Annual Sessions of IESL, pp. [59 - 65], 2018

Application of Steel-Concrete Composite Columns in Building Construction

B. Kiriparan, W. J. B. S. Fernando, W. Bhathiya, P. Mendis, A. D. De Alwis, H. Dilina

Abstract: The steel concrete composites namely concrete filled steel tubular columns (CFST) and encased steel reinforced concrete (SRC) columns are becoming increasingly popular in the building industry due to the features like high strength, stiffness, fire resistance and constructability. Steel jacketing is a useful technique available for the strengthening of existing reinforced concrete columns to withstand additional loads applied from alteration such as addition of stories in existing buildings. Recent revolution in the design and application of these steel-concrete composites provides numerous advantages such like reduction in the sizes of vertical element, facilitate columns with higher slenderness, enhancing capacity of existing columns to meet the increased demands, minimize the cost involved for the fire protection and increase the construction speed.
The application of design methods available in the codes, detailing of connections and construction techniques are some of the vital challenges for the designers as well as the contractors. This paper intended summarize the basic aspects to be considered in the design of a CFST column, design provisions given in EN 1994-1-1:2004, its practical application, detailing of composite columns and their connections and constructability aspects. Further, the design and construction methods of steel jacketing technique for the strengthening of existing columns will be discussed. The case studies selected from the projects involved by the Authors will be included to demonstrate applications of for CFST and steel jacketing in the building construction. Finally, based on the literature review conducted recommendation is made for further studies in areas requires lack of reference in the design and application of CFST.

Keywords: Steel-Concrete composites, composite column design, CFST Connections, steel jacketing

1. Introduction

Reinforced concrete (RC) and steel columns (SC) are commonly adopted in building construction. Using structural steel sections and reinforced concrete in composite form is becoming increasingly popular due to the reasons such as:

- High strength and stiffness allows to reduce the cross sectional areas and permit to design members with higher slenderness
- Good fire resistance assist to reduce the cost required in fire protection applications
- Inherent ductility resulting in better performance under earthquake loading
- Convenience of construability reduce the execution time of the project.

Encased Steel Reinforced Concrete (SRC) column (steel sections embedded in concrete, Figure 1(a)) Concrete Filled Steel Tubular columns (tubular structural steel sections filled with concrete, Figure 1(b)) are two different form of composite columns. In the recent past the application of composite columns in the building industry becoming feasible due to the advancement of its design methodology through researches, development of international design guidelines and the advance construction technology. However, unlike design of reinforced concrete or steel columns, only limited number of references are available for the composite column design. Further, significant variations could be observed between the design methodologies specified in the existing international design codes.

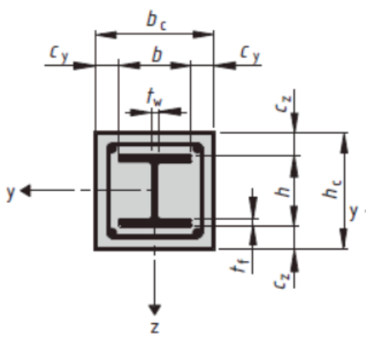


Figure 1 (a): SRC column section

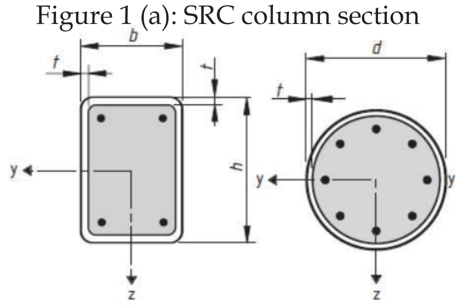


Figure 1 (b): CFST column section

Eng. B.Kiriparan,, *B.Sc. Eng. (Peradeniya), Structural Engineer, Civil and Structural Engineering Consultants (pvt)Ltd.*

This paper intended to present the overview of different factors to be considered in the design of Concrete filled steel tubular columns (CFST) and design provisions available EN 1994-1-1:2004. The scope of this paper is limited only to the CFST column purely subjected to the axial force for the simplicity. Further, the practical application of these design methodologies is elaborated through case studies selected from projects involved by the Authors. In addition to the design, detailing and construction aspects of CFST columns and its connections are demonstrated accordingly.

