Axial Behaviour Of Rehabilitated Fire Exposed HSS Tubular Members Using CFRP Strips

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Abstract:*Hollow structural steel (HSS) have more industrial and commercial applications from its superior properties such as high strength to weight ratio, seismic resistant capacity like large energy absorption capacity and also have good aesthetic appearance. Although main disadvantage of steel member was very sensitive to fire and the behaviour of steel in fire was complex and indeterminate. When steel column in fire at elevated temperature above 400 degree Celsius, its strength and stiffness gets reduced rapidly. Hence rehabilitation of member is very essential. Conventional rehabilitation methods like steel plating increasing member size and weight and introduce additional corrosion. Using CFRP (carbon fibre reinforced polymer) composite contracts those drawbacks. This paper presents behaviour of fire exposed short square HSS column strengthened using CFRP strips under axial compression. Totally 15 specimens were tested that includes three control specimens (CS), three control fire exposed specimen (FS) and remaining are wrapped with 30mm width of CFRP strips with a spacing of 20mm up to three layers. Experiments were undertaken until column failure and the behaviour of strengthened fire exposed short square HSS column, failure modes and enhancement of load carrying capacity were studied. From the experimental results it is found that CFRP strips increase load carrying capacity of column with increasing number of layers and also it is revealed that strengthening of short square HSS column using CFRP strips is feasible.*

Keywords: CFRP strips, short HSS columns, Fire exposure

I. INTRODUCTION

Hollow structural steel (HSS) tubular members play a vital role in the overall infrastructure development whose application ranges from architectural, infrastructural, general engineering to power plants, solar power plants, steel industry, railways, airports, etc. Since they are more versatile than ordinary steel sections, by virtue of its shape. And also, it have high radius of gyration in higher concentric strength. They are highly cost-effective, because of its low weight and it leads to save in material, transportation and also in fabrication. The advantage of less surface area composed to equivalent conventional (open) section results savings in paint and labour cost, it tend to saving more maintenance cost. On the other hand, due to its less weight characteristics, the erection progress becomes an easy task. Generally the HSS requires minimum gusset plate for connection, which naturally expedites be fabrication process.

There are various types of sections such as square, rectangle, circular, elliptical are available in the market, circular, square and elliptical has higher torsional rigidity and better resisting capacity on more axis. This makes the bending process much easier compared to open sections. Those things makes HSS member as good supporting (compression) element in multi-storey building.

Corrosion and fire exposure are not uncommon phenomenon which hinders the properties of the steel. All normal indoor and outdoor temperatures, the performance of steel is as good as that of in laboratory condition, giving a good yield point by diverging the elastic and inelastic portion of stress-strain curve and thereby exhibits a linear behaviour. But when it is exposed to higher temperature more than 500 degree Celsius the behaviour of the specimen becomes complex and the stress-strain behaviour is non-linear. The strength and stiffness of member get reduced rapidly at short period of exposure. Hence it is mandatory to rehabilitation these element when prone to fire accident.

Conventional method of rehabilitation using welding steel plates and sandwich concreting increases the size and weight of the members which further requires heavy machineries for installation at the cost of time and money. Fibre Reinforced Polymer (FRP) composites addresses these issue. Promptly in both cost, labour and time aspects. Carbon fibre reinforced polymer (CFRP) composite was invented at 1960. It has more excellent mechanical properties such as light weight, corrosion resistance, and high strength to weight ratio, high tensile strength and durable.

Lam and Teng [1]carried out the experimental and theoretical investigation on fiber-reinforced plastic FRP confined circular concrete specimens, leading to a variety of models for predicting their axial compressive strengths. . **Jerome F. Hajjar et al** [2] has proposed a polynomial equation to estimate the three-dimensional cross section strength of square and rectangular concrete-filled steel tube beam-columns. Accuracy of equation was verified against experimental tests of short, square CFST members. **Kenji Sakino et al** [3] observed the behavior of centrally loaded concrete filled steel tube short columns based on experimental results of 114 specimens with parameters such as tube shape, tube diameter to thickness ratio and concrete strength. Finally, design formulae to estimate the ultimate axial compressive load capacities of CFST columns for both circular and square sections were proposed that includes the scale effect.

