ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

CONFINEMENT EFFECT OF STRUCTURAL STEEL AND TRANSVERSE REINFORCEMENT ON AXIAL COMPRESSION RESISTANCE OF CONCRETE ENCASED COMPOSITE COLUMN

A Thesis in Structural Engineering

By: Eseteselase Berhanu

September 2020

Addis Ababa, Ethiopia

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

CONFINEMENT EFFECT OF STRUCTURAL STEEL AND TRANSVERSE REINFORCEMENT ON AXIAL COMPRESSION RESISTANCE OF CONCRETE ENCASED COMPOSITE COLUMN

By

Eseteselase Berhanu

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

(STRUCTURAL ENGINEERING)

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

September 2020

Addis Ababa, Ethiopia

The undersigned have examined the thesis entitled **‘Confinement Effect of Structural Steel and Transverse Reinforcement on Axial Compression Resistance of Concrete Encased Composite Column’** presented by **Eseteselase Berhanu**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

Dr. Ing. Girma Zerayohannes		
Advisor	Signature	Date
Dr. Ing. Adil Zekaria		
Internal Examiner	Signature	Date
Dr. Esayas Gebreyohannes		
External Examiner	Signature	Date
Dr. Ing. Mebruk Mohammed		
Chair Person	Signature	Date

Declaration

I, hereby declare that this research work titled "Confinement Effect of Structural Steel and Transverse Reinforcement on Axial Compression Resistance of Concrete Encased Composite Column" is my original work. The work has not been presented elsewhere for assessment. And all source of materials used for this thesis have been properly acknowledged.

(Signature of the student)
Eseteselase Berhanu
September, 2020

Abstract

This thesis presents the procedure to develop a new analytical model to define the axial capacity of concrete encased composite column by considering confinement effect on the core concrete from structural steel and transverse reinforcement. First a method to define the unconfined, partially confined, and highly confined concrete areas ware developed. To define this, arching action was assumed to act in the form of second-degree parabola with an initial tangent slope of 45^0. The arching action is expected to occur horizontally between longitudinal bars and the tips of structural steel flange and vertically between transverse reinforcement. Then a mathematical formulation was developed to define the lateral confining pressure from both transverse reinforcement and structural steel on the partially and highly confined concrete. By using the lateral confining pressure, the partially and highly confined compressive strength of concrete was determined. Finally by using the defined area of concrete and by their corresponding confined compressive strength, analytical model to define the axial compression resistance of concrete encased composite column was developed. And the analytical model is verified using eleven experimental concrete encased composite column results. It was showed that the analytical model have a good approximation with the experimental result.

Parametric study was carried out to investigate how material and geometrical variables affect the confinement effectiveness in axial compression resistance of concrete encased composite columns. Compressive strength of concrete, yield strength of structural steel, and yield strength of transverse reinforcement ware selected as a material variables. Moreover, thickness of structural steel flange, width of structural steel flange, distribution of longitudinal reinforcement, and spacing of transverse reinforcement ware selected as a geometrical variables. From the result, it was observed that partially confined concrete highly affected by the transverse reinforcement spacing, compressive strength of concrete, and yield strength of transverse reinforcement. In addition, highly confined concrete highly affected by the compressive strength of concrete, transverse reinforcement spacing, and yield strength of structural steel. Additionally by developing a finite element model the effect of structural steel yield strength on the confinement effect is showed.

Key words: Concrete encased composite column, confinement effect, partially confined concrete, highly confined concrete

Table of Contents

List of Tables

List of Figures

List of Symbols

Latin upper case letters

A_a	Cross-sectional area of structural steel section
A_c	Cross-sectional area of concrete
$A_{e,a}$	Area of effectively confined concrete by structural steel
$A_{e,s}$	Area of effectively confined concrete by transverse reinforcement
A_{hc}	Highly confined concrete area
A_{pc}	Partially confined concrete area
A_s	Cross-sectional area of longitudinal reinforcement
A_{sy}	Area of transverse reinforcement in y-direction
A_{sz}	Area of transverse reinforcement in z-direction
A_{uc}	Unconfined concrete area
E_a	Modulus of elasticity for structural steel
E_s	Modulus of elasticity for reinforcing steel
E_{cm}	Secant modulus of elasticity for concrete
I_a	Second moment of area of the structural steel section
I_s	Second moment of area of the steel reinforcement
I_c	Second moment of area of the un-cracked concrete section
$M_{pl,a,Rd}$	Plastic resistance moment of the steel section
$M_{pl,N,Rd}$	Plastic bending resistance taking into account the normal force
$M_{pl,Rd}$	Plastic resistance moment of the composite section
N_{cr}	Elastic critical normal force
$N_{cr,eff}$	Critical normal force by using effective flexural stiffness for the relevant axis

N_{Ed}	Total design normal force
$N_{G,Ed}$	Normal force that is permanent
$N_{pl,Rd}$	Design value of the plastic resistance to compression
$N_{pl,Rk}$	Characteristic value of the plastic resistance to compression
$P_{Analytical}$	Compression resistance of concrete encased composite column determined from developed analytical model
P_{Code}	Compression resistance of concrete encased composite column determined from EN 1994-1-1:2004 code
P_{FEM}	Compression resistance of concrete encased composite column determined from developed finite element model
S	Center-to-center spacing of transverse reinforcement
S'	Clear spacing between transverse reinforcement
V_{Ed}	Vertical shear force
V_{Rd}	Shear resistance

Latin lower case letters

b	Width of structural steel flange
b_c and h_c	Outer dimensions of concrete encased composite column
b_s and h_s	Dimensions of transverse reinforcement
c_z	Nominal value of concrete cover in mm
$c_{z,min}$	Minimum concrete cover
$f'_{1,a}$	Effective lateral confining pressure from structural steel
$f_{1,a}$	Lateral confining pressure from structural steel
$f'_{1,s}$	Effective lateral confining pressure from transverse reinforcement
$f_{1,s}$	Lateral confining pressure from transverse reinforcement

$f'_{1y,h}$	Effective lateral confining pressure on highly confined concrete in y-direction
$f'_{1z,h}$	Effective lateral confining pressure on highly confined concrete in z-direction
f_{ck}	Characteristic value of the compressive strength of unconfined concrete
$f_{ck,c}$	Confined characteristics compressive strength of concrete
f_{cd}	Design value of the cylinder compressive strength of concrete
f_{sd}	Design value of the yield strength of reinforcing steel
f_{sk}	Characteristic value of the yield strength of reinforcing steel
f_{yd}	Design value of the yield strength of structural steel
f_{yk}	Characteristic value of the yield strength of structural steel
h	Height of structural steel
k_{pc}	Confinement factor for partially confined concrete
k_{hc}	Confinement factor for highly confined concrete
k_a	Confinement contribution from the structural steel
t_f	Thickness of structural steel flange
t_w	Thickness of structural steel web
w_i	Spacing between longitudinal reinforcement

Greek lower case letters

β	Equivalent moment factor
σ_2	Effective lateral compressive stress due to confinement
$\varepsilon_{c2,c}$	Confined concrete strain at reaching the maximum strength
ε_{c2}	Unconfined concrete strain at reaching the maximum strength
$\varepsilon_{cu2,c}$	Confined concrete ultimate strain

ε_{cu2}	Unconfined concrete ultimate strain
$\rho_{y,s}$	Ratio of the transverse reinforcement area to the confined concrete in y-direction
$\rho_{z,s}$	Ratio of the transverse reinforcement area to the confined concrete in z-direction
$\rho_{z,a}$	Ratio of structural steel area to the confined concrete in z-direction
φ_t	Creep coefficient

Acknowledgements

First and foremost, I want to express my deepest gratitude to the Almighty God for everything happened in my life and for making me the person who I am today.

I really would like to forward my sincere appreciation and gratitude to my advisor Dr. Ing. Girma Zerayohannes for his constructive advice throughout the course of this thesis.

Last but definitely not the least, I truly would like to thank my family members and friends for their priceless support and helpful advice. It would not be possible to conduct this thesis without their help.

1 Introduction

1.1 Background

Concrete encased composite column are one type of composite column which consist structural steel section encased in reinforced concrete. In high rising buildings using concrete encased composite column are an economical way of having higher bearing capacity, higher stiffness and used for having high ductile behavior for the entire system (Zhao et al. 2012). Composite structures use both concrete and structural steel advantages on a construction. Concrete has good fire resistance, low material cost and it is easy to place. Steel has high stiffness or strength to weight ratio and high ductility. Additionally the concrete encasement can serve as a fire protection for the steel section.

In the design of earthquake resistance structural members, ductility is a fundamental requirement, which is determined either as the ability of structural member to undergo large inelastic deformations without significant loss in strength, or as the ability of the members to dissipate the imposed seismic energy. In plastic hinge region, the behavior of structural elements can be enhanced by the confinement effect to a considerable extent in the overall behavior of the structural system.

According to EN 1994-1-1:2004 the axial compression resistance of the concrete encased composite column section to compression is calculated by considering the capacity of the structural steel section, the concrete section and the longitudinal reinforcing bars only. Many experimental studies are carried out to estimate the ultimate strength of the concrete encased composite column. When a column is subjected to compression, tensile strain on the concrete is developed due to Poisson’s effect. The lateral expansion of the concrete is restrained by the transverse reinforcement and structural steel flange and exert a lateral confining force toward the core concrete. This confinement effect increases confined compressive strength of concrete and compressive strain at peak stress.

Earlier studies Sherif and Gregory (1999), Enrico and Sherif (2004), Chen and Lin (2006), Junji et al. (2012), and Aparnal et al. (2018) shows capacity of concrete section in composite column with H-shaped and cross-shaped structural steel section give high result compared to other shapes of equivalent steel section such as I-shaped and T-shaped structural steel section. Due to wider flange of H-shaped section the lateral confining force toward the concrete core is increased than other structural steel shapes (Chen and Lin, 2006).

In concrete encased composite column the lateral expansion of the concrete is confined by the transverse reinforcement and by the structural steel flange. The confinement effect due to the transverse reinforcement is studied in many earlier studies. Mander et al. (1998) proposed a unified stress-strain model for confined concrete for members with different cross sections under various loading conditions. This model is used for concrete confined by the transverse reinforcement.

To address the concrete confinement effect from both transverse reinforcement and structural steel on the overall axial capacity of the concrete encased composite column during design, additional investigation is needed to determine the effect of confinement especially from lateral confining pressure from the structural steel.

1.2 Statement of the Problem

While determining the axial compression resistance of concrete encased composite column section, the current code EN 1994-1-1:2004 does not include the confinement effect of the structural steel and the transverse reinforcement on the core concrete. So there need to be some other method to consider the confinement effect on the axial compression resistance of concrete encased composite column.

1.3 Objectives

1.3.1 General Objective

The objective of this thesis was to develop a new analytical model which can determine the axial compression resistance of concrete encased composite column by considering the confinement effect from transverse reinforcement and structural steel. And also by using the developed analytical model, the other objective is to study the confinement effect on the axial compression resistance of concrete encased composite column by varying material and geometrical properties.

1.3.2 Specific Objective

- Develop a mathematical model to define the unconfined, partially confined, and highly confined concrete area.

- Determining and developing a mathematical model which can define the lateral pressure from both transverse reinforcement and structural steel on the core concrete.
- Determining and developing a mathematical model which can define partially and highly confined compressive strength of concrete
- Study how the selected parameters affect the concrete confinement behavior
- Investigate the effect of concrete confinement on the axial compression resistance of concrete encased composite column

1.4 Scope

This thesis will only address the “I” or “H” steel sections of concrete encased composite column

Furthermore this study is also limited to the following parameters:

Material parameter:	• Compressive strength of concrete
	• Yield strength of structural steel
	• Yield strength of Transverse reinforcement
Geometrical parameter:	• Thickness of structural steel flange
	• Width of structural steel flange
	• Configuration of longitudinal reinforcement
	• Spacing of transverse reinforcement

1.5 Content Organization

This thesis is organized into five chapters. Chapter 2 provides detailed literature review on the concrete encased composite column, confinement effect and a brief review of current specification for analysis and design of composite columns according to Eurocode 4, EN 1994-1:2004. Additionally earlier published analytical and experimental investigation of concrete encased composite columns are reviewed. Chapter 3 presents the procedure of developing the analytical model to define the axial compression resistance of concrete encased composite column by considering the confinement effect. In chapter 4, some material and geometrical parameters are selected and parametric study is carried out to show the parameters effect on the confinement effectiveness and on the axial compression resistance of concrete encased composite column. Then chapter 5 summarizes this thesis and present conclusions and recommendations. In the Annex a sample concrete encased composite column is analyzed by the developed analytical model.

2 Literature Review

2.1 Introduction

The Composite column is a compression member, which support an axial load with or without bending moment. Composite column combines reinforced concrete or a plane concrete with structural steel by taking an economical advantage over the use of both materials. Due to various type of concrete and structural steel combinations generally, composite columns can be divided into three main categories. (EN 1994-1-1:2004)

1. Concrete encased composite column
2. Partially encased composite column
3. Concrete filled composite column

Concrete encased composite columns are composite compression members when the structural steel is encased in the concrete. Initially, the structural steel was encased in the wet mix of low strength concrete for fire protection. Until the 1950's the concrete contribution is neglected during the strength and stability analysis of the column and it was designed as of uncased structural steel. Tests showed that using a better quality concrete to encase the steel section will enhance the resistance of the composite column. After many tests, the concrete is known to resist a small axial load and reduce the effective slenderness of the steel member which led to an increase in buckling load. (Johnson, 2004)

Concrete encased composite column have the following advantages over other columns

- Have an adequate seismic performance because of their high stiffness, strength, and ductility
- Cost-effective for multi-story buildings with horizontal loads
- Due to their high stiffness and due to the encasement of structural steel by concrete, the effective slenderness of the column is reduced and the buckling load is increased
- It will increase the usable floor area because of its high strength to cross-section ratio
- By altering structural steel thickness, concrete compressive strength and reinforcement bars, identical cross-section with different load and moment resistance can be used to proceed using a constant outer dimension for many floors in a building which will simplify the construction and architectural details

2.2 Component of Concrete Encased Composite Column

In concrete encased composite column the structural steel resist axial load, bending moment and transverse shear force. The flange of the structural steel confine the core concrete and reduce the transverse reinforcement demand for the composite column.

The Concrete in concrete encased composite column have a high fire and weather resistance and most of the constitute materials except the cement and additives all are usually available at low cost or at small distance from the construction site. And it is primarily used for members subjected to compression because the concrete compressive strength can be made like that of natural stone. On the other hand concrete is a brittle material whose tensile strength is relatively small from its compressive strength. (Arthur et al., 2010)

When concrete encase the structural steel, the concrete provide compression resistance for the composite column and provide fire protection and corrosion resistance for the structural steel and reinforcement bars. Because of the concrete cover for structural steel, the effective slenderness is reduced and the probability of structural steel to buckle is reduced.

In the concrete encased composite column, reinforcement is used in two ways, as a longitudinal reinforcement bar, and as a transverse reinforcement bar. When the column is subjected to an eccentric axial load, and the bending action produce tensile forces over a part of the cross-section. In addition to that, cracks can also be develop whenever there are shrinkage or temperature changes which will give rise to tensile stresses. (White and MacGregor, 2012)

As described earlier, the concrete has low tensile strength. Therefore longitudinal reinforcements have to be provided to resist the tension force developed during the compression. Furthermore, the longitudinal reinforcement contributes to the overall resistance of the concrete encased composite column.

