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Behavior of FRP strengthened CFST slender members - An analytical investigation

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Abstract: The concrete filled steel tubular (CFST) members have been used widely in high-rise buildings and bridges due to their large deformation and energy absorption capacity and its efficient interaction between the steel tube and the concrete core. However, CFST column has the drawback of local buckling at steel tube due to the deterioration of the confinement effect. And also, the members may be deficient because of the environmental effects (climate, corrosion etc.) and ageing. The fibre reinforced polymers (FRPs) will provide solution not only to improve the behavior of those members and also to protect them from corrosion due to their advantages such as high fatigue strength, light in weight, high stiffness and resistance to corrosion. In this paper, an analytical investigation has been carried out to investigate the behavior of bare and FRP strengthened slender CFST members in terms of confinement ratio, lateral confining pressure, material degradation parameter and load carrying capacity using various codal provisions and literatures. The analytical study is also focused on the effects of diameter-to-thickness ratio, slenderness of the columns and the stiffness of the FRP jacket. The results revealed that the FRP jacket either substantially delayed or completely suppressed the local buckling failure of the steel tubes.

Keywords: CFST members, strengthening, FRP jacket, corrosion, compression

Introduction

Among the composite structures, concrete filled steel tubular (CFST) structures are gaining more popular in high-rise buildings, bridge piers etc (3). The CFST member also has variety of applications such as columns supporting platforms in offshore structures, roofs of oil storage tanks, large industrial workshops and tall structures, bridges and open-air overhead traveling cranes and also used as piles in foundation. Their use in multi-storey building has increased load carrying capacity for reduced cross section resulting in net floor space has been realized. They have been increasingly used in earthquake resisting structures particularly in Japan (4). In the CFST structures, CFST columns are widely used because of its structural and constructional advantages. Here the steel tube will act as a formwork and so, economical effects can also be expected (5). When a CFST column is subjected to an axial compression load, the infill concrete laterally expands due to Poisson's effect and the expansion is confined by circular steel tube (6). The steel tube stiffened by concrete core can prevent inward buckling of steel tube and so increases the strength and stability of column (7). Besides, the compressive strength and ductility capacity is also improved by means of infill concrete.

However, there is a major shortcoming of adopting CFST columns, which is the imperfect interface bonding between concrete and steel tube during initial elastic stage because steel dilates more than concrete. This imperfect bonding will reduce the confining pressure provided by the steel tube and thus reduce the initial stiffness and elastic strength of columns. According to the past study on concentric compression behavior of CFST column, the ultimate axial strength of CFST column is considerably affected by the thickness of steel tube as well as by shape of cross sections (8). Also there is an increase in construction costs because of the complicated beam-column connections (9). During their service life, columns can undergo deterioration caused by environmental effects or fatigue of its constituent materials thus leading to the reduction of the column's strength. Instead of demolishing and then rebuilding the columns, retrofitting or strengthening can be taken as an alternative way to maintain the columns.

In order to overcome the failure of columns, reinforcements with an additional layer of steel plate was employed in construction previously. Stiffeners were also used to control the local buckling of CFST columns. However, reinforcement with steel plates has drawbacks; increased weight due to the additional layer of steel plate, the complicated process, changes in material property due to steel plate welding, and deteriorated durability against climatic changes. The necessity for new reinforcement materials has emerged in order to solve these problems. In recent years, research has been carried out on FRP strengthening for structural members. FRP are suited as it has high strength-to-weight ratio, good fatigue properties, and excellent resistance to corrosion

(10). Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members. Because FRPs are applied quickly and easily, their use minimizes labor costs and can lead to significant savings in the overall costs of a project. Wrapping FRP transversely with respect to column's axial axis was mostly used in the studies. These studies proved that circumferential FRP wraps provide considerable confinement pressure to the concrete core under compressive loads delaying the crushing of concrete and buckling of longitudinal steel reinforcement, as a result, increasing the compressive strength and deformation capacity of the column.

For the cyclic tests, seismic capacity also improves because delaying local buckling occurred at the end of the column by additional confining FRP. The confinement by FRP delayed local buckling and the confining effect became obvious as the number of layers increased. The main purpose of this study is to optimize the FRP wrapping techniques by considering slenderness, diameter to thickness ratio, number of wrapping etc., by using various codes and literatures.

