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Concrete Filled Steel Tubular (CFST) Columns in Composite Structures

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Abstract: *RCC and steel frames have been the most common frame systems for long times whereas composite frame system has also emerged as popular system for high rise buildings for few decades. Multi-storey composite frames are generally composed of structural steel members made composite with concrete. The use of concrete filled steel tubes (CFST) in building construction has seen renaissance in recent years due to their numerous advantages, apart from its superior structural performance making a typical composite frame structure. Their usage as columns in high-rise and multi-story buildings, as beams in low-rise industrial buildings and as arch bridges, has become extensive in many countries in last four decades with abundant examples. But, their usage in India is a new concept. Hence, this paper shall primarily emphasis to investigate the various aspects of CSFT members in the building industry; primarily considering the various aspects of these members which have turned its unique phase with the advancement of technology.*
Keywords *- concrete filled steel tubes, CFST Columns, composite frames and confinement*

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I. Introduction

A simple definition of structural system in context with building is, "a system of connected members to support the load that results from the usage of building or only presence of building to the ground". There are several structural systems according to purpose, size, scale and loading to which the building is subjected to. Moment resisting frame is foremost one amongst all the structural systems. Various materials are used to make columns and beams which are vital components of any structural system. Concrete and steel are pioneer materials amongst these. The choice of material depends upon numerous factors like type and purpose of building, size of building, availability of materials, topography of land, climatology and budget. RCC and steel frames have been the most common frame systems for long times whereas composite frame system has also emerged as popular system for high rise buildings for few decades. Multi-storey composite frames are generally composed of structural steel members made composite with concrete. The use of concrete filled steel tubes (CFST) in building construction has seen renaissance in recent years due to their numerous advantages, apart from its superior structural performance making a typical composite frame structure. Their usage as columns in high-rise and multi-story buildings, as beams in low-rise industrial buildings and as arch bridges, has become widespread in countries like China and many other countries in last few decades with abundant examples. But, their usage in India is a new concept. Hence, this study shall primarily emphasis to investigate the various aspects of CSFT members as beams and columns and as part of frames in the building industry; primarily considering the various aspects of these members which have turned its unique phase with the advancement of technology.

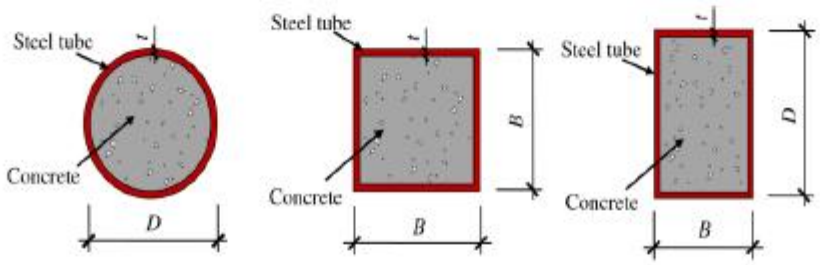
1.1 Various Types of CFST Columns

There are two types of composite columns generally used in buildings, steel section encased in concrete and steel section in-filled with concrete. A concrete filled steel tubular (CFST) structure consists of steel tube of square, rectangular or circular cross-section filled with plain or reinforced concrete. Various forms of latter type of CFST composite columns are represented in Fig. 1. Following are the various types of CFST columns:

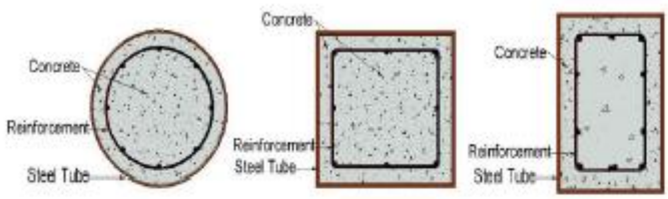
- i Composite column systems
- ii Reinforced composite column systems
- iii Concrete-filled double skin tubes (CFDST)
- iv Reinforced Concrete-filled double skin tubes (CFDST)
- v Concrete-encased CFST columns
- vi Stiffened CFST columns

Concrete filled steel tubular (CFST) members comprise of a steel hollow section of circular or rectangular shape filled with plain or reinforced concrete. They exploit the advantages of both steel and concrete. They are extensively used in high-rise and multistory buildings as columns and beam-columns, and as beams in low-rise industrial buildings where a strong and efficient structural system is required.

