Behaviour of Concrete-Filled Steel Tubular Columns: A State of the Art Review

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Abstract: *Concrete-filled steel tubular (CFST) sections are efficient, attractive and are increasingly used in modern construction. CFST columns have enhanced compressive load carrying capacity due to the confinement of concrete provided by the steel tube and delay in local buckling of the steel tube due to the concrete core. This paper presents the review of research carried out on CFST columns with emphasis on experimental and analytical work. The study also discusses the design* specifications *adopted by various codes like AISC-LRFD and Eurocode 4.*

Keywords: Concrete-filled steel tube(CFST), local buckling, composite column, load carrying capacity, cross-section.

INTRODUCTION

Concrete-filled steel tubes (CFST) are widely used in structures to support large compressive loads. It consists of steel tubes that are in-filled with concrete that can delay the local buckling of steel tube under loading. The forming and stripping costs are reduced because the steel tube acts as stay in place formwork during casting of the concrete and it laterally confines the infilled concrete.The compressive strength of concrete, ductility of concrete and axial capacity of columns are enhanced. Many types of concrete filling may be used which includes plain concrete, high strength concrete, reinforced concrete, light weight concrete, polymer concrete etc.In recent years, CFST columns are generally adopted to resist compressive strength of more than 60MPa. The cross-section is the key element to enhance the strength of CFST profiles and it controls the three fundamental buckling modes: local, distortion and global. This paper reviews the experimental and analytical research carried out worldwide on CFST columns. Fig.1 shows the typical CFST shapes.

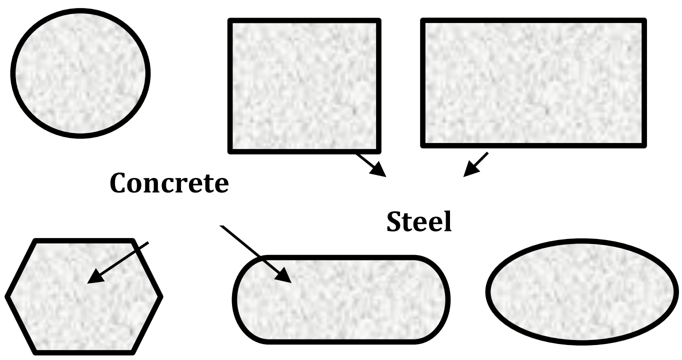


Fig.1.Shapes of CFST

Rectangular CFST columns are the most commonly used in modern construction. They have higher bearing capacity better plasticity and ductility. Circular CFST columns are bi-axially stressed in the hoop and axial directions.Square CFST columns provide confinement to the concrete infill and in return the concrete infill prevents inward local buckling of the steel tube. Elliptical CFST column are found to have higher rigidity and strength than the steel tubular columns.

Research framework

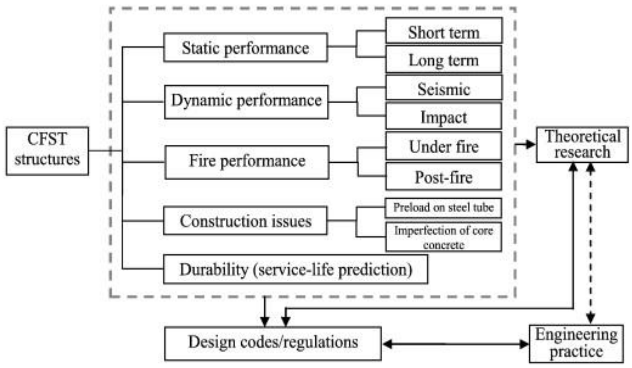


Fig.2. A Framework of Research on CFST structures[Lin-Hai Han et. al.(2014)]

Fig.2 shows the frame work of research carried out on CFST structures. CFST members have good impact resistance.

Stress-strain properties

Confinement of infilled concrete is the main advantage of CFST sections. Fig.3 shows the stress-strain behaviour of confined concrete. The reinforcing steel is assumed to be elastic until the yield strain ϵ_y and perfectly plastic for strains between ϵ_y and the hardening strain or until the limit strain ϵ_{sv},represented by tri-linear relationship. However,bi-linear stress-strain relationship is still being used, and simply expressed as

$f_s = E_s\,\epsilon_s$ for $\epsilon_s \leq \epsilon_y$

f_y=f_y, if $\epsilon_s > F_y$

f_s - Stress in reinforcing steel at any level y due to ϵ_s

E_s - Modulus of elasticity of reinforcing steel.