Material specifications

Concrete

For the analytical study the grade of concrete used is M25

Carbon Fiber

The unidirectional carbon fibre called MBrace 240, fabricated by BASF India Inc was used in this study. It is a low modulus CFRP fibre having modulus of elasticity of 240 KN/mm^2 and the tensile strength of 3800 N/mm^2. The thickness and width of the fibre was 0.234mm and 500mm respectively.

Adhesive

The MBrace saturant supplied by BASF India Inc was used in this study to get sufficient 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 (B: H).

Steel tube

The circular hollow steel tube confirming to IS 1167 - 1998 and having varying diameter (42.4, 48.3, 60.3, 76.1, 88.9mm) and thickness (medium and heavy) were used in this study. The height of the circular hollow steel tube was 1500mm. The yield strength of the tube was 310MPa.

Analytical study

Eurocode 4

EC4 uses limit state design concepts to achieve the aims of safety and serviceability by applying partial safety factor to load and material properties. Eurocode4 is the only code that treats the effects of long-term loading separately. The ultimate axial capacity of CFST column given by EC4 is as follows:

$$N_{pl,Rd} = A_a \eta_2 f_y / \gamma_{ma} + A_c \left(0.8 f_{ck} / \gamma_c\right)\left(1 + \eta_1 \frac{t}{d} \frac{f_y}{0.8 f_{ck}}\right)$$

Where-A_a and A_c are the cross sectional area of the structural steel and concrete respectively, t is the wall thickness of the steel tube, η_1 and η_2 are coefficients calculated by following equations.

$$\eta_{10} = 4.9 - 18.5\lambda + 17\lambda^2 \quad \text{but} \geq 0$$

$$\eta_{20} = 0.25(3 + 2\lambda) \quad \text{but} \leq 1$$

When e = 0, the values of η_1 and η_2 can be directly taken from Table 4.5 of the code and $\lambda = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}}$ is the relative slenderness ratio of CFST column in the plain bending and N_{cr} is the elastic crippling load evaluated by using Euler's equation. Here $N_{pl,Rd}$ is replaced by $N_{pl,R}$ according to clause 4.8.3.7 of the code when $\gamma_{Ma,}\gamma_{c,}$ are taken as 1.0. For slender columns under long-term loading, the creep and shrinkage of concrete will cause a reduction in the effective elastic flexural stiffness of the composite column, thereby reducing the buckling resistance. However, this effect is significant only for slender columns. As a simple rule, the effect of long term loading should be considered, if the buckling length to depth ratio of a composite column exceeds 15. The effect of long-term loading may be ignored for concrete filled tubular sections with $\bar{\lambda} \leq 2.0$ provided that δ is greater than *0.6* for braced (or non-sway) columns, and *0.75* for unbraced (and/or sway) columns. According to EC4 clause 4.8.3.8, the resistance of members to axial compression is given by $N_{Sd} \leq \chi N_{pl,Rd}$ where χ is the reduction coefficient for the relevant buckling mode given in EC3 in terms of the relative slenderness $\bar{\lambda}$ and the relevant buckling curve.

ACI 318-1999

In the American Concrete Institute (ACI), compression composite members are considered as regular reinforced concrete members and they used the same approach for predicting the composite section's squash load. In the theoretical approach it doesn’t consider, the increment in the confined concrete's axial capacity, which is given by,

$$Pu = Asfy + 0.85Acfc$$

However, 15% of the concrete segment is reduced to account for its uncertainties. To account for local buckling of the structural steel tube, a limiting thickness is specified which is not to be exceeded. The magnitude of this thickness is based on the achievement of yield stress in the empty steel tube, when subjected to axial monotonic loading. Moreover, this formula does not differentiate between different cross-sectional shapes. They appeared to be very conservative, due to the fact that concrete confinement is ignored in their estimation of axial load capacity.

The theoretical capacity of CFST sections are calculated using ACI 318-1999 and results are tabulated. From that it can be easily understood that the axial load carrying capacity of sections is increased with the increase in D/t ratio.