Transverse reinforcement in concrete encased composite columns provide an adequate shear strength for the column and hold the longitudinal reinforcement in place. Transverse reinforcement are provided in the form of ties or closely spaced spirals. When closely spaced normal ties are used, the unsupported length of the longitudinal bars is reduced and the danger of buckling of the longitudinal reinforcements as it approaches its yield stress is reduced. The transverse reinforcement also provide a passive confinement for the core concrete under axial loads. When the lateral expansion of the core concrete is restrained failure of the core concrete is delayed and the column becomes more ductile.

The reinforcement bars have to be covered by an appropriate thickness of concrete cover for corrosion prevention, fire protection and to have sufficient embedding to enable them to be stressed without slipping. The thickness is determined depend on environmental condition and type of structural member.

The whole component have to act as one member to have all the useable effects in each component. Therefore throughout the length of the column, slip and slip strain everywhere have to be zero, and it is taken as plane section remain plane. This condition is known as full interaction. In concrete encased composite column, the transfer of shear from steel to concrete was assumed to occur by bond or adhesion at the concrete interface. When the steel is encased in concrete, no shear connectors need to be provided. (Johnson, 2004)

2.3 Confined Concrete

In column, as a result of Poisson's effect the increase of axial load makes the concrete to expand laterally. In the case of concrete encased composite column the structural steel and transverse reinforcement restrain the lateral expansion of concrete. This restraining effect on the lateral expansion of concrete is called confinement effect. The confinement effect lead the compression stress state of concrete from uniaxial to multiaxial state of stress. Which increase load resisting capacity and ductility of the column. Confined concrete generally fails in a ductile manner, whereas unconfined concrete fails in a brittle manner.

From literatures and personal findings the following material and geometrical parameters are identified which have the effect on confinement effectiveness

- Composite column
    - Type of composite column
    - Cross-sectional size
    - Column slenderness
- Concrete
    - Compressive strength of concrete
    - Area of effectively confined concrete core
    - Effect of aggregate

  - Bond between the paste and aggregate
  - Concrete cover
- Transverse reinforcement
  - Volumetric ratio of transverse reinforcement
  - Diameter of transverse reinforcement
  - Spacing of transverse reinforcement
  - Yield strength of transverse reinforcement
  - Configuration of transverse reinforcement
- Longitudinal reinforcement
  - Volumetric ratio of longitudinal reinforcement
  - Diameter of longitudinal reinforcement
  - Spacing between longitudinal reinforcement
  - Yield strength of longitudinal reinforcement
  - Configuration of longitudinal reinforcement
- Structural steel
  - Cross-section of structural steel
  - Yield strength of structural steel
  - Thickness of structural steel
- Loading
  - Eccentricity of the load – Axial load, uniaxial bending and biaxial bending
  - Rate of loading and strain gradient

2.4 Confinement Mechanism in Concrete Encased Composite Column

The concrete section in concrete encased composite column classified into three different areas. (1) a highly confined concrete area that concrete lateral expansion is restrained by both the transverse reinforcement and structural steel flange; (2) a partially confined concrete area that concrete lateral expansion is restrained by the transverse reinforcement only; and (3) an unconfined concrete that concrete lateral expansion is not restrained at all.

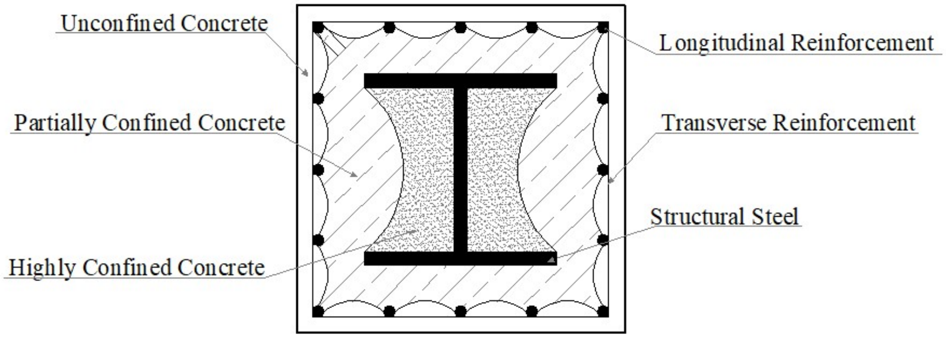


Figure 2.1 Regions of concrete in a concrete encased composite section

Since there is a difference in degree of confinement effect in each part, the concrete stress-strain relationship is different in each area. Stress-strain relationship for confined concrete with increased characteristic strength and strains in EN 1992-1-1:2004 is given as;

$$f_{ck,c} = f_{ck}\left(1 + \frac{5\sigma_2}{f_{ck}}\right) \quad for\ \sigma_2 \le 0.05 f_{ck}$$

$$f_{ck,c} = f_{ck}\left(1.125 + \frac{2.5\sigma_2}{f_{ck}}\right) \quad for\ \sigma_2 \ge 0.05 f_{ck}$$

$$\varepsilon_{c2,c} = \varepsilon_{c2}\left(\frac{f_{ck,c}}{f_{ck}}\right)^2$$

$$\varepsilon_{cu2,c} = \varepsilon_{cu2} + 0.2\sigma_2/f_{ck}$$

Where:

$f_{ck,c}$ − Confined characteristics compressive strength of concrete

f_{ck} − Unconfined characteristics compressive strength of concrete

σ_2 − Effective lateral compressive stress due to confinement

$\varepsilon_{c2,c}$ − Confined concrete strain at reaching the maximum strength

ε_{c2} − Unconfined concrete strain at reaching the maximum strength

$\varepsilon_{cu\ ,c}$ − Confined concrete ultimate strain

ε_{cu2} − Unconfined concrete ultimate strain

Continuous confining pressure can be assumed until the steel reaches yielding point, and after the steel yield, because of the steel strain increases with little or no increment in stress the stress-strain relationship of confined concrete progressively decreases.

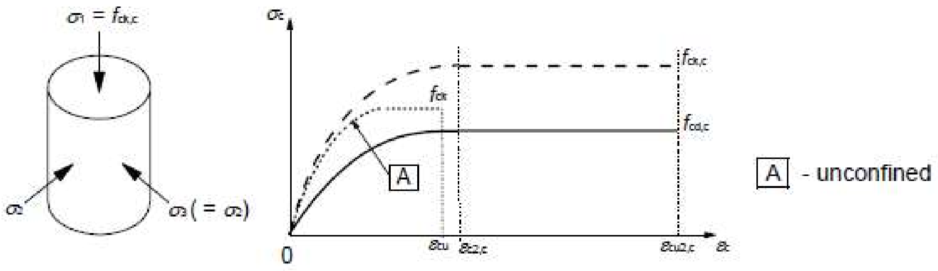


Figure 2.2 Stress-strain relationship for confined concrete (EN 1992-1-1:2004)

2.5 Review of Design Code, EN 1994-1-1:2004 for Concrete Encased Composite Column

According to Eurocode – 4 Composite columns are classified as concrete encased section, partially encased section, and concrete filled rectangular and circular tubes. EN 1994-1-1:2004, states that all composite columns should be checked for member resistance, local buckling resistance, introduction of load, and shear resistance between the steel and concrete.

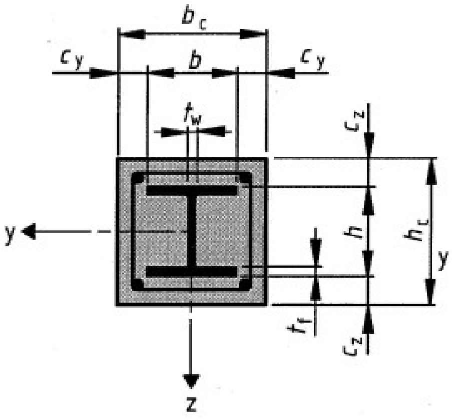


Figure 2.3 Typical cross-sections of concrete encased composite columns and notation (EN 1994-1-1:2004)

There are two methods of design for composite columns. For members with non-symmetrical or non-uniform cross-sections over the column length general method is used. In addition, for members with doubly symmetrical and uniform cross-section over the member length, simplified method is used. Since the selected concrete encased cross-section for this particular thesis is doubly symmetrical and uniform cross-section over the member length, only simplified method for concrete encased section is reviewed.

Simplified method of design

Limitations for the use of this method;

- Cross-section have to be doubly symmetrical and uniform throughout the member length
- Not used if the structural steel component consists two or more separated section
- Steel grade S235 to S460
- Normal weight concrete of strength classes C20/25 to C50/60
- Steel contribution ratio δ, 0.2 to 0.9

  Where: $\delta = \frac{A_a f_{yd}}{N_{pl,Rd}}$

  A_a – Cross-sectional area of structural steel section

  f_{yd} – Design value of the yield strength of structural steel

  $N_{pl,Rd}$ – Design value of the plastic resistance to compression
- Relative slenderness $\bar{\lambda}$ have be less than or equal to 2.0

  Where: $\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}$

  $N_{pl,Rk}$ – Characteristic value of the plastic resistance to compression, which is given by equation by $N_{pl,Rd}$, if characteristic vales are used instead of design strength

  N_{cr} – Elastic critical normal force for the relevant buckling mode, calculated by using the effective flexural stiffness $(EI)_{eff}$ which is given by: $N_{cr} = \frac{\pi^2 (EI)_{eff}}{L^2}$
- Minimum thickness of concrete cover for fully encased steel section is limited to $c_z \leq 0.3h$ and $c_y \leq 0.4b$
- Cross-sectional area of longitudinal reinforcement A_s have to be less than 6% of the concrete area A_c.
- Cross-section depth to width ratio is limited to be in between 0.2 and 5.0

Resistance of cross-section

For concrete encased section $N_{pl,Rd}$ is calculated by adding plastic resistance of each component and tensile strength of the concrete should be neglected.

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd}$$

Where:

A_c – Cross-sectional area of concrete
f_{cd} – Design value of the cylinder compressive strength of concrete
A_s – Cross-sectional area of reinforcement
f_{sd} – Design value of the yield strength of reinforcing steel

If the shear force $V_{a,Ed}$ on the steel section exceeds 50% of the design shear resistance $V_{pl,a,Rd}$ of the steel section, the influence of transverse shear forces on the resistance to bending and normal force should be considered when determining interaction curve. The influence is taken by reducing steel strength by $(1-\rho) f_{yd}$ in the shear area A_v.

Where: ρ is a parameter related to reduced design bending resistance accounting for vertical shear which is given by $\rho = (2V_{Ed}/V_{Rd} - 1)^2$

V_{Ed} – Vertical shear force

V_{Rd} – Shear resistance

$V_{pl,a,Rd} = \frac{A_v (f_{yk}/\sqrt{3})}{\gamma_{M0}}$, $\gamma_{M0} = 1$

The vertical shear force V_{Ed} unless analysis that is more accurate is required, may be distributed into $V_{a,Ed}$ on the structural steel and $V_{c,Ed}$ on the reinforced concrete section. For further simplification, all V_{Ed} can be assumed to be resisted only by the structural steel.

$$V_{a,Ed} = V_{Ed} \frac{M_{pl,a,Rd}}{M_{pl,Rd}}$$

$$V_{c,Ed} = V_{Ed} - V_{a,Ed}$$

Where: $M_{pl,a,Rd}$ – Plastic resistance moment of the steel section

$M_{pl,Rd}$ – Plastic resistance moment of the composite section

For cross-section subjected to combined compression and bending, the corresponding interaction curve can be replaced by a polygonal diagram for simplification.

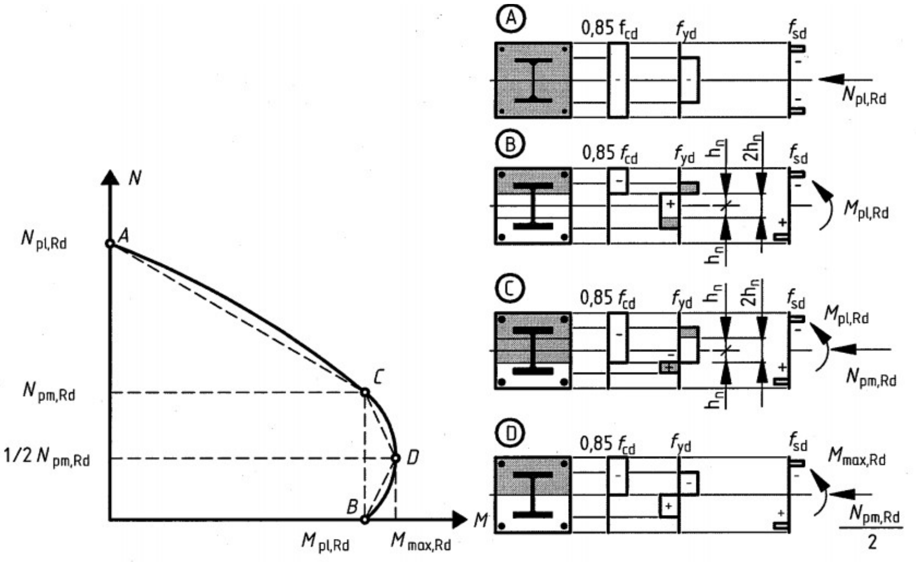


Figure 2.4 Simplified interaction curve and corresponding stress distributions

The polygonal diagram is developed by the points A to D, which are described in Table 2.1.

Table 2.1 Axial force and bending moment resistance

Point	Axial force resistance, N	Bending moment resistance, M
Point A – axial load capacity of a composite section	$N_{pl,Rd}$	0
Point B – plastic moment resistance of a composite section	0	$M_{pl,Rd}$
Point C – Plastic moment resistance with resultant axial compression of a composite section	$N_{pm,Rd} = 0.85 f_{cd} A_c$	$M_{pl,Rd}$
Point D (Balanced point) – maximum moment carrying capacity of a composite section	$\frac{N_{pm,Rd}}{2}$	$M_{Max,Rd}$

The composite column cross-sectional effective flexural stiffness $(EI)_{eff}$, should be calculated as $(EI)_{eff} = E_a I_a + E_s I_s + K_e E_{cm} I_c$

Where: E_a – Modulus of elasticity for structural steel
E_s – Modulus of elasticity for reinforcing steel
E_{cm} – Secant modulus of elasticity for concrete
I_a – Second moment of area of the structural steel section
I_s – Second moment of area of the steel reinforcement
I_c – Second moment of area of the un-cracked concrete section
K_e – Correction factor that should be taken as 0.

Method of analysis and member imperfections

The members have to be verified by considering second-order linear elastic analysis. For determining the internal force the design value of effective flexural stiffness $(EI)_{eff,II}$ which is given by $(EI)_{eff,II} = K_0\left(E_a I_a + E_s I_s + K_{e,II} E_{cm} I_c\right)$.