Sivasankar et al. [4] conducted a detailed investigation on behaviour of strengthened HSS tubular columns using CFRP composite strips under axial compression including their failure modes, ductility index. From experimental results, it showed that CFRP strips delays the failure and enhance buckling resistance capacity of section.**Zhong Tao and Lin-Hai Han [5]** presents the test results of fire exposed concrete filled steel tubular (CFST) beam and column repaired by complete wrapping of unidirectional CFRP composites and showed that the strength of all damaged beam columns has not been fully restored due to the long exposure time of them in fire. **Ganesh Prabhu et al. [6]** investigated the compressive behaviour of circular CFST columns externally reinforced using CFRP composites. The CFRP strips are effectively delaying the local buckling and increase the load carrying capacity up to 30% of unconfined CFST member**. Kian Karimi et al. [7]** creates analytical model was used to study the effect of the concrete strength and ultimate tensile strength of the CFRP wraps on the compressive behaviour of composite columns. This study also introduced a simple, cost-effective and reliable technique to enhance axial behaviour of steel columns.

A very few number of experimental and analytical work has been done on the area of rehabilitation of fire exposed member, they were mostly on slender HSS column with plastic and compact sections and using full wrapping of CFRP composite to rehabilitated the fire exposed member. But full wrapping of CFRP composite is more expensive than conventional rehabilitation method. To overcome those drawbacks, CFRP composite strips with varying spacing is introduced. Hence there is need to study the behaviour of fire exposed short semi-compact square HSS column under axial compression and check the effectiveness of rehabilitation using CFRP strips layers with spacing.

A. *AIM OF THE STUDY*

The main objectives of study areas follows,

1. To study the behaviour of fire exposed short square semi-compact section under axial compression. Fire is applied as per ISO 834 standard fire curve.
2. Fire exposed members are rehabilitated with CFRP strips of width 30mm with the spacing of 20mm and tested under compression to observe the failure mode and load enhancement.
3. To compare the test results of control columns with rehabilitated column specimens to find out the suitability of rehabilitation using CFRP strips.

II. MATERIAL AND SPECIMEN SETUP

A. MATERIALS

1. Steel:

The square hollow steel tube confirming to IS 4923-1997 and IS 1161-1998 having a dimension of 50 mm x 50 mm was used in this study. The thickness and height of the square hollow steel tube were 1.2 mm and 300mm respectively. The steel section belongs to Class 3 section as semi-compact section. The specification of square hollow steel tube conforming to IS 1161-1998 was presented in table I.

Table I. specification of steel tube

Details	**Specification**
Cross section	50 mm x 50 mm
Height	300 mm
Thickness	1.2 mm
Yield strength	252 N/mm^2

2. Carbon fibre

The unidirectional carbon fibre reinforced polymer composite called MBrace 240, fabricated by BASF India Inc. was used in this study. It is a low modulus CFRP composite having young's modulus of 240 N/mm2. The thickness and width of the fibre are 0.234 mm and 600 mm respectively. It is fabric type and can be tailored into required shape and size. The properties of unidirectional CFRP composite supplied by manufacturer given in the Table II.

Table II. Properties of CFRP composites

S.NO	Details	Specification
1	Young's modulus	240 N/mm^2
2	Tensile strength	3800 N/mm^2
3	Thickness	0.234 mm
4	Weight of fibre	1.7 g/cm^2

3. Adhesive

The MBracesaturant supplied by BASF India Inc. was used in this study to get good bonding between steel tube and carbon fibre. It is a two part systems, a resin and a hardener and the mixing ratio was 100:40. The properties of MBraceSaturant supplied by the manufacturer are summarized in table III.

Table III. Properties of MBraceSaturant

S.NO	Properties	Value
1	Mixed density	1.13$\pm$ 0.03 kg/litre
2	Mixed viscosity (at 25)	4000 $\pm$ 500
3	Setting time	Greater than 3 hours at 25
4	Weight of fibre	1.7 g/cm^2

B. *EXPERIMENTAL INVESTIGATION*

1. Description of specimens

Among 15 specimens, three without fire exposed specimens are called as control specimens (CS), three with fire exposed but without rehabilitated specimens are called as fire exposed specimens (FS) and remaining 18 fire exposed specimen were rehabilitated with CFRP strips of 30mm with spacing of 20mm and 40mm. Fig. shows wrapped specimens with different spacing. To identify the specimens easily, the columns were named such as RFS 30-20-T1 (1), RFS 30-20-T2 (2) and RFS 30-20-T3 (3).For examples RFS 30-20-T3 (3) describes that third fire exposed specimen rehabilitated with three layer of CFRP strip of width 30mm with spacing of 20mm.

2. *Specimen fabrication*

a. Fire exposure

A Hollow structural steel (HSS) tube of length 6m supplied by Shankara infrastructure and materials Ltd., Madurai. In preparing of specimens, the tube was accurately machined to required length of 300mm. The test starts at a temperature of 20 degree Celsius. The furnace temperature was controlled as close as possible to the ISO-834 standard fire curve. The fire exposure period (t) for all relevant specimens were set to be 15 minutes. When the specimens heating temperature exceeds 550 degree Celsius and an oxide layer was formed over surface of specimen. Figure 1 shows a general view of specimens after exposure to elevated temperature.