Statistical method

X.M.Yu and B.C.Chen using EC4 and CECS codes developed a simplified method. They have chosen confinement-strengthening effect from CECS and relative slenderness from EC4 as governing parameters in their study and they predicted the load carrying capacity of CFST columns. They attributed both parameters to a single factor η. The η is assumed to be a second order function of ξ and λ which was derived statistically from a large number of results. According to them the load carrying capacity of column Nu as

$$Nu = Ncr \qquad \text{for } \lambda \geq 1$$
$$Nu = Aafa + \eta Acfc \qquad \text{for } \lambda \geq 1$$

By using second order curve fitting function in MATLAB they approximately calculated η by,

$$\eta = -0.0260\,\xi^2 + 2.0665\lambda^2 - 0.5211\xi\lambda + 0.5872\,\xi - 2.8880\lambda + 1.5081$$

where η is the factor taking confinement and slenderness effects.

Numerical simulations4

When concrete is subjected to laterally confining pressure, the uniaxial compressive strength f ’cc and the corresponding strain cc are much higher than those of unconfined concrete. The relations between f’cc, f’c and between f’*cc*, f’*c*, are estimated by the following equations (Mander, Priestley, and Park 1988) as

$$f'_{cc} = f'_c + k_1 f$$
$$f_{cc} = f'_c\,(1 + k_2\,(f_l/f'_c))$$

where f_l represents the confining pressure around the concrete core. The k_1 and k_2 are constants and can be obtained from experimental data. Meanwhile, the constants k_1 and k_2 were set as 4.1 and 20.5 based on the studies of Richart et al.(1928). According to ACI committee f''_c is suggested as 0.003

Proper material constitutive models for CFST columns are proposed and verified by the nonlinear finite element program ABAQUS against experimental data of Schneider (1998) and Huang et al (2002) by Hsuan-Teh Hu, M. et al (6). Via the numerical analyses, it is shown that for circular CFT columns, the tubes can provide a good confining effect to the concrete especially when the D/t ratio is small (D/t ≤ 40). From the results of numerical simulations, two empirical equations may be proposed for f_l / f_y as follows:

$$f_l / f_y = 0.043646 - 0.000832(D/t) \qquad (21.7 \leq D/t \leq 47)$$
$$f_l / f_y = 0.006241 - 0.0000357(D/t) \qquad (47 \leq D/t \leq 150)$$

Here the behavior CFST column are highly influenced by a parameter called material degradation parameter k_3 of concrete core. For finding k_3 they proposed two empirical equations,

$$k_3 = 1 \qquad (21.7 \leq D/t \leq 47)$$
$$k_3 = 0.0000339(D/t)^2 - 0.010085(D/t) + 1.3491 \qquad (47 \leq D/t \leq 150)$$

Table 1 Comparison of load carrying capacity using various codes

Table 2 Variation Relative Slenderness (λ)

Sl.No	Diameter (mm)	Thickness (mm)	D/t	L/D	Relative Slenderness λ	EC4 (kN)	ACI 318 (kN)	Statistical (kN)
1	42.4	3.2	13.25	35.38	1.47	129.53	143.76	66.79
2	42.4	4	10.60	35.38	1.47	152.73	169.16	78.79
3	48.3	3.2	15.09	31.06	1.29	152.72	169.72	101.59
4	48.3	4	12.08	31.06	1.29	179.87	199.45	120.69
5	60.3	3.6	16.75	24.88	1.04	220.89	245.74	226.84
6	60.3	4.5	13.40	24.88	1.03	259.63	288.18	270.84
7	76.1	3.6	21.14	19.71	0.84	298.85	333.39	313.85
8	76.1	4.5	16.91	19.71	0.82	348.90	388.21	368.41
9	88.9	4	22.23	16.87	0.72	394.96	440.88	430.01
10	88.9	4.8	18.52	16.87	0.71	447.66	498.6	492.98

Factors influencing the behavior of slender circular CFST columns

Load carrying capacity

In initial stage of loading the circular CFST column are subjected to axial load while Poisson's ratio for concrete is lower than that for steel. As the load increases, longitudinal strain reaches critical strain and leads to buckling of columns because of slenderness. The theoretical capacity of CFST sections developed using all the three codes denotes that increase in D/t ratio at constant diameter is leading to capacity enhancement, which is due to enhancement of tube strength. Slenderness ratio also plays an important role in strength calculation and behavior of columns. As the slenderness ratio increases the ultimate strength of the column decreases. For L/D=16.87, the ultimate capacity is 447.66KN and for L/D=35.38 the capacity is 129.53KN.

