Concrete filled steel tubular columns-a critical review

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ABSTRACT

The State of the art of concrete filled steel tubular columns is presented in this paper. Experimental data has been collected and compiled in a comprehensive format listing parameters involved in the study. Areas of further research are presented and results of ongoing experimental and numerical investigations are also shown.

Introduction

Concrete-filled steel tubular (CFST) columns possess excellent earthquake-resistant properties such as high strength, high ductility, and large energy absorption capacity. In the last decades, they have gained increasing popularity in buildings, bridges and other structural applications.

The advantages of CFT columns can be attributed to the composite action between the steel tube and the concrete infill. The steel tube works not only as longitudinal reinforcing bars to resist the loads but also as ties or spirals to confine the concrete infill. Therefore, both strength and ductility of the concrete are enhanced. On the other hand, the risk of local buckling of the steel tube is significantly reduced because the rigid concrete infill prevents it from buckling inward. From the construction viewpoint, much economy can be achieved due to the absence of formwork, since the steel tube can serve as formwork for the infilled concrete during construction.

More mechanical and economical benefits can be achieved if CFT columns are constructed from high-strength materials. High-strength columns require a smaller cross-section to withstand the load, which is appreciated by architects and building engineers. In spite of the advantages, the application of high-strength CFT columns in the construction industry is still limited due to the lack of understanding of their structural behaviour and insufficient recommendations in current design codes. In order to fully utilize the advantages of high-strength CFT columns, research needs exist to extensively investigate their behaviour and to develop design specifications.

Composite columns

Types and structural performance

Composite columns include the following

- Fully encased: steel members with cross-sections fully encased in concrete;
- Partially encased: steel members with cross-sections partially covered by concrete;
- Concrete-filled: steel hollow sections filled by concrete.

Concrete, either reinforced or plain, prevents the onset of local buckling phenomena (Boyd et al., 1995). The latter typically affect bare steel structures and erode their stiffness, resistance and ductility. Local buckling is inhibited in fully encased members, while its occurrence is minimized in partially encased beam-columns. Additionally, steel confines concrete thus augmenting the compressive resistance, particularly in concrete-filled columns. The increase in resistance is generally limited for rectangular cross-sections, but is significant for circular sections.

The concrete shell ensures fire and corrosion resistance, especially for fully encased members in which the degradation of mechanical properties with high temperatures can be lowered (Cosenza et al., 1994; Nigro et al., 1998).

From the technological standpoint, composite columns generally exhibit easy of construction as they do not require formworks. Indeed, for concrete-filled members, concrete is cast within the steel shell, while in partially encased components, the cast is carried out horizontally and the element rotated to fill-up each side. Partially encased elements can be thus prefabricated in the workshop and completed on site by using special filler and/or joint devices.

In composite beam-columns, the detailing is of paramount importance. It may vary significantly as a function of the cross-section and the type of composite members. Quality of concrete cast, shrinkage, loading condition, e.g. static and/or cyclic, and load transferring affect structural response of composite beam-columns.

Circular Concrete-Filled Steel Tubes

Circular tubular columns have an advantage over all other sections when used in compression members, for a given cross-sectional area, they have a large uniform flexural stiffness in all directions. Filling the tube with concrete will increase the ultimate strength of the member without significant increases in cost. The main effect of concrete is that it delays the local buckling of the tube wall and the concrete itself, in the restrained state, is able to sustain higher stresses and strains that when is unrestrained.

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The use of CFTs provides large saving in cost by increasing the lettable floor area by a reduction in the required cross-section size. This is very important in the design of tall buildings in cities where the cost of letting spaces are extremely high.

These are particularly significant in the lower storey of tall buildings where stubby columns usually exist.

CFTs can provide an excellent monotonic and seismic resistance in two orthogonal directions. Using multiple bays of composite CFT framing in each primary direction of a low- to medium-rise building provides seismic redundancy while taking full advantage of the two-way framing capabilities of CFTs [1].