2. Behaviour and Design Philosophies of CFST Columns

The design methodology of reinforced concrete (RC) and steel columns (SC) itself are differed to each other's in number of fundamental ways. Overall buckling and slenderness, local buckling effects and axial force moment interaction are few of such considerations. Consequently, the design method of composite columns are sophisticated compare to the former. Thus number of experimental and numerical studies are conducted in the past and being continued in the present to formulate the capacity prediction methods for the composite columns. Based on the researches, provisions for composite column design are included in the international standards such as BS 5400-5, BS 5950-1:2000, ACI-318:83, AISC-LRFD:1986, EN 1994-1-1:2004, AIJ and Chinese standards. As per the literature review conducted by the Authors, it is observed that number of discrepancies and limitations exists between these design standards in the provision for design of composite columns. Further, lack of adequate provisions for design and detailing are found in most of the existing guidelines. The simplified design method set out in EN 1994-1-1:2004 is providing more detailed provisions compare to others and considered throughout this discussion.

2.1 Local Buckling

In reinforced concrete column local buckling of reinforcing steel is restrained by surrounding concrete and stirrups, whereas in design of steel columns the capacity is reduced based on limiting aspect ratio of compression element. In the CFST the concrete fill prevent the buckling of the steel plates. For CFST columns local buckling can be neglected if the slenderness of the plate element is not exceeding the limiting values of $(b/t) \leq 90\sqrt{235/f_y}$ for circular CFST and $(h/t) \leq 52\sqrt{235/f_y}$ for rectangular CFST as specified in Table 6.3 of EN 1994-1-1:2004. These limits are higher than that specified in Table 5.2 of EN 1993-1-1:2005 indicates that allowance has been made to take in to account the restraint provided by the concrete fill. Further studies shows (Bridge et al. [1]), local buckling strength of thin square steel tubes increased as the inwards buckling is prevented by the concrete whereas a little influence is observed for circular tubes as the main buckling mode is outward buckling around the circumference (elephant's foot buckling). However, no direct guidance is specified in EN 1994-1-1:2004 to consider the influence of local buckling if these limits are exceeded.

2.2 Overall Buckling and Slenderness

The overall buckling is typically considered in the steel column design by using a reduced design strength corresponding to the slenderness ratios are determined from column curves. On the other hand, a minimum applied end eccentricity and a moment magnification is indirectly adopted in the reinforced concrete column design to take into account the slenderness effect. In the composite column design as per EN 1994-1-1:2004 column curves provided for steel columns in of EN 1993-1-1:2005 are used to determine the overall buckling effect with a reduced effective relative slenderness due to the concrete infill. The effective slenderness of CFST column is limited to 2.0 in the simplified design approach of EN 1994-1-1:2004.

2.3 Ultimate Strength

Ultimate axial load carrying capacity of the CFST rectangular column cross section (squash load) can be determined from eq.1. (EN 1994-1-1:2004)

$$N_{pl,Rd} = A_a f_{yd} + A_c f_{cd} + A_s f_{sd} \quad \ldots\ldots\ldots\text{(eq.1)}$$

The capacity of a CFST column shall be obtain by modifying the squash load with the slenderness reduction factor obtained from EN1993-1-1:2005. The capacity of Circular Sections filled with concrete shall be determined form eq.2 (EN 1994-1-1:2004)

$$N_{pl,Rd} = \eta_a A_a f_{yd} + A_c f_{cd}\left\{1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right\} + A_s f_{sd} \quad \text{(eq.2)}$$

2.4 Concrete Confinement

The strength of the concrete core in the CFST columns is enhanced due to the confinement pressure from the steel tube. This phenomenon has been taken in to account for square/rectangular hollow section in eq.1.

For circular hollow section this enhancement due to confinement is found to be more effective and the increment could be determined based on factors such as steel section dimensions, material strength, and relative slenderness as shown in eq.2. Figure, 1 show the variation of confinement effect with the slenderness of the circular CFST. Further, the reduction on effective yield strength of structural steel section is made in eq.2. to take in to account circumferential tensile stresses developed in the wall.

