CHAPTER 3

CODAL PROVISIONS AND DESIGN METHODS

3.1 PREAMBLE

The axial capacities of concrete-filled columns are predicted based on the provisions given in Eurocode4-1994 [10], AISC-2005[11], AISC-LRFD-1999 [20], ACI 318-1999 [23] and AS 3600-1994 [25]/AS 4100-1998 [26]. The methods suggested in each code are presented in a detailed manner in this chapter. The limits of flat width or diameter to thickness ratio to avoid premature local buckling, slenderness limits and limits of steel contribution ratio considered while selecting dimensions for column specimens are given. The effect of confinement of concrete as included in the capacity prediction is also discussed. The design equations suggested by previous researchers Muhammad et al. [42] and Giakoumelis and Lam [27] are also given.

3.2 AXIAL COMpressive STRENGTH OF FILLED COLUMNS

The axial compressive strength of CFT columns suggested in various international codes is discussed in this section.

3.2.1 Eurocode4-EC4-1994: Eurocode4 Design of Composite Steel and Concrete Structures

It is based on limit state method of design, applying partial safety factor to load and materials. It covers concrete encased, partially encased steel
sections and concrete filled sections with or without reinforcement. This is the only code to include effect of long term loading and confinement effect for design. For hollow sections filled with high strength concrete, the factor 0.85 must be omitted. Limit for steel tube slenderness, to avoid premature local buckling is also given. The use is restricted to composite columns with steel yield stress and concrete cylinder strength upto 355MPa and 50MPa respectively.

It considers confinement effect explicitly for the circular sections when relative slenderness, $\lambda$ has value less than 0.5. The effect of confinement was included in this study since relative slenderness, $\lambda$ falls below 0.5 Clause 4.8.3 of Eurocode 4-1994 [10] has been referred for finding effective elastic flexural stiffness, non-dimensional slenderness and the capacity reduction factor.

The ultimate load can be calculated from the following equations (3.1) to (3.8).

For square CFTs,

The ultimate load,

$$N_u = A_x f_y + A_c F_c$$ (3.1)

For circular CFTs,

The plastic resistance,

$$N_{pl, rd} = A_x \eta_2 f_y + A_c f_{cd} \left[ 1 + \eta_1 \left( \frac{l}{D} \right) \left( \frac{f_y}{f_{ck}} \right) \right]$$ (3.2)

where $\eta_1$ and $\eta_2$ are confinement factors.

The strength of concrete is increased by $\eta_1$ because enhancement of strength occurs under triaxial state of stress. The strength of steel tube is decreased by $\eta_2$ because steel is under hoop stress.
The non-dimensional slenderness, $\overline{\lambda}$, as per Cl.4.8.3.7(2) of EC4 is,

\[
\overline{\lambda} = \frac{N_{pl,R}}{N_{cr}}
\]  

(3.5)

Where $N_{pl,R} = \text{Plastic resistance of the cross-section with } \gamma_s = \gamma_c = 1$ and $N_{cr} = \text{Elastic critical buckling load} = \frac{\pi^2 (EI)e}{l^2}$

(3.6)

Effective elastic flexural stiffness,

\[
(\text{EI})_e = 0.8 E_{cd} I_c + E_s I_s
\]  

(3.7)

The design resistance of CFT column,

\[
N_{sd} = \chi N_{pl,Rd}
\]  

(3.8)

where $\chi$ is reduction factor due to column buckling.

Fig 3.1 shows European buckling curves according to Eurocode 3-1993 [49], which includes reduction factor ($\chi$) due to column buckling. Curve a can be referred for concrete-filled hollow sections. The reduction factor $\chi$ is a function of the non-dimensional slenderness, $\overline{\lambda}$ of the composite column.

3.2.2 ACI 318-1999: American Concrete Institute-Building code requirements for Structural Concrete

According to this code, a composite column can be defined as a concrete column reinforced with a structural steel shape or tubing in addition to reinforcing bars. Equivalent radius of gyration and flexural stiffness are to be considered to include slenderness effects. Radius of gyration must be taken as zero except for sustained load. The limiting thickness of steel tube to prevent local buckling based on yield stress is also specified for CFTs. Creep of concrete under sustained load is considered.
Fig. 3.1 European buckling curves
The ultimate load, \( P_u \) is given by equation (3.9),

\[
P_u = A_s f_y + 0.85 A_c F_c
\]  


The principle in design using AISC-LRFD 1999 [20] is the same as ACI 318-1999 [23] code. Axial and flexural strength calculations are similar to those for RCC columns using ACI 318-1999 [23] whereas AISC- 2005 [11] gives bilinear interaction formula which is similar to that for steel columns. Strength is estimated based on the ultimate load resistance but suitable reduction factors are applied to account for slenderness ratio. Flexural stiffness is underestimated. Effect of confinement of steel tube on concrete core which is influencing strength and ductility of CFT column is ignored. Creep of concrete is also ignored. The use is limited to composite columns with steel yield stress and concrete cylinder strength upto 415 MPa and 55 MPa respectively. The new version AISC- 2005 [11] raises these values to 525 MPa and 70 MPa respectively. It also modifies the minimum steel wall thickness and contains design provisions for both round and rectangular shapes. Compared to 1999 version, 2005 Standards adopts the concept of effective stiffness with different adjustment coefficients. Resistance factor is lowered to 0.75 from 0.85. Minimum Steel ratio is kept at 4% for encased columns but it is lowered to 1% for CFT columns.