Research on Concrete Filled Tubular Columns

Experimental research on CFT columns has been ongoing worldwide for many decades, with significant contributions having been made particularly by researchers in Australia, Europe, and Asia. The vast majority of these experiments have been on moderate scale specimens (less than 200 mm in diameter) using normal and high-strength concrete. Neogi et al. [2] investigated numerically the elasto-plastic behaviour of pin ended, CFT columns, loaded either concentrically or eccentrically about one axis. It was assumed complete interaction between the steel and concrete, triaxial and biaxial effects were not considered. Eighteen eccentric loaded columns were tested, in order to compare the experimental results with the numerical solution. The conclusions were that there was a good agreement between the experimental and theoretical behaviour of columns with L/D ratios greater than 15, inferred that triaxial effects were small for such columns. Where for columns with smaller L/D ratios, it showed some gain in strength due to triaxial effect A series of tests had been carried out by O'Shea and Bridge [3] on the behaviour of circular thin-walled steel tubes. The tubes had diameter to thickness ratio D/t ranging between 55 and 200. The tests included; bare steel tubes, tubes with unbounded concrete with only the steel section loaded, tubes with concrete infill with the steel and concrete loaded simultaneously and tubes with concrete infill loaded alone. The test strengths were compared to strength models in design standards and specifications. The results from the tests showed that the concrete infill for the thin-walled circular steel tubes have little effect on the local buckling strength of the steel tubes. However, O'Shea and Bridge [4] found that concrete infill can improve the local buckling strength for rectangular and square sections. Increased strength due to confinement of high-strength concrete can be obtained if only the concrete is loaded and the steel is not bonded to the concrete. For steel tubes with a D/t ratio greater than 55 and filled with 110–120 MPa high-strength concrete, the steel tube provides insignificant confinement to the concrete when both the steel and concrete are loaded simultaneously. Therefore, they considered that the strength of these sections can be estimated using Eurocode 4 with confinement ignored. The influence of local buckling on behaviour of short circular thin-walled CFTs has been examined by O'Shea and Bridge [4]. Two possible failure modes of the steel tube had been identified, local buckling and yield failure. These were found to be independent of the diameter to wall thickness ratio. Instead, bond between the steel and concrete infill determined the failure mode. A proposed design method has been suggested based upon the recommendations in Eurocode 4 [5].

Kilpatrick et al. [6,7] examined the applicability of the Eurocode 4 for design of CFTs which use high-strength concrete and compare 146 columns from six different investigations with Eurocode 4. The concrete strength of the columns ranged from 23 to 103 MPa. The mean ratio of measured/predicted column strength was 1.10 with a standard deviation of 0.13. The Eurocode safely predicted the failure load in 73% of the columns analysed. Brauns [8] stated that the effect of confinement exists at high stress level when structural steel acts in tension and concrete in compression and that the ultimate limit state of material strength was not attained for all parts simultaneously. In his study, the basis of constitutive relationships for material components, the stress state in composite columns was determined taking into account the dependence of the modulus of elasticity and Poisson's ratio on the stress level in the concrete. O'Shea and Bridge [9] tried to estimate the strength of CFTs under different loading conditions with small eccentricities. All the specimens were short with a length-to-diameter ratio of 3.5 and a diameter thickness ratio between 60 and 220.

The internal concrete had a compressive strength of 50, 80 and 120 MPa. From those experiments, O'Shea and Bridge concluded that the degree of confinement offered by a thin-walled circular steel tube to the internal concrete is dependent upon the loading condition. The greatest concrete confinement occurs for axially loaded thin-walled steel with only the concrete loaded and the steel tube used as pure circumferential restraint. Euro code 4 has been shown to provide the best method for estimating the strength of circular CFTs with the concrete and steel loaded simultaneously.