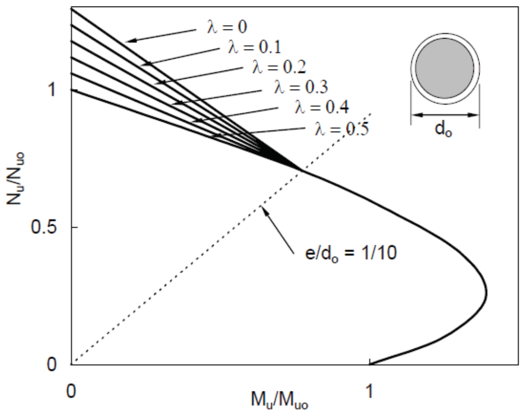


Figure 2: Effect of concrete confinement (EN 1994-1-1:2004)

2.5 Interaction between steel and concrete

All the existing codes assume full interaction between steel and concrete surfaces of CFST, provided some imposed restrictions on shear stress at the interface is satisfied. The load applied to the CFST column after it's become composite is assumed to be distributed between the steel and concrete infill proportional to their axial rigidities. In CFST columns loading is first applied on the steel section through the connecting the beams at floor levels. During this load transfer higher stresses may occur closer to the floor levels where the axial load is added. It is important to make sure no slip occur at the interface which would invalid the assumption made in the design. There is no well-established method to calculate the longitudinal shear stress at the interface. EN 1994-1-1:2004 recommends to limit the average shear stress over a load induction length to the design shear resistance trough interface friction. A limiting shear stresses of 0.55 N/mm^2 and 0.40 N/mm^2 are recommended (EN 1994-1-1:2004) for Circular and Rectangular CFST columns respectively where an unpainted steel surface free from oil and grease is present. If the interface shear stress exceeds the design frictional resistance EN 1994-1-1:2004 recommends to provided shear connectors capable to transfer whole of the shear. However, literatures available regarding the Interaction between steel and concrete are very limited.

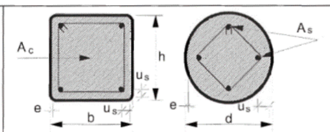
2.6 Steel and concrete contribution

The simplified design method proposed in EN 1994-1-1:2004 limits the contribution from the steel for the plastic section capacity of the composite column in between 20% to 90%. If the steel contribution is less than 20% the column should be designed as reinforced concrete column whereas the contribution exceeded 90% column should be designed as steel column.
Longitudinal reinforcement in the composite column is recommended between 0.3% and 6% of the concrete are in simplified design approach of EN 1994-1-1:2004. However, significant deviations are observed in these limits in other design standards.

2.7 Fire design of CFST

Strength and stiffness of the steel will reduced during the temperature rise and steel will begin to shed the load in to concrete core. With the time concrete will begins to degrade as its temperature raise. The degradation includes driving off of water which is present as free moisture and from the hydrated constituents of the mix. This produces a marked plateau in the concrete's temperature time profile as a considerable amount of heat is absorbed in converting this moisture to stream. It is imperative that venting is provided in the steel shell in order to allow this stream to escape. EN 1994-1-2:2005 recommends that the section should contain at least one hole with minimum diameter of 20 mm at the top and bottom of the each storey. Further presence of longitudinal reinforcement in the concrete core will improve the fire resistance of the CFST column. The requirements for minimum reinforcement and minimum axis of distance for CFST column to withstand the axial load during the fire condition is summarized in Table 2 (reproduced from EN-1994-1-2:2005) based of the fire rating.

Table 1: CFST columns fire design requirements (EN-1994-1-2:2005)



	steel section: $(b/e) \geq 25$ or $(d/e) \geq 25$	Standard Fire Resistance R30	R60	R90	R120	R180
1	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}28$					
1.1	Minimum dimensions h and b or minimum diameter d [mm]	160	200	220	260	400
1.2	Minimum ratio of reinforcement $A_S / (A_C + A_S)$ in (%)	0	1,5	3,0	6,0	6,0
1.3	Minimum axis distance of reinforcing bars u_S [mm]	-	30	40	50	60
2	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}47$					
2.1	Minimum dimensions h and b or minimum diameter d [mm]	260	260	400	450	500
2.2	Minimum ratio of reinforcement $A_S / (A_C + A_S)$ in (%)	0	3,0	6,0	6,0	6,0
2.3	Minimum axis distance of reinforcing bars u_S [mm]	-	30	40	50	60
3	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}66$					
3.1	Minimum dimensions h and b or minimum diameter d [mm]	260	450	550	-	-
3.2	Minimum ratio of reinforcement $A_S / (A_C + A_S)$ in (%)	3,0	6,0	6,0	-	-
3.3	Minimum axis distance of reinforcing bars u_S [mm]	25	30	40	-	-

3. Application of CFST Columns

The application of CFST columns in building industry becoming significant due to the advantages highlighted at the beginning of this paper. Here, few of such applications in Sri Lanka context are presented.

