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Axial behaviour of HSS tubular sections strengthened by CFRP strips: an experimental investigation

Muthukamatchi Chelliah Sundarraja[1,*] and Sandrasekaran Sivasankar[2]

[1] Civil Engineering, Thiagarajar College of Engineering, Madurai, Tamilnadu, India, e-mail: mcsciv@tce.edu

[2] Thiagarajar College of Engineering, Madurai, Tamilnadu, India

* Corresponding author

Abstract

The main objective of this investigation is to assess the feasibility of strengthening square hollow steel tubular sections subjected to compression and to develop or predict the suitable wrapping scheme of fibre reinforced polymer (FRP) to enhance the structural behaviour of it. For this study, compact mild steel tubes were used with the main variable being FRP characteristics. Carbon fibre has been considered and used as strips with several other parameters such as the number of layers, width and spacing of strips, the sectional area of strips, and wrapping scheme. Experiments were undertaken until column failure to fully understand the influence of FRP characteristics on the compressive behaviour of square hollow steel tubes including their failure modes, stress-strain behaviour, enhancement in load carrying capacity and effect of distribution of CFRP layers. The behaviour of externally bonded hollow steel tubular sections was compared with one another and also with the control specimen. From the test results, it was found that CFRP strengthening significantly increases the load carrying capacity and ductility of the hollow steel tubular members further.

Keywords: compression; CFRP fabrics; externally bonded; steel tubes; strengthening.

1. Introduction

Externally bonded fibre reinforced polymer (FRP) composites applied to reinforced concrete (RC) structures have been used around the world since the mid-1980s. Since then, the application of FRP reinforcement has expanded to include masonry structures, timber and, to a lesser degree, metals [1, 2]. However, research related to FRP applications to steel structures has started only recently despite the urgent need for the rehabilitation of structural steel components such as bridges, offshore platforms, large mining equipment and buildings. Traditionally, the most common method to repair and/or rehabilitate a steel structure has been by welding additional steel plates. This not only adds weight to the structure, but the heat involved in welding can affect the stress distribution and may be critical for structures exposed to fatigue loads. In addition, steel plates would be exposed to corrosion damage and frequently this repairing method requires the use of scaffolding and heavy machinery as well as long periods of service interruption. By contrast, rehabilitation methods using FRP composites do not exhibit any of these drawbacks. Other advantages of FRP over steel plates include the low weight of the bonded material, easy applicability and the capacity to cover areas with limited access, where the use of traditional techniques would be impractical [3]. High stiffness fibres, such as carbon fibres, can effectively enhance the structural properties of steel structures; additionally, composites could also enhance the fatigue life of steel structures. However, there has been limited research in this area. There are uncertainties concerning the long term-behaviour of these applications and the bonding between the composite materials and steel [3]. One useful application of FRP composite materials is for hollow structural steel section (HSS), and HSS is the focus of this study.

The hollow steel tubular sections possess excellent structural and earthquake-resistant properties such as high strength and high ductility, and have gained increasing popularity in buildings, bridges and other structural applications as either onshore or offshore structures [3]. However, they are exposed to deterioration, fire and corrosion due to severe environmental conditions or to the development of fatigue cracks when the structure is subjected to cyclic loads. The use of FRP technology to increase the strength of tubular steel structures (retrofitting) in both offshore and onshore applications will bring considerable benefits to the industry. In an investigation using CFRP for tubular steel sections [4], butt-welded, very high strength circular steel tubes (VHS) reinforced with unidirectional CFRP sheets were tested under tensile load. The results showed that the strength increase varied from 25% to 76%, which proved that CFRP wrapping was an effective method to strengthen VHS tubes. Shaat and Fam [5] 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 13–23% for long columns. They recommended that further studies be conducted on thin-walled sections with larger width-to-thickness ratios, where local buckling could be more critical for short columns. Shaat and Fam [6] also 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. [7] 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. [8] also carried out tests on concrete-filled steel hollow section short columns strengthened by CFRP. More research is needed to investigate the effect of number of layers, the fibre orientation, and the gap between CFRP and steel on the behaviour and strength.

Seica and Packer [3] investigated the flexural performance of compact CHS beams strengthened by CFRP sheets (two layers in the longitudinal direction and one in the transverse direction). In addition to strength increase, they found that a class 2 section wrapped with CFRP can reach a moment capacity above the plastic moment capacity, with increased ductility and rotation capacity. However, the number of tests was not sufficient to show whether a class 2 section can be upgraded through wrapping CFRP sheets to a class 1 section. Haedir et al. [9] conducted tests on class 4 circular hollow section (CHS) beams strengthened by CFRP sheets. They showed that a class 4 section can be upgraded to a class 2 section if CFRP strengthening is applied in both longitudinal and hoop directions. It was found that the hoop layers played a more important role in restraining or delaying the local buckling which is often in the form of an ovalisation for CHS. The longitudinal layers played a more important role in increasing the moment capacity, due to the contribution of CFRP in the tension zones. More tests are required to derive an optimal combination of these factors of fibre orientation, number of layers and sequence in applying CFRP layers. Research is also needed to investigate the behaviour of rectangular hollow sections and other classes of CHS strengthened by CFRP.