Where: $K_{e,II}$ – Correction factor that should be taken as 0.5
K_o – Calibration factor that should be taken as 0.9

To consider the long term effect on the effective elastic flexural stiffness, modulus of elasticity of concrete E_{cm} have to be reduced to the value $E_{c,eff}$ which is given by $E_{c,eff} = E_{cm} \frac{1}{1+(N_{G,Ed}/N_{Ed})\varphi_t}$

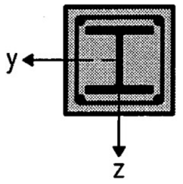
Where: φ_t – creep coefficient
N_{Ed} – total design normal force
$N_{G,Ed}$ – part of normal force that is permanent

If the internal force or moment caused by the deformations given by first-order analysis is less than 10% and if the elastic critical load is determined by using effective flexural stiffness$(EI)_{eff,II}$, second order effects can be neglected.

To account influence due to geometrical and structural imperfection, equivalent geometrical imperfection can be taken as described in the

Table *2.2*.

Table 2.2 Buckling curve and member imperfection for concrete encased composite column

Cross-Section	Axis of buckling	Buckling curve	Member imperfection
Concrete encased section 	y-y	b	$L/200$
	z-z	c	$L/150$

If second order effect in the analysis have to be accounted, it may be allowed by multiplying the greatest first-order design bending moment by a factor of k.

Where: $K = \frac{\beta}{1-N_{Ed}/N_{cr,eff}} \geq 1.0$

$N_{cr,eff}$ – critical normal force by using effective flexural stiffness for the relevant axis

β – is an equivalent moment factor

When the end moments are zero the equivalent moment factor $\beta = 0$, and for the moment distribution with different end moments M_{Ed} and rM_{Ed} where r is in between -1 and $1, \beta = 0.66 + 0.44r$.

In fully encased composite column the effect of local buckling may be neglected for the steel section when the provided concrete cover is greater than maximum of 40mm or one-sixth of the breadth b of the flange.

Resistance of members in axial compression

When the column is subjected to axial load only, the member have to be verified by the following equation:

$$\frac{N_{Ed}}{\chi N_{pl,Rd}} \leq 1.0$$

In EN 1993-1-1:2004 Reduction factor for the relevant buckling mode is χ given by

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \leq 1$$

$$\phi = 0.5[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2]$$

Where: α – imperfection factor taken corresponding to appropriate buckling curve

When the buckling curve is b, the imperfection factor α is 0.34, and for buckling curve is c, the imperfection factor α is 0.49.

Resistance of members combined compression and uniaxial bending

When the column is subjected to axial compression and uniaxial bending, the member have to be verified by the following equation:

$$\frac{M_{Ed}}{M_{pl,N,Rd}} = \frac{M_{Ed}}{\mu_d M_{pl,Rd}} \leq \alpha_M$$

Where: $M_{pl,N,Rd}$ – plastic bending resistance taking into account the normal force N_{Ed}, given by $\mu_d M_{pl,Rd}$

α_M – 0.9 for steel grade between S235 and S355,

– 0.8 for steel grades S420 and S460

Combined compression and biaxial bending

The member have to verified for each axis when the column is subjected to combined compression and biaxial bending, and the combined effect also have to be checked by the following equation:

$$\frac{M_{y,Ed}}{\mu_{dy} M_{pl,y,Rd}} \leq \alpha_{M,y} \qquad \frac{M_{y,Ed}}{\mu_{dy} M_{pl,y,Rd}} \leq \alpha_{M,z}$$

$$\frac{M_{y,Ed}}{\mu_{dy} M_{pl,y,Rd}} + \frac{M_{y,Ed}}{\mu_{dy} M_{pl,y,Rd}} \leq 1.0$$

Shear connection and load introduction

When compression members are subjected to significant transverse shear due to local transverse loads or due to end moments, provision shall be made for the transfer of the corresponding longitudinal shear stress at the interface between steel and concrete.

If the composite column is subjected axially, longitudinal shear outside the areas of load introduction need not be considered. And if design shear strength τ_{Rd}, is exceeded at the interface between steel and concrete, shear connecters are provided in load introduction area and in areas with change of cross section.

In the absence of more accurate method, the introduction length should not be exceed 2d or L/3, where d is the minimum transverse dimension of the column and L is the column length.

Frictional force that develop due to prevention of lateral expansion of the concrete by the adjacent steel flanges may be taken into account in determining resistance of the shear connectors when shear connectors are attached to the web of fully or partially concrete encased section.

For concrete encased steel sections the transverse reinforcement should be designed for the longitudinal shear that results from the transmission of normal force, N_{c1} from the parts of concrete directly connected by shear connectors into the parts of the concrete without direct shear connection.

If the full interface between the concrete section and endplate is permanently in compression, no shear connection need to be provided for load introduction area. In the absence of more accurate method to determine the longitudinal shear at the interface, elastic analysis is used by considering long term effects and cracking of concrete.

For concrete encased steel sections with 40mm minimum concrete cover, and if transverse and longitudinal reinforcement are detailed in accordance with EN 1992-1-1:2004, the value for design shear strength 0.3N/mm^2 can be taken. For greater concrete cover and adequate reinforcement, higher value of $\beta_c \tau_{Rd}$ can be used.

$$\beta_c = 1 + 0.02c_z \left(1 - \frac{c_{z,min}}{c_z}\right) \leq 2.5$$

Where: c_z is the nominal value of concrete cover in mm

$c_{z,min}$ = 40mm is the minimum concrete cover

Detailing provisions

1. Concrete cover

For flange in a fully encased steel section concrete cover should not be less than 40mm, nor less than one-sixth of the breadth b of the flange. For the reinforcement the cover should be in accordance with EN 1992-1-1:2004.

2. Longitudinal and transverse reinforcement

Longitudinal reinforcement in fully encased steel section should be not less than 0.3% of the concrete cross-section. Additional requirement to design and detailing of transverse and longitudinal reinforcement should be taken from EN 1992-1-1:2004.

For concrete encased composite columns, where environmental conditions are class X0 according to EN 1992-1-1:2004, and longitudinal reinforcement is neglected in design, a minimum longitudinal reinforcement of diameter 8mm and 250mm spacing and a transverse reinforcement of diameter 6mm and 200mm spacing should be provided. Alternatively welded mesh reinforcement of diameter 4mm may be used.

2.6 Earlier Studies and Experimental Result on Concrete Encased Composite Column

Matsui (1979) carried experimental investigation to observe the effect of slenderness on the ultimate capacity and failure mode of concrete-encased composite column. Three specimens were tested by taking the length of the column, slenderness ratio, concrete compressive strength, and structural steel yield strength as a variable. From the test results, it is reported that as slenderness ratio increases the ultimate capacity of the column decreases. Also, it is observed that less slender columns ware failed due to concrete crushing followed by the yielding of structural steel.

Morino et al. (1984) conducted a research work to observe the reduction of ultimate capacity and failure behavior due to changes in eccentricity angle and slenderness of concrete encased composite column subjected to biaxial eccentric compression load. The experimental parameters ware eccentricity, slenderness ratio, and angle location between the applied load point and the major axis. From the result, it is observed that when eccentricity is changed from minor to major axis, there is 35% reduction in the ultimate load carrying capacity of the column. In short columns, it is observed that the columns ware failed because of concrete crushing and in slender columns P-delta effect was more pronounced in the results.

Chen and Yeh (1996) analyze ten experimental specimens to determine the ultimate capacity of concrete encased composite column with different structural steel shape (I-shaped H-shaped, and cross-shaped), concrete compressive strength, and yield strength of structural steel. The result showed that, column with cross-shaped structural steel have higher ultimate load carrying capacity because of high confinement effect on the core concrete from the steel flange. And columns with closely spaced transverse reinforcement showed higher ultimate load carrying capacity.

Cheng-Chin Chen, and Nan-Jiao Lin (2005) propose an analytical model for predicting axial capacity and behavior of concrete encased composite columns by using earlier experimental results. The parameters on the experimental specimens were structural steel shape and transverse reinforcement spacing. The analytical model is developed by normalizing the ultimate strength of the column which is gain from the experiments by the squash load P_{Squas} .

Where: $P_{Squ} \quad = A_a f_{yk} + 0.85 A_c f_{ck} + A_s f_{sk}$

A_a − Cross-sectional area of structural steel section

f_{yk} − Yield strength of structural steel

A_c − Cross-sectional area of concrete section

f_{ck} − Compressive strength of concrete

A_s − Cross-sectional area of longitudinal reinforcement

f_{sk} − Yield strength of reinforcing steel

The analyzed result shows the composite column with cross-shaped steel section have high confinement effect on the core concrete than I & H-shaped steel section. It is also showed that as the transverse reinforcement spacing decreases the capacity of the concrete encased composite column will increase.

Kim et al. (2012) carried experimental study on eccentrically loaded concrete encased composite column using high strength concrete and high strength structural steel. The experimental parameters were eccentricity of the axial load and spacing of the transverse reinforcement. The result showed columns with highly spaced transverse reinforcement have inadequate lateral confinement, so the load carrying capacity was limited by the early crushing of concrete. After the concrete crushed, all specimens showed ductile flexural behavior because of high structural steel strength.

T.-H. Shih et al. (2013) six full scaled concrete encased composite columns with two interlocking spirals were experimentally and analytically investigated to examine axial compressive capacity and load-displacement behavior of composite columns. The analytical model was developed by taking into account the concrete confinement effect due to; the structural steel, the transverse reinforcement, and distribution of the longitudinal reinforcement. To generate the stress-strain model for confined concrete, the proposed model by Mander et al. (1998) is used in the analytical model. The study conclude that, to achieve a higher load carrying capacity and to have a higher ductile behavior the spiral transverse reinforcement shall be used instead of rectilinearly tied transverse reinforcement. And the developed analytical model showed a good agreement with the test result.

Rahman (2016) presented experimental and numerical investigation on concrete encased composite column under concentric and eccentric axial loads. Thirteen concrete encased composite column with different cross-sectional size, percentages of structural steel and concrete compressive strength were tested experimentally to observe the failure behavior, the ultimate load carrying capacity and axial deformation at the ultimate load. Additionally numerical simulation is conducted on concrete encased composite column under axial compression and bending using finite element model. Using the numerical model parametric study was conducted to investigate the influence of geometric and material properties of concrete encased composite column subjected to axial compression and bending about strong axis of the steel section. The selected parameters ware percentage of structural steel, column slenderness, eccentricity ratio, and spacing of transverse reinforcement as a geometrical variables and as a material variables the study takes compressive strength of concrete and yield strength of structural steel. It was observed that structural steel ratio and concrete compressive strength has significant effect on the strength, ductility and failure behavior of concrete encased composite column. And as slenderness ratio increases or as the position of the load changes from concentric to eccentric the strength of the column is decreased.

3 Analytical Model of Concrete Encased Composite Column

3.1 Introduction

In concrete encased composite column two mechanism to restrain the lateral expansion of concrete, one by transverse reinforcement and another by structural steel. The concrete area is classified depend on the mechanism of restraining the concrete lateral expansion. Then the lateral confining pressure from both transverse reinforcement and structural steel section is determined. In addition, the confined compressive strength of concrete is determined according to their corresponding concrete area. Using confined concrete compressive strength and with the defined confined concrete area the analytical model is developed to determine the total axial compression resistance of concrete encased composite column and the results are validated with earlier experimental result and compared with EN 1994-1-1:2004.

In the process of developing the analytical model the following points are assumed;

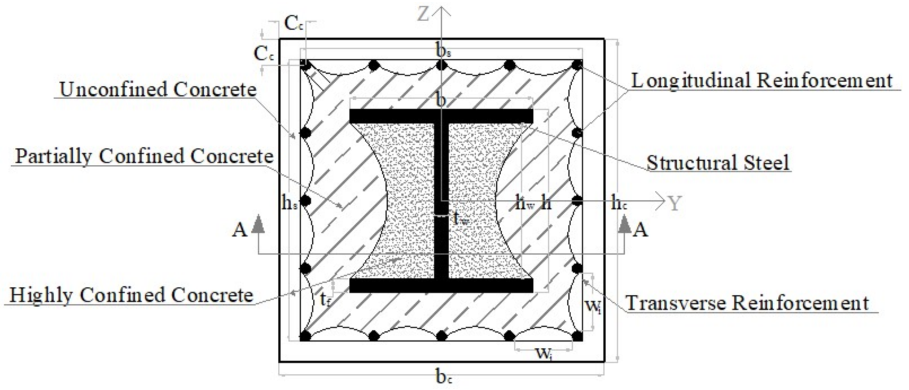
- Until failure occur full interaction is assumed between concrete, reinforcement and structural steel
- Longitudinal reinforcement and structural steel are subjected to the same amount of strain as the surrounding concrete
- Plane section remain plane after deformation
- The tensile strength of concrete is neglected
- The concrete encased composite column section is doubly symmetrical
- Distribution of the longitudinal reinforcement and the diameter is uniform throughout the cross-section

As described previously concrete encased composite columns are a composition of concrete, structural steel, longitudinal reinforcement and transverse reinforcement. From earlier studies and experimental results, it is known that restraining the lateral expansion of the concrete will enhance the carrying capacity and ductility of the column. The lateral expansion of concrete in the case of concrete encased composite column is restrained by the transverse reinforcement and structural steel. Based on this mechanism of restraining the concrete lateral expansion in concrete encased composite column, concrete section can be classified into three sections. Which are unconfined concrete, partially confined concrete and highly confined concrete section.

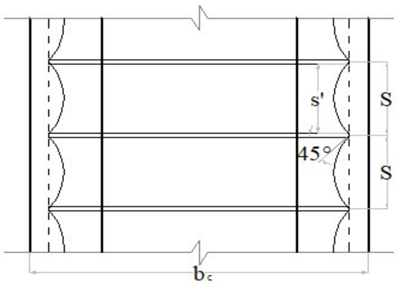
Unconfined concrete section is a part of the concrete, which is not restrained neither by the transverse reinforcement nor by the structural steel and will finally become ineffective after the compressive strength is attained. Partially confined concrete section are the concrete section which is restrained only by the transverse reinforcement. Highly confined concrete section is the rest of the concrete section in which the lateral expansion of concrete is restrained by both the transverse reinforcement and structural steel.