Georgios Giakoumelis, Dennis Lam proposed an equation with a co-efficient for the ACI/AS equation to take into account the effect of concrete confinement on the axial load capacity of concrete filled steel tube, a revised equation was proposed as follows:

$$NU = 1.3\ Ac\ f\ c\ + As\ fy$$

Where Nu= Predicted Failure load

Research On Self Compacting Concrete Filled Tubular Columns

In recent years, the use of self-consolidating concrete (SCC), or self-compacting concrete, in such kinds of columns has been of interest to many structural engineers. Due to its rheological properties, the disadvantage of vibration can be eliminated while still obtaining good consolidation. Apart from reliability and constructability, advantages such as elimination of noise in processing plants, and the reduction of construction time and labor cost can be achieved. It is expected that SCC will be used in concrete-filled HSS columns in the future because of its good performance. However, the composite members are susceptible to the influence of concrete compaction.

The self-compactability of concrete refers to the capability of the concrete to flow under its own weight and fill in the formwork in casting process.

Experimental research on CFT columns using self-compacting concrete has been ongoing worldwide for last decade.

i) Lin Hai Han, Guo Huang Yao (2004) examined 38 HSS to investigate the influence of concrete compaction methods on the member capacities of the composite columns are reported. The specimen tests allowed for the different conditions likely to arise in the manufacture of concrete: cured, well compacted with a poker vibrator, well compacted by hand, and self-consolidating without any vibration. The main parameters varied in the tests are: (1) column section type, circular and square; (2) tube diameter (or depth) to thickness ratio, from 33 to 67; and (3) load eccentricity ratio (e=r), from 0 to 0.3 mm.

The main objectives of this research were threefold. The first was to report a series of new tests on composite columns filled with SCC. The specimen tests allowed for the different conditions likely to arise in the manufacture of concrete: cured, well compacted with a poker vibrator, well compacted by hand, and self-consolidating without any vibration. The Second was to compare the predicted ultimate strengths using existing codes such as AIJ , AISC-LRFD , BS5400, DL/T5085-1999 , EC4 and GJB4142-2000 . The final objective was to evaluate the possibility of using SCC in thin-walled HSS columns in practice.

Based on the results of this study, the following conclusions was drawn within the scope of these tests:

1. It was found that the features of the specimens with SCC compacted without any vibrations, with SCC compacted with a poker vibrator and with SCC compacted by hand was very similar.

2. The stub columns with SCC compacted without any vibration had a section capacity value slightly lower than but comparable to the specimens with concrete compacted with a poker vibrator.

3. Good concrete compaction resulted in slightly higher beam-column member capacities. It was found that, in general, the ultimate strengths (Nue) of the members compacted with a poker vibrator were 1.4–6.8% and 8.3–14% higher than those of columns of circular section with concrete compacted by hand and compacted without any vibration, respectively. For the composite columns of square section, the ranges were 1.4–6.3% and 10.7–11.6%, respectively. Quality control in the pouring of concrete is very important in achieving good strengths for long HSS beam-columns filled with SCC.

4.Comparisons were made with predicted column strengths using existing codes such as AIJ (1997), AISC-LRFD (1999), BS5400 (1979), DL5085/T-1999 (1999), EC4 (1994) and GJB4142-2000 (2001). It was found that generally, these codes are acceptable for the design of the ultimate strength of HSS columns filled with SCC.

ii) H. El Chabib, M. Nehdi, M.-H. El Naggar (2005)

