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# Numerical Study on the Flexural Behaviour of Concrete Filled Steel Tube Beam Strengthened with CFRP

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**Abstract.** Concrete filled steel tubular (CFST) beams are composite structural members with high strength and ductility than the conventional concrete and steel members. In this study the flexural behaviour of CFST beams strengthened with carbon fibre reinforced polymer (CFRP) were investigated. CFST beam of dimensions 91.5×91.5×3.6 mm strengthened with CFRP of 0.5 mm thickness have been considered. Flexural behaviour was investigated by considering the effect of single layer, two layers and three layers of CFRP with different wrapping length. The study concluded that flexural strength increases with the multilayer wrapping of CFRP up to 75% length of beam and effect of wrapping length of single layer CFRP is not significant in the strength enhancement.

**Keywords**: CFST beam, CFRP sheet, Flexural strengthening, Finite element analysis

## 1. Introduction

Composite steel-concrete structural members have been widely used in the design and construction of modern steel framed buildings. Concrete Filled Steel Tubes (CFST) are one of the recently used composite structure in bridges [1], electrical power transmission structures, underground structures, heavy industrial buildings as well as in high-rise structures. It consists of a steel tube infilled with concrete and whose combined action resists the load acting on them. The composite action is developed due to the interface stresses between steel and concrete. The structure offers numerous benefits, including high strength and fire resistances, favourable ductility and large energy absorption capacity.

Compared to conventional reinforced concrete or structural steel, CFSTs have many advantages. Steel tube confines the concrete infill due to which a triaxial state of compression is developed, that increases the strength and strain capacity of the infill. Local and global buckling of steel tube is restrained by concrete infill, and hence the deformation capacity of a CFST member compared to hollow tube is increased and the steel and concrete combined action efficiently improves the stiffness and load carrying capacity. Fig.1 shows CFST beam used in a bridge at Shinkansen – Japan [1].


**Fig.1.** CFST beam in Bridge of Shinkansen –Japan [1]

Commonly used CFST cross sections are concrete filled in Circular Hollow Section (CHS), Square Hollow Section (SHS) and Rectangular Hollow Section (RHS), which are given in Fig.2 where *B* and *D* are the outer dimensions and *t* is the thickness of steel tube [2]. Circular cross section is better than the other two cross sections, since it provides more confinement to the concrete. But square and rectangular cross sections are widely used due to the easiness of construction and because of the aesthetic reasons.

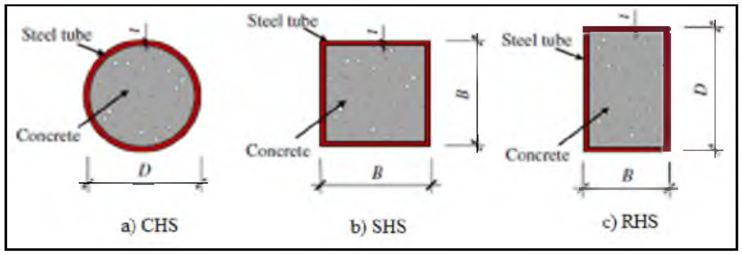



**Fig.2.** Typical CFST sections [2]

There are some other members included in the CFST family such as Concrete Filled Double skin Steel Tubes (CFDST), Concrete-encased CFST, CFST with additional reinforcement and Stiffened CFST.

The behaviour of CFST beam mainly depends on the interaction between steel and grout, difference in the Poisson's ratio of steel and concrete and load condition [3]. In order to work as a structural composite element, the load has to be transferred across the contact surface. The load will be transferred as shear stresses. Four mechanisms involved in the transferring of shear stresses are adhesion, micro interlocking, friction and binding. Binding mechanism is the dominant shear transfer mechanism for CFST subjected to pure bending and it is inactive in pure axial compressive loading. Micro interlocking mechanism is obtained due to the surface irregularities in the steel tube and it will assist to the shear transfer until crushing of grout is taken place. Adhesion is due to the vacuum generated in the capillaries due to the chemical process in the concrete. When two surfaces come into contact, the resistance of their internal tangential slip is expressed as friction. Buckling or plastic hinge formation is the main failure mechanism in the CFST [3]. This mechanism is generally affected by the way in which load is applied, width to thickness ratio and material strength.