Fig 1: Specimens after exposure to elevated temperature

It should be noted that because of the limitation of the furnace faculty, the column specimens were not loaded during the fire exposure, which does not reflect the actual fire damage situation. However, the test data should provide the basis for further theoretical studies of the post fire rehabilitation of HSS columns.

b. Surface preparation

To achieve good bonding between steel and CFRP composite, surface preparation of metal substrate to be CFRP wrapped is very important. The strength of the adhesive bond is directly proportional to the quality of the surfaces to which it is bonded. Hence the exposed surface of the tubular specimen was blasted by the coarse sand to remove the rust and also to make the surface rough.

Before rehabilitation, the entire sand blasted surface of specimens was cleaned by acetone to remove all contaminant materials. Prior to the specimens strengthened by CFRP composites, thin glass fibre layer was introduced between the steel surface and CFRP composites to eliminate the galvanic corrosion.

Finally, the unidirectional CFRP strips of constant width 30mm with spacing of 20mm was bonded to the exterior surface of the tubular members in the transverse direction with different layers. During wrapping of fibre fabrics, the resin and hardener are correctly proportioned and thoroughly mixed together as per manufacturer guide lines. Wrapping was done in count of one layer per day to attain enough strength before applying next layer of CFRP strips and the excess epoxy and air were removed using a ribbed roller moving in the direction of the fibre. In this study, strengthening of specimen is done up to three layer of CFRP wrapping which is shown in figure 2. Wrapping of every layer is done after ensuring the previous layer harden/completely dried. All specimens were allowed to curing period of 7 days in room temperature. After curing, nominal M25 concrete mix pumped into both ends of HSS specimens to improve support stiffness for elephant foot like buckling, reduce imperfection and maintain uniform loading applied on both ends of specimen.

Fig 2: Fire exposed specimens wrapped with 20mm of CFRP strips

III. EXPERIMENTAL SETUP

The HSS columns were tested in compression testing machine of capacity 2000 kN. Centre line of machine was marked on both axis of machine. 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 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 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 load and respective axial deformation data.

At the beginning, a small load of 20 kN was applied slowly, so that the columns settled 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 axial compressive load in small gradual increments and the observations such as axial deformation and ultimate load were carefully recorded with corresponding designation of specimens. The load at which the CFRP starts rupturing and the nature of failure were also noted for each column.

A. Failure mode

The columns were tested under axial compressive load up to failure to understand the influence of CFRP strips on the axial behaviour of fire exposed semi-compact short square HSS column members. The failure of control specimens was generally observed by inward and outward buckling at 30mm from the bottom support which proves that pumped concrete layer in both ends eliminates the elephant foot like buckling by providing effective confinement at supports. The failure of control specimen CS (2) is shown in Figure 3. The ultimate load carrying capacity of CS (1), CS (2) and CS (3) are noted as 77.49 kN, 78.48 kN and 72.59 kN respectively.

Fig 3: failure modes of CS (2)

For fire exposed without rehabilitation specimens, the oxide layers formed during the fire exposure began to peel when the applied load attained 42–53% of the ultimate load in the pre-peak stage. At the same time, the axial deformation of the fire exposed specimens exceeded their permissible limit. The failure of FS (1), FS (2) and FS (3) specimens occurred at 58.86 kN, 67.69 kN and 66.71 kN respectively. The failure mode of FS specimens is shown in Figure 4.

From this, it was found that failure was mainly via local inward and outward buckling. The initial response of axial behaviour of rehabilitated fire exposed specimens is similar to that of fire exposed specimens without rehabilitation and when the load was increased, the performance of rehabilitated column was much better than that of FS specimens.

Fig 4: Failure mode of FS (2)

In the case of fire exposed HSS specimens RFS 30-20-T1 (1) and RFS 30-20-T1 (2), both were rehabilitated by one layer of 30mm CFRP strips with 20mm spacing local inward and outward buckling occurred at 30mm from bottom of the column at 67.69 kN and 80.44 kN. RFS 30-20-T1 (1) specimen failed very close to ultimate load of fire exposed specimen FS (2). In the case of specimen RFS 30-20-T1 (3), local inward and outward buckling occurred at 30mm from top of the column at 71.61 kN. The failure mode of RFS 30-20-T1 specimens are shown in Figure 5**.**

Fig 5: Failure mode of RFS 30-20-T1

The similar failure mode was observed in the case of specimens rehabilitated with two layers CFRP strips with 20mm spacing [RFS 30-20-T2 (1), RFS 30-20-T2 (2) and RFS 30-20-T2 (3)] , local inward and outward buckling occurred at 30mm from bottom of the column at 100.06 kN, 83.39 kN and 106.93 kN.The observed failure mode were similar to one layer of CFRP strips but load attained much higher than previous one.