Bambach et al. [10] studied the axial compressive behaviour of CFRP strengthened cold-formed square hollow sections using 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 four times. However, they only considered two layouts of CFRP. More tests are required to derive an optimal combination of fibre orientation, number of layers and sequence in applying CFRP layers.

In summary, a thorough literature review has shown that the strength improvements of HSS tubes using CFRP sheets are feasible. To date, limited research has been undertaken on hollow square and rectangular steel tubular members, although they are increasingly used in offshore and onshore applications. Further research is needed to investigate the effect of number of layers, the fibre orientation, and the gap between CFRP and steel on the behaviour of such composite columns to derive an optimal combination of these factors of fibre orientation, number of layers and sequence in applying CFRP layers. The aims of this investigation are to assess the feasibility of strengthening of hollow tubular steel members subjected to compression and to develop an adequate repair method for in-air applications using FRP technology.

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 with modulus of elasticity of 240 kN/mm^2 and tensile strength of 3800 N/mm^2. The thickness and width of the fibre was 0.234 mm and 600 mm, 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 to obtain the good bonding between steel tube and carbon fibre. It is a two-part system, a resin and a hardener, and the mixing ratio was 100:40 (B:H).

2.3. Steel tube

A square hollow steel tube, in accordance to IS 4923-1997 and IS 1161-1998 with a dimension of 91.5×91.5 mm, was used in this study. The thickness and length of the square hollow steel tube were 3.6 mm and 600 mm, respectively. The yield strength of steel tubes was predicted by coupon tests and it was 250 N/mm^2.

3. Experimental programme

3.1. Description of specimens

Among 20 specimens, 18 were externally bonded by CFRP strips with a constant width of 30 mm wrapped with the spacing of 20 mm, 40 mm and 60 mm, and the remaining two specimens were unbonded. The wrapping schemes are shown in Figure 1. The size and length of the columns used were 91.5×91.5×3.6 mm and 600 mm, respectively. To identify the specimen easily, the columns were designated with the names such as HS-30-20-T1, HS-30-20-T2, HS-30-20-T3, HS-30-40-T1, HS-30-40-T2, HS-30-40-T3, HS-30-60-T1,

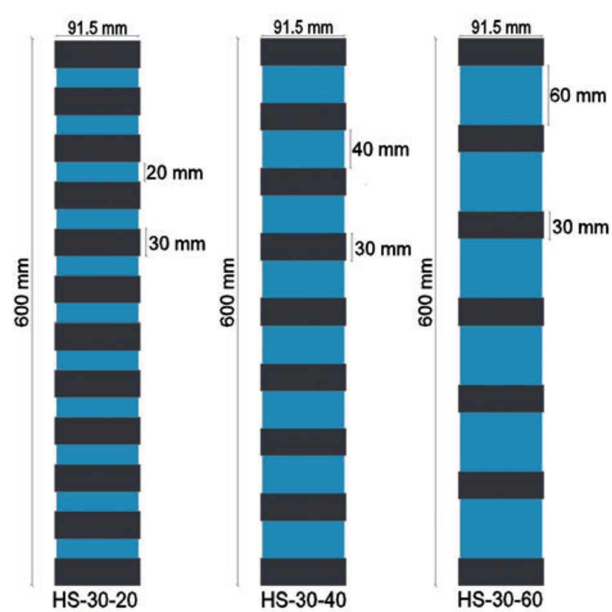

Figure 1 Wrapping schemes.

HS-30-60-T2 and HS-30-60-T3. For example, the specimen HS-30-20-T3 specifies that it was strengthened by three (3) layers of 30 mm width horizontal strip (HS) of CFRP fabrics in transverse direction (T) with the spacing of 20 mm. The control column is specified as CC1 and CC2.