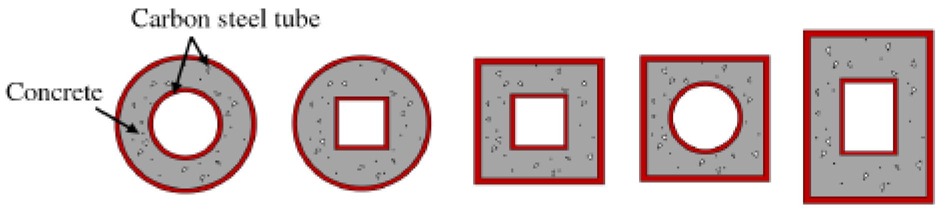
The hollow tubes are designed in such a way that they are capable of supporting the floor load up to three or four floors. The hollow steel tubes are either fabricated or rolled to be erected first to support the construction load of the upper floors. Such structural system has the additional advantage of both steel and reinforced concrete frame. It has the structural stiffness and integrity of a reinforced concrete structure. The ease of erection and handling of a structural steel members make possible to explore new possibilities of construction. After the completion of upper floors, the concrete is pumped into the tubes from the bottom. To facilitate easy pumping the tubes are continuous at the floor level. With the help of contemporary pumping technology and self-compacting concrete, pumping of concrete up to three to four storey is easily achievable. Due to the simplicity of the construction sequence, the structure can be completed at a great pace.



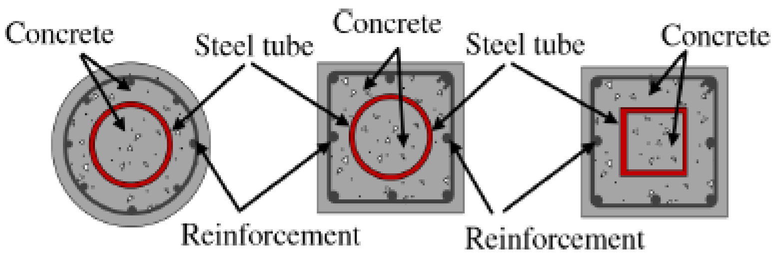
(a) Various forms of typical simple composite column systems



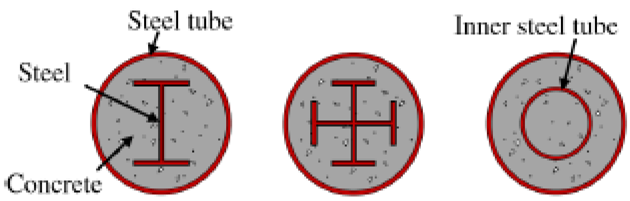
(b) Various forms of typical reinforced composite column systems



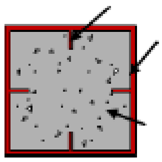
(c) Concrete-filled double skin tubes (CFDST)



(d) Reinforced Concrete-filled double skin tubes (CFDST)



(e) Concrete-encased CFST columns



(f) Stiffened CFST columns

Fig. 1 Various types of CFST members

The application of CFST structures has emerged as a popular structural system in recent years as they construct a strong and efficient structural system with the advantage of both steel and reinforced concrete frame. CFST structural system has numerous advantages.

1.1.1 Advantages of CFST structural system

There are a number of distinct advantages related to such structural systems in both terms of structural performance and construction system. The distribution of materials in the cross section also makes the system very efficient in term of its structural performance. The steel lies at the outer perimeter where it performs most effectively in tension and bending. It also provides the greatest stiffness as the material lies furthest from the centroid. This, combined with the steel's much greater modulus of elasticity, provides the greatest contribution to the moment of inertia. The essential buckling problem related to thin-walled steel tubes is either prevented or delayed due to the presence of the concrete core. Furthermore, the performance of the concrete in-fill is improved due to confinement effect exerted by the steel shell. The concrete core gives the greater contribution to resisting axial compression. Comparison of axial compressive behavior of CFST stub column done by Han et al. (2014) is presented in figure 2.