The crushing of resin with the huge modulation was observed in the case of specimens RFS 30-20-T3 (1), RFS 30-20-T3 (2) and RFS 30-20-T3 (3) at the initial stage of loading. The specimens RFS 30-20-T3 (1) and RFS 30-20-T3 (2) exhibited sudden failure at the bottom of specimen once they reached the ultimate loads of 106.93kNand 93.2 kN respectively.

RESULTS AND OBSERVATIONS

A. Axial load-deformation

The axial load-deformation behaviour of strengthened column compared with control column and fire exposed column and percentage of load enhancement summarised in Table IV. Also comparison results represented in graphical manner which is shown in Figures. From graph, it was noted that at the initial stage the control, fire exposed columns and CFRP confined columns exhibited linear elastic behaviour followed by inelastic response when increasing the load further.

The specimens RFS 30-20-T1 (3), RFS 30-20-T2 (2) and RFS 30-20-T3 (3) showed significant control over the axial deformation and enhancement of load carrying capacity when compared to control specimen CS (2) and fire exposed specimen FS (3) which is shown in Figure 6. The graph showed that the behaviour of RFS 30-20-T2 (2) was especially good in axial deformation control when compared to other rehabilitated specimens

The specimens RFS 30-20-T1 (3), RFS 30-20-T2 (2) and RFS 30-20-T3 (3) showed significant control over the axial deformation and enhancement of load carrying capacity when compared to control specimen CS (2) and fire exposed specimen FS (3) which is shown in Figure 5.9. The graph showed that the behaviour of RFS 30-20-T2 (2) was especially good in axial deformation control when compared to other rehabilitated specimens.

At respective failure load of control specimen CC2, axial deformation of specimens RFS 30-20-T1 (3), RFS 30-20-T2 (2) and RFS 30-20-T3 (3) were noted as 4.13mm, 3.44mm and 3.67mm respectively and their enhancement in axial deformation control compared to control column CC2 was 1.7%, 18.1% and 12.62% respectively. It can be noted that the axial deformation control of column RFS 30-20-T1 (3) was very small which is due to insufficient amount of confining pressure generated by CFRP strips.

From the figure, it can be seen that rehabilitation using two layer of CFRP strips with spacing 20mm tend to have more ability to control axial deformation compared to those columns confined by one and three layers of CFRP. The reason were one layer of CFRP strip induced very small confining pressure and three layer of CFRP strips induced more confining pressure compared to other which should be highly compress the fire exposed specimen, it cause initiation of inward buckling of specimen under loading. But it had higher load carrying capacity than others.

Hence, it can be concluded that, the columns with more number of layers CFRP strips have better axial stress-strain behaviour except rehabilitation of CFRP strips with 20mm spacing. But observed the enhancement in axial deformation control was not proportional. The reason for nonlinearity in axial deformation control was crushing of resin lying in between the fibres. When the resin started to crush, a sudden drop in substantial load transfer was occurred. As a result, nonlinearity in axial deformation control was observed. Furthermore, by increasing the number of layers of CFRP, the number of resin layers also increased so that more nonlinearity in axial deformation control was observed.

Table IV. Experimental results

Designation of column	**Failure load (kN)**	**Maximum axial deformation (mm)**	**% of reduction in axial deformation compared to CS (2)**	**% of increase in axial load carrying capacity compared to FS (2)**
CS (1)	74.556	3.52	-	-
CS (2)	78.48	4.2	-	-
CS (3)	70.632	4.2	-	-
FS (1)	58.86	3.87	-	-
FS (2)	67.69	3.14	-	-
FS (3)	66.71	3.95	-	-
RFS 30-20-T1 (1)	67.69	3.87	-	0
RFS 30-20-T1 (2)	80.44	3.23	23.57	18.84
RFS 30-20-T1 (3)	71.61	4.13	1.67	5.79
RFS 30-20-T2 (1)	100.06	4.06	8.33	47.82
RFS 30-20-T2 (2)	83.39	3.5	18.1	23.19
RFS 30-20-T2 (3)	106.93	4.12	9.52	57.97
RFS 30-20-T3 (1)	106.93	4.53	2.86	57.97
RFS 30-20-T3 (2)	93.2	4.29	2.86	37.69
RFS 30-20-T3 (3)	101.04	3.99	12.62	49.27

