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Behavior of CHS short columns strengthened with CFRP composites under axial compression

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ABSTRACT: *The use of hollow steel structures is increasing rapidly due to the many advances in construction technologies. However, the behaviour 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 by discovering new technologies. Existing methods utilize steel plates that are bolted or welded to the structure. However, some drawbacks are allied with those methods. Composite system has emerged as an alternative strengthening technique for steel structures. The advanced properties of FRP make them well promising for strengthening 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 behaviour of it.*

Keywords: *axial compression, circular hollow sections, FRP, local buckling, strengthening*

I. INTRODUCTION

A momentous part of the modern architecture and historical patrimony is made up of metallic structures, specifically hollow tubular structures such as rectangular hollow sections (RHS), square hollow sections (SHS), and circular hollow sections (CHS). In the last decades, hollow steel sections have got growing attention in many structural applications, since they own a number of advantages concerning earthquake resistance (e.g. high strength, high ductility and large energy absorption). Indeed, a considerable amount of aging civil infrastructure has been reported with hollow steel structures. Lack of sufficient maintenance, corrosion, as well as fatigue, are the main reasons of their degradation. In addition, it is a renowned reality that the failure modes influenced by local buckling is obvious in the behavior 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]. The strengthening techniques presently used for either renovating or increasing the load bearing capacity of a metallic structure are based on the application of steel plates, either by bolting or welding. This however has several drawbacks.

The use of FRP conquers many of the complexities related with the use of traditional retrofitting materials. Their high tensile strength to weight ratio, ability to be formed into different shapes, resistance to environmental conditions and other advantages they possess over other traditional materials make FRP composites a better substitute for inventive construction. The use of FRP is well-situated also in strengthening older metallic structures, since the mechanical properties of the FRP combine well with the steel [2].

There have been more studies presented regarding the performance of FRP composites as a confining material to steel sections under compression, steel joints, sections in bending; combined bending and compression, load bearing members, hollow steel beams and tension members. Teng and Hu [3] investigated the behavior of FRP jacketed circular steel tubes and cylindrical shells under axial compression. The results showed that FRP jacketing is an effective method for strengthening steel tubes and cylindrical shells. They concluded from their experimental and finite element modeling results that the provision of a thin FRP jacket enhanced the ductility of the steel tube. And as the thickness of the FRP jacket increases, the outward buckling is restrained making inward buckling deformations increasingly. Shaat A. and Fam A. [4] presented results of a non linear finite element analysis of axially loaded slender HSS columns, strengthened using high modulus CFRP sheets. The study demonstrated the effectiveness of high modulus CFRP in increasing stiffness and strength of slender columns. It was found that the hoop layers played an important role in delaying the local buckling. Bambach et al. [6] studied the axial compressive behaviour of CFRP strengthened cold formed square hollow sections under large deformation axial compression. The section dimensions ranging from slender to compact sections according to AS4100 [7] standards were used. The result showed that the application of CFRP delayed local buckling, and the elastic buckling strength was increased by upto 4 times. The experimental studies have been conducted by Narayanan et al. [8] to investigate the axial and bending load behaviour of HSS members by changing slenderness ratio below 200. In the HSS tubes with relatively low diameter to thickness ratios (D/t < 40), the failure occurs through a combination of yielding of steel and local buckling of steel whereas, the HSS with thin-walled steel tubes (D/t > 60) are very susceptible to local buckling.

The studies and tests, reported in the literature, emphasize that the use of FRPs in strengthening metallic structures is versatile and trustworthy as well as in constant increase. 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. This paper is focused on investigating the structural behaviour of CHS sections including axial strength enhancement and various failure modes. Though the parameters under consideration included the effect of D/t ratio, effect of number of CFRP layers and effect of size and spacing of the strips, the most important test parameter is the thickness of the CHS which is supposed to directly influence the axial strength, failure modes and deformability.

II. MATERIAL PROPERTIES

2.1 Carbon fibre

The CFRP used in this study is a normal 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.

2.2 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).

2.3 Circular Steel Tubes

The circular hollow steel tubes confirming to IS 1239: 1983 were used in this study. The steel tubes were chosen with two different thicknesses (4.5mm and 4.8mm) so as to have different D/t ratio for the same diameter. 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 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 fourteen CHS specimens consisting of seven HS (4.5) specimens and seven HS (4.8) specimens under pure axial compression.

3.1 Specimen Preparation

The 600mm long circular hollow tubular specimens were cut from 6m long hollow steel tubes. The surfaces of the steel specimens were first roughened by sand blasting and then 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 steel substrate 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. Careful attention was given to the effectiveness of the bonding between the steel substrate and fibre.

3.2 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

3.3 Details of the test Specimens

The strengthened specimens were nominated as 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)-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. The control specimens were designated as HS (4.5)-CC and HS (4.8)-CC.