A total of 36 cylindrical specimens were prepared and tested in this study. Eighteen 150 • 300 mm (6 • 12 in.) short cylindrical specimens were tested under uniaxial compression to investigate the confinement effect of GFRP on axially loaded normal concrete and self-consolidating concrete made with either ordinary Portland cement (OPC) or expansive cement (EC). Eighteen 150 • 1100 mm (6 • 43 in.) cylindrical specimens were tested under transverse load to investigate the confinement effect of GFRP tubes on normal concrete and SCC subjected to transverse loading along the effect of using expansive cement and a shrinkage-reducing admixture on the interfacial contact and slippage between the concrete and the confining tube. Short cylindrical specimens tested in compression included six plain concrete control cylinders (three NC and three SCC) and 12 concrete cylinders confined by GFRP tubes. The confined specimens included three cylinders made of normal concrete using OPC, three cylinders made of SCC using OPC, and three cylinders of each (NC and SCC) made using expansive cement. Similarly, the specimens tested under transverse load included six plain concrete control specimens (three NC and three SCC) and 12 specimens confined in GFRP tubes (3-OPC-NC, 3-OPC-SCC, 3-expansive-cement-NC and 3-expansive-cement-SCC). The following conclusions was drawn from this investigation:

1. SCC-filled GFRP tubes had a comparable behavior to that of NC filled-GFRP tubes under both uniaxial compression and transverse load.

2. The most significant difference between the behavior of NC and SCC-filled GFRP specimens was in the transition region of the response curves, in which the shift from a linear to a non-linear behavior in the load–deformation and stress–strain curves subsequent to the failure of the concrete core was more sudden for the tested SCC-filled GFRP specimens.

However, the use of an expansive cement and a shrinkage-reducing admixture made the behavior of SCC-filled GFRP tubes similar to that of NC-filled GFRP tubes.

3. The use of expansive cement in concrete delayed the occurrence of slippage between the GFRP tube and the concrete core, creating a somewhat better interfacial contact between the two materials, but did not fully prevent slippage. Likewise, the use of localized lateral steel bars placed through the GFRP tube and concrete core did not prevent slippage. Shear connectors or ribs placed inside the GFRP tubes may provide better performance.

4. GFRP tube confinement of concrete cylinders increased their ultimate load by 2.5 times and their axial deformation at failure by 12 times under uniaxial compression. It also enhanced their ultimate load by 20 times and their mid-span deflection at failure by 100 times under transverse load.

5. Self-consolidating concrete–GFRP composites offer an easy to construct and corrosion-free alternative to the construction of deep pile foundations, columns,etc. Further research is needed to investigate their large-scale field implementation and performance.

iii) Lin-Hai Han, Guo-Huang Yao, Xiao-Ling Zhao(2005) conducted on experiments a total of 50 specimens were tested

The main objectives of this research were fourfold. First, to report a series of new tests on composite columns filled with SCC. Second, to analyse the axial load versus axial deformation behaviour for concrete-filled HSS stub columns based on the unified theory, which was presented by Han and Han et al. . Third, to develop a simplified model for calculating the sectional capacity   the axial load versus axial deformation relationships of the composite stub columns. And fourth, to compare the predicted ultimate strengths using the existing codes, such as ACI , AIJ , AISC-LRFD, BS5400 and EC4 .

A total of 50 Specimens were tested. The main parameters varied in the tests were : (1)sectional types: circular and square; (2) steel yielding strength: from 282 to 404 MPa; and (3) tube diameter or width to wall thickness ratio (D/t or B/t): from 30 to 134.

On the basis of the results of this study, the following conclusions were drawn within the scope of these tests:

(1) 50 stub column test results, with a wide range of diameter (width)-to-thickness ratio for HSS sections filled with SCC, were reported in this paper.

(2) A simplified model is developed for calculating the section capacity and the axial load versus axial deformation relationships of the composite stub columns.

(3) Comparisons are made with predicted section capacity using existing codes, such as ACI-1999, AIJ-1997, AISC-LRFD-1999, BS5400-1979 and EC4-1994. It seems that
the conclusion regarding predictions using existing design codes made for NC-filled HSS stub columns remains the same for SCC-filled HSS stub columns.