## 2. Strengthening of CFST beam

CFST beam may require strengthening like other conventional structural members due to several reasons. They may require upgrading so that they can carry extra loads or need to be repaired due to degradation attributed to aging, fire and fatigue. Commonly used strengthening are section enlargement and external bonding of steel plate and fibres. Strengthening by replacing or adding new steel part is not economical because it needs heavy equipments and it is very time consuming. Therefore external bonding of Fibre Reinforced Polymer (FRP) had been proposed as an efficient and cost effective method. One of the popular types of FRP is the Carbon Fibre Reinforced Polymer (CFRP) fabric sheet. They are perfect for resisting environmental degradation.

Several researchers have extensively investigated the efficiency of using the CFRP material to strengthen CFST beam. Experimental investigation [4,5] on flexural behaviour of CFRP reinforced CHS, SHS and RHS tubes subjected to in-plane bending showed that strengthening effect of CFRP improved with the increase in strength ratio ($\beta$) of CFRP. The effect of CFRP strengthening on flexural behaviour of Concrete Filled Aluminium alloy circular hollow section Tubes (CFAT) is also carried out [6]. The results showed that the ultimate strength enhanced by reinforcing with the CFRP, but the ductility is deteriorated. Increase in number of CFRP layer has little influence on the ultimate strength, flexural stiffness and ductility for CFAT specimens. Strengthening of CFST beam depends on various parameters such as depth to thickness ratio, compressive strength of concrete, shear span to depth ratio, depth to width ratio, yield strength of steel tube [7]. It was found that the depth to thickness ratio, yield strength of steel tube and depth to width ratio has significant effect on ultimate moment carrying capacity of CFST beam. The performance of circular CFST beam externally reinforced by CFRP sheets under the combined actions of tension and bending were studied [8]. The main parameters considered in this study are fibre orientation, load eccentricity, number of CFRP layer. They obtained efficient increasing strength for CFRP with fibre oriented in the longitudinal direction. From literature studies, the importance for more studies to investigate the flexural behaviour of CFST beam with CFRP wrapping was identified. The effect of multiple layers and different length of CFRP sheet were investigated and is being outlined.

## 3. Idealisation of the beam

### 3.1 Concrete

Linear and non linear properties assigned for concrete. For linear properties, modulus of elasticity and Poisson's ratio were given. Poisson's ratio was given a value of 0.2 and modulus of elasticity was determined with 28 days compressive strength of concrete strength [12]. The average compressive strength of concrete was taken as 38.5 N/mm$^2$ and density is 2500 kg/m$^3$ [13].

$$E_c = 5000\sqrt{f_{ck}} \qquad (1)$$

Where $E_c$ is the elastic modulus of concrete and $f_{ck}$ is the 28 days cube compressive strength of concrete.

The uniaxial stress-strain relationship [14] for concrete was constructed by compression using the following relations.

$$\varepsilon_0 = \frac{2f_{ck}}{E_c} \qquad (2)$$

$$f = E_c \frac{\varepsilon}{1 + \frac{\varepsilon^2}{\varepsilon_0{}^2}} \qquad (3)$$

Where $f$ is the stress at any strain ε and $\varepsilon_0$ is the strain at ultimate compressive strength. Simplified stress strain relationship for concrete in compression is obtained and is shown in Fig.3.