3.2 Area of Concrete Sections in Concrete Encased Composite Column

When axial load is applied on concrete encased composite column, arching action is expected to occur horizontally between longitudinal reinforcement and the tips of structural steel flange (Figure 3.1 a), and vertically between transverse reinforcement (Figure 3.1 b). Arching action is assumed to act in the form of second-degree parabola with an initial tangent slope of 45^0.



a. Cross-sectional view of concrete encased composite column



b. Section A-A

Figure 3.1 Concrete section partition in concrete encased composite column

Therefor by assuming arching action the concrete area for the three concrete areas are defined as follows. Partially confined concrete area is dependent on the distribution of the longitudinal and transverse reinforcement. And the highly confined concrete area is dependent on the dimension of the structural steel.

$$A_{hc} = 2\left(\left(\frac{b-t_w}{2}\right)\left(h-2t_f\right) - \frac{\left(h-2t_f\right)^2}{6}\right) \tag{3.1}$$

$$A_{pc} = \left(b_s h_s - \sum_{i=1}^{n}\frac{{w_i}^2}{6}\right)\left(1-\frac{s'}{2b_s}\right)\left(1-\frac{s'}{2h_s}\right) - A_a - A_s - A_{hc} \tag{3.2}$$

$$A_{uc} = A_c - A_{hc} - A_{pc} \tag{3.3}$$

Where:

A_{hc} – is highly confined concrete area

A_{pc} – is partially confined concrete area

A_{uc} – is unconfined concrete area

A_c – is the total concrete area

b – width of structural steel flange

t_f – thickness of structural steel flange

h – height of structural steel

t_w – thickness of structural steel web

b_s and h_s – dimensions of transverse reinforcement

b_c and h_c – outer dimensions of concrete encased composite column

w_i – spacing between longitudinal reinforcement

S' - clear spacing between transverse reinforcement

3.3 Lateral Confining Pressure on the Concrete

3.3.1 From Transverse Reinforcement

To define the lateral confining pressure on the core concrete due to transverse reinforcement, theoretical stress-strain model for confined concrete by Mander et al. (1998) is adopted. Since the area of concrete with in the centerline of the transverse reinforcement is greater than the area of effectively confined concrete, the effective lateral confining pressure, $f'_{1,s}$ is;

$$f'_{1,s} = f_{1,s} k_{e,s} \qquad (3.4)$$

Where:

$f'_{1,s}$ – is the effective lateral confining pressure from transverse reinforcement

$f_{1,s}$ – is the lateral confining pressure from transverse reinforcement

$$k_{e,s} = \frac{A_{e,s}}{b_s h_s - A_a - A_s} \qquad (3.5)$$

$$A_{e,s} = A_{pc} + A_{hc} \qquad (3.6)$$

$A_{e,s}$ – is area of effectively confined concrete by transverse reinforcement

A_a – is the area of structural steel

A_s – is the area of longitudinal reinforcement

Due to the configuration of transverse reinforcement the lateral confining pressure on the concrete might be different in different directions. But since this model is developed for doubly symmetrical section there will be the same lateral confining pressure in both direction $f_{1,s} = f_{1y,s} = f_{1z,s}$.

$$f_{1y,s} = \rho_{y,s} f_{sk} \quad , \quad f_{1z,s} = \rho_{z,s} f_{sk} \qquad (3.7)$$

$$\rho_{y,s} = \frac{A_{sy}}{S h_s} \quad , \quad \rho_{z,s} = \frac{A_{sz}}{S b_s} \qquad (3.8)$$

Where:

$\rho_{y,s}$ – is ratio of the transverse reinforcement area to the confined concrete area in y-direction

$\rho_{z,s}$ – is ratio of the transverse reinforcement area to the confined concrete area in z-direction

f_{sk} – is characteristic value of the yield strength of reinforcing steel

S – is center-to-center spacing of transverse reinforcement

A_{sy} – is the area of transverse reinforcement in y-direction

A_{sz} – is the area of transverse reinforcement in z-direction

3.3.2 From Structural Steel

In concrete encased composite column with I or H-shaped structural steel section, the confining pressure from the structural steel is not applied in all four sides of the concrete core. As Shown in Figure 3.1 (a), the three sides of highly confined concrete are confined with the flange and web of the structural steel and in the other remaining side the lateral expansion of concrete is restrained by the transverse reinforcement.

The effectively confined concrete in structural steel is less than the area of concrete with in the centerline of the structural steel flange and web. To account this the lateral confining pressure from structural steel is decreased by a factor of $k_{e,a}$.

$$f'_{1,a} = f_{1,a}k_{e,a} \tag{3.9}$$

Where:

$f'_{1,a}$ – is the effective lateral confining pressure from structural steel

$f_{1,a}$ – is the lateral confining pressure from structural steel

$$k_{e,a} = \frac{A_{e,a}}{\left(\frac{b}{2}\right)(h-t_f)} \tag{3.10}$$

$$A_{e,a} = A_{hc}/2 \tag{3.11}$$

$A_{e,a}$ – is area of effectively confined concrete by structural steel

There is a difference in lateral confining pressure on highly confined concrete core in y and z-direction. In y-direction the confining pressure is from transverse reinforcement. And in z-direction it is from top and bottom flange of structural steel.

The lateral confining pressure from structural steel in y and z-direction are;

$$f_{1y,a} = f_{1y,s} = \rho_{y,s}f_{sk} \quad , \quad f_{1z,a} = \rho_{z,a}f_{yk} \tag{3.12}$$

$$\rho_{y,s} = \frac{A_{sy}}{Sh_s} \quad , \quad \rho_{z,a} = \frac{t_f}{h'} \tag{3.13}$$

Where:

$\rho_{z,a}$ – is ratio of structural steel area to the confined concrete area in z-direction

h' – is a unit length

f_{yk} – is characteristic value of the yield strength of structural steel

3.4 Compressive Strength of Confined Concrete

3.4.1 Compressive Strength of Partially Confined Concrete

As described earlier, partially confined concrete is confined by transverse reinforcement only. Therefore Compressive strength of confined concrete is calculated by adopting the equation used in Mander et al. (1998). As a result compressive strength of partially confined concrete f_{pcc} is;

$$f_{pcc} = f_{ck} k_{pc} \tag{3.14}$$

Where:

k_{pc} – is the confinement factor for partially confined concrete

$$k_{pc} = \left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_{1,s}}{f_{ck}}} - \frac{2 f'_{1,s}}{f_{ck}} \right) \tag{3.15}$$

f_{ck} – is characteristic value of the compressive strength of unconfined concrete

3.4.2 Compressive Strength of Highly Confined Concrete

And for highly confined concrete, which is confined by transverse reinforcement in y-direction and by top and bottom structural steel flange in z-direction. The effective lateral confining pressure on highly confined concrete is;

In y-direction

$$f'_{1y,h} = f'_{1,s} \tag{3.16}$$

In z-direction

$$f'_{1z,h} = k_{e,a} f_{1z,a} \tag{3.17}$$

Where:

$f'_{1y,h}$ – is the effective lateral confining pressure on highly confined concrete in y-direction

$f'_{1z,h}$ – is the effective lateral confining pressure on highly confined concrete in z-direction

Effective lateral confining pressure on highly confined concrete $f'_{1,h}$

$$f'_{1,h} = \frac{\left(f'_{1y,h}(h-t_f)\right)+\left(f'_{1z,h}b/2\right)}{(h-t_f)+b/2} \tag{3.18}$$

The compressive strength of highly confined concrete $\mathrm{f_{hcc}}$ is;

$$f_{hcc} = f_{ck}k_{hc} \tag{3.19}$$

Where:

k_{hc} – is the confinement factor for highly confined concrete

$$k_{hc} = \left(-1.254 + 2.254\sqrt{1+\frac{7.9f'_{1,h}}{f_{ck}}} - \frac{2f'_{1,h}}{f_{ck}}\right) \tag{3.20}$$

3.5 Compression Resistance of Axially Loaded Concrete Encased Composite Column

The analytical model to determine compression resistance of axially loaded concrete encased composite column, $P_{Analytical}$ is given by adding the multiplication of each component strength to their corresponding area;

$$P_{Analytical} = f_{ck}A_{uc} + f_{pcc}A_{pc} + f_{hcc}A_{hc} + f_{sk}A_s + f_{yk}A_a \tag{3.21}$$

3.6 Verification and Comparison of the Analytical model

Earlier experimental result are used to verify the analytical model which has been presented in this chapter. And also the results are compared with EN 1994-1-1:2004 results to show the developed analytical model is a batter way of defining compression resistance of concrete encased composite columns. A total of eleven concentrically loaded concrete encased composite columns from published literature Chen and Yeh (1996) and Rahman (2016) are used to validate the analytical model. The analytical model is applied on this eleven axially loaded concrete encased composite column test specimens and the results are compared with experimental result. The test specimen geometrical and material properties are presented in Table 3.1.

EN 1994-1-1:2004 provide an equation to calculate compression resistance of axially loaded concrete encased composite column, P_{Code} is given by;

$$P_{Code} = 0.85 f_{ck} A_c + f_{sk} A_s + f_{yk} A_a \tag{3.22}$$

Table 3.1 Material and geometrical property of the test specimen

Tested By	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Chen and Yeh (196)	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	SRC2	28.1	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c75
	SRC3	29.8	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c35
	SRC7	28.1	350	303	280x280	75x150x7x5	12ϕ16	ϕ8c/c140
	SRC8	26.4	350	303	280x280	75x150x7x5	12ϕ16	ϕ8c/c75
	SRC9	28.1	350	303	280x280	75x150x7x5	12ϕ16	ϕ8c/c140
	SRC10	29.8	350	303	280x280	75x150x7x5	12ϕ16	ϕ8c/c75
Rahman (2016)	SCN4A	28	470	350	100x100	20x30x5x5	4ϕ8	Φ6c/c50
	SCN4B	28	470	350	100x100	25x35x5x5	4ϕ8	Φ6c/c50
	SCH6A	42	470	350	150x150	30x40x5x5	4ϕ8	Φ6c/c75
	SCH6B	42	470	350	150x150	45x55x5x5	4ϕ8	Φ6c/c75

From Chen and Yeh (1996) seven test specimen are selected which are designated as SRC1, SRC2, SRC3, SRC7, SRC8, SRC9, and SRC10. This specimens take concrete compressive strength and yield strength of structural steel as a material property variable.

And as a geometrical property variable, structural steel size and transverse reinforcement spacing are taken.

From Rahman (2016) four test specimen are selected which are designated as SCN4A, SCN4B, SCH6A, and SCH6B. This test specimens have concrete strength as a material property variable and cross-sectional size of the concrete encased composite column, structural steel shape and transverse reinforcement spacing as a geometrical variable.

Concrete cover from the center of longitudinal reinforcement is 34mm for all Chen and Yeh (1996) specimens and 25mm for all Rahman (2016) specimens. By using a mathematical formulation, which are developed in this thesis the unconfined concrete area, partially confined concrete area, highly confined concrete area, compressive strength of partially confined concrete and compressive strength of highly confined concrete are determined and presented in Table 3.2.

Table 3.2 Material properties used for the analytical model

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_c (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	f_{ck} (MPa)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)
SRC1	3910	2412.7	72077	12957	6519.3	52601	29.5	1.096	32.32	1.199	35.38
SRC2	3910	2412.7	72077	12957	17326	41794	28.1	1.273	35.77	1.315	36.96
SRC3	3910	2412.7	72077	12957	24914	34206	29.8	1.609	47.96	1.531	45.62
SRC7	1730	2412.7	74257	3354.7	18301	52601	28.1	1.106	31.09	1.117	31.38
SRC8	1730	2412.7	74257	3354.7	29108	41794	26.4	1.296	34.2	1.269	33.51
SRC9	1730	2412.7	74257	3354.7	18301	52601	28.1	1.106	31.09	1.117	31.38
SRC10	1730	2412.7	74257	3354.7	29108	41794	29.8	1.265	37.69	1.241	36.98
SCN4A	300	201.06	9498.9	166.67	589.81	8742.5	28	1.378	38.58	1.313	36.77
SCN4B	375	201.06	9423.9	291.67	389.81	8742.5	28	1.351	37.83	1.297	36.32
SCH6A	450	201.06	21849	450	2475	18924	42	1.117	46.9	1.117	46.93
SCH6B	675	201.06	21624	1125	1575	18924	42	1.11	46.62	1.119	46.98

As shown in Table 3.2 the compressive strength of concrete is enhanced by transverse reinforcement in partially confined concrete and by transverse reinforcement and structural steel in highly confined concrete. From Chen and Yeh (1996) and Rahman (2016) partially confined compressive strength of concrete is improved from 9.6 to 60.9% from unconfined compressive strength concrete. And highly confined compressive strength of concrete is improved from 11.7 to 53.1% from unconfined compressive strength concrete.

Based on the material and geometrical properties of the test specimen and by using partially and highly confined concrete compressive strength, the resistance to compression is estimated using the analytical model and EN 1994-1-1:2004 equation. Then compared with the actual experimental test result P_{Test} and the results are presented in Table 3.3.

Table 3.3 Eurocode and Analytical model result comparison with the test result

Specimen Label	P_{Test} (kN)	P_{Code} (kN)	$P_{Analytical}$ (kN)	P_{Test} $/P_{Code}$	P_{Test} $/P_{Analytical}$
SRC1	4220	3809.16	4222.67	1.108	0.999
SRC2	4228	3723.39	4274.79	1.136	0.989
SRC3	4399	3827.54	4807.18	1.149	0.915
SRC7	3788	3142.28	3520.98	1.205	1.076
SRC8	3683	3034.98	3580.08	1.214	1.029
SRC9	3630	3142.28	3520.98	1.155	1.031
SRC10	3893	3249.59	3835.38	1.198	1.015
Average:				1.166	1.008
Coefficient of variation:				0.032	0.045
SCN4A	491	425.574	473.17	1.154	1.038
SCN4B	516	450.039	495.88	1.147	1.041
SCH6A	1117	1032.01	1184.01	1.082	0.943
SCH6B	1240	1102.72	1251.84	1.124	0.991
Average:				1.127	1.003
Coefficient of variation:				0.025	0.040

From Chen and Yeh (1996) experimental tests, concentrically loaded concrete encased composite column are tested with different compressive strength of concrete, yield strength of structural steel, structural steel ratio and spacing of transverse reinforcement.

The difference in material and geometrical property will show the analytical model will work on different condition. The estimated compressive resistance of axially loaded concrete encased composite column by the analytical model shows a very close result to the experimental result. The ratio of $P_{Test}/P_{Analytical}$ range from 0.915 to 1.076 with the average ratio of 1.008 and the coefficient of variation is 0.045.

EN 1994-1-1:2004 estimate lower compressive resistance of concentrically loaded concrete encased composite column compared to the experimental result. The ratio of P_{Test}/P_{Code} range from 1.108 to 1.214 with the average ratio of 1.166 and the coefficient of variation is 0.032. EN 1994-1-1:2004 estimate the axial compression resistance by average of 16.6% less than the actual test result.

In addition to Chen and Yeh (1996) test specimens from Rahman (2016) will show the analytical model will work with different column cross-section, compressive strength of concrete, structural steel ratio and spacing of transverse reinforcement. Like Chen and Yeh 1996 the estimated compressive resistance of axially loaded concrete encased composite column by the analytical model shows a very close result to the experimental result.

The ratio of $P_{Test}/P_{Analytical}$ range from 0.943 to 1.041 with the average ratio of 1.003 and the coefficient of variation is 0.04. The ratio of P_{Test}/P_{Code} range from 1.154 to 1.082 with the average ratio of 1.127 and the coefficient of variation is 0.025. EN 1994-1-1:2004 estimate the axial compression resistance by an average value of 12.7% less than the actual test result.

Generally Based on this results the developed analytical model is the more accurate approach to predict the compression resistance of concentrically loaded concrete encased composite column by considering the confinement effect on the core concrete due to the lateral confining pressure from both transverse reinforcement and structural steel. From all specimen results the analytical model determine compression resistance of concentrically loaded concrete encased composite column by 99.4% approximation with the experimental result.

4 Parametric Study

4.1 Introduction

This parametric study is carried out to show how geometrical and material parameter affect the confinement effectiveness on concrete encased composite column. As described earlier the concrete encased composite column is a composite of concrete, structural steel, longitudinal reinforcement and transverse reinforcement. For this thesis the selected parameters for each part of the concrete encased composite column are shown below and the results are discussed in subsequent section.