Lateral confining pressure

When D/t ratio is small (for 10.60), the steel tube provides lateral support to concrete core and so the lateral confining pressure fl achieves a large value (of 10.80N/mm^2). On the other hand when D/t is large (for 22.23), then the steel tube provides weak support resulted in decrement of confining pressure (7.80N/mm^2).

Material degradation parameter

From the theoretical study, for smaller D/t ratio, the material degradation parameter k_3 is 1. It interprets that the strength of concrete does not degrade beyond yield point. It was proved by Hsuan- Teh Hu.M et al., that the axial force – axial strain curves of CFST columns for D/t 40 have not showed the degrading effect.

Strengthening improvement ratio

The ratio of compressive strength of confined and unconfined concrete is called strengthening improvement ratio. For constant diameter, the strengthening improvement ratio increases for increasing thickness as there is improvement in their cross sections. For varying diameter, the ratio decreases gradually as their decrement in cross sections.

Confinement ratio

The ratio between the lateral confining pressures to concrete core to the compressive strength of unconfined concrete is called confinement ratio. It also follows the same as the strengthening improvement ratio.

Table 2 Variation of influencing factors

Sl.No	Diameter (mm)	Thickness (mm)	f_l (N/mm^2)	k_3	f'_{cc}/f_{cc}	f_{cc}/f_{co}	f_l/f_{co}
1	42.4	3.2	10.11	1	9.29	2.66	0.41
2	42.4	4	10.80	1	9.85	2.77	0.43
3	48.3	3.2	9.64	1	8.90	2.58	0.39
4	48.3	4	10.42	1	9.54	2.71	0.42
5	60.3	3.6	9.21	1	8.55	2.51	0.37
6	60.3	4.5	10.07	1	9.26	2.65	0.40
7	76.1	3.6	8.08	1	7.62	2.33	0.32
8	76.1	4.5	9.17	1	8.52	2.51	0.37
9	88.9	4	7.80	1	7.39	2.28	0.31
10	88.9	4.8	8.75	1	8.18	2.44	0.35

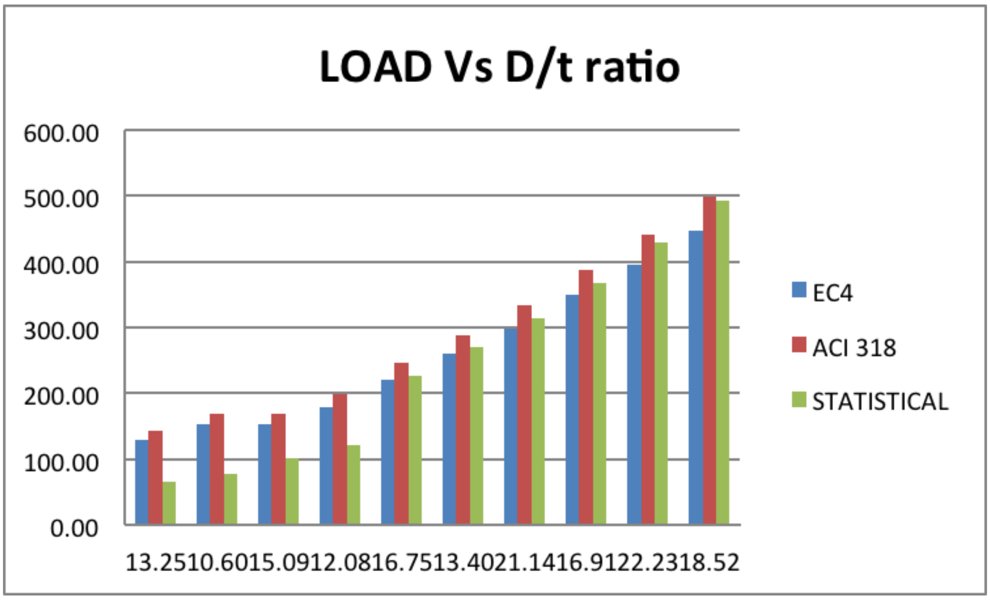

Fig 1 Load Variation Vs D/t ratio using varying codes

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