(4) The test results were compared to examine the limiting diameter (width)-to-thickness ratio for the composite columns. It was found that, from the viewpoint of the maximum strength, the current limitation of diameter (width)-to-thickness ratio in

AIJ-1997, i.e.the limit value of 1.5 times that of unfilled steel tube, is appropriate.

iv) S. Ramana Gopal, P. Devadas Manoharan(2006) Conducted the experimental study 0n twelve slender steel tubular columns of circular sections filled with both plain and fibre reinforced concrete. The specimens were tested under eccentric compression to investigate the effects of fibre reinforced concrete on the strength and behaviour of slender composite columns. The slenderness ratio was considered to be the main test parameter. Hollow steel sections of similar specimens were also tested as reference columns.

The results obtained from the tests conducted on slender composite columns had following conclusions drawn.

1. The use of FRC has resulted in considerable improvement in the structural behaviour of slender composite columns subjected to eccentric loading.

2. The slenderness ratio has a very remarkable effect on the strength and behaviour of CFST columns under eccentric loading. The contribution by the FRC to the load capacity was most favorable for columns with large slenderness ratio.

3. FRC filled steel tubular columns has relatively high stiffness compared with plain concrete filled columns.

4. The ductility is found to be almost equal for both plain and FRC filled steel tubular columns.

5. The use of FRC in the steel tube results in an enhanced energy absorption capacity of the composite columns.

6. The use of FRC as a filling material increases the load bearing capacity to a much greater extent compared with that of unfilled columns and reduces the lateral displacements

v) P.K. Gupta, S.M. Sarda, M.S. Kumar (2007) conducted tests on Eighty-one specimens to investigate the effect of diameter and D/t ratio of a steel tube on the load carrying capacity of the self compacting concrete filled tubular columns. The effect of the grade of concrete and volume of flyash in concrete was also investigated. The effect of these parameters on the confinement of the concrete core was also studied. Diameter to wall thickness ratio between 25 < D/t < 39, and the length to tube diameter ratio of 3 < L/D < 8 was investigated. Strength results of Concrete Filled Tubular columns were compared with the corresponding findings of the available literature. Also a nonlinear finite element model was developed to study the load carrying mechanism of CFTs using the Finite Element code ANSYS.

The Following conclusions are drawn,

1) In the CFT columns, which fail essentially by local buckling, as the concrete strength increases the confinement effect of the concrete core decreases.

2. The failure mode of the 50 mm diameter CFT specimen was found to be Euler buckling and the deflected shape matches with the experimental deformed shape.

3. It was seen that for smaller D/t ratio, a steel tube provides good confinement effect to concrete.

4. From the bare tube results it was observed that the load carrying capacity of the steel tube per unit volume decreases as the D/t ratio increases. Hence it is suggested to fix the correct D/t ratio in order to make optimum usage of the material.

5. It was observed that at a given deformation the energy absorbing capacity decreases with the increase in flyash up to 20% but at 25% flyash it again increases

v) Qing Yu, Zhong Tao, Ying-Xing Wu (2008)

Twenty-eight specimens, including eight stub columns and 20 beam-columns were tested. Based on the results of the study the following conclusions can be drawn:

(1) Failure mode of square stub column was local (outward folding) failure mechanism, while that for circular stub columns was a shear failure mode. Typical failure mode for beam-columns was overall buckling failure.

(2) The ductility for very high strength SCC filled steel tubes is generally smaller than that for normal strength concrete filled steel tubes, especially for axially loaded columns. Thus particular attention should be paid when used in seismically active regions.

(3) Comparisons are made with predicted section capacity using the existing codes, such as AISC [11], EC4 [12] and DBJ13-51-2003 [13]. It was found that generally, these codes are acceptable for prediction of the member capacities of high strength SCC filled HSS columns. However, it seems some codes do give slightly higher predictions on the member capacities of columns with square sections.

vi) Muthu.K.U, Ravi Kumar.H and. Kumar N.S (2011)

This paper presents an analytical study on the behaviour and ultimate load carrying capacity of axially compressed concrete filled steel tubular columns. Two theoretical Equations were derived for the prediction of the ultimate axial load strength of concrete filled steel tubed columns .The results from prediction were compared with the experimental data. Validation to the experimental results was made. The detailed experimental data and material properties employed in this study are based on Previous experimental data by the researchers (10-15). About 213 samples data was taken for formulating a mathematical model relation, the following relations were obtained.