Relationship between stress and strain depends on basic material composition, initial conditions, state of strain, direction of strain, history of strain, time since initial strain, temperature, cyclic strain and rate of strain change.

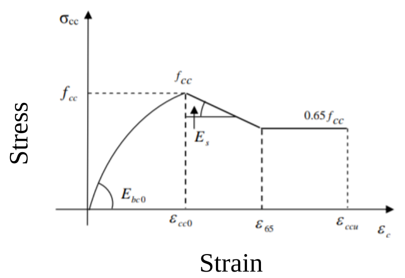


Fig.3 Stress-strain behaviour of confined concrete [Y.Bouafia et. al.(2018)]

Where,

E_s – Slope of the descending curve

ϵ_{65} – Strain corresponding to the stress equal to $0.65f_{cc}$

σ_{cc} – Confined concrete stress

f_{cc} – Compressive strength of unconfined concrete

E_{bc0} – Initial confined concrete Young modulus

ϵ_{cc0} – Confined concrete strain compounding to the peak stress

ϵ_{ccu} – Confined concrete ultimate strain

ϵ_c – Confined concrete strain

Behaviour of CFST column during loading

Due to initial concentric axial loading of the CFST column both concrete infill and structural steel will deform longitudinally. Therefore, it is assumed that concentric loading is applied uniformly across the CFST section. Thus,the lateral expansion of confining tube is larger than the confined concrete. At a certain strain, the expansion of concrete infill gradually increases until it reaches the lateral expansion of steel. Expansion of structural steel remains constant and micro-cracking in the concrete begins to takes place. Longitudinal stress in the confining tube varies based on the transfer of force between steel and concrete. In the second stage of loading where the confinement of concrete is present, circumferential stresses are developed due to longitudinal stresses from loading and lateral pressure from concrete dilation.

Failure Modes

There are various modes of failure for the CFST column based on material properties and geometric configuration. The most important failure mode is local buckling. Fig.4. shows the changes in buckling mode due to the presence of infill. CFST column can delay the local buckling due to the presence of concrete core when compared with empty steel tube.The schematic failure modes of hollow steel tube, plain concrete and CFST column is shown in fig.5

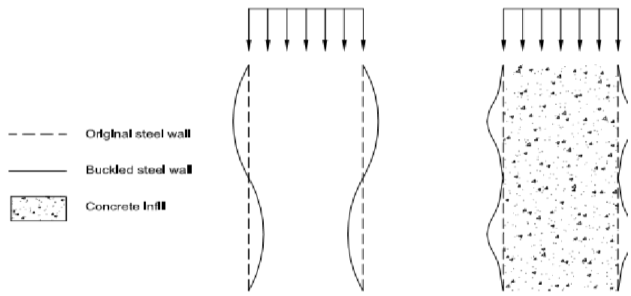
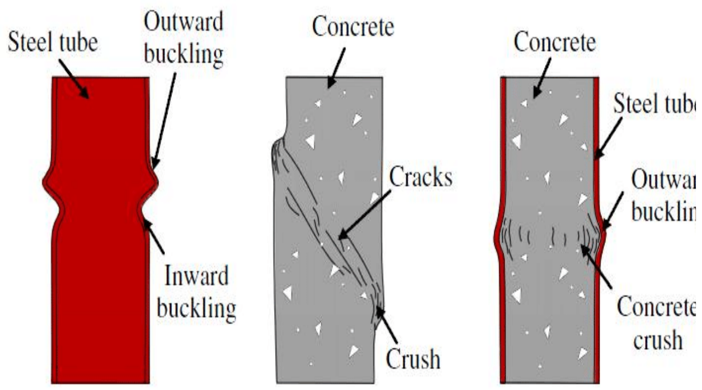


Fig.4.Changes in buckling mode with length due to the presence of infill[S.Abdalla(2012)]



(a).Hollow steel tube(b).Plain concrete (c).CFST

Fig.5.Schematic failure modes[P.Sangeetha et. al.(2018)]

Review of design codes

The specifications for the design of CFST columns as per Eurocode 4(EC4) and AISC-LRFD are discussed below

Concrete-filled sections

In concrete-filled sections the effect of local buckling is greatly reduced due to the presence of in-fill compared to hollow sections. Whereas the reduction in resistance due to overall buckling in the case of slender columns, effects of residual stresses and initial imperfections should be accounted for in the design. Moreover, the second-order effects in slender columns as well as the effect of creep and shrinkage of concrete under long-term loading must be taken into account. In addition to this the reduction in flexural stiffness due to cracking of concrete in the tension area should also be considered. Also concrete-filled sections exhibit enhanced resistance due to the confinements effect of the concrete by the surrounding steel shell. Concrete-filled sections exhibit confinement effects predominantly at the corners. All these aspects must be taken into account for the design of concrete-filled composite sections.Of the commonly used methods available for the design of composite sections, the design provisions presented in the Eurocode 4 Part 1.1 and AISC-LRFD are discussed in detail in the following sections.