IV. RESULTS AND DISCUSSION

4.1 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.

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.3 (a). 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. 2 Failure modes of Control 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.3 (b). 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.

a) One Layer wrapped (T1) b) Two Layers wrapped (T2)

Fig. 3 Failure modes of partially (Strips) wrapped 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.3 (b). 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.

4.2 Axial stress -strain behaviour

The axial stress -strain behaviour of unwrapped and CFRP wrapped column specimens under axial compression is shown in Fig.4. 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.

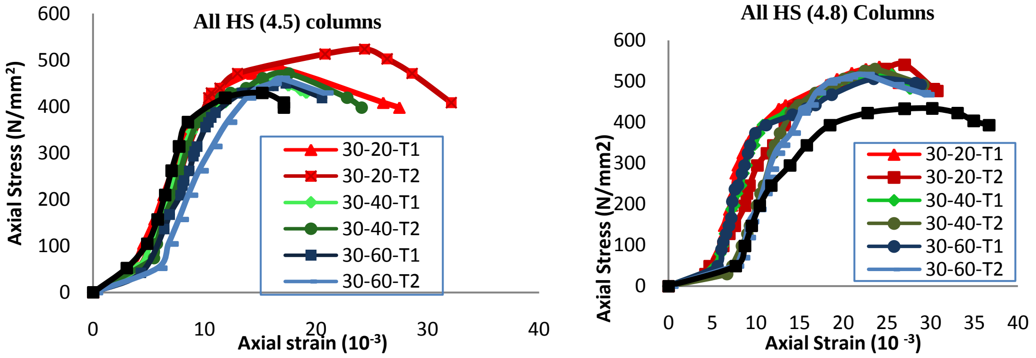

Fig.4 Axial stress -strain behaviour- comparison

4.3 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.

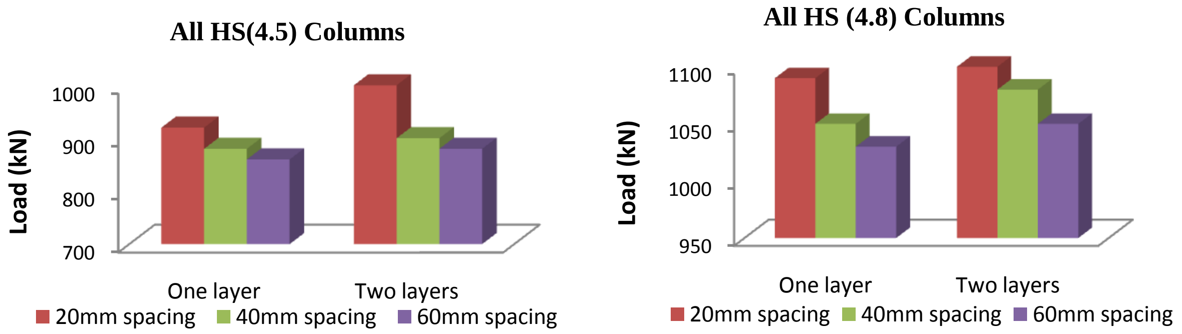

Fig.5 Ultimate load of all columns –Comparison

The experimental observations are tabulated in Table 1.and the ultimate load comparison is illustrated in the Fig.5. From the chart it can be seen that in the strengthened 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 considerably high when compared to HS (4.5) specimens.

4.4 Deformation Control

The control of deformation is clearly observed in strengthened columns when compared with control columns as shown in Fig 6. 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.

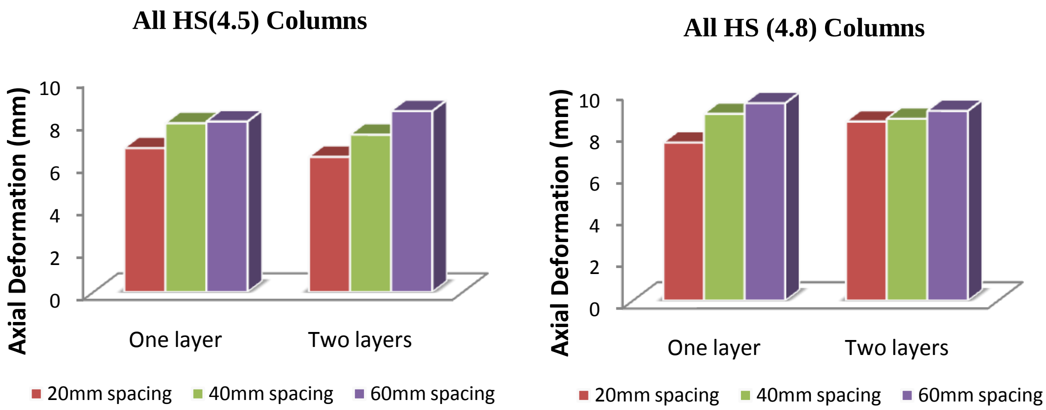

Fig. 6 Deformation Control of All columns – Comparison

V. PARAMETRIC STUDY

5.1 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 CFRP 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.