1)Based on Compressive strength of Concrete, Area of Concrete, Yield Strength of Steel, Area of Steel the following relation has been obtained for predicting the failure load

P the$= C\ A_c\ f_c + A_s\ f_y$,………………………… (Equation 1)

Where *C=1.18 Constant, which is obtained by previous experimental data of researchers.

*Individual C Values are worked out by using equation P the$= C\ A_c\ f_c + A_s\ f_y$ equating to P exp

Therefore $C = (P\ exp\ x\ 1000 - A_s\ f_y)\ /\ A_c\ f_c$ and average value of C is worked out from 213 sample data of previous experimental data of the researchers.

2) Based on External diameter of Tube, Thickness of Tube, Yield Strength of Steel and Compressive Strength of Concrete the following relation has been obtained for predicting the failure load

P the$= 1.71C(D/t)^a\ (f_y/f_{ck})^b\ A_c f_c + A_s f_y$ …..... (Equation 2)

Where a & b are constants. Based on multiple regression analysis a & b were found a = -0.35,b=0.45 and new average value of C is obtained as 0.60.

The Following conclusions were drawn 1) Based on Compressive strength of Concrete, Area of Concrete, Yield Strength of Steel, Area of Steel the following relation has been obtained for predicting the failure load

P the$= C\ A_c\ f_c + A_s\ f_y$ where C=1.18 Constant was evaluated.

2)Based on External diameter of Tube, Thickness of Tube, Yield Strength of Steel & Compressive Strength of Concrete the following relation has been obtained for predicting the failure load P the$= =1.71C\ (D/t)^a\ (f_y/f_{ck})^b\ A_c\ f_c + A_s\ f_y$ where a & b are constants. Based on multiple regression analysis a & b were found a=-0.35, b=0.45 and new average value of C is obtained as 0.60.

3)Based on formula Predicted equation 1 the average of Predicted Theoretical Load /Experimental load for 213 Data is 1.01 and co-efficient of Variation is 0.30. Hence the formula may be used for predicting the load carrying capacity.

4)Based on formula predicted equation 2 the average of Predicted Theoretical Load /Experimental load for 213 Data is 0.92 and coefficient of Variation is 0.21. Hence this formula may be used for predicting the load carrying capacity.

Conclusions

Considerable progress has been made during the last two decades in the investigation of steel–concrete composite columns and use of self-compacting concrete, and information available is summarized in this paper. Fundamental knowledge on composite construction system such as ultimate strength has already been obtained by the research carried out so far.

Based on work done by S.Ramana Gopal &P.Devardas Manoharan . FRC filled steel tubular   columns have relatively high stiffness compared   with plain concrete filled columns. The ductility   was found to be almost equal for both plain and   FRC filled steel tubular columns, The use of FRC in   the steel tube results in an enhanced energy absorption capacity of the composite columns. The use of FRC as a filling material increases the load bearing capacity to a much greater extent compared with that of unfilled columns and reduces the lateral displacement.

Thus there is need of using self-compacting concrete with steel fibres as infill in tubular columns and study their effects of FRC on the strength and   behaviour of composite columns

Based on the literature review & codes such as AISC-LRFD (1991), ACI-318 (2002), Eurocode-4 (1994), BS-5400 (BS 11979) have incorporated simplified methods for analysis and design of composite columns. But these provisions are generally extrapolated from either R.C.Column/Steel column design codes which indicate further numerical and experimental research is a much to understand about structural behavior of these elements. Intensive research is required on the interaction between steel and concrete, the effect of concrete restraining local buckling of steel plate elements, effect of steel section, confining concrete, etc. Research is underway to develop a more sophisticated analytical tool to include other important factors, such as local buckling effect of steel tube and the strain hardening or softening of the materials.

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