3.2. Specimen fabrication

The 600-mm length square hollow tubes were cut from 6-m hollow tubes. To obtain a flat surface, both ends of the steel tube were surfaced by the surface grinding machine. Surface preparation of the metal substrate is very important to achieve good bonding between steel tube and CFRP fabrics. The strength of the adhesive bond is directly proportional to the quality of the surfaces to which it is bonded. Thus, the exposed surface of the tubular specimen was blasted by the coarse sand to remove the rust and also to make the surface rough. The tubular specimens after surface preparation are shown in Figure 2. The entire sand-blasted surface was cleaned by using acetone to remove all contaminant materials before being retrofitted with the fibres. Prior to the columns being strengthened by carbon fibre, the glass fibre fabric was introduced between the steel surface and CFRP composites to eliminate the galvanic corrosion. Finally, the carbon fibres were bonded to the exterior surface of the tubular members in the transverse direction with different thicknesses. During wrapping of fibre fabrics, the resin and hardener are correctly proportioned and thoroughly mixed together and the excess epoxy and air were removed using a ribbed roller moving in the direction of the fibre. The bonding of FRP with the tubular sections is shown in Figure 3.

3.3. Experimental setup

The HSS tubular columns were tested in a compression testing machine of capacity 2000 kN. Each member was positioned on the supports taking care to ensure that its centre line was exactly in line with the axis of the machine. The verticality of the specimens was checked using a plumb bob and sprit level. The specimens were instrumented to measure longitudinal axial compression. 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 by using a 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. At the beginning, a small load of 20 kN was applied slowly, so that the columns settle properly on its supports. Then the load was removed after checking the proper functioning of the instrumentation. The trial load was applied again slowly and the column was then tested to failure by applying the compressive load in small increments and the observations such as axial deformation and ultimate load were carefully recorded. The load at which the CFRP starts rupturing and the nature of failure were also noted for each column. The experimental setup is shown in Figure 4.

Figure 2 Specimens after sand blasting.

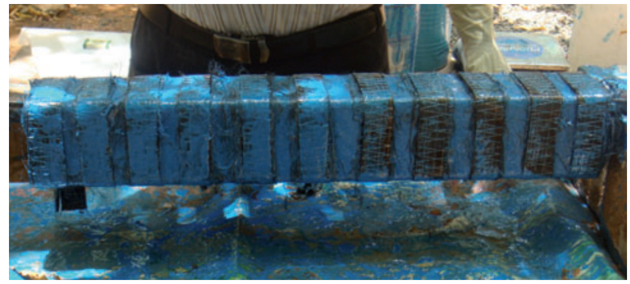

Figure 3 Wrapping of CFRP.

4. Results and discussion

The ultimate load carrying capacity and percentage increase in it of all specimens are summarized in Table 1. From the test results, it can be seen that CFRP plays a vital role in increasing the load carrying capacity of HSS tubular columns. In addition,

Figure 4 Experimental setup.

Table 1 Specimen details and test results.

Sl. no.	Designation of columns	Ultimate load (kN)	% of increase in load
1	Control column	560.00	–
2	Control column	557.00	–
3	HS-30-20-T1(1)	654.00	16.78
4	HS-30-20-T1(2)	642.00	14.64
5	HS-30-20-T2(1)	672.00	20.00
6	HS-30-20-T2(2)	679.00	21.25
7	HS-30-20-T3(1)	686.00	22.5
8	HS-30-20-T3(2)	701.00	25.17
9	HS-30-40-T1(1)	581.00	3.75
10	HS-30-40-T1(2)	578.00	3.21
11	HS-30-40-T2(1)	586.00	4.64
12	HS-30-40-T2(2)	598.00	6.78
13	HS-30-40-T3(1)	624.00	11.43
14	HS-30-40-T3(2)	612.00	9.28
15	HS-30-60-T1(1)	574.00	2.5
16	HS-30-60-T1(2)	575.00	2.67
17	HS-30-60-T2(1)	578.00	3.21
18	HS-30-60-T2(2)	581.00	3.75
19	HS-30-60-T3(1)	588.00	5.00
20	HS-30-60-T3(2)	584.00	4.28

Figure 5 Failure mode of CC-1.

there is more gain in increasing of load carrying capacity when the number of layers of CFRP fabrics was increased.

4.1. Failure modes

The columns were loaded up to failure to understand the influence of carbon fibre fabrics on the axial behaviour of CFST members. Figure 5 shows the failure mode of the control column. In the case of the control specimen, buckling of the column called elephant's foot buckling [3] was observed at the bottom, similar to the results of Teng et al. [11]. Here the column is allowed to observe the axial deformation and buckling. This investigation is carried out with the aim of preventing buckling that occurred in the specimens. Figures 6–8 show the failure modes of columns HS-30-20-T1, HS-30-20-T2 and HS-30-20-T3 strengthened with 30-mm width of FRP strips with the spacing of 20 mm. Among above, inward buckling was observed nearer to the top edge of the column after rupture of FRP occurred at the failure load in the case of columns strengthened by using one layer of horizontal CFRP strips (HS-30-20-T1). Similar failure was observed in the case of specimens retrofitted with two layers of FRP strips with the spacing of 20 mm and 40 mm (HS-30-20-T2, HS-30-40-T2), and at the same time outward buckling was observed at the perpendicular faces. Owing to this lateral buckling, the load was completely transferred at the end of the column and this led to rupture of FRP at the edge.