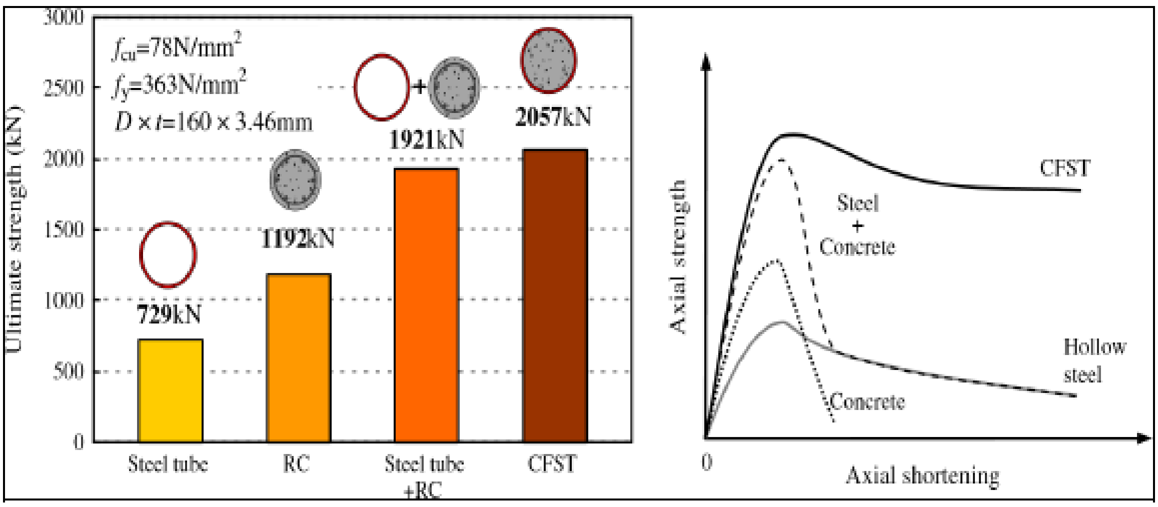


Fig.2Axial Compressive Behavior of CFST Stub Column (Han et al. 2014)

The main advantages of CFT structural system in comparison with ordinary steel or reinforced concrete system are listed below.

Improvement of Structural Performance

Due to material properties:

i The steel tube acts as an external reinforcement. The steel ratio in the CFST cross section is much higher than those in the reinforced concrete sections.
ii Steel of the CFST section is well plasticized under bending since it is located on the outside of the section.
iii The improvement of properties of the concrete in-fill is enhanced due to confinement pressure exerted by the steel tube.
iv The characteristic buckling problem of thin-walled steel tubes is controlled due to the presence of the concrete in-fill and the strength deterioration after the local buckling is decreased due to the restraining effect of concrete.
v Shrinkage and creep of concrete are much smaller than ordinary reinforced concrete.

Due to Geometrical properties:

i It provides the maximum stiffness as the material lies farthest from the centroid and provides the greatest contribution to the moment of inertia.
ii The steel as the outer part of core concrete performs most effectively both in tension and bending. whereas the concrete core gives the greater contribution to resisting axial compression.

Improvement of Constructional Performance

During fabrication:

i They are simple to fabricate and construct compared to conventional reinforced concrete, where skilled workers are needed to cut and bend complex forms of reinforcement.
ii Steel tube of CFST columns are generally less than 40 mm thick and easily available. Hence, are convenient to fabricated and assemble.
iii The constructional procedure is fast due to easy handling and erection.

During Construction:

i Formwork is not required as the steel tube acts as permanent formwork thus saving costly and time-consuming formwork.
ii Casting of concrete is done by pumping method, which saves both the manpower and constructional cost and time.
iii The infill concrete is less likely to be affected by adverse temperature and winds.
iv The infill concrete is generally cured quickly.
v Erection schedule is not dependent on concrete curing time.

During finishing:

i Reduced construction depth, in turn, reduces the storey heights, foundation costs, paneling of exteriors, heating, ventilating and air-conditioning spaces.
ii The concrete filling is protected against mechanical damage.
iii Slender columns reduce the application time and cost of applied finishes.

Improvement of Post Constructional Performance:

i Concrete improves the fire resistance performance, and the amount of fireproof material can be reduced or its use can be omitted.
ii The seismic behaviors of CFST column are better than that of steel column.
iii They exhibit better corrosion resistance capability than steel columns.

Larger spans of columns and beams:

i The larger spans of columns can be opted resulting in more inside space. The size of CFST column is smaller than that of RC column, hence, usable floor area and visibility is increased.
ii The span of frame beam 7-8m even more can be used as steel beams are used as beams.
iii Aesthetically pleasing

Foundations

i The foundations are reduced with the reduction of columns size; hence, the economic benefits are more. Owing to the large span of columns, the vertical loads acting on columns are increased and the compressive bearing capacity of CFST columns can be brought into play adequately.

ii The CFST columns are lighter than that of RCC columns. As a result, the foundation cost is reduced and the resulting earthquake force is also reduced. CFST columns are safer and more dependable in the seismic regions as generally the high-strength concrete is used and the brittle failure can be prevented.