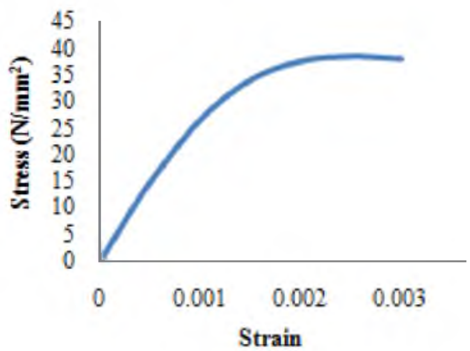



**Fig.3.** Stress strain relationship for concrete in compression

### 3.2 Steel

Cold Formed Square Hollow Section with outside dimensions of 91.5 mm square and 3.6 mm thickness [13] (91.5 x 91.5 x 3.6CF SHS) and grade YSt 240 @ 9.67 kg/m conforming to IS 4923 – 1997 and IS 1161 – 1998 [9, 10] was used in this study. Non-linear behaviour of steel was considered by specifying yield stress and tangent modulus. The tangent modulus of the steel was assumed as 0.5 percentage of its Young's modulus and the yield stress was 240 MPa. Elastic properties such as Young's Modulus and Poisson's ratio were given as 200000 N/mm$^2$ and 0.3 respectively for all the specimens [11]. Density of the steel is 7500 kg/m$^3$.

### 3.3 CFRP

Unidirectional CFRP sheet with thickness 0.5 mm was used in this study. Since the properties of CFRP composite are not same in all the directions, they were considered as an orthotropic material. The tensile strength and density of CFRP was 3800 N/mm$^2$ and 1720 kg/m$^3$ respectively. Orthotropic properties of CFRP are shown in Table 1.

**Table 1.** Properties of CFRP [13]

| Property | | Value |
|---|---|---|
| Modulus of Elasticity (MPa) | $E_x$ | 230000 |
| | $E_y$ | 17900 |
| | $E_z$ | 17900 |
| Poisson's ratio | $\upsilon_{xy}$ | 0.22 |
| | $\upsilon_{yz}$ | 0.30 |
| | $\upsilon_{xz}$ | 0.22 |
| Shear modulus (MPa) | $G_{xy}$ | 11790 |
| | $G_{yz}$ | 6880 |
| | $G_{xz}$ | 11790 |

The effect of CFRP on flexural behaviour of CFST beam was evaluated for multiple layers CFRP with different wrapping length. Different wrapping lengths of CFRP sheet were applied in 50%, 75% and 100% of the effective length of beam. Details of CFST beam specimens are shown in Table 2.

**Table 2. Specimen details of CFST beam**

| Parameter | Specimen's designation | No. of CFRP layer |
|---|---|---|
| Beam without CFRP | S0 | — |
| Beam with CFRP in 50% effective length | S50-1 | 1 |
| | S50-2 | 2 |
| | S50-3 | 3 |
| Beam with CFRP in 75% effective length | S75-1 | 1 |
| | S75-2 | 2 |
| | S75-3 | 3 |
| Beam with CFRP in 100% effective length | S100-1 | 1 |
| | S100-2 | 2 |
| | S100-3 | 3 |

### 3.4 Adhesive

The adhesive material used in the study was MBrace saturant. It is a two part system, a resin and a hardener. The Young's modulus and Poisson's ratio of the material was 17 MPa and 0.4. It had an ultimate tensile strength of 1138 MPa. The average thickness of each adhesive layer was about 0.8 – 1.0 mm. For the present study adhesive layer of 0.8 mm was considered.

### 3.5 CFST beam

The simply supported CFST beam had a cross sectional dimension and total length of 91.5x 91.5 x 3.6 mm and 1500 mm respectively. CFRP is provided in the bottom flange of beam for an effective length of 1400 mm. The dimensions of beam are illustrated in Fig.4.