Figures 9–11 show the failure mode of columns HS-30-40-T1, HS-30-40-T2 and HS-30-40-T3 strengthened using FRP strips with the spacing of 40 mm. In the case of column HS-30-40-T1, initial buckling occurred at the bottom in the unbonded region similar to that of the control specimen. Similar failure was observed at the top of the region where the fibre was not present in the case of specimen HS-30-40-T2 but it was at the centre in the case of specimen HS-30-40-T3, due to more numbers of layers being provided to arrest the elephant's foot buckling at the bottom and thus load carrying

Figure 6 Failure mode of HS-30-20-T1.

Figure 7 Failure mode of HS-30-20-T2.

Figure 8 Failure mode of HS-30-20-T3.

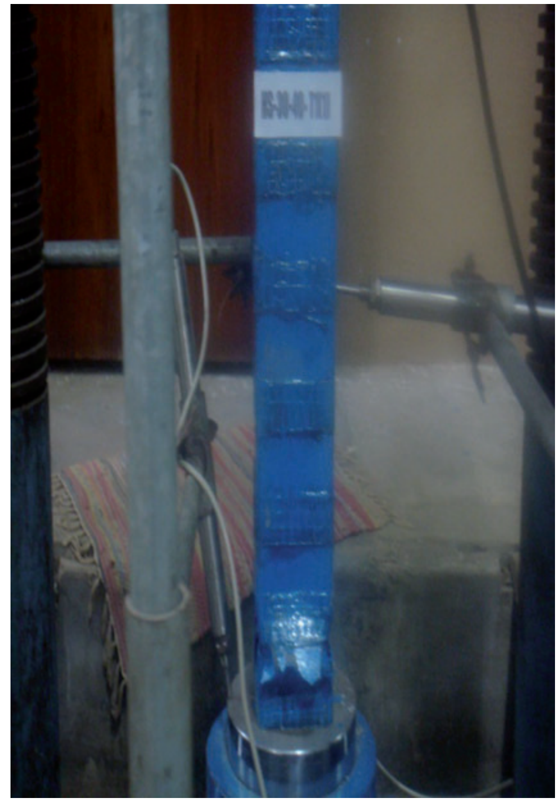

Figure 9 Failure mode of HS-30-40-T1.

Figure 10 Failure mode of HS-30-40-T2.

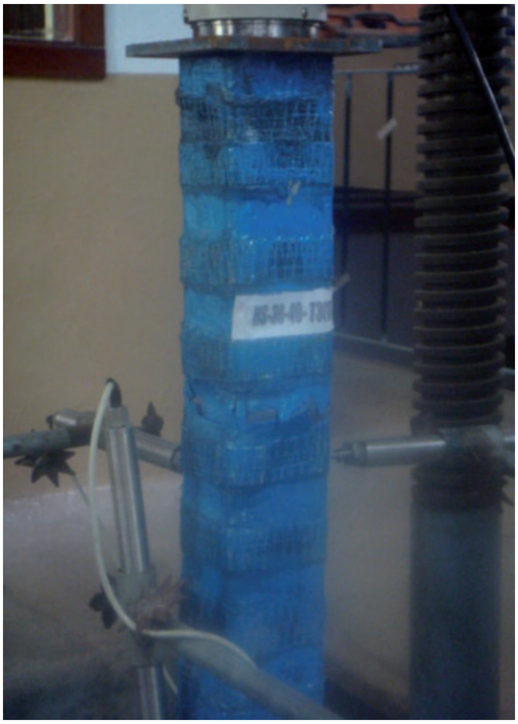

Figure 11 Failure mode of HS-30-40-T3.

Figure 12 Failure mode of HS-30-60-T1.

capacity was improved. Unfortunately, no delamination of FRP was observed in all specimens.

Figures 12–14 show the failure mode of columns HS-30-60-T1, HS-30-60-T2 and HS-30-60-T3 strengthened using FRP strips with the spacing of 60 mm. In the case of column HS-30-60-T1, initial buckling of the specimen occurred at the top region where FRP was not present. Similar failure was observed in other specimens and because the spacing between the fibre strips is more, the load carrying capacity of specimens was reduced and the columns failed under buckling but no rupture of FRP was observed.