5.2 Effect of D/t Ratio on load capacity and deformation control

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.

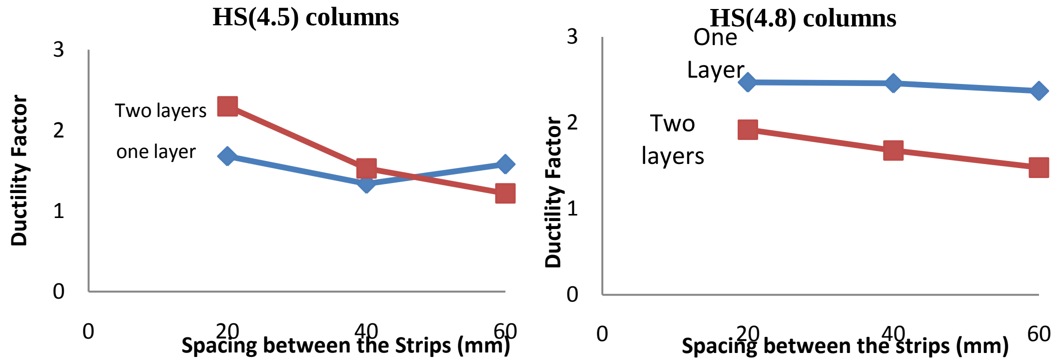

Fig. 7 Ductility Factor vs Spacing between the strips

5.3 Ductility Factor

Ductility factor is defined as the ratio between the ultimate deformation and the yield deformation which is calculated from the stress- stain diagram of all columns. From the Fig. 7 it is evident that the ductility factor generally decreases with the increase in spacing between the strips. Hence it can be concluded that the columns with larger spacing between the fibre strips are not preferable. And it is also seen from the graphs that ductility of two layers wrapped specimens are higher in general when compared with one layer wrapped specimens for HS (4.5) columns. But it is not the case of HS (4.8) columns. Hence the conclusion may be drawn as HS (4.5) columns are outperformed with two layers wrapping and HS (4.8) columns are preferable with one layer wrapping. The influence of D/t ratio plays good in the aspect of ductility.

Table.1 Experimental Observations

Specimen Designation	Ultimate Load (kN)	Axial Deformation corresponds to failure load of control specimen (mm)	% increase in axial load carrying capacity with CC	% reduction in deformation with CC	Ductility Factor
HS(4.5)-CC	820	9.1	-	-	1.79
HS(4.5)-30-20-T1	920	6.76	12.20	25.71	1.68
HS(4.5)-30-20-T2	1000	6.35	21.95	30.22	2.3
HS(4.5)-30-40-T1	880	7.93	7.32	12.86	1.34
HS(4.5)-30-40-T2	900	7.39	9.76	18.79	1.53
HS(4.5)-30-60-T1	860	8.01	4.88	11.98	1.58
HS(4.5)-30-60-T2	880	8.5	7.32	6.59	1.22
HS(4.8)-CC	882	18.11	-	-	1.63
HS(4.8)-30-20-T1	1090	7.59	23.58	58.09	2.47
HS(4.8)-30-20-T2	1100	8.6	24.72	52.51	1.92
HS(4.8)-30-40-T1	1050	8.97	19.05	50.47	2.46
HS(4.8)-30-40-T2	1080	8.73	22.45	51.80	1.68
HS(4.8)-30-60-T1	1030	9.48	16.78	47.65	2.37
HS(4.8)-30-60-T2	1050	9.11	19.05	49.70	1.48

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 and the maximum axial deformation is also significantly controlled by the confinement of CFRP layers. 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 enhancement of deformation control. Sections with larger D/t ratio were well performed in the aspect of deformation control.

The one ply wrapped specimens of HS (4.5) columns showed a significant increase in load carrying capacity when compared to the control column in the range of 5% -12.2%, while T1 specimens of HS (4.8) columns showed 17%- 24% increase in axial load capacity when compared to control specimens.

Two layers CFRP wrapped columns of HS(4.5) case showed 7% - 22% increase in load carrying capacity as compared to the control column, while the T2 specimens of HS (4.8) columns demonstrated increase in load capacity in the range of 19% - 25% when compared to control specimens.

The decrease in 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 in the range of 7% to 30% as compared to control specimen whilst the HS (4.8) strengthened columns exhibited increase in deformation control in the range of 47% to 58% which is significantly greater.

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