3.2.3.1 AISC-LRFD-1999

The squash load $P_n$ can be calculated from the following equations (3.10) to (3.14).

$$P_n = A_s F_{cr}$$  \hspace{1cm} (3.10)

Critical stress,

$$F_{cr} = 0.658 \lambda_c^2 F_{my}$$  \hspace{1cm} (3.11)

Slenderness,

$$\lambda_c = \left( \frac{KL}{\pi r_m} \right) \sqrt{\frac{F_{my}}{E_m}}$$

Modified yield strength,

$$F_{my} = f_y + 0.85 f_c \left( \frac{A_c}{A_s} \right)$$  \hspace{1cm} (3.13)

Modified Elastic modulus,

$$E_m = E_s + 0.4 E_c \left( \frac{A_c}{A_s} \right)$$  \hspace{1cm} (3.14)

where $r_m$ is the modified radius of gyration of steel tube.

3.2.3.2 AISC-2005

The design compressive strength $P_d$ as per Clause I 2.2b is calculated from the following equations (3.15) to (3.21).

$$P_d = 0.75 P_n$$  \hspace{1cm} (3.15)

$$P_n = P_o \left[ 0.658^{P_o/P_c} \right]$$ \hspace{1cm} if $P_c \geq 0.44 P_o$  \hspace{1cm} (3.16)
\[ P_n = 0.877 P_e \] if \( P_e < 0.44P_o \) \hspace{1cm} (3.17)

\[ P_o = A_s f_y + C_2 A_c F_c \] \hspace{1cm} (3.18)

\[ P_e = \pi^2 \frac{E I_{eff}}{(K L)^2} \] \hspace{1cm} (3.19)

Effective Stiffness,

\[ E I_{eff} = E_s I_S + C_3 E_c I_c \] \hspace{1cm} (3.20)

\[ C_3 = 0.6 + 2 \frac{A_s}{(A_c + A_z)} \leq 0.9 \] \hspace{1cm} (3.21)

where \( C_2 = 0.85 \) for rectangular and 0.95 for circular sections.

3.2.4 \hspace{0.5cm} **AS 3600-1994 / AS 4100-1998 Australian Standards**


The ultimate load is the same as ACI 318-1999 [23] given in equation 3.9.

3.2.5 \hspace{0.5cm} **Summary**

The design procedures and equations for the design of square and circular CFT columns suggested in various International codes have been discussed.
3.3 LOCAL BUCKLING OF STEEL TUBE

The premature local buckling of steel in CFT columns can be avoided by choosing specimens in accordance with the limits of flat-width/diameter to thickness ratio specified in various codes such as Eurocode 4-1994 [10] and ACI 318-1999 [23] and AISC 2005 [11].

3.3.1 Eurocode 4-1994

The limits of flat width/diameter to thickness ratio of CFTs suggested in EC4 1994 [10] (Cl.4.8.2.4) to avoid premature local buckling are given by equations (3.22) and (3.23).

For circular CFTs,
\[ \frac{D}{t} \leq \frac{90 \times 235}{f_y} \]  \hspace{1cm} (3.22)

For square CFTs,
\[ \frac{B}{t} \leq 52 \sqrt{\frac{235}{f_y}} \]  \hspace{1cm} (3.23)

3.3.2 ACI 318-1999

The limits of flat width/diameter to thickness ratio of CFTs suggested in ACI 318-1999 [23] are given by equations (3.24) and (3.25).

For circular CFTs,
\[ \frac{D}{t} \leq \frac{8E_s}{\sqrt{f_y}} \]  \hspace{1cm} (3.24)

For square CFTs,
\[ \frac{B}{t} \leq \frac{3E_s}{\sqrt{f_y}} \]  \hspace{1cm} (3.25)
3.3.3 AISC-LRFD-1999/AISC-2005

AISC-LRFD-1999 [20] [Cl. 12.1(e)] uses the same limits as prescribed in ACI 318-1999 [23]. AISC-2005 [11] [Cl.12.2(a)] suggests the limits of flat width/ diameter to thickness ratio as given by equations (3.26) and (3.27).

For circular CFTs,

\[
\frac{D}{t} \leq \frac{0.15E}{f_y}
\]  

(3.26)

For square CFTs,

\[
\frac{B}{t} \leq 2.26 \sqrt{\frac{E}{f_y}}
\]  

(3.27)

3.3.4 Summary

To avoid premature local buckling of composite columns, design codes have been referred to check the maximum limits of flat width/diameter to thickness ratio of circular and square sections. These limits were considered while selecting dimensions of composite columns.

3.4 SLENDERNESS LIMITS

The limits specified in various design codes to exclude slenderness effects have been discussed in this section.