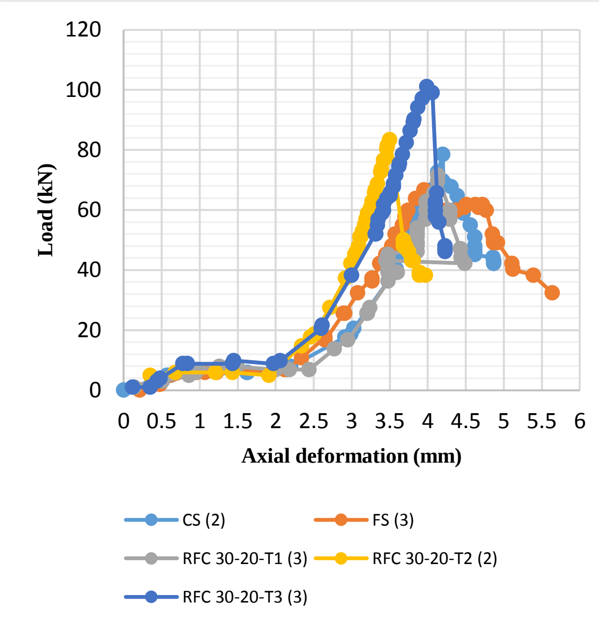

Fig 6: Comparison of axial load-deformation behaviour

B. Axial load carrying capacity

The maximum load carrying capacity of all specimens and percentage increase in load carrying of rehabilitated column compared to fire exposed column was summarised in Table IV. The load carrying capacity of all rehabilitated specimen was enhanced considerably by external wrapping of CFRP strips. Especially the columns rehabilitated by three layers of CFRP strips in all spacing were outperformed.

Compared to fire exposed specimen FS (2), the enhancement of load carrying capacity of RFS 30-20-T1 (2), RFS 30-20-T2 (1) and RFS 30-20-T3 (1) specimens were noted as 18.84%, 47.82% and 57.97% which is shown in figure 7.

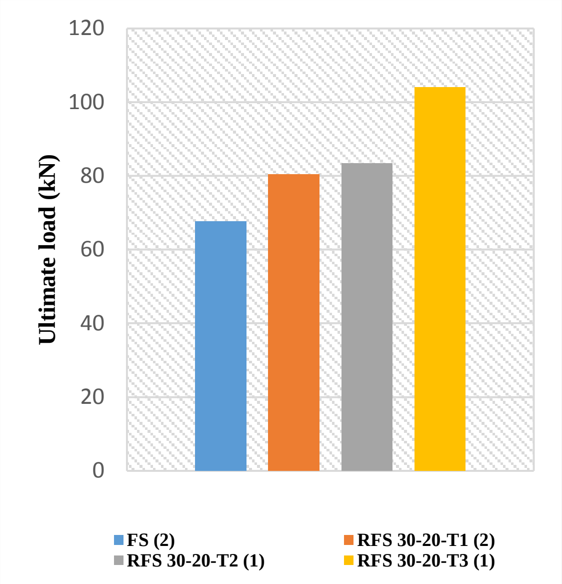

Fig 7: Comparison chart for 20mm CFRP strips specimens with FS (2)

From above test results, there is a good bonding action exist between the CFRP strips and steel tube and also external bonding of CFRP strips can be able to provide necessary confining pressure to the column was revealed. It can also be seen from Figure 5.12that the specimens rehabilitated by CFRP strips with smaller spacing and more number of layers have more axial load carrying capacity.

IV. CONCLUSIONS

When the HSS tubular column specimens were exposed to elevated temperature, the strength and capacity of member gets reduced. In the present investigation, the fire exposed column specimens were rehabilitated with 30mm CFRP strips with 20mm and 40mm spacing to restore the original structural behaviour and load carrying capacity. Based on experimental results, the following conclusions can be made.

1. All rehabilitated specimens possess better load carrying capacity and deflection control than the fire exposed control specimens.
2. The specimens with two layered CFRP strips with 20mm spacing showed 32.14% more in load carrying capacity when compared to respective specimen with single layer of CFRP strips.
3. From experimental results, it was observed that the specimens with 40mm spacing of double layered CFRP strips was more effective and it also restored the original capacity of fire exposed specimen.
4. From experimental results, it was observed that the specimens with 20mm spacing of double layered CFRP strips was more effective and it also restored the original capacity of fire exposed specimen.

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