Bond Between Steel and Concrete

AISC-LRFD

AISC-LRFD recognizes force transfer by bond between steel and concrete as long as connections are detailed to limit local deformations, but no guidelines are available for structures other than fixed offshore platforms.

Eurocode 4

Eurocode assumes full composite action between the concrete core and the steel shell until failure. Provision is made for internal forces and moments applied from members connected to the ends of a column to be distributed between the steel shell and concrete core taking into account the shear resistance at the interface between steel and concrete. The design shear strength due to bond and friction of concrete-filled hollow sections is taken as 0.4N/mm^2. If the limiting shear stress is exceeded,direct bearing or shear connectors are to be provided.

Local Buckling of the Steel Shell

AISC-LRFD

The effect of local buckling of the outer steel shell is taken into account by specifying a limit for the minimum thickness of the steel section.The thickness of the steel section is limited to $B\sqrt{\sigma_y/E_s}$

Where

B - Overall Width of the Compression flange

E_s – Modulus of Elasticity of Steel

Eurocode 4

Eurocode neglects the effects of local buckling of the outer steel section

If $D/t \leq 52\sqrt{235/\sigma_y}$

Where,

D – Greater overall dimension of the section parallel to the principal axis

σ_y – Yield stress of steel

Slenderness Ratio

Both the AISC-LRFD and EC4 take into account the effect of the slenderness of the column by means of a slenderness parameter as shown below

AISC-LRFD

The column slenderness λ_c is given by the formula

$$\frac{I_e}{r_m \pi}\left(\frac{\sigma_y + 0.85\, f'_c (A_c/A_s)}{E_s + 0.4E_c(A_c/A_s)}\right)^{1/2}$$

Where,

A_s – Area of the steel section

A_c – Area of concrete

f'_c – Characteristic cylinder strength of concrete

r_m – Radius of gyration of the steel shell (or) 0.3 times the overall thickness of the composite cross-section in the plane of buckling

l_e – Effective length

Eurocode 4

For the relative slenderness, λ' of columns, the following expression is suggested

$$\frac{I_e}{\pi}\left(\frac{A_s\sigma_y + f'_c A_c}{E_s I_s + 0.8E_{cm}(I_c/1.35)}\right)^{1/2}$$

Where,

I_c – Second moment of area of the concrete section

I_s – Second moment of area of the steel section

E_{cm} – Secant modulus of concrete

Effect of Concrete Confinement

AISC-LRFD

AISC-LRFD provisions do not consider confinement effects on strength or ductility of the members analysed explicitly.

Eurocode 4

Eurocode omits the reduction factor proposed for concrete strength in the design of concrete-filled composite columns since concrete achieves better strength gain when protected against environment.

Design Model

AISC-LRFD

Composite columns and beam-columns are designed in the AISC-LRFD specification as if they are steel members, but with modified cross-sectional and material properties to account for the presence of concrete. The strength of axially loaded concrete-filled rectangular hollow section is found as per the specifications suggested for hollow steel columns by substituting the value of E by E_m, σ_y by σ_{ym} and r by r_m where,

$E_m = E_s + 0.4E_c(A_c/A_s)$

$\sigma_{ym} = \sigma_y + 0.85f'_c\,(A_c/A_s)$

Eurocode 4

The resistance of a cross-section subjected to axial loads, N_p is given as the summation of the resistance of individual components.

$N_p = A_s\sigma_y + f'_c A_c$

The resistance of a composite section subjected to combined bending and compression is determined using an interaction curve for the cross-section. The member is said to be sufficiently resistant to the combined action of axial compression and uniaxial bending if it satisfies the following equation.

$M_{min} \leq 0.9\mu' M_p$

Where,

M_{min} – Minimum design bending moment

M_p – Plastic Moment

μ' - Moment resistance ratio obtained from the interaction curve

For the design of a composite section under combined compression and biaxial bending separate checks are suggested for uniaxial design moments for each principal axis in addition to a check for the biaxial capacity as given below

$M_x \leq 0.9\ \mu'_x\ M_{px}$

$M_y \leq 0.9\ \mu'_y M_{py}$

$\{M_x/(\mu'_x\ M_{px})\} + \{M_y/(\mu'_y\ M_{py})\} \leq 1.0$

The subscripts x and y refer to the relevant principal axis.