3.1 CFST for column with higher slenderness

Figure 3(a) and 3(b) shows two low rise buildings with a requirement to use columns freestanding over three stories to support the roof slab. These circular columns positioned according to the Architectural requirements are freestanding over 12 m and outer diameter of the columns to be limited to 300 mm. Though the suggested slenderness limit of $L_0/b<60$ in the BS 8110-1:1997 and $Le/r<180$ in BS 5950-1:2000 are not exceeded, both reinforced concrete and steel columns become as unrealistic solution due to the following facts;

- Higher deflection induced moment (BS 8110-1:1997) due to excessive slenderness of the reinforced concrete column requires enormous longitudinal reinforcement well beyond the allowable limit of BS 8110-1:1997 and found to be impracticable.
- Very low design compressive strength (BS 5950-1:2000) due to increased slenderness ratio requires significantly higher wall thickness for steel circular column section. The standard market available hot rolled steel sections doesn't make the bare steel column solution viable and built up sections become uneconomical.

In order to overcome these limitations, steel and reinforced concrete is used in composite form as CFST. The design is carried out as per the requirements set out by BS EN 1994-1-1:2004 as described above (section 2). CFST is found to be very effective for this application as the wall thickness of the steel tube is reduced due to the effective stiffness, the composite section increase the design strength and infill improve the resistance to local buckling of steel. However, in this case the concrete strength enhancement due to confinement affect is neglected as the slenderness is high.

Further, as per the simplified design provision given in BS EN 1994-1-2:2005 six percent of the longitudinal bars ($As/Ac+As=6.0\%$) are to be provided to obtain the two hour of fire resistance. Considering the constructability approximately 1% of longitudinal reinforcement is provided whereas the fire resistance is obtained through the application of intumescent protection coating. Self-compaction concrete mix with higher followability and small aggregate size is adopted to construct the infill.

Figure 3(a): CFST slender columns – building 1

Figure 3(b): CFST slender columns – building 2

The connection of the CFST column at the base and the roof slab is shown in Figure 4 and 5 respectively. Baseplate with the hole equivalent to the column internal diameter is used for the base connection facilitating the erection of the column with continuity of longitudinal bars to the foundation. The low level of axial load present in the columns make this base plate configuration satisfied to meet the allowable bearing strength on concrete stub.

Further, the unified column head developed in conjunction with architectural design is utilized to satisfy the punching shear design requirement of flat slab system adopted for the roof.

Figure 4: Base plate for CFST column

Figure 5: CFST column head detail at flat slab

3.2 CFST in intermediate rise steel building
Columns in steel framed buildings are subjected to higher level of axial loads due to the long spans. Using the composite columns inform of SRC or CFST is economically viable compare to bare steel columns due to the facts highlighted at the beginning of this paper. Figure 6 shows a CFST column adopted for a fifteen storied parking and office building. Here, CFST is found to be more feasible over bare steel and SRC due to following reasons,

- Reduction is steel consumption allows for cost saving
- Reduction in column size
- High stiffness minimize problems inevitable due to elastic axial shortening
- Connection with beams is convenience
- Formwork not required
- Construction speed is high

Figure 6: CFST column in an intermediate rise building

Figure 7 shows the connection of CFST at the foundation level. Here, providing holes for entire internal dimension of box section similar to the previous case is found to be impossible due to the higher bearing stresses exerted on foundation by the steel. Consequently, a base plate with holes only to accommodate the continuity of fire reinforcement is adopted. This require the high level of accuracy with minimum tolerance in positioning of rebar embedded in the foundation to facilitate the column erection.

Figure 7: Base plate for CFST column

A typical connection of CFST with steel beams at floor level is shown in Figure 8. The proposed connection detailed facilitate the convenience erection proceeds of the steel frame and found to be more viable to minimize the defects during the transportation from the fabrication workshop to the site. Addressing the constructability aspects in the design and the importance of detailing of connection is the CFST at various locations are well established from this case study.

Figure 8: CFST column connection at floor level

In both of these case studies presented above (in section 3.1 and 3.2) the full interaction between steel and concrete in the interface is considered as the shear stresses induced in the induction zone defined in EN 1994-1-1:2004 is found to be with in the allowable limits of interface shear due to friction.