Material parameter:

- Compressive strength of concrete
- Yield strength of structural steel
- Yield strength of Transverse reinforcement

Geometrical parameter:

- Thickness of structural steel flange
- Width of structural steel flange
- Configuration of longitudinal reinforcement
- Spacing of transverse reinforcement

4.2 Design of the Parametric Study

A doubly symmetrical concrete encased composite column SRC1 specimen from Chen and Yeh (1996) test result was taken as the reference section. The geometrical and material property of SRC1 test specimen is as described in Table 3.1. Different specimens are developed by altering geometrical and material parameters of SRC1 to study the confinement effectiveness on axial compression resistance of concrete encased composite column. To see the effect of each parameter the columns are developed by keeping other parameters constant. Cross section of the concrete encased composite column used in this parametric study are listed in Table 4.1 to Table 4.7.

4.2.1 Compressive Strength of Concrete

The design procedure of EN 1994-1-1:2004 for concrete encased composite column is applied to column with normal weight concrete strength from C20/25 to C50/60. By using this range eight different compressive strength of concrete between 20 to 50Mpa is used in the parametric study. The other parameter of the column is described in Table 4.1.

Table 4.1 Material and geometrical property of group-1 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-1	CECC-1	20	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-2	25	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-3	30	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-4	35	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-5	40	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-6	45	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-7	50	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140

4.2.2 Yield Strength of Structural Steel

EN 1994-1-1:2004 applies on composite columns with steel grades S235 to S460. Therefore to see the confinement effect by changing the yield strength of structural steel four specimens are developed by using standard steel grade between S235 and S460. The material and geometrical property of specimens to study the effect of yield strength of structural steel on the confined concrete compressive strength is described in Table 4.2Table *4.2*.

Table 4.2 Material and geometrical property of group-2 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-2	CECC-8	29.5	350	235	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-9	29.5	350	275	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-10	29.5	350	355	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-11	29.5	350	450	280x280	150x150x10x7	12ϕ16	ϕ8c/c140

4.2.3 Yield Strength of Transverse Reinforcement

As described in EN 1992-1-1:2004 to use Eurocode rules for design and detailing, the yield strength of reinforcement should be in a range between 400 MPa to 600 MPa. So six specimens developed to investigate the effect of transverse reinforcement yield strength on the confined compressive strength of concrete and described on Table 4.3.

Table 4.3 Material and geometrical property of group-6 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-3	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-12	29.5	400	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-13	29.5	450	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-14	29.5	500	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-15	29.5	550	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-16	29.5	600	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140

4.2.4 Thickness of Structural Steel Flange

To see how the thickness of structural steel flange affect the confined compressive strength of concrete the dimension of the structural steel on specimen SRC1 is kept constant except thickness of the flange. Four specimens with different thickness of structural steel flange as shown in Table 4.4 are developed. The selected structural steel cross section is checked for maximum width-to-thickness ratio which is stated in EN 1993-1-1:2005.

Table 4.4 Material and geometrical property of group-3 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-4	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-18	29.5	350	296	280x280	150x150x12x7	12ϕ16	ϕ8c/c140
	CECC-19	29.5	350	296	280x280	150x150x14x7	12ϕ16	ϕ8c/c140
	CECC-20	29.5	350	296	280x280	150x150x16x7	12ϕ16	ϕ8c/c140

4.2.5 Width of Structural Steel Flange

By keeping all cross-sectional dimensions of structural steel constant except width of the flange, the effect of structural steel flange width on the confined compressive strength of concrete is studied. Four specimens are developed with different structural steel width as shown in Table 4.5. As arranged in previous group of structural steel section the maximum width-to-thickness ratio for this group is also checked.

Table 4.5 Material and geometrical property of group-4 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-5	CECC-20	29.5	350	296	280x280	75x150x10x7	12ϕ16	ϕ8c/c140
	CECC-21	29.5	350	296	280x280	100x150x10x7	12ϕ16	ϕ8c/c140
	CECC-22	29.5	350	296	280x280	125x150x10x7	12ϕ16	ϕ8c/c140
	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140

4.2.6 Configuration of Longitudinal Reinforcement

To see how the configuration of longitudinal reinforcement affect the confined compressive strength of concrete, constant area of longitudinal reinforcement is used. Moreover, the corresponding equivalent number and diameter of longitudinal reinforcement is calculated and listed on Table 4.6.

Table 4.6 Material and geometrical property of group-5 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-6	CECC-23	29.5	350	296	280x280	150x150x10x7	4ϕ27.7	ϕ8c/c140
	CECC-24	29.5	350	296	280x280	150x150x10x7	8ϕ9.6	ϕ8c/c140
	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-25	29.5	350	296	280x280	150x150x10x7	16ϕ13.8	ϕ8c/c140

4.2.7 Spacing of Transverse Reinforcement

As studied in many earlier studies it is clearly showed that in reinforced concrete column, spacing of the transverse reinforcement have a pronounced effect on confined compressive strength of concrete. To compute and see the effect of spacing of transverse reinforcement in concrete encased composite column four specimens described in Table 4.7 are selected.

Table 4.7 Material and geometrical property of group-7 specimens

Group	Specimen Label	Material Property			Column section	Structural Steel section	Reinforcement	
		f_{ck} (MPa)	f_{sk} (MPa)	f_{yk} (MPa)	$b_c * h_c$ (mm)	$b * h * t_f * t_w$ (mm)	Longitudinal	Transverse
Group-7	SRC1	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c140
	CECC-26	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c125
	CECC-27	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c100
	CECC-28	29.5	350	296	280x280	150x150x10x7	12ϕ16	ϕ8c/c75

4.3 Result and Discussion

A total of thirty-two concrete encased composite column specimens are developed to see how the selected parameters affect the confinement effect on confined compressive strength of concrete and compression resistance of axially loaded concrete encased composite column. The specimens are analyzed by the developed analytical model in this thesis from equation 3.1 to equation 3.21. The output values that are extracted from the analysis result were compressive strength of partially confined concrete, f_{pcc}, compressive strength of highly confined concrete, f_{hcc}, and compression resistance of axially loaded concrete encased composite column, $P_{Analytical}$. The obtained result from the analysis were organized and presented in subsequent section to show effect of each parameter.

4.3.1 Compressive Strength of Concrete

As shown in Table 4.1 seven specimens are developed by altering the compressive strength of concrete to see the effect of compressive strength of concrete on confined compressive strength of concrete and compression resistance of axially loaded concrete encased composite column. Because the same cross-sectional area was used for concrete, structural steel and longitudinal reinforcement, the obtained unconfined concrete area, partially confined concrete area, and highly confined concrete area is the same for all seven specimens in group-1 concrete encased composite columns. Because of this the lateral confining pressure from both structural steel and transverse reinforcement for all specimens are the same.

Table 4.8 Analysis result for group-1 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
CECC-1	3910	2412.7	12957	6519.3	52601	1.139	22.77	1.285	25.7	3535
CECC-2	3910	2412.7	12957	6519.3	52601	1.112	27.8	1.232	30.81	3897
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-3	3910	2412.7	12957	6519.3	52601	1.094	32.82	1.196	35.89	4259
CECC-4	3910	2412.7	12957	6519.3	52601	1.081	37.83	1.17	40.95	4620
CECC-5	3910	2412.7	12957	6519.3	52601	1.071	42.84	1.15	45.99	4981
CECC-6	3910	2412.7	12957	6519.3	52601	1.063	47.85	1.134	51.02	5342
CECC-7	3910	2412.7	12957	6519.3	52601	1.057	52.86	1.121	56.05	5703

For the reason that confinement factor for both partially and highly confined concrete is dependent on the unconfined compressive strength of concrete, confinement factor, k_{pc} & k_{hc} were chosen to see the effect and Figure 4.1 shows the result. As the concrete encased composite column compressive strength of concrete increases, the confinement factor for partially confined concrete and confinement factor for highly confined concrete decrease. This showed that the confinement effectiveness is lower for the higher compressive strength of concrete. The behavior of concrete becomes more brittle and the ductility decreases as the compressive strength of concrete increases. This is because modulus of elasticity for higher concrete strength is higher that lead the concrete to exhibits less lateral expansion under axial compression, therefor the confining reinforcement and structural steel comes to play later in the process which makes the efficiency of confinement reduced.

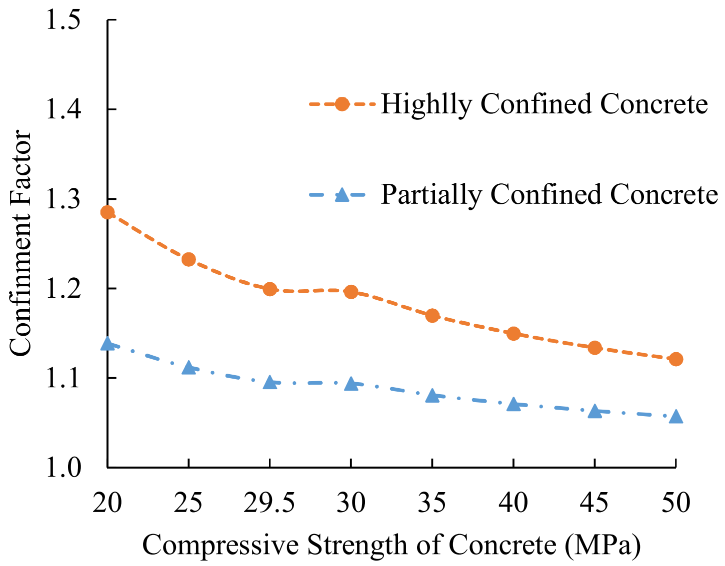


Figure 4.1 Confinement factor verses compressive strength of concrete

In general from group-1 specimens results partially confined compressive strength of concrete is improved by a minimum of 5.7% to a maximum of 13.9% from unconfined compressive strength of concrete. And in highly confined compressive strength of concrete they are improved by a minimum of 12.1% to a maximum of 28.5% from unconfined compressive strength of concrete. This result also showed that the lateral confining pressure of transverse reinforcement is smaller than the lateral confining pressure of structural steel. As a final point the result clearly showed that, as the column compressive strength of concrete increases the total compression resistance of the concrete encased composite column increases.

4.3.2 Yield Strength of Structural Steel

Specimens from CECC-8 to CECC-11 are used to show the effect of yield strength of structural steel on the confined compressive strength of concrete and the overall compression resistance of the concrete encased composite column. All four specimens have the same area of concrete and structural steel and the same number and distribution of longitudinal reinforcement.

Since the partially confined compressive strength of concrete is independent of the yield strength of structural steel, all four specimens in group-2 have the same partially confined compressive strength of concrete. There will be a change on highly confined compressive strength due to the change in yield strength of structural steel and the result is presented in Table 4.9.

Table 4.9 Analysis result for group-2 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
CECC-8	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.172	34.58	3974
CECC-9	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.19	35.11	4137
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-10	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.225	36.14	4463
CECC-11	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.265	37.33	4850

It is known that the maximum effective lateral confining pressure is activated when the stresses on the structural steel reach to their yield strength. The yield strength of structural steel measure the upper limit of lateral confining pressure applied to the core concrete. The higher the strength of the structural steel, the higher the lateral confining pressure that can exert.

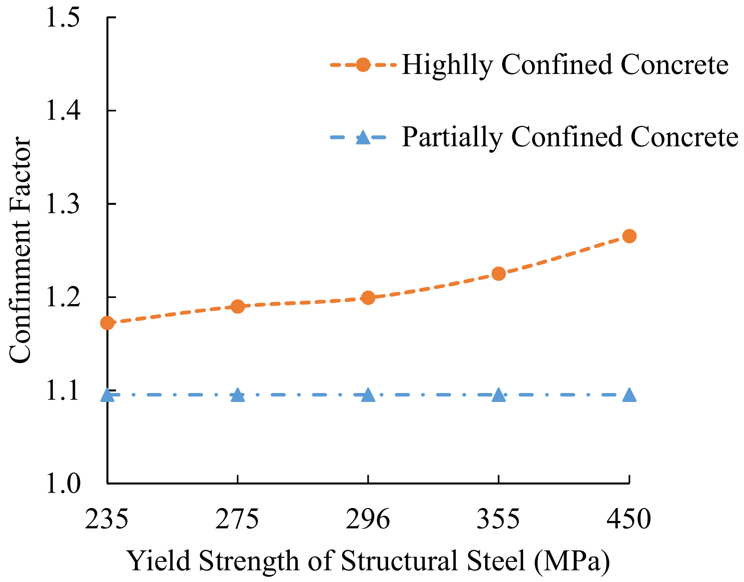


Figure 4.2 Confinement factor verses yield strength of structural steel

From the result partially confined compressive strength of concrete is enhanced by 9.6% from the unconfined compressive strength of concrete which is the same for all four specimens. And for the highly confined compressive strength of concrete it is enhanced by 17.2% to 26.5% from the unconfined compressive strength of concrete as the yield strength of structural steel increases. In general as yield strength of structural steel increases, the compression resistance of group-2 concrete encased composite columns are increased.

4.3.3 Yield Strength of Transverse Reinforcement

From the formulation of the analytical model, both partially confined and highly confined compressive strength of concrete is dependent on the yield strength of transverse reinforcement. To examine the effect of transverse reinforcement yield strength, five concrete encased composite column in group-3 from CECC-12 to CECC-16 are developed. All five specimens have the same area of concrete and structural steel and the same number and distribution of longitudinal reinforcement. The result is presented in the following Table 4.10.

Table 4.10 Analysis result for group-3 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-12	3910	2412.7	12957	6519.3	52601	1.109	32.71	1.207	35.62	4349
CECC-13	3910	2412.7	12957	6519.3	52601	1.122	33.09	1.215	35.85	4475
CECC-14	3910	2412.7	12957	6519.3	52601	1.135	33.47	1.223	36.08	4601
CECC-15	3910	2412.7	12957	6519.3	52601	1.147	33.85	1.231	36.31	4727
CECC-16	3910	2412.7	12957	6519.3	52601	1.160	34.22	1.239	36.54	4853

As same as the yield strength of structural steel, maximum effective lateral confining pressure is activated when the stresses on the transverse reinforcement reach to their yield strength. Also the yield strength of transverse reinforcement measure the upper limit of lateral confining pressure from transverse reinforcement which is applied to the core concrete.

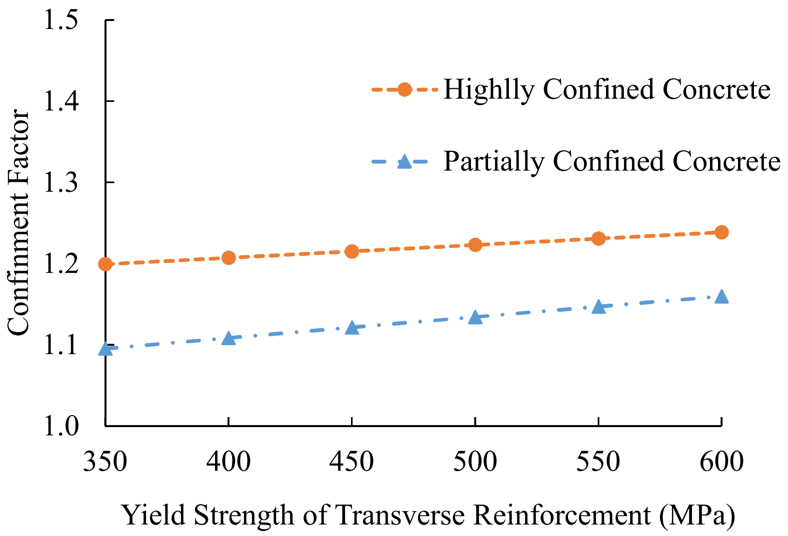


Figure 4.3 Confinement factor verses yield transverse reinforcement

From the analyzed five specimen, the result showed that as the yield strength of transverse reinforcement increased the partially confined compressive strength of concrete is increased by 9.6% to 16.0% from the unconfined compressive strength of concrete. And the highly confined compressive strength of concrete is increased by 19.9% to 23.9% from the unconfined compressive strength of concrete. As of the final results, increasing of the yield strength of transverse reinforcement definitely increase the compression resistance of concrete encased composite columns.