4.2. Axial stress-strain behaviour

The stress-strain behaviour for unconfined and confined HSS tubular specimens under axial loading condition is shown in Figures 15–18. It was observed that all specimens confined by CFRP wraps showed a considerable increase in ultimate strength over unconfined specimens. The columns confined with two layers of 30-mm width CFRP strips (HS-30-20-T2) of 20 mm spacing having more axial strain than that of columns with one layer of CFRP strip (HS-30-20-T1). Similar behaviour was also observed in the case of columns confined with two layers of 30-mm width CFRP strips (HS-30-40-T2 and HS-30-60-T2) with spacing of 40 mm and 60 mm. This enhancement in ultimate strain depends on spacing and thickness of CFRP strips. From the graphical representation, it can be seen that the stress-strain behaviour and load carrying capacity as well as the stiffness of strengthened specimens enhanced with the increase in number of CFRP layers. In the case of specimens confined with three layers of 30-mm width

Figure 13 Failure mode of HS-30-60-T2.

Figure 14 Failure mode of HS-30-60-T3.

horizontal CFRP strips (HS-30-20-T3), they showed better performance in stress-strain behaviour compared with the columns confined with one and two layers of horizontal CFRP strips. In addition, the columns confined with 30-mm width of CFRP strips (HS-30-20-T1, HS-30-20-T2 and HS-30-20-T3) of 20 mm spacing had more axial strain than that of columns with 40 mm spacing of FRP strips (HS-30-40-T1, HS-30-40-T2 and HS-30-40-T3) and 60 mm spacing of FRP strips (HS-30-60-T1, HS-30-60-T2 and HS-30-60-T3). Finally, it can be concluded that the stress-strain behaviour of HSS specimens with three layers of external CFRP horizontal strips with 20 mm spacing (HS-30-20-T3) showed better performance than that of all other columns. Hence, it can be stated that the columns with more numbers of layers and with closer spacing of CFRP strips showed better axial stress-strain behaviour.

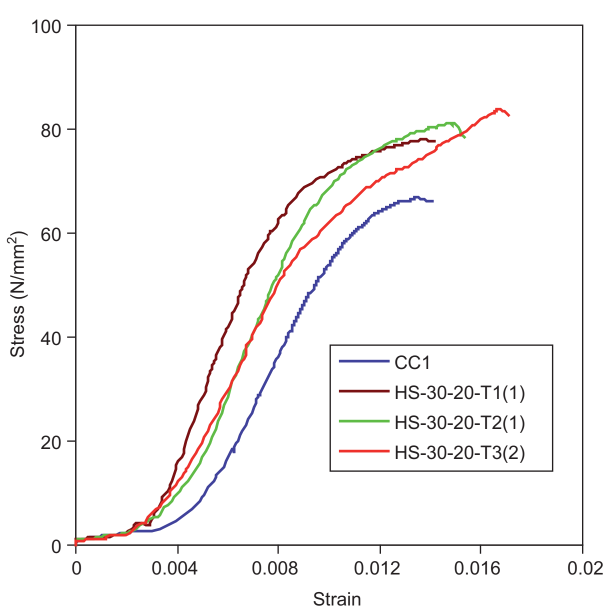

Figure 15 Comparison of axial stress-strain behaviour of columns HS-30-20.

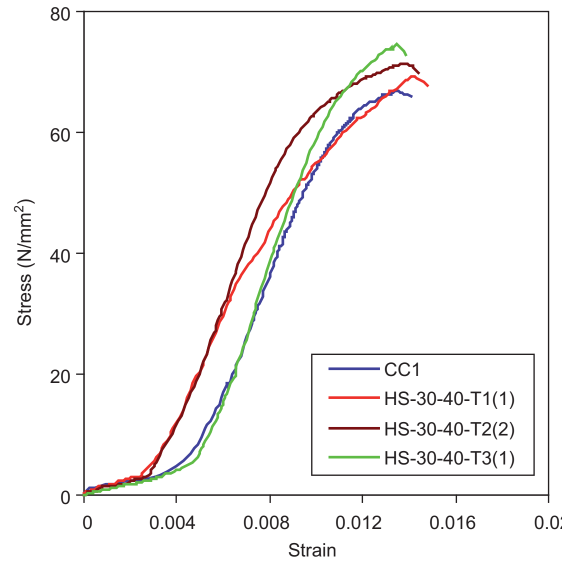

Figure 16 Comparison of axial stress-strain behaviour of columns HS-30-40.