Cost reduction

i The dimension of CFST column is nearly with the outline dimension of a steel column. Hence, the space occupied by CFST column is not more than that of a steel column making it equivalent in terms of space.

ii Further, as the volume of core concrete of CFST column is about 10% of total volume of the column and the density of concrete is one-third of the density of steel. Thus, the weight of CFST column does not more than that of a steel column.

iii The lesser concrete is used in CFST columns and lesser steel is required than that in RC columns. This reduces the carbon footprint on the environment.

iv CFST columns use approximately half the steel in comparison with a steel column. This decreases the cost to a larger extent making it very efficient and judicious to use.

v The cost of transportation and assembly of columns is reduced because they are built by erecting the hollow steel tube first, then pouring concrete into it.

vi These structures need low maintenance.

Because of the merits listed above, a better cost performance is obtained by replacing a steel or RCC structure by CFT structure. Major drawback of the traditional CFT system is the compactness of concrete around the beam-to-column connection, especially in the case of inner and through type diaphragms. But self-compacting concrete is common construction practice these days to cast a high-quality concrete with low water content and good workability by the use of a super plasticizers.

1.1.2 As Sustainable Construction

A 'green' building is one that optimizes energy efficiency, conserves natural resources, generates less waste and provides healthier spaces for occupants, as compared to a conventional building. These days, there is increasing pressure to build all living and working spaces in such a way minimum use of scarce resources like energy and water is there and least societal as well as environmental impact take place. The environmental burden can be reduced by omitting the formwork, and using concrete made from recycled aggregates. CFST system has all the merits which bring it into the category of Sustainable Construction system as it reduces the cost of construction in many ways mentioned above and below helps to save resources. Above all steel which is a major constituent material of CFST frame, itself being almost totally recycled material is a green material.

1.1.3 Application of CFST sections

The application of CFST in tall buildings has been adopted in the form of partial columns in early days, then their usage as full columns was adopted. This process has been very short, only a decade long. There is no staying area for construction. It made the construction rather difficult. There are a lot of new technology and experiences in design, fabrication, and construction of this building. It offers a good example of the adoption of CFST columns in super tall buildings. It can also promote the development of CFST structures in our country to a higher level.

The first engineering adopted CFST structure is the No.1 subway of Beijing. All the columns for Beijing No.2 subway. The steel ingot work- shop of Benxi steel company built in 1972, was the first industrial building with CFST columns. The highest tall building which adopted CFST is Shenzhen SEG Plaza building was completed in 2000. It is the highest one in China and abroad. The CFST members were used as the external columns of the frame as well inside as concrete shear walls. The diameter of the columns used in the building ranges from 900mm to 1600mm. They were brought to the site in lengths of three storeys and concrete was poured from the top of the column. The critical design loads for the SEG Plaza building were seismic and wind loads. Therefore, rigid connections between the steel beams and the concrete filled tubes were used. A CFST Arch Bridge was also constructed in china, of the span 115m over the china's Wenchang river.

The Canton tower is one of the most spectacular structures of recent times built using CFST members. With a height of 612m becomes the highest TV tower in the world, surpassing the CN Tower in Toronto with 553m. The entire tower was completed in 2010 and put into operation for the Asian Games that year.

According to incomplete statistics, at present, there are over 200 constructed engineering adopted CFST structures in China. In India use of steel buildings is still at infancy stage. The cost factor is the main influencing factor behind. But in today's scenario, when green buildings have become the focus of designers, CFST structures can be a better alternative to traditional structures of concrete and steel structures due to their numerous potentials.

II. Historical Development

The research work on concrete-filled steel tubular structures can generally be classified as the research dealing with members, connections/joints and structural systems. These studies aim to provide design formulas and recommendations, to improvise the design codes or standards, and to encourage the applications of this composite structures in real civil engineering projects.

1.2.1 CFST Columns

Many studies have been carried out to investigate the behaviour of CFST columns subjected to various types of loadings. Furlong (1967), Knowles and Park et al (1969), Neogi et al (1969) and Tomii et al (1977) are some of the earliest researchers who studied the behavior of concrete filled steel tubular columns subjected to concentric compression and observed that the compressive strength enhances due to concrete confinement and the yield strength of steel tube decreases due to the development of hoop stresses in the steel tube.

In past two decades, experimental and theoretical studies, researchers concluded that the ultimate load of circular CFSTs is significantly larger due to the confinement of the concrete and strain hardening of the steel. Knowles and Park (1969) proposed a value of 44 for KL/r (the ratio of effective length to radius of gyration) approximately equal to L/D of 12. Above this value confinement does not occur. Bridge et al (1995) have agreed with a slenderness ratio equal to 15 as this boundary.