4.3.4 Thickness of Structural Steel Flange

To see the effect of structural steel flange thickness on confined compressive strength of concrete four concrete encased composite columns are analyzed in group-4 specimens from CECC-17 to CECC-19. By keeping all concrete encased composite column parameters constant and by only changing the thickness of structural steel flange the result showed that, all four specimens have different structural steel area, partially confined concrete area, and highly confined concrete area. But because of the concrete cover and the configuration of longitudinal reinforcement are not changed for all four specimens, all four of them have the same unconfined concrete area. All the compiled results are presented on the next Table 4.11.

Table 4.11 Analysis result for group-4 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-17	4482	2412.7	12726	6177.9	52601	1.094	32.27	1.225	36.13	4382
CECC-18	5054	2412.7	12485	5847.3	52601	1.092	32.22	1.25	36.87	4541
CECC-19	5626	2412.7	12233	5527.3	52601	1.090	32.17	1.275	37.6	4699

As the thickness of the structural steel increases the area of the overall structural steel increase. Due to the structural steel area increment from the total cross-sectional area of the concrete encased composite column, the partial and highly confined concrete areas are decreased.

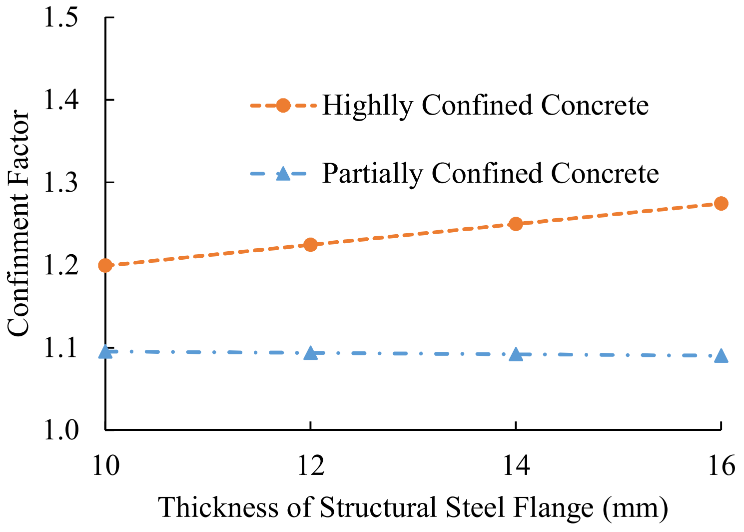


Figure 4.4 Confinement factor verses thickness of structural steel flange

The lateral confining pressure applied from transverse reinforcement on the core concrete is the same for all four specimens. But the area between the centerline of the transverse reinforcement is greater than the area of effectively confined concrete, the effective lateral confining pressure on the concrete is directly dependent on the effectively confined concrete area. Therefore as the area of partially confined concrete decreases, while other parameters used to define compressive strength of partially confined concrete are kept constant the effectiveness of confinement is going to be decreased. From group-4 results, compressive strength of partially confined concrete is enhanced from a maximum of 9.60% to a minimum of 9.0% from the unconfined compressive strength of concrete.

As the thickness of the structural steel flange increases, the lateral confining pressure from the structural steel increases. Even if highly confined concrete area is decreased while the thickness of the structural steel flange increases, the effectiveness of the confinement on highly confined concrete increases. From Table 4.11 group-4 specimen results, the compressive strength of highly confined concrete is enhanced from a minimum of 19.9% to a maximum of 27.5% from the unconfined compressive strength of concrete. To end with the final point from the group-4 result concrete encased composite columns showed that, increasing thickness of structural steel flange in fact increase the compression resistance of concrete encased composite columns.

4.3.5 Width of Structural Steel Flange

Same as increasing the thickness of structural steel flange, increasing width of structural steel flange have almost the same effect on partially and highly confined compressive strength of concrete. Group-5 concrete encased composite column specimens from CECC-20 to CECC-22 are examined to see the effect and the result are as presented in Table 4.12.

Table 4.12 Analysis result for group-5 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
CECC-20	2410	2412.7	3206.7	17769	52601	1.100	32.44	1.121	33.07	3792
CECC-21	2910	2412.7	6456.7	14019	52601	1.098	32.4	1.151	33.96	3931
CECC-22	3410	2412.7	9706.7	10269	52601	1.097	32.36	1.177	34.72	4075
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223

When width of structural steel flange increases, the total area of structural steel and the highly confined concrete area confined by the structural steel flange are increased and the area of partially confined concrete which is confined by the transverse reinforcement is decreased. But since the concrete cover and configuration of longitudinal reinforcement is not changed for all four concrete encased composite columns, they all are going to have the same area of unconfined concrete.

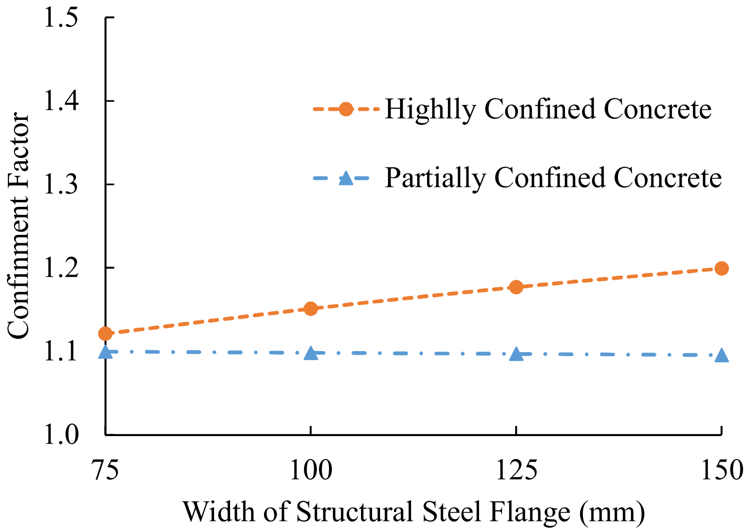


Figure 4.5 Confinement factor verses width of structural steel flange

As described earlier on the effect of structural steel flange thickness on the partially confined compressive strength of concrete, the lateral confining pressure applied from transverse reinforcement on the core concrete is the same for all four specimens. But due to the difference in the area between the centerline of transverse reinforcement and the area of effectively confined concrete, the effective lateral confining pressure on the concrete is directly dependent on the confined area of the concrete. Therefore while other parameters used to define compressive strength of partially confined concrete are kept constant and the area of partially confined concrete decreases, the effectiveness of confinement is decreased. Result of group-5 concrete encased composite column specimens showed that as width of structural steel flange increases the compressive strength of partially confined concrete is enhanced from a maximum of 10.0% to a minimum of 9.6% from the unconfined compressive strength of concrete.

Increasing the width of structural steel flange lead to the increment on the highly confined concrete area by the flange. As the effectiveness of the confinement is mostly dependent on the effectively confined concrete area, increasing the highly confined concrete area will increase compressive strength of highly confined concrete. From group-5 concrete encased composite columns results which is presented in Table 4.12 it was clearly showed that as the width of structural steel flange increases the confinement effectiveness on highly confined concrete is increased. The compressive strength of highly confined concrete is enhanced from a minimum of 12.1% to a maximum of 19.9% from the unconfined compressive strength of concrete. In general increasing width of structural steel flange increases the overall compression resistance of concrete encased composite columns.

4.3.6 Configuration of Longitudinal Reinforcement

As described earlier in the development of the analytical model, the unconfined and partially confined concrete area is dependent on the distribution of the longitudinal reinforcement. So to see how the confinement effectiveness is affected by longitudinal reinforcement configuration group-6 specimens from CECC-23 to CECC-25 are used and the results are presented in Table 4.13. While axial load is applied on concrete encased composite column, arching action is expected to occur horizontally between longitudinal reinforcements. As the gap between the longitudinal reinforcement is decreased, the unconfined concrete area is decreased and the partially confined concrete area is increased.

Table 4.13 Analysis result for group-6 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
CECC-23	3910	2412.7	12957	1556.6	57564	1.062	31.32	1.179	34.78	4199
CECC-24	3910	2412.7	12957	5630.6	53490	1.087	32.07	1.194	35.23	4217
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-25	3910	2412.7	12957	6791.3	52329	1.100	32.44	1.202	35.45	4225

The confinement effectiveness on the compressive strength of partially confined concrete is increased as the area of the partially confined concrete increases. Increasing the partially confined concrete area can be attained by decreasing the gap between the longitudinal reinforcement. From the result partially confined compressive strength of concrete is enhanced by 6.2% to 10.0% from the unconfined compressive strength of concrete as the gap between the longitudinal reinforcement decreases.

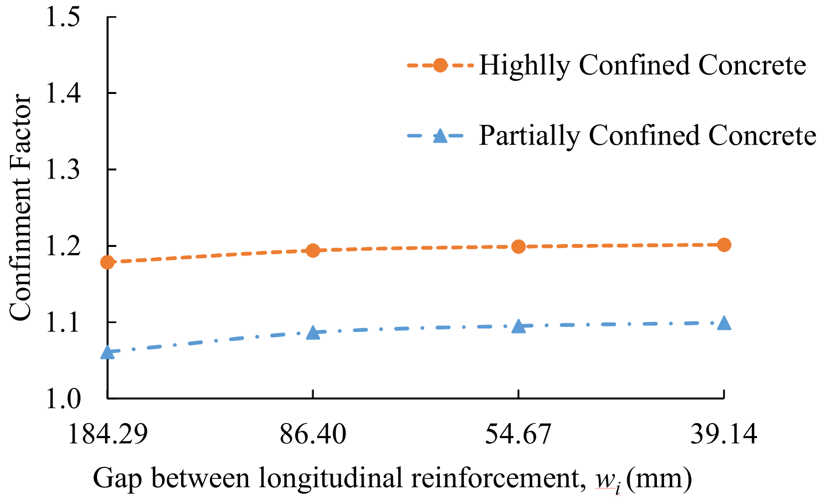


Figure 4.6 Confinement factor verses gap between longitudinal reinforcement

Even if the highly confined concrete area is independent of the longitudinal reinforcement configuration and they are all the same for all four specimens, the highly confined compressive strength of concrete is deferent for all four specimens. The lateral pressure on the highly confined concrete area is the sum of the lateral confining pressure from both transverse reinforcement and structural steel. Accordingly as the lateral confining pressure from the transverse reinforcement is also dependent on the configuration of longitudinal reinforcement, the compressive strength of the highly confined concrete is changed as the configuration of longitudinal reinforcement is changed. From Table 4.13 concrete encased composite columns result, it is showed that decreasing the gap between the longitudinal reinforcement will increase the compressive strength of highly confined concrete. From those selected specimens decreasing the gap between the longitudinal reinforcement increases the compressive strength of highly confined concrete by 17.9% to 20.2% from the unconfined compressive strength of concrete. As a whole point, decreasing the gap between the longitudinal reinforcement increases the overall compression resistance of concrete encased composite columns.

4.3.7 Spacing of Transverse Reinforcement

In Table 4.7 four specimens are developed by changing the spacing of transverse reinforcement to show the effect of transverse reinforcement spacing on confined compressive strength of concrete and compression resistance of axially loaded concrete encased composite column. The developed analytical model analyzes the selected four specimens and the results are presented on Table 4.14. Since the area of unconfined and partial confined concrete are dependent on the vertical arching action shaped between the spacing of the transverse reinforcement, as the transverse reinforcement spacing increased the partially confined concrete area is increased and in the other way, the unconfined concrete area is decreased.

Table 4.14 Analysis result for group-7 specimens

Specimen Label	A_a (mm^2)	A_s (mm^2)	A_{hc} (mm^2)	A_{pc} (mm^2)	A_{uc} (mm^2)	k_{pc}	f_{pcc} (MPa)	k_{hc}	f_{hcc} (MPa)	$P_{Analytical}$ (kN)
SRC1	3910	2412.7	12957	6519.3	52601	1.096	32.32	1.199	35.38	4223
CECC-26	3910	2412.7	12957	8845.8	50275	1.119	33	1.213	35.8	4241
CECC-27	3910	2412.7	12957	12947	46174	1.173	34.6	1.247	36.78	4288
CECC-28	3910	2412.7	12957	17326	41794	1.261	37.2	1.302	38.4	4377

When decreasing transverse reinforcement spacing, which lead to increasing the confined area of concrete, the effectiveness of confinement on the core concrete is increased. And closer transverse reinforcement improves the confinement pressure distribution over the column height by increasing the effectively confined area. From the results, it is showed that decreasing transverse reinforcement spacing increases the compressive strength of partially confined concrete from a minimum of 9.6% to a maximum of 26.1% from the unconfined compressive strength of concrete.

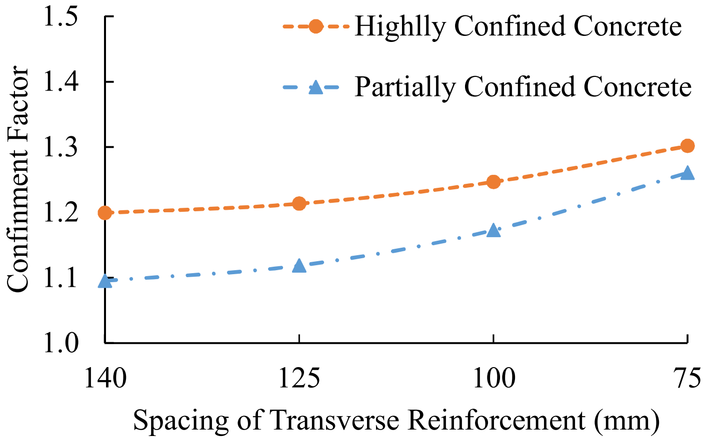


Figure 4.7 Confinement factor verses spacing of transverse reinforcement

Since the highly confined concrete compressive strength is also dependent on the lateral confining pressure from the transverse reinforcement, decreasing transverse reinforcement spacing will enhance the compressive strength of highly confined concrete. It is from a minimum of 19.9% to a maximum of 30.2% from the unconfined compressive strength of concrete. Generally decreasing transverse reinforcement spacing increases the overall compression resistance of concrete encased composite columns. Also after spalling of the concrete cover, making the transverse reinforcement spacing closer can prevent premature buckling of longitudinal reinforcement.

4.4 Conclusion

To see which parameter have the greatest effect on the confinement effectiveness, the confinement factor result for each specimen is normalized by the confinement factor of SRC1 and the result is obtained as follows.

Table 4.15 Normalized confinement factor for partially confined concrete

Group	1	2	3	4	5	6	7
Normalized K_{pc}	1.039 1.015 1.000 0.999 0.987 0.978 0.971 0.965	1.000 1.000 1.000 1.000 1.000	1.000 1.012 1.024 1.036 1.047 1.059	1.000 0.998 0.997 0.995	1.004 1.003 1.001 1.000	0.969 0.992 1.000 1.004	1.000 1.021 1.071 1.151
Cov:	0.023	0.000	0.020	0.002	0.001	0.014	0.055

The result showed that the confinement effectiveness for partially confined concrete is highly affected by the transverse reinforcement spacing, compressive strength of concrete, and yield strength of transverse reinforcement.