4.3. Axial load carrying capacity

The experimental axial load carrying capacity of all retrofitted specimens is presented in Table 1 along with the percentage increase in it compared with the control specimens. It can be understood that from Figure 19 there is a significant increase in

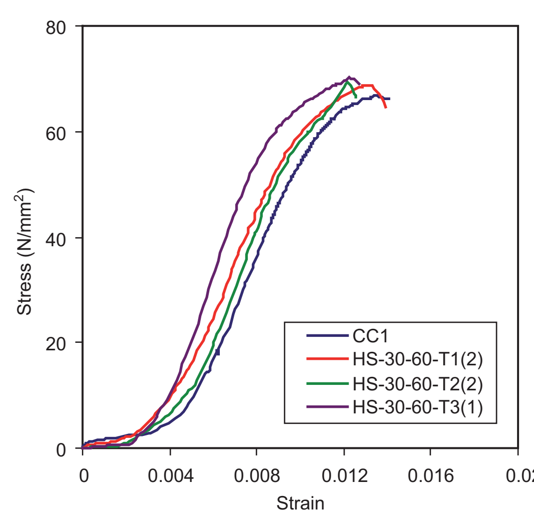

Figure 17 Comparison of axial stress-strain behaviour of columns HS-30-60.

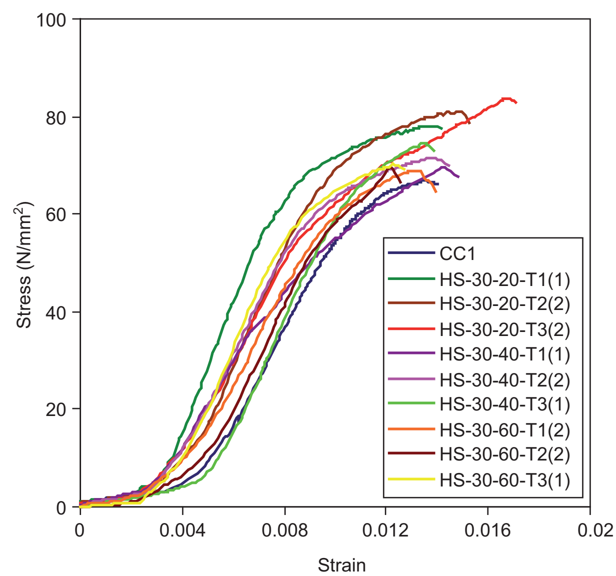

Figure 18 Comparison of axial stress-strain behaviour of all columns.

axial capacity resulting from CFRP applications. The addition of more numbers of layers of CFRP fabrics helped to enhance the ultimate load capacity further. It is also clear that tubular sections investigated are fully effective at ultimate and, therefore, did not suffer from elastic buckling. According to Figure 19, it can be seen that the column confined with one layer (HS-30-20-T1) of CFRP strips shows better enhancement in ultimate load than that of the control column. Similarly, the columns confined with two and three layers of CFRP (HS-30-20-T2 and HS-30-20-T3) had 21.5% and 25.17% more load carrying capacity than that of the control specimen (CC1). Among the above three specimens, the column confined with three layers of CFRP obtained higher ultimate load when compared to columns confined with one and two layers of CFRP and also the unbonded column. This also occurred in the case of specimens confined externally by 30-mm width of FRP strips with the spacing of 40 mm and 60 mm. Figure 20 shows that columns wrapped with two and three layers of FRP strips with 40-mm spacing obtained 6.78% and 11.43% more load

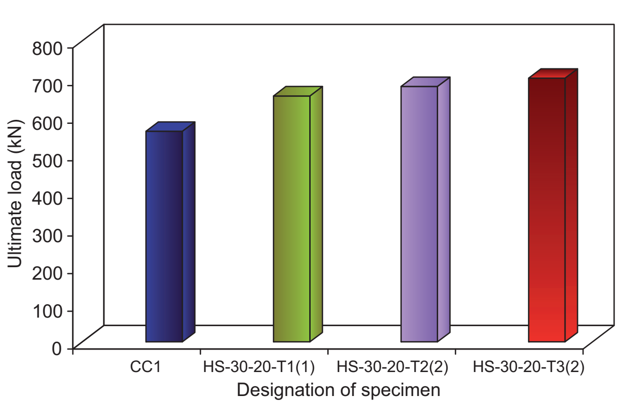

Figure 19 Comparison of ultimate load of beams HS-30-20.

