2	1000	6.35	21.95	30.22
HS(4.5)-30-40-T1	880	7.93	7.32	12.86
HS(4.5)-30-40-T2	900	7.39	9.76	18.79
HS(4.5)-30-60-T1	860	8.01	4.88	11.98
HS(4.5)-30-60-T2	880	8.5	7.32	6.59
HS(4.8)-CC	882	18.11	-	-
HS(4.8)-FWT1	1190	5.32	34.92	70.62
HS(4.8)-FWT2	1230	4.57	39.46	74.77
HS(4.8)-30-20-T1	1090	7.59	23.58	58.09
HS(4.8)-30-20-T2	1100	8.6	24.72	52.51
HS(4.8)-30-40-T1	1050	8.97	19.05	50.47
HS(4.8)-30-40-T2	1080	8.73	22.45	51.80
HS(4.8)-30-60-T1	1030	9.48	16.78	47.65
HS(4.8)-30-60-T2	1050	9.11	19.05	49.70

* - corresponding to the ultimate load of control specimen
** - with respect to control column

VI. Conclusion:

From the experimental study, the following conclusions are made.

- It is observed that the use of CFRP confinement greatly enhances the load carrying capacity of circular steel tubes.
- The increase percentage of strengthened columns over bare steel columns were in the range of 22% - 35% for the HS (4.5) specimens. The similar pattern is observed in the case of HS (4.8) specimens also. Compared to the HS (4.8)-CC specimen the enhancement in ultimate axial load carrying capacity of HS (4.8)-FWT1 and HS (4.8)-FWT2 specimens was 34.92% and 39.46% respectively.
- The decrease in axial deformation corresponding to the ultimate load of control specimen was much greater in case of HS (4.8) strengthened specimens over HS (4.5) strengthened columns. The HS (4.5) strengthened columns showed increase in deformation control ranging from 5% to 35% as compared to control specimen whilst the HS (4.8) strengthened columns exhibited increase in deformation control in the range of 47% to 74% which is significantly greater.
- The increase in axial load carrying capacity is not that much affected by D/t ratio variation. However D/t ratio plays a significant role in the enhancement of deformation control.
- Sections with larger D/t ratio were well performed in the aspect of deformation control.

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