Many research projects on the ultimate capacity of rectangular CFST columns have also been carried. Fujimoto et al. (1995) and Uy (2001) carried out an experimental study for square CFST columns with high strength steel. Furthermore, Uy (2001) investigated the effect of local buckling due to geometrical imperfections and residual stresses. Han (2002) performed tests on 24 rectangular short composite columns with varying H/t or B/t and L/H and concluded that the ultimate capacity was influenced by the confining factor, material properties and aspect ratio.

The square/rectangular columns are preferred over the circular columns by the designers due to architectural reasons despite of their excellent mechanical behavior because of more effective the confinement effect and better post-yield behaviour than square CFST columns (Schneider,1998). Most importantly the beam to column connections are more convenient for square/ rectangular CFST columns than for circular columns, and the stiffness of square CFST columns is more than circular columns with a same sectional size as a whole.

1.2.2 CFST sections as flexural members

Many researchers have investigated the concrete filled tubular sections subjected to flexural loads for better prediction. Zhang et al. (1994), Zhao et al. (1999, 2002), Elchalakani et al. (2001), and Han et al. (2004) conducted experiments on concrete filled steel tubes to predict flexural behaviour of CFST members. They obtained that filling of steel hollow tube with concrete increased the flexural strength. Liang et al. (2005), used the finite element method to investigate the flexural and shear strengths of simply supported composite beams under combined bending and shear. The test conducted by Prabhavathy et al. (2006) in filled frames, showed that concrete in-filled beams give additional stiffness, which further delays the failure of the columns. Kang et al. (2007) carried experimental investigations of the flexural behavior of CFST members, with variety of the filling material and concluded that concrete-filled steel tube girders have good ductility and maintain their strength up to the end of the loading. Arivalagan et al. (2008, 2010) experimentally studied the behaviour and ultimate moment capacity of unfilled and concrete-filled rectangular hollow sections subjected to cyclic reversible loading to study the effect of filler materials, section slenderness, load-deflection response, moment-strain behaviour, ductility, stiffness degradation and energy absorption of concrete -filled RHS beams.

The results of mentioned studies conclude that filling of steel tube with concrete enhances the flexural strength, moment carrying capacity and stiffness. It prevents the local buckling of the steel shell, and it also contributes to the inertia of the section and internal forces, which increases the flexural strength and stiffness of the member.

1.2.3 CFST Frames

Multi-storey composite frames are commonly composed of structural steel members made composite with concrete. In fact, most multi-storey steel construction makes use of composite action in the column members. Therefore, in order to consider the exact behaviour of the CFST frame, the composite action between steel and concrete should not be ignored. Previous research on advanced analysis in steel framed structures is limited in its application. Several state of the art reports or papers have been published on CFST structures, such as Shams and Saadeghvaziri 1997, Shanmugam et al.2001, Gourley et al. 2001 and Nishiyama et al. 2002

Whereas many studies have been done to assess the performance of CFST sections subjected to flexural loads. No study is available in literature where CFST members beam and columns are used as part of CFST composite frame. Though many studies are available for CFST composite frames in which CFST columns and steel beams are part the frame.

III. Gaps In The Research Area

Many researchers have proved the usefulness of CFST columns as columns whereas many have tested these sections under flexural loads successfully and concluded that filling of steel tube with concrete enhances the flexural strength, moment carrying capacity and stiffness. But CFST sections have not been used as part of frames. The literature available reveals that all the studies carried on such frames use CFST column with open section steel beams. No study of the behaviour of CFST column connected to CFST beams is available.

It has been observed from the literature review that relatively few researchers have performed finite element analysis of square/rectangular CFST sections. So, there is a requirement of FEM based numerical model to model and investigate the true behaviour of these incredibly useful sections.

Finite element methods are the most effective way to study the behaviour of CFST structures because the experimental method is highly expensive and time-consuming even though it provides dependable results about the performance of CFST structures. Hence, more studies are required for the development of such kind of methods. The behaviour of composite frames is not fully understood hence the requirement for accurate and reliable analysis of a composite frame is very clear.

Though many studies are available for CFST composite frames in which CFST columns and steel beams are part the frame, very limited research is available in literature where CFST members beam and columns are used as part of CFST composite frame.

IV. Conclusions

The paper discusses the basic properties and theoretical information about the behaviour of CFST columns at all stages, in brief. The paper also includes the few projects which include the application of CFST columns around the world. In India use of steel buildings is still at infancy stage. The cost factor is the main influencing factor behind. It can be concluded that in today's scenario, when green buildings have become the focus of designers, CFST structures can be a better alternative to traditional structures of concrete and steel structures due to their abundant advantages.

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