3.4.1 Eurocode4-1994

The limits of slenderness suggested by Eurocode4-1994 [10] [Cl.4.8.3.5(2)] is given by equation (3.28).

Length / Depth or Diameter < 15 

(3.28)
3.4.2 ACI 318-1999

To check for slenderness limit, ACI 318-1999 [23] suggests the equations as given in (3.29) and (3.30).

For square columns,

\[
\frac{\text{Length}}{\text{Side}} < 10.2 \quad (3.29)
\]

For circular columns,

\[
\frac{\text{Length}}{\text{Diameter}} < 8.5 \quad (3.30)
\]

3.4.3 Summary

Slenderness ratio of columns plays an important role in deciding the capacity of column and its behavior. The limits specified in various design codes to exclude slenderness effects have been checked.

3.5 CONFINEMENT OF CONCRETE

The confinement effect in circular and square columns is shown in Fig. 3.2 and 3.3 respectively. The concrete confinement is fully effective in circular columns because of uniform flexural bending whereas in square columns the effect is reduced because of plate bending. For circular concrete infilled composite columns, the confinement effect of concrete increases the concrete resistance and decreases the axial resistance of steel section. The provisions given in Eurocode 4-1994 [10] and AISC 2005 [11] to include confinement of concrete in capacity prediction of CFTs has been discussed.
Fig 3.2 Confinement effect in Circular Columns

Fig 3.3 Confinement effect
3.5.1 Eurocode4-1994

Eurocode4-1994 [10] (Cl. 4.8.3.3(3)) considers confinement effect more methodically for the circular sections when relative slenderness, \( \bar{\lambda} \), has value less than 0.5. The concrete confinement depends on the ratio of steel to concrete resistance (\( f_y / f_{ck} \)), diameter to thickness ratio (D/t) and column slenderness (L/D) through confinement factors \( \eta_1 \) and \( \eta_2 \). The reduction of concrete strength by 0.85 may be omitted for concrete-filled circular composite columns since the development of concrete strength is better achieved due to protection against the environment and against splitting of concrete. Cl 4.8.3.3(4) of Eurocode4-1994 [10] suggests design equations to include confinement effect. The Eurocode4-1994 [10] provisions are discussed in a detailed manner in section 3.2.1.

3.5.2 AISC-2005

AISC-2005 [11] includes confinement effect in the form of a constant, irrespective of cross-section dimension or column slenderness. The increase in concrete resistance of circular CFTs is 11% compared to rectangular CFTs.

3.5.3 Summary

The design equations suggested for circular composite columns in Eurocode 4-1994 [10] and AISC-2005 [11] have been referred to include confinement effect.
3.6 STEEL CONTRIBUTION RATIO


3.6.1 Eurocode4-1994

The range of Steel contribution ratio, $\delta$ (ratio of the contribution of the steel section to total axial strength) specified in Eurocode4-1994[10] [Cl.4.8.3.1(3)] is given by equation (3.31).

$$0.2 \leq \delta \leq 0.9$$  \hspace{1cm} (3.31)

3.6.2 AISC-LRFD-1999/AISC-2005

The limits of steel contribution ratio (ratio of steel cross-sectional area to total cross-sectional area) specified in AISC-LRFD-1999[20] and AISC-2005[11] (Cl.12.2a) are given in equation (3.32) and (3.33) respectively.

$$\frac{A_s}{A_g} \leq 4\%$$  \hspace{1cm} (3.32)

$$\frac{A_s}{A_g} \leq 1\%$$  \hspace{1cm} (3.33)

3.6.3 Summary

The steel contribution ratio, $\delta$ must be checked to design a composite column. According to Eurocode 4-1994 [10], if $\delta$ is less than 0.2, the column may be designed according to Eurocode 2-2004 [50] and if it is larger than 0.9, the column can be designed as a steel section.
3.7 DESIGN METHODS SUGGESTED BY PREVIOUS RESEARCHERS

The axial compressive strength of circular and square CFT columns as per design methods suggested by previous researchers is discussed in this section.

3.7.1 Circular Columns

Giakoumelis and Lam [27] proposed a coefficient to be included in ACI318-1999 [23] equation to take into account, the effect of concrete confinement on the axial strength of circular concrete infilled steel tubular columns. This equation is found to be giving fair results.

The modified equation of ACI318-1999 [23] suggested by Giakoumelis and Lam [27] as applicable to circular CFT columns is given as equation (3.34).

\[ P_u = A_s f_y + 1.3A_c F_c \]  \hspace{1cm} (3.34)

3.7.2 Square Columns

A modified equation for finding axial strength of square CFT columns is suggested by Muhammad et al. [42]. The applicability of this equation needs to be checked with more test results of columns, which do not meet the requirements of B/t as suggested by codes.
The modified equation of ACI318-1999 [23] suggested by Muhammad et al. [42] as applicable to square CFT columns is given as equation (3.35).

\[ P_u = A_s f_y + 1.1A_c F_c \]  

(3.35)

3.7.3 Summary

The design procedures and equation for the design of circular and square CFT columns suggested by previous researchers have been discussed.