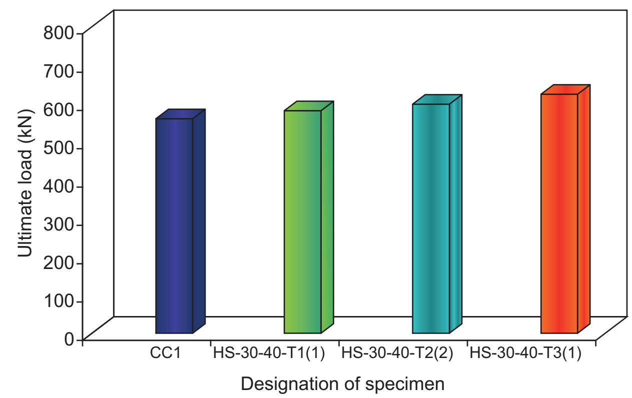

Figure 20 Comparison of ultimate load of beams HS-30-40.

carrying capacity than that of the control specimen. Figure 21 shows that columns wrapped with two and three layers of FRP strips with 60-mm spacing obtained 3.75% and 5.0% more load carrying capacity than that of the control specimen. From the test results, it can be seen that the addition of more numbers of layers of CFRP fabrics helped to further increase the ultimate load capacity. Figure 22 compares the ultimate load of all FRP confined columns with one another and also with the unconfined column. Among the three series of specimens, it can be seen that the column confined with three layers of CFRP strips with 20-mm spacing [HS-30-20-T3(1)] had 12.33% higher ultimate load than that of the column with 40-mm spacing of fibre strips [HS-30-40-T3(1)] and 16.12% higher than that of 60-mm spacing of fibre strips [HS-30-60-T3(1)]. This was mainly because of spacing between the strips. Finally, it can be concluded that the lesser spacing of CFRP strips with more numbers of layers showed significant increases in ultimate load than CFRP strips of greater spacing.

4.4. Ductility index

The ductility of each column was observed by calculating the ductility index as the ratio between the deflection of the column at failure load and its deflection at yield load, as shown in Figure 23. For all strengthened columns, it was clearly observed that strengthening with externally bonded

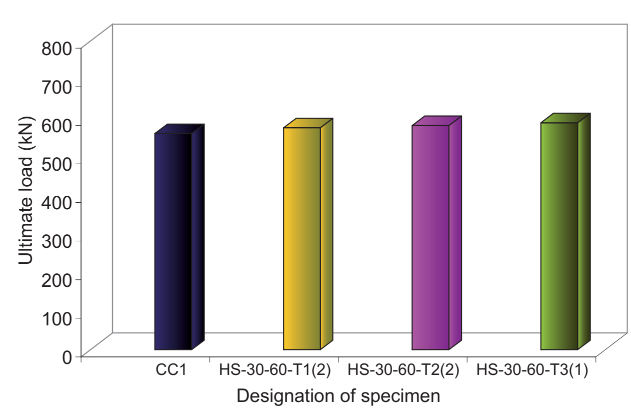

Figure 21 Comparison of ultimate load of beams HS-30-60.

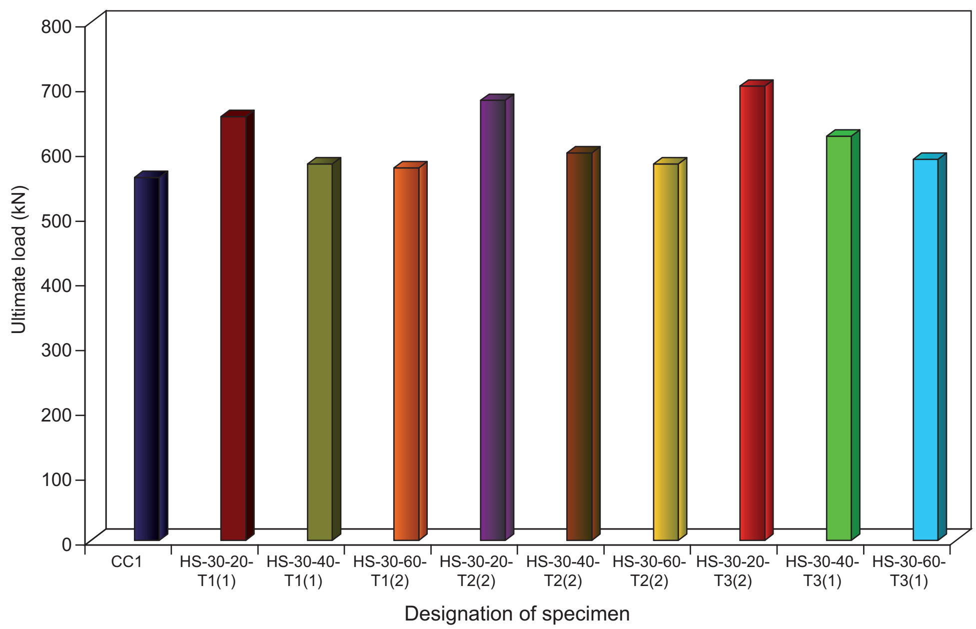

Figure 22 Comparison of ultimate load of all columns.