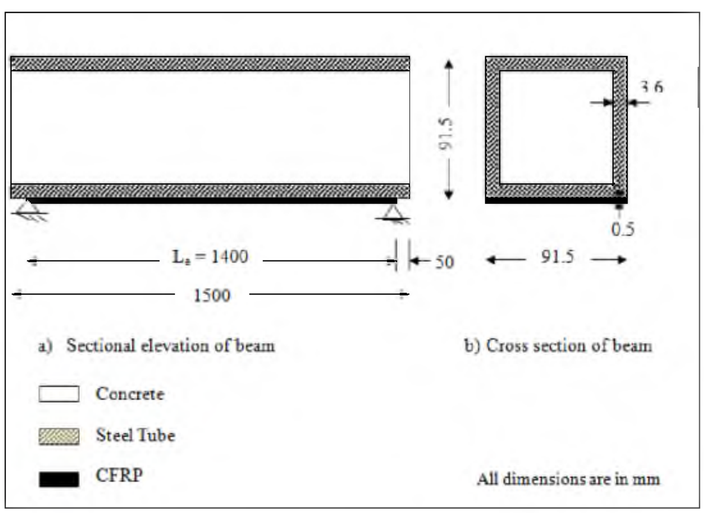



**Fig.4.** Dimensions of CFST beam [13]

The CFRP patch technique [15] was proposed to represent the multiple CFRP layer, including the adhesive layer in between them and transferring them to one equivalent layer. Here total three numbers of layers was considered. The present study assumed that all of the adhesive layers which are located in between CFRP layers have constant thickness and width. The total thickness of CFRP patch was evaluated as follows:

$$t_{cfrp.patch} = (n\, t_{cfrp}) + (n-1)\, t_{ad} \tag{4}$$

Where $t_{cfrp.patch}$, $t_{cfrp}$ and $t_{ad}$ are the equivalent thickness of CFRP patch, thickness of single CFRP sheet and thickness of single adhesive layer respectively, and n is the number of CFRP layer used in CFRP patch.

## 4. Finite Element Analysis

The structural behaviour of square CFST beam with CFRP strengthening was investigated by finite element method using ANSYS software.

Concrete, steel tube and CFRP was modelled using eight noded brick elements having three translation degrees of freedom at each node. For concrete Solid 65 element was used. It has special cracking and crushing capabilities along with the ability of creep and plastic deformation. For steel tube and CFRP Solid 185 element was used. It has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. Concentrated loads were applied at one third span of the steel tube from both the ends. For simply supported beam condition, the vertical displacement of bottom flange of steel tube was restrained and also all the rotational degree of freedom were released to allow rotation. The whole beam was discretised longitudinally with elements of 20 mm size.

## 5. Validation of CFST beam

The CFST beam was validated by comparing the numerical study presented here with the experimental investigation of Sundarraja and Prabhu (2011). The comparison of load – midspan deflection of CFST beam with and without CFRP is depicted in Fig.5 and Fig.6 respectively.

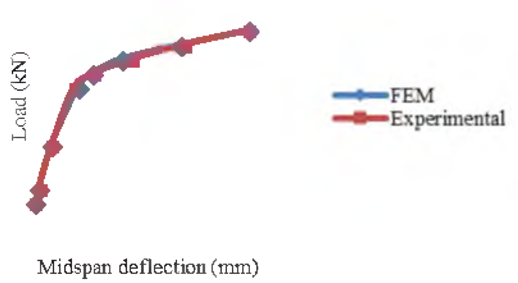



**Fig.5.** Load- Midspan deflection of validated beam without CFRP

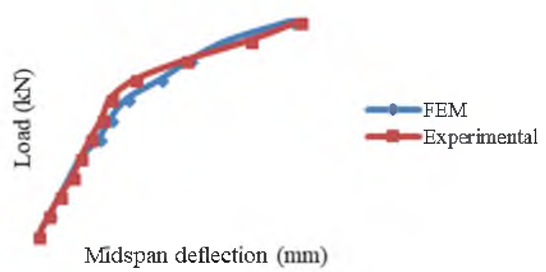


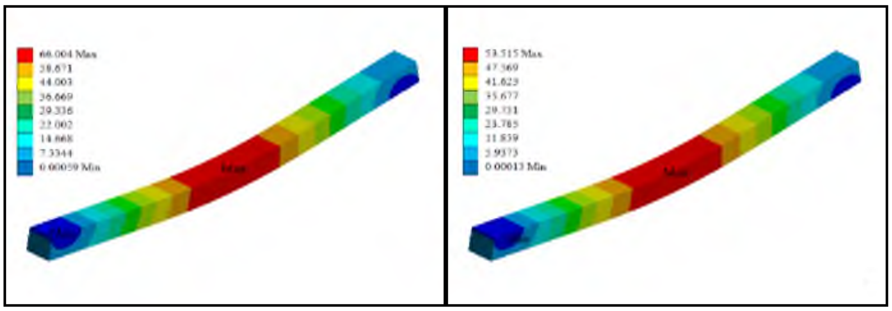

**Fig.6.** Load- Midspan deflection of validated beam with single layer of CFRP

The pattern of load – midspan deflection is almost same for numerical and experimental investigation [13] in both the cases. Thus the developed CFST beam is capable of showing the response under similar loading conditions.