Table 4.16 Normalized confinement factor for highly confined concrete

Group	1	2	3	4	5	6	7
Normalized K_{hc}	1.082 1.032 1.000 0.997 0.972 0.952 0.937 0.924	0.977 0.992 1.000 1.021 1.055	1.000 1.007 1.013 1.020 1.026 1.033	1.000 1.021 1.042 1.063	0.935 0.960 0.981 1.000	0.983 0.996 1.000 1.002	1.000 1.012 1.039 1.085
Cov:	0.050	0.027	0.011	0.023	0.025	0.007	0.032

The result showed that the confinement effectiveness for highly confined concrete is highly affected by the compressive strength of concrete, transverse reinforcement spacing, and yield strength of structural steel.

5 Finite Element Model for Concrete Encased Composite Column

5.1 Introduction

From this document, the parametric study showed that from the studied parameter the confinement effectiveness for highly confined concrete is affected by yield strength of structural steel. To see the effect in detail, Finite Element Models (FEM) are developed in order to simulate the effect of altering the yield strength of structural steel on confinement effectiveness of highly confined concrete and on axial compression resistance of concrete encased composite column. First the developed FEM is validated with earlier experimental result. In addition to the experimental samples, four specimens from the parametric study which are in group-2 are developed by using FEM to study the effect of the selected parameters on confinement effectiveness and axial compression resistance of the concrete encased composite column.

The FEM model is developed using Abaqus/CAE 6.14-2 finite element program. Abaqus/CAE is a finite element program which consists consistent interface for crating the model, interactively submitting and monitoring the job, and evaluating results from the simulation.

5.2 Geometric Properties of the FEM

The material and geometric property of the specimens are as described on Table 3.1 and Table 4.2.

5.3 Material Property

5.3.1 Concrete material property model

Concrete damage property is used to account the plastic behavior of the concrete material. It assumes the main failure of concrete material are tensile cracking and compressive crushing. The development of failure surface is controlled by two hardening variables, which are compressive equivalent plastic strain $\tilde{\varepsilon}_c^{pl}$ and tensile equivalent plastic strain $\tilde{\varepsilon}_t^{pl}$. Experimentally verified Carreira & Chu (1985) Stress-Strain relationship model is used to develop concrete material property both in compression and in tension.

Under axial compression the response is assumed to be linear up to 30% of the ultimate stress f_c', followed by stress hardening and strain softening after the stress reach its ultimate compressive stress. For Abaqus data input; the relation beyond elastic property is given in terms of inelastic strain $\tilde{\varepsilon}_c^{in}$. Under tension the stress-strain response of concrete is linearly elastic until the failure stress f_t'. This failure stress is the beginning of micro-cracks in the concrete material. Beyond the failure the response is followed by softening stress-strain response and it is defined for Abaqus input as a cracking strain $\tilde{\varepsilon}_t^{ck}$.

The complete data for stress-strain relationship for concrete in compression and tension are developed using the following formulas, which are adopted from Carreira & Chu (1985) and Abaqus documentation.

Table 5.1 Concrete property for FEM

Concrete Property	Compression	Tension
Maximum Stress:	f_c'	$f_t' = 0.33\sqrt{f_c'}$
Corresponding Strain to Maximum Stress:	$\varepsilon_c' = 0.002$	$\varepsilon_t' = 0.0002$
Stress:	$\frac{f_c}{f_c'} = \frac{\beta\left(\frac{\varepsilon_c}{\varepsilon_c'}\right)}{\beta - 1 + \left(\frac{\varepsilon_c}{\varepsilon_c'}\right)^{\beta}}$	$\frac{f_t}{f_t'} = \frac{\beta\left(\frac{\varepsilon_t}{\varepsilon_t'}\right)}{\beta - 1 + \left(\frac{\varepsilon_t}{\varepsilon_t'}\right)^{\beta}}$
	$\beta = \left(\frac{f_c'}{32.4}\right)^3 + 1.55$	
Strain:	Inelastic Strain: $\tilde{\varepsilon}_c^{in} = \varepsilon_c - \varepsilon_{0c}^{el}$	Cracking Strain: $\tilde{\varepsilon}_t^{ck} = \varepsilon_t - \varepsilon_{0t}^{el}$
Elastic Strain:	$\varepsilon_{0c}^{el} = f_c'/E_c$	$\varepsilon_{0t}^{el} = f_t'/E_c$
Modulus of Elasticity:	$E_c = 0.0736w^{1.51}(f_c')^{0.3}$	
Poisson's Ratio:	0.2	
Density:	$w = 25\ kN/mm^3$	

Table 5.2 Plastic model for concrete damaged plasticity

	Dilation angle (^{0})	Eccentricity	fb0/fc0	k	Viscosity Parameter
Default Values:	30	0.1	1.16	0.666667	0

5.3.2 Steel material property model

The steel material property for structural steel section and longitudinal and transverse reinforcement, were modeled with an elasto-plastic model. Hardening curve with true stress $\mathrm{f}_{\mathrm{true}}$ and logarithmic strain $\varepsilon_{\ln}^{\mathrm{pl}}$ graph is used to model the material behavior of steel. The material data nominal or engineering stress $\mathrm{f}_{\mathrm{nom}}$, and nominal or engineering strain $\varepsilon_{\mathrm{nom}}$ used to define the curve is obtained from earlier test results for the reference test specimen.

Table 5.3 Steel material property model

Steel Property	Structural Steel	Longitudinal & Transverse Reinforcement
True Stress:	$f_{true} = f_{nom}(1 + \varepsilon_{nom})$	
Logarithmic Strain:	$\varepsilon_{ln}^{pl} = ln(1 + \varepsilon_{nom}) - \frac{f_{true}}{E_s}$	
Modulus of Elasticity:	$E_s = 210\ GPa$	$E_s = 200\ GPa$
Poisson's Ratio:	0.3	
Density:	$w = 78.5\ kN/mm^3$	

5.4 Assembly of Concrete Encased Composite Column

The FEM of concrete encased composite column is modeled on 3D modeling space with four components, which are concrete, structural steel, longitudinal reinforcement and transverse reinforcement. The concrete section is modeled using C3D8R element. This element is a 3D solid shape with 8 node linear brick element, in which each node has three translation degree of freedom. The Structural steel section is modeled using S4R shell element which have four node and one integration point on its mid-surface to form the element vector. So five integration point through the thickness of the element are used, which is considered as sufficient for modeling the nonlinearity behavior under monotonic loading. Each node have three translational and three rotational degrees of freedom. T3D2 Three dimensional two node truss element is used to model the longitudinal and transverse reinforcement with each node having three translational degree of freedom. To create a proper bonding between concrete section and the encased reinforcement and structural steel, the concrete is defined and modeled as a host to embed the structural steel and the reinforcement.

5.5 Load and Boundary Condition

Rigid body constraint is used to assign the boundary condition. For concentrically loaded concrete encased composite column, the real experimental simulation is when the steel and concrete are in contact with the stiff plates of the testing machine directly. So by considering the end friction provided by the testing machine, all degrees of freedom at both top and bottom end of the column can be restrained except the vertical displacement at the top of the column. The load is applied by using Displacement control method. This method apply displacement through the free vertical degree of freedom at the top.

To trace a stable peak and post peak response Riks solution strategy was implemented. Since high geometrical nonlinear behavior is expected in the step, large-displacement formulation is used. To allow this formulation non-linear geometric (NLGEOM) option have to be toggle on in the step.

5.6 Verification of the model

Earlier experimental result are used to verify the developed FEM, which has been presented in this chapter. Seven concentrically loaded concrete encased composite columns from published literature Chen and Yeh (1996) are used to verify the analytical model. The material and geometrical property of the specimens are described on Table 3.1. Axial load versus axial deformation of each specimens are used to verify the FEM with the test result.

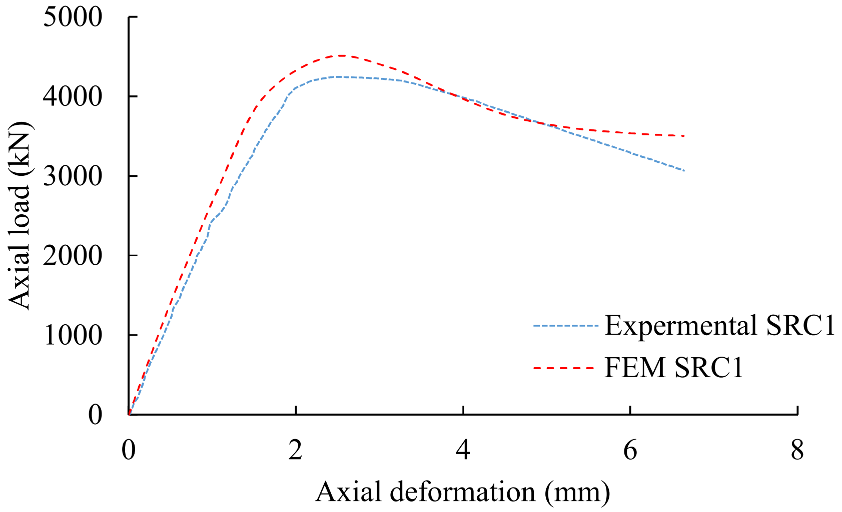


Figure 5.1 Experimental and FEM load versus deformation curve for SRC1

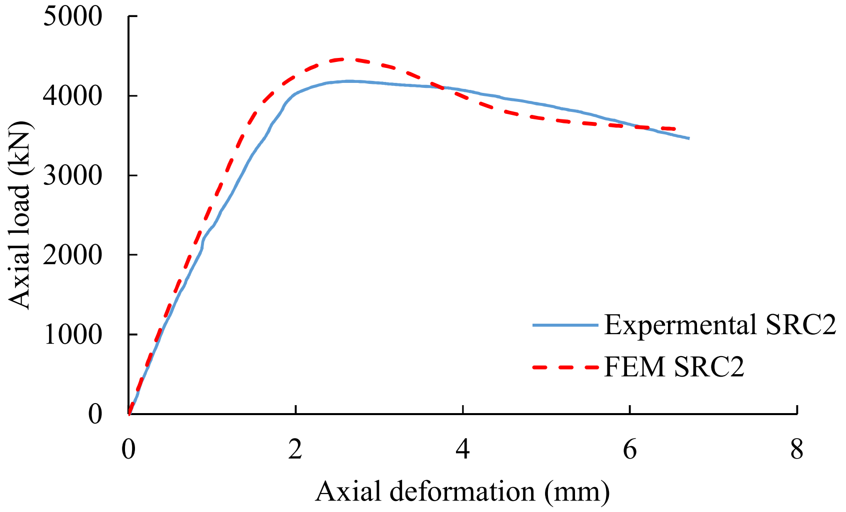


Figure 5.2 Experimental and FEM load versus deformation curve for SRC2

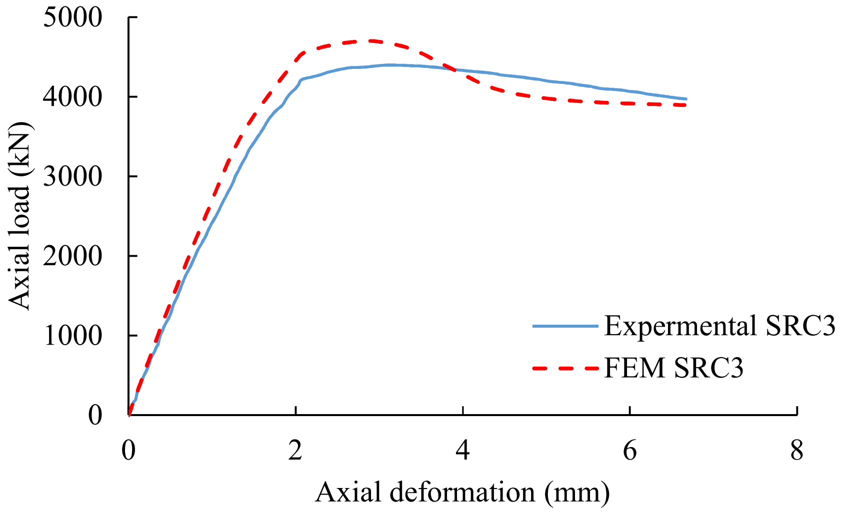


Figure 5.3 Experimental and FEM load versus deformation curve for SRC3

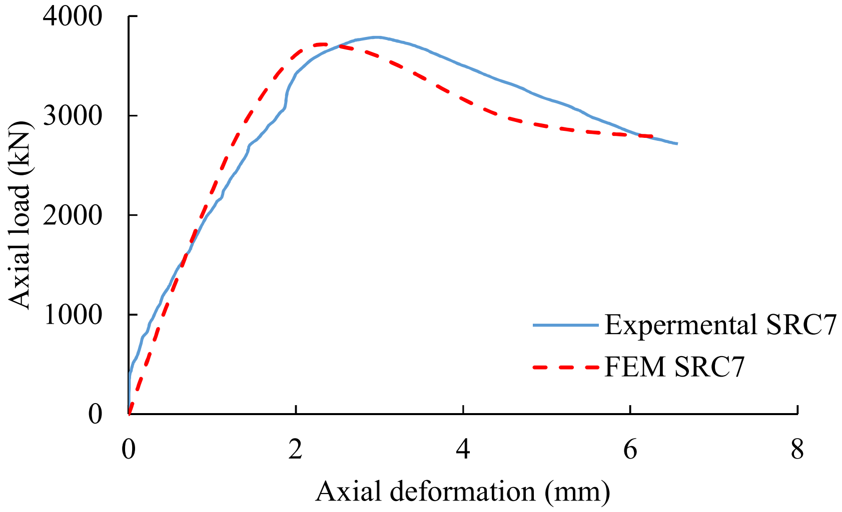


Figure 5.4 Experimental and FEM load versus deformation curve for SRC7

The developed finite element model showed a good agreement with the experimental test result.

5.7 Effect of structural steel yield strength on the confinement effectiveness

To study how structural yield strength affect the confinement effectiveness on concrete encased composite column, group-2 specimens from the parametric study are used. The FEM are developed for each specimens in group-2 the material and geometrical property of each specimens are as described on Table *4.2*. The obtained results are presented in subsequent section.

When the concrete encased composite column is subjected to compression, as a result of Poisson’s effect the concrete develop tensile strain and expand laterally. The lateral expansion of concrete will make the structural steel flange to be yielded and the structural steel flange will exert a lateral confining pressure on the highly confined concrete area. This confining pressure on highly confined concrete is in addition to the lateral confining pressure from the transverse reinforcement.