Research on CFST columns

S.No	Authors	Country	Ref.No.	Year	Shape of section	Type of loading	Analytical -A Design-D Experimental (E)	No. of Specimen	Variables studied	Remarks
1	Guofeng Du et. al.	China	36	2020	L-Shape I-Shape	Axial	E/A	32	Confinement index,Built-in steel ratio, Slenderness ratio,Load deflection curves,Bearing capacity.	FEA model was verified against experimental results
2	Wei Li et. al.	China	33	2020	Tubular	Axial	D/A	9	Ductility coefficient, Damping coefficient, Inter-storey drift angle,Rigidity coefficient, displacement,Plastic resistance moment	Comparison made for joints with different connection details
3	Xiaolian Liu et. al.	China	31	2020	Tubular	Static Cyclic	A	21	Stirrup ratio,Friction coefficient, Bolt pretension force, End plate thickness, Diameter of longitudinal reinforcement,Axial load ratio	ABAQUS model was verified using test results.
4	Hui-hui Ywan et. al.	China	16	2020	Tubular	Axial,Cyclic	E/A	7	Shear rigidity coefficient, Amplification coefficient of slenderness ratio, Axial Compression ratio, Moment of inertia,Lateral stiffness,Drift ratio	Proposed method was verified using test data and FEM results
5	Tao Wang et. al.	China	18	2020	Square, Rectangular	Axial	E	21	Temperature, Wall thickness, Shape of cross-section	Eurocode 4 equations have been proposed for the predictions of ultimate compressive resistance at low temperatures.
6	Bin Wang et. al	China	26	2019	Diagrid	Cyclic	E	10	Stress characteristic of inclined CFST columns, Hysteresis behaviour, and Ductility	The restraining effect for CFST columns in compression ensures higher capacity, deformability and energy dissipation capacity.
7	Esra Mete Guneyisi et. al.	Turkey	8	2019	Circular	Axial	A	92	Thickness of FRP layers,Type, Elastic modulus of FRP,Exposure condition	A new model is proposed to calculate the axial capacity of FRP confined CFST columns
8	Tao Pi et. al.	China	30	2019	Circular,Square	Axial	E/A	27	Steel area ratio,Young's modulus,	A simplified formula was proposed to calculate the ultimate

									Eccentricity ratio,Section type,Ductility coefficient	bearing capacity of double inner square steel tubes CFST stub columns.
9	Dan-Yang Ma et. al.	China	6	2019	Tubular	Axial, Cyclic	E/A	13	Joint type, Connection type, Beam longitudional rebar ratio, Rigidity degradation, Strength degradation.	Seismic performance of proposed composite joints was compared with other conventional joints
10	Xuhong Zhou et. al.	China	35	2019	Square	Axial	A/D	9	Diagonal rib detailing, Welding position,Width to thickness ratio	Proposed a design equation for diagonal ribs stiffened square CFST column