# 6. Results and Discussion

## 6.1. Effect of retrofitting with CFRP

The flexural behaviour of CFST beam with and without CFRP layer was analysed. The deflection behaviour of S0 and S100-1under same loading of 120 kN is shown in Fig.7. Maximum deflection was occurring at the midspan of the beam. Comparison of load- midspan deflection curve of S0 and S100-1 is shown in Fig.8. From that there was a maximum reduction of 21% for S100-1 from S0 due to external bonding of CFRP.



(a) (b)

**Fig.7.** Deflection behaviour of (a) S0 and (b) S100-1

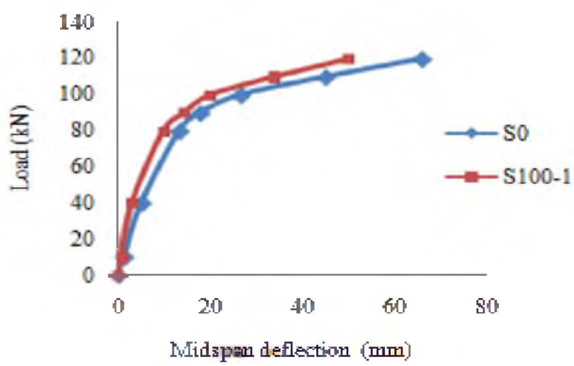



**Fig.8.** Comparison of load- midspan deflection behaviour of beam S0 and S100-1

## 6.2. Effect of length and multiple layer of CFRP

The variations in midspan deflection of the beams with increase in number of CFRP layer for 50%, 75% and 100% wrapping length were compared with CFST beam without any CFRP layer.

The load- midspan deflection of beam with multiple layers CFRP in 50% beam length is illustrated in Fig.9. It can be seen that there is a gradual reduction in the midspan deflection of beam by increasing the number of layers. The results showed that the midspan deflection was reduced by 17.75%, 34.3% and 42.27% for beam with one, two and three layer of CFRP respectively from beam without CFRP strengthening. During the initial loading stage, no changes were observed in the deflection until they achieved the ultimate capacities. For 50% wrapping of CFRP the slight change in the reduction of deflection is due delamination failure. This failure may be attributed to the enormous amount of peeling stress, which occurred along the bonding surfaces between steel and CFRP sheet. Because CFRP sheet with 50% strengthening lengths were located within the high peeling stress zone and large bending stress at the peeling points result in delamination failure. Generally the peeling stress is proportional to bending stress.

The load- midspan deflection of beam with multiple layers CFRP in 75% and 100% beam length are shown in Fig.10 and Fig.11.

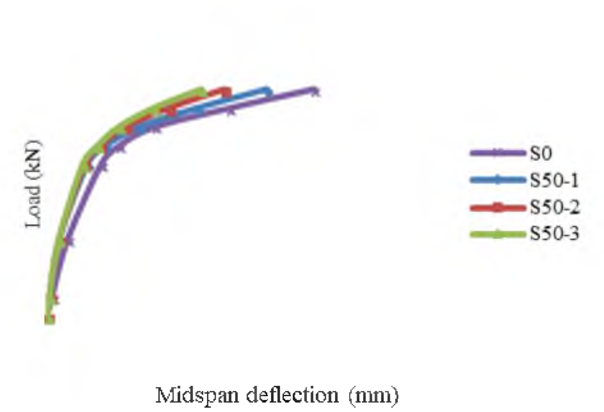



**Fig.9.** Comparison of load – midspan deflection for beam with CFRP in 50% length

For 75% strengthening lengths, the peeling stress could be overcome by the bonding strength between the CFRP sheet and steel tube, thus preventing the delamination failure. Thus there is an enhancement in the reduction of midspan deflection for beam with CFRP in 75% length. It can be observed that midspan deflection was reduced by 18% for single layer of CFRP and the percentage reduction was increases to 42.47% and 67.23% when strengthened with two and three layer respectively.