3.3 Steel Jacketing for Strengthening of existing reinforced concrete column
Significant requirements arise for strengthening of existing RC columns in the building industry due to the factors such as, design alteration with additional floors, construction defects, change in floor functions etc. Reinforced concrete jacketing, wrapping of fibre reinforced polymers (FRP) and steel jacketing are commonly known techniques available for such strengthening work. Figure 9 shows a tall building project site which had a requirement to increase 10 number of floors after the construction columns above the foundation level. As a results, the capacity of the certain columns had to be increased by more than 30% of the currently available capacity. Based on the desktop study conducted steel

jacketing technique is found to be the most feasible solution compare to the others to meet the increased level of axial force demand with the minimum disturbance to the floor functional requirements.

Figure 9: Existing columns to be strengthened due to addition of floors

Composite column design provisions of BS EN 1994-1-1:2004, ACI 318M-99 design criteria and the research findings of Bsisu et al. [2] and Richart et al. [3] are utilized with the judgement of Authors in the design of proposed strengthening. The literature review conducted by the Authors during the said activity express that the lack of publication on experimental investigation, design guideline and construction methodology of steel jacketing strengthening is exist. However, only an emphasize of the case study is made here for the conciseness of this publication.

In contrast to the full interaction between steel and concrete considered in the composite design approach discussed in previous two cases, here mechanical shear connectors (as indicated in Figure 10) are provided as the interface shear demand is much higher than the allowable interface shear.

Figure 10: Shear connectors for steel jacketing

4. Summary and Discussion

The following points can be highlighted from this study regarding the application of CFST columns in the Sri Lankan building industry.

- CFST columns can be very effectively used in building applications making use of benefits of both concrete and steel in the composite form. Selected case studies in local context are elaborated.
- Significant discrepancies and limitations were observed among the international guidelines available for the design of CFST columns. EN 1994-1-1:2004 provides a detailed design methodology for the design of CFST columns. The design basis of CFST columns are summarized and discussed in this paper.
- Importance of detailing connections for CFST columns was found through presented case studies.
- Steel Jacketing technique for the strengthening of existing RC column was found to be a useful solution.
- Harmonization of existing design standards for CFST columns will assist the designers to obtain more precise information.

4. Recommendation for Future Studies

Current trend in application of CFST columns in local building construction practice is outlined highlighting the design provisions set out in EN 1994-1-1:2004. Further, the limitations and lack of references observed during this exercise are emphasized as appropriate. Accordingly, Authors identify following areas where requirement for further studies requires.

- Detailed comparison between design provisions existing in different international codes, identify the discrepancies and harmonization.
- Extended studies regarding load transfer mechanism and bond strength between steel and concrete.
- Detailing of connections for CFST and constructability aspects.
- Formulate the detailed design methods for steel jacketing strengthening method.

5. Acknowledgement

The author/s wishes to acknowledge Chuan Eu International Pte Ltd. (vendor for the steel construction of intermediate rise building discussed) for the assistance given from the design to construction stage.

6. References

1. Bridge, R.Q., Pham, L. and Rotter, J.M. (1986), "Composite Steel and Concrete Columns - Design and Reliability", Proceedings, 10th Australasian Conference on the Mechanics of Structures and Materials, Adelaide, Aug, 1986, pp. 33-38.
2. Bsisu,K.I 2002, Retrofitting of square reinforced concrete columns with steel jackets, Ph.D. Thesis, University of Jordan.
3. Richart, F.E., Brandtzaeg,A., and Brown. R.L. 1928. A study of the failure of concrete under combined compressive stresses. Engineering Experimental station, Bulletin No.185, University of Illinois, Ilinois, USA.
4. EN 1994-1-1:2004 "Design of Composite Steel and Concrete Structures",
5. EN 1993-1-1:2005 "Design of Steel Structures"
6. EN 1992-1-1:2004 "Design of Concrete Structures"
7. BS 5950-1:2000, "Structural Use of Steelwork in Buildings"
8. EN 1994-1-2:2005 "Fire Design of Composite Steel and Concrete Structures",
10. K. A. S. Susantha , hanbin ge & tsutomu usami,(2008), "A capacity prediction procedure for concrete filled steel columns" Journal of Earthquake Engineering.
11. Susantha, K.A.S., Kiriparan, B. and Nirusan, A. (2013). "Dynamic characteristics of stiffened steel rigid frames." 4th International Conference on Structural Engineering and Construction Management 2013, ICSECM, Kandy Sri Lanka, December 2013.
12. Bridge, R.Q., O'Shea, M.D. and Zhang, J.Q. (1997), "Load-Moment Interaction Curves for Concrete Filled Tubes", Proceedings, 15th Australasian Conference on the Mechanics of Structures and Materials, Melbourne, 8-10 Dec., pp. 141-146.