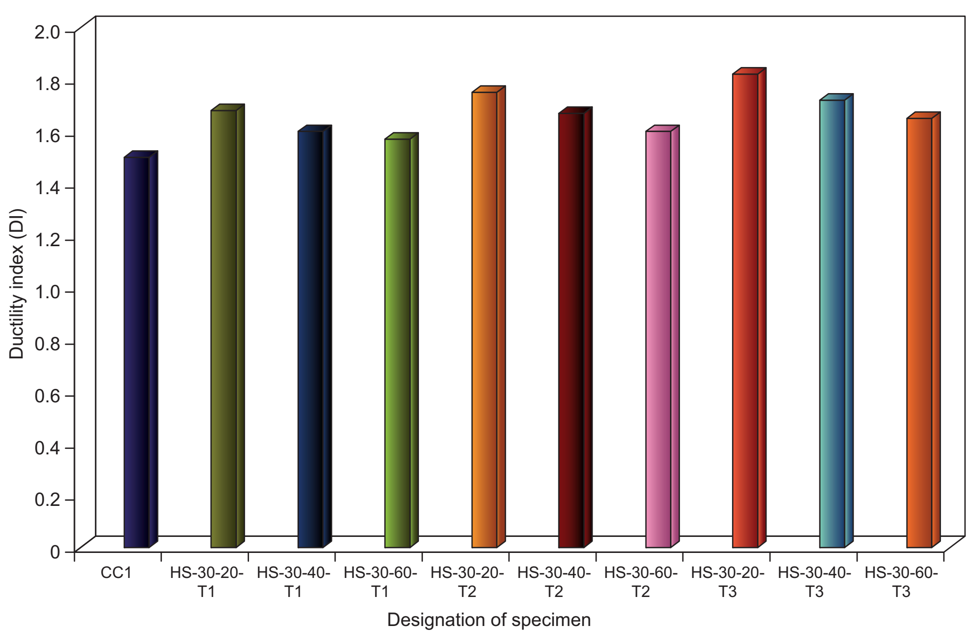

Figure 23 Comparison of ductility index of all columns.

CFRP fabrics under axial loads increased the ductility of the strengthened columns compared with the control column. The enhancement in ductility index of columns HS-50-20-T1, HS-50-20-T2 and HS-50-20-T3 was found to be 12%, 16.67% and 21.33% more than that of control column (CC1), respectively. In a similar manner, the ductility index of the columns HS-50-40-T1, HS-50-40-T2 and HS-50-40-T3 were 6.70%, 11.33% and 14.67%, and the columns HS-50-60-T1, HS-50-60-T2 and HS-50-60-T3 were 4.67%, 6.70% and 10% more than that of the control column, respectively. In Figure 23, it can be seen that the column strengthened with the three layers of 20-mm width CFRP strips had a higher ductility index compared to other columns. Hence, it can be concluded that the columns with closer spacing of CFRP strips showed better performance than that of all other columns.

5. Conclusions

From the experimental data obtained, the failure modes, axial stress-stain behaviour, ultimate load carrying capacity and the contribution of FRP fabrics on HSS tubular columns were discussed. Based on the compressive tests on 18 specimens wrapped with CFRP strips with different spacing and with different layers, the following conclusions can be made.

- The specimens confined with three layers of horizontal CFRP strips showed better performance in stress-strain behaviour compared with the columns confined with one and two layers of horizontal CFRP strips.
- All HSS tubular specimens strengthened with CFRP strips showed reasonable increases in load carrying capacity. The enhancement in ultimate strength capacity is based on thickness of CFRP fabrics. The column strengthened with CFRP strips of 20-mm spacing with three layers showed better load carrying capacity than that of other columns.
- The load carrying capacity of columns HS-30-20-T1, HS-30-20-T2 and HS-30-20-T3 were 16.73%, 21.25% and 25.17%, respectively, more than that of the control column, whereas the load carrying capacity of columns HS-30-40-T1, HS-30-40-T2 and HS-30-40-T3 were 3.75%, 6.78% and 11.43%, respectively, and for columns HS-30-60-T1, HS-30-60-T2 and HS-30-60-T3, it was 2.67%, 3.75% and 5.0%, respectively, more than that of the control column.
- The enhancement in ductility index of columns HS-50-20-T1, HS-50-20-T2 and HS-50-20-T3 was found to be 12%, 16.67% and 21.33% more than that of the control column (CC1), respectively. In a similar manner, the ductility index of the columns HS-50-40-T1, HS-50-40-T2 and HS-50-40-T3 were 6.70%, 11.33% and 14.67%, and the columns HS-50-60-T1, HS-50-60-T2 and HS-50-60-T3 were 4.67%, 6.70% and 10% more than that of the control column, respectively. Hence, it can be concluded that the columns with more numbers of layers and with closer spacing of CFRP strips showed better performance than that of all other columns.

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