11	Yong-Bo Zhang et. al.	China	37	2019	Hexagonal	Axial	A	18	Confinement factor,Dilation angle,Mesh sensitivity study,Geometric internal angle,Width to thickness ratio	Simplified analytical formulae was derived based on the parametric analysis of hexagonal multi-cell stub columns
12	Yu-Hang Wang et al.	China	38	2018	Tubular, Square and Rectangular	Cyclic	E	3	Stiffness,Hysteresis behaviour,Shape of steel tube,Hollow ratio	Circular columns are stronger than square and rectangular columns
13	Chengquing Wu et. al.	Australia	29	2018	Tubular	Static and dynamic	E/A	2	Bearing capacity,Plastic behaviour,Toughness,Thickness,Diameter to thickness ratio	Comparison of failure loads between the tests and the design codes was verified
14	Hongying Dong et. al.	China	14	2018	Rectangular	Uniaxial	E/A	6	Lateral constraint stress,Tangent angle,Strain,Axial displacement, Bearing capacity	Proposed a bearing capacity calculation method
15	Jingming Cai et. al.	China	19	2018	Tubular	Axial, Cyclic	E	11	Confinement index,Sand-binder ratio,Deterioration coefficient,Water-binder ratio,Fiber content,	Hysteresis behaviour of Engineered Cementitious Composite CFST column was studied.
16	Jingming Cai et. al.	China	20	2018	Tubular	Eccentric	E	7	Thickness of the steel tube, Stirrup reinforcement ratio, Load eccentricity	The failure process and failure mechanisms for each column was investigated.
17	Lin-Hai Han	China	27	2018	Square and Circular	Axial	E	24	Correction factor, Ductility index	Compressive behaviour of CFST columns was compared with conventional ones
18	A.K.H.Kwan et. al.	China	23	2018	Square	Axial	A	92	Hydrostatic length,Code angle,Out of roundness,Friction parameter,Cohesion parameter	Parametric studies revealed better confinement effect with larger corner radius
19	Jingming Cai et. al.	USA	21	2018	Tubular	Axial	E	6	Confinement effect,Ductility index,Strain softening,Fiber content,Water binder ratio,Sand binder ratio,Steel tube ratio	A new calculation method was proposed and verified
20	Qian-YI Song et.al.	China	28	2018	Circular	Eccentric	E/A	7	Film thickness,Temperature	Effect of intumescent fire coating under ISO-834 standard fire was studied.
21	M.F.Hassanein et.al.	Egypt	13	2018	Octagonal	Axial	A	20	D/t ratio,Flow stress ratio,Dilation angle	The material constitution model for the confined concrete in octagonal CFST columns is presented
22	Y.Ouyang	Australia	25	2017	Circular	Eccentric	A	95	Cohesion Parameter, Friction angle	A new calculation

										method was proposed and verified
23	Ankur Tailor et al.	India	4	2017	Square and Circular	Static and dynamic	A	12	Lateral displacement	Square columns are better at lateral displacement
24	Farhad Aslani et. al.	Australia	11	2017	Tubular	Static	A/E	20	Buckling behaviour,Welds spiral geometry,Imperfections	Local buckling failure governs
25	J.C.M.Ho et. al.	Australia	15	2017	Circular	Eccentric	A	46	Normal stiffness Orientation angle,Flexural stiffness	A new FE model considering lateral dilation of concrete has been developed
26	Esra Mute Guneyisi et. al.	Turkey	7	2016	Circular	Static	A	15	Outer diameter of column,Thickness,Length of column	Proposed a design equation for axial load carrying capacity of CFST columns..
27	Shiyong Jiang et.al.	China	22	2016	Tubular	Blast	A	21	Blast condition,Column dimension,Steel ratio,Axial load ratio	Blast loads result in loss of bearing capacity to a certain extent due to the damage imparted.
28	Xiao-Ling Zhao et. al.	Australia	32	2016	Tubular	Cyclic	A	6	Longitudional reinforcement ratio, Stirrup characteristic value,Steel ratio	Proposed a moment-curvature hysteretic model for concrete-encased CFST columns
29	Cheng Quing Wu et. al.	Australia	10	2015	Tubular	Static and dynamic	E/A	8	Cross-section, Thickness, Deflection	A numerical model is developed for prediction of the structural responses of CFST columns.
30	G.Ganesh Prabhu et. al.	Korea	12	2015	Circular	Axial	A/E	21	Thickness,Height,Ductility index,Width to thickness ratio	CFRP strips were used to strengthen the CFST columns with two different spacing.
31	M.H.Lai et. al.	Australia	24	2015	Spiral	Uni-axial	E/A	38	Ductility,Thickness of steel tube,Diameter of steel tube	Proposed use of continous spirals in CFST columns
32	Xiushu Qu et. al.	China	34	2013	Rectangular	Eccentric	E	17	Concrete compressive strength,Steel strength,Cross-section properties,Eccentricity	A factor β was proposed to enhance the steel strength account for the concrete contribution to the resistance

CONCLUSIONS

Based on the study, so far carried out by several researchers, the following conclusions are drawn

- EC4 assumes full composite action between steel and concrete upto failure whereas,AISC-LRFD specifies shear limits based on suitable detailing.
- AISC-LRFD ignores the influence of creep of concrete.
- EC4 uses limit state concepts to achieve the aims of serviceability and safety by applying partial safety factor to loads and material properties.
- The AISC-LRFD expression for calculating the strength interaction between axial and flexural effects are based on bilinear interaction formulae which have the same form as those of hollow steel columns.
- CFST section provides high ductility, high strength, and stiffness properties.

- The behaviour of CFST columns under the performance of fire protection is not yet fully comprehended.
- There is a need to study the behaviour of CFST columns with addition of innovative concrete infilling materials such as geo-polymer concrete , self compacting concrete etc.

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