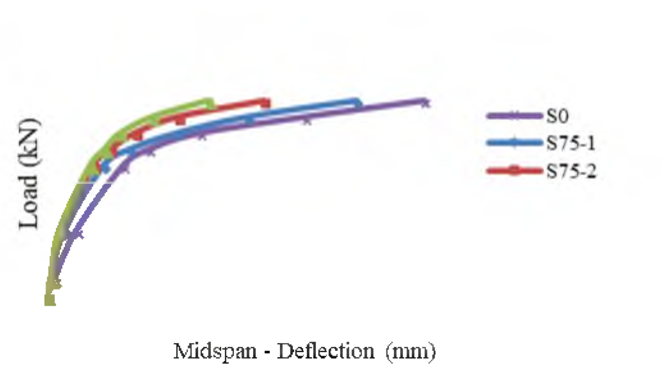



**Fig.10.** Comparison of load – midspan deflection for beam with CFRP in 75% length

Similar load – midspan deflection behaviour were observed for 100% wrapping length. It can be observed that midspan deflection was reduced by 21% for single layer of CFRP and the percentage reduction was 25.67% and 46.6% higher the value of 1 layer CFRP strengthening for two and three layer respectively.

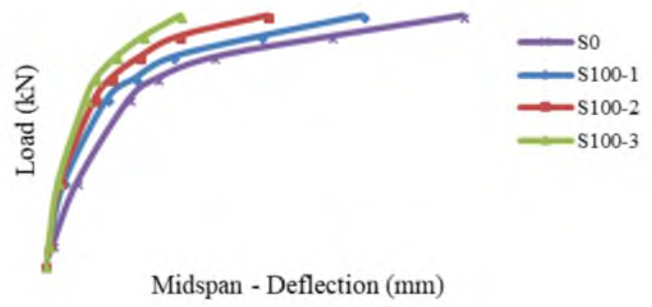



**Fig.11.** Comparison of load – midspan deflection for beam with CFRP in 100% length

A comparative study of percentage reduction of midspan deflection for different wrapping length with multiple layers CFRP listed in Table 3. The midspan deflection of the CFST beam was decreased with strengthening using CFRP. But there was no significant enhancement in the reduction of midspan deflection for CFST beam wrapped in 50%, 75% and 100% of their effective lengths when applied with one layer of CFRP sheet. It is also observed that there was not much difference between the midspan deflection values of the beam wrapped with 75% and 100% of their lengths when the CFRP patch was increased up to three layers.

**Table 3.** Percentage reduction of midspan deflection from CFST beam without CFRP

| Wrapping length (%) | % reduction of midspan deflection for | | |
|---|---|---|---|
| | 1 layer | 2 layer | 3 layer |
| 50 | 17.75 | 34.30 | 42.27 |
| 75 | 18.00 | 42.47 | 67.23 |
| 100 | 21.00 | 46.47 | 67.60 |

The load carrying capacity of the strengthened CFST beams with three number of CFRP layer increased by 7%, 21% and 23.5% for 50%, 75% and 100% wrapping length respectively when compared with CFST beam without any CFRP strengthening.

## 7. Conclusions

The numerical analysis of CFST beam strengthened with CFRP was conducted and the flexural behaviour was studied. Based on the investigation the following conclusions were arrived.

- The effect of CFRP retrofitting in CFST beam shows an improvement in flexural strength.
- Effect of wrapping length of single layer of CFRP is not significant in the strength enhancement. Because almost same percentage reduction in deflection was obtained for 50%, 75% and 100% wrapping length.
- Flexural strength increases with the multiple layers wrapping of CFRP up to 75% length of beam. That is, almost same percentage reduction of midspan deflection was achieved for 75% and 100% wrapping length. Hence, CFRP strengthening up to 75% length can be consider as an effective method for retrofitting CFST beam

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