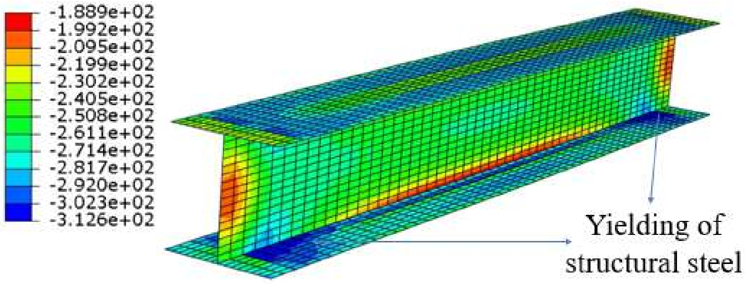


Figure 5.5 Stress contour in structural steel for SRC1 specimens

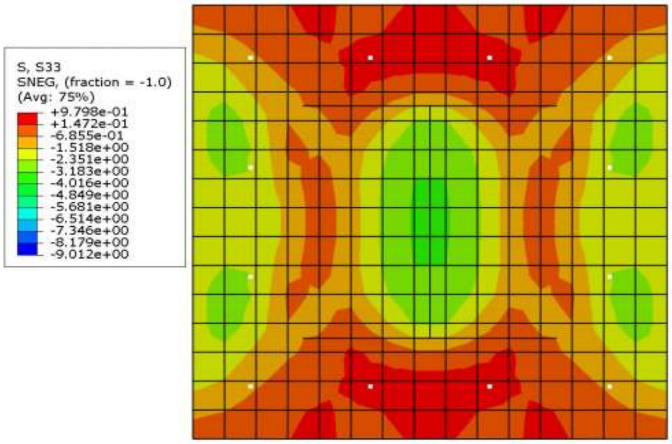


Figure 5.6 Lateral stress contour for SRC1 specimen

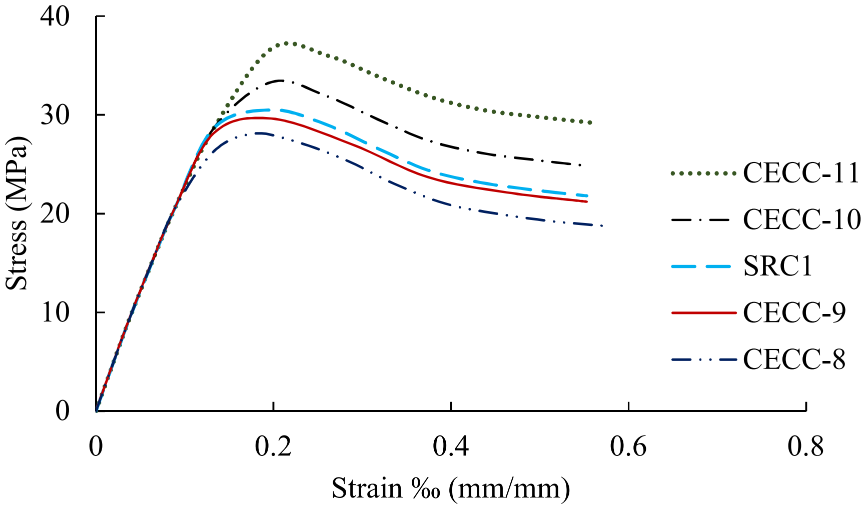


Figure 5.7 FEM stress versus strain curve for highly confined concrete in group-2 specimens

Table 5.4 Compressive strength of Highly confined concrete for group-2 specimens from the developed FEM

	CECC-8	CECC-9	SRC1	CECC-10	CECC-11
$f_{yk}(MPa) =$	235	275	296	355	450
$f_{ck}\ (MPa) =$	29.5	29.5	29.5	29.5	29.5
$f_{hcc}\ (MPa) =$	29.6253	30.0605	30.5191	33.3502	36.7971
$k_{hc} =$	1.004	1.019	1.034	1.131	1.247

Due to increasing of structural steel yield strength, which lead to much confinement to the concrete core. In addition, increasing the yield strength will increase the compression resistance of the concrete encased composite column and it is showed in the next figure.

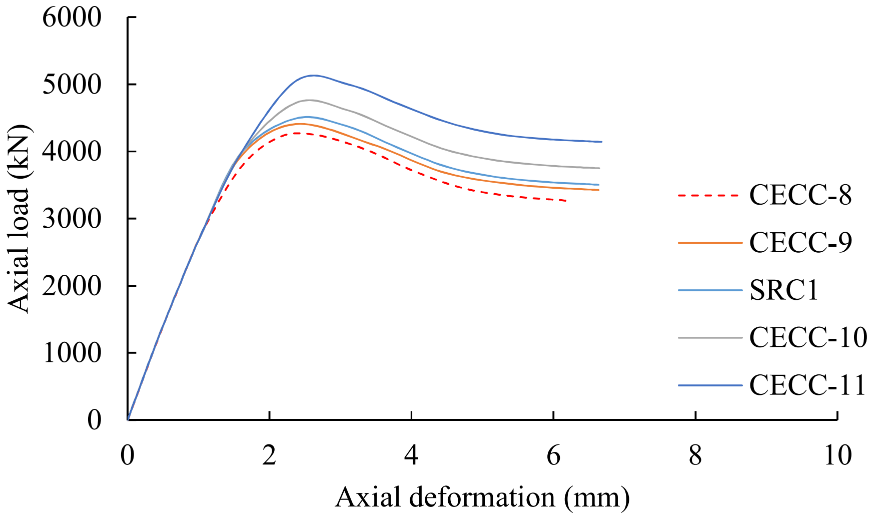


Figure 5.8 FEM load versus deformation curve for group-2 specimens

6 Conclusion and Recommendation

6.1.1 Conclusion

EN 1994-1-1:2004 estimate the axial compression resistance of concrete encased composite column less than the actual compression resistance, because of not considering the confinement effect on the core concrete due to transverse reinforcement and structural steel. The analytical model developed in this thesis consider the confinement effect on the partially and highly confined concrete due to both transverse reinforcement and structural steel. The developed analytical model can determine the axial compression resistance of concentrically loaded concrete encased composite column by 99.9% approximation with the experimental results. In parallel with this, from the parametric study the following observations and conclusions are made.

1. It is clearly showed that there is a lateral confining pressure from structural steel that confine the highly confined concrete area. Considering the confinement effect on partially and highly confined concrete increases the axial compression resistance of the column.
2. The confinement effectiveness is lower for the higher compressive strength of concrete this is because modulus of elasticity for higher concrete compressive strength is higher. This makes the concrete to exhibit less lateral expansion under axial compression. The confining transverse reinforcement and structural steel comes to play later in the process which makes the efficiency of confinement to be reduced as the compressive strength of concrete increases.
3. Yield strength of structural steel and transverse reinforcement measures the upper limit of lateral confining pressure from structural steel and transverse reinforcement on the confined concrete.
4. From the studied parameter, partially confined compressive strength of concrete is highly affected by transverse reinforcement spacing, compressive strength of concrete, and yield strength of transverse reinforcement.
5. For highly confined compressive strength of concrete, from the studied parameters it is mostly affected by compressive strength of concrete, transverse reinforcement spacing, and yield strength of structural steel.
6. From all the cases shown in the parametric study confinement effectiveness is dependent on the confined area of the concrete.

6.1.2 Recommendation

This thesis address the confinement effect on square doubly symmetrical concrete encased composite column with ‘I’ or ‘H’ structural steel cross-section and develop analytical model to determine the axial compression resistance of concrete encased composite column. For future investigations the following recommendations are made:

1. Additional analytical model can be developed for concrete encased composite columns with different concrete section and structural steel shape.
2. The effect of eccentricity of the applied load and slenderness of the column on the confinement effect can be investigated and the effect can be incorporated on axial compression resistance of concrete encased composite column analytical model.
3. This paper focuses only on the axial compression resistance of concrete encased composite column by considering the confinement effect this paper can be extended to study the resistance of concrete encased composite column in combined compression and uniaxial or biaxial bending by considering the confinement effect.

7 References

[1] B. Zhao, J. He, X. Lu, B. Zhou and L. Yu, 2012. On Seismic Design of Composite High-Rise Buildings with SRC Column, Steel Beam and RC Core Tube, State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, P. R. China.

[2] EN 1994-1-1:2004, Eurocode 4: Design of Composite Steel and Concrete Structures-Part 1-1: General Rules and Rules for Buildings.

[3] Sherif El-T., and Gregory G. D., 1999. Strength and Ductility of Concrete Encased Composite Columns, Journal of Structural Engineering, ASCE.

[4] E nrico S., and Sherif E.T., 2004. Nonlinear Analysis of Steel-Concrete Composite Structures: State of the Art, Journal of Structural Engineering, ASCE.

[5] Chen CC., Lin NJ., 2006. Analytical Model for Predicting Axial Capacity and Behavior of Concrete Encased Steel Composite Stub Columns, Journal of Constructional Steel Research.

[6] Junji S., Hiroshi K. and Juan J. C., 2012. Structural Performance of Concrete Encased Steel Columns with H-Shaped Steel, Osaka University, Osaka, Japan.

[7] V Aparna1, D Vivek1, K Neelima and B Karthikeyan, 2018. Experimental Investigations on Steel-Concrete Composite Columns for Varying Parameters, Hydrabad, India.

[8] Mander JB, Priestley MJN, Park R., 1998. Theoretical Stress–Strain Model for Confined Concrete. Journal of Structural Engineering, ASCE.

[9] EN 1992-1-1:2004, Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings.

[10] R.P Johnson, 2004. Composite Structures of Steel and Concrete 3rd Ed., Blackweel Publishing, UK.

[11] Darko D., Boris A., and Ivan L., 2015. Composite Structures according to Eurocode 4, Berlin, Germany.

[12] Arthur H. N., David D., and Charles W. D., 2004. Design of Concrete Structure. McGraw-Hill, New York.

[13] J. K. Wight, and J. G. MacGregor, 2012. Reinforced Concrete Mechanics and Design 6th Ed. Pearson Education, United State of America.

[14] Morino S., Matsui C., and Watanabe H., 1984. Strength of Biaxial Loaded SRC Columns. American Society of civil Engineers. New York.

[15] Saaticoglu M., and Razvi S., 1962. Strength and ductility of Confined concrete, Journal of structural Engineer, Vol. 118, No.6

[16] MD. Soebur Rahman, 2016. Behavior and Strength of Fully Encased Composite Columns, PhD Thesis, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

[17] EN 1993-1-1:2005, Eurocode 3: Design of Steel Structures - Part 1-1: General Rules and Rules for Buildings.

[18] Selamawit Dege, 2015. Uniaxial Interaction Charts for Fully Encased Composite Columns, MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

[19] Tedros Kiros, 2018. Experimental and Analytical Investigation on Spiral and Circular Hoop Confinement of Concrete, MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

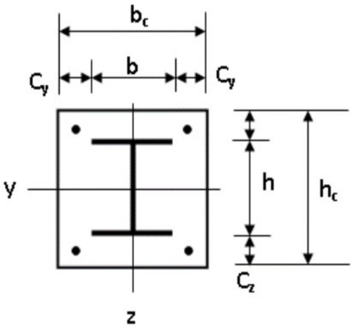
[20] Melat Ayele, 2010. Experimental and Analytical Investigation on Confined Reinforced Concrete Column, MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Appendix A

Sample calculation for axial compression resistance of concrete encased composite column is presented in this section. In this sample calculation SRC1 from Chen and Yeh (1996) test specimen is selected.

1. Input Data:

1.1. Geometrical Property



$h_c =$ 280 mm

$b_c =$ 280 mm

$L =$ 1200 mm

$b =$ 150 mm

$h =$ 150 mm

$t_f =$ 10 mm

$t_w =$ 7 mm

$c_y =$ 65 mm

$c_z =$ 65 mm

Longitudinal Reinforcement: 12 ϕ 16

Transverse Reinforcement: ϕ 8 c/c 140 mm

1.2. Material Property

Concrete: $f_{ck} =$ 29.5 MPa

Reinforcing steel: $f_{sk} =$ 350 MPa

Structural steel: $f_{yk} =$ 296 MPa

2. Area

Concrete: $A_a =$ 3910 mm^2

Reinforcing steel: $A_s =$ 2412.743 mm^2

Structural steel: $A_c =$ 72077.257 mm^2

By using equations 3.1, 3.2, and concrete area divided as

Highly Confined Concrete: $A_{hc} =$ 12956.67 mm^2

Partially Confined Concrete: $A_{pc} =$ 6519.253 mm^2

Unconfined Concrete: $A_{uc} =$ 52601.337 mm^2

3. Lateral confining pressure

3.1. From transverse reinforcement

Area of effectively confined concrete by transverse reinforcement, $A_{e,s}$ from equation 3.6

$$A_{e,s} = 19476 \quad mm^2$$

From equation 3.5

$$K_{e,s} = 0.3945$$

Since the selected section is a doubly symmetrical section, the ratio of transverse reinforcement area to the confined concrete area, $\rho_{y,s}$ and $\rho_{z,s}$ are the same in both direction. From equation 3.8

$$\rho_{y,s} = \rho_{z,s} = 0.00304$$

Lateral confining pressure, $f_{1,s} = f_{1y,s} = f_{1z,s}$ from equation 3.7

$$f_{1,s} = f_{1y,s} = f_{1z,s} = 1.065 \quad MPa$$

Effective lateral confining pressure, $f'_{1,s}$ from equation 3.4

$$f'_{1,s} = 0.4201 \quad MPa$$

3.2. From structural steel

Area of effectively confined concrete by transverse reinforcement, $A_{e,a}$ from equation 3.11

$$A_{e,a} = 6478.3 \quad mm^2$$

From equation 3.10

$$K_{e,a} = 0.617$$

Ratio of structural steel area to the confined concrete area, $\rho_{z,a}$ from equation 3.13

$$\rho_{z,a} = \quad 0.01$$

Lateral confining pressure, $f_{1y,a}$ and $f_{1z,s}$ from equation 3.12

$$f_{1y,s} = \quad 0.4201 \quad MPa$$

$$f_{1z,a} = \quad 1.826 \quad MPa$$

4. Compressive strength of confined concrete

4.1. Partially confined compressive strength of concrete

Confinement factor for partially confined concrete, k_{pc} from equation 3.15

$$K_{pc} = \quad 1.096$$

Compressive strength of partially confined concrete, f_{pcc} from equation 3.14

$$f_{pcc} = \quad 32.32 \quad MPa$$

4.2. Highly confined compressive strength of concrete

Effective lateral confining pressure on highly confined concrete in y-direction, $f'_{1y,h}$ from equation 3.16

$$f'_{1y,h} = \quad 0.42 \quad MPa$$

Effective lateral confining pressure on highly confined concrete in z-direction, $\mathrm{f}'_{\mathrm{1z,h}}$ from equation 3.17

$$f'_{1z,h} = \quad 1.826 \quad MPa$$

Effective lateral confining pressure on highly confined concrete, $f'_{1,h}$ from equation3.18

$$f'_{1,h} = \quad 0.911 \quad MPa$$

Confinement factor for highly confined concrete, k_{hc} from equation 3.20

$$K_{hc} = \quad 1.199$$

Compressive strength of partially confined concrete, f_{hcc} from equation 3.19

$$f_{hcc} = \quad 35.38 \quad MPa$$

5. **Compression resistance of axially loaded concrete encased composite column, $\boldsymbol{P_{Analytical}}$**

From equation 3.21

$$P_{Analytical} = \quad 4222.67 \quad MPa$$

6. **Validation and comparison of the analytical model**

6.1. Test result

$$P_{Test} = \quad 4220 \quad MPa$$

6.2. EN 1994-1-1:2004

From EN 1994-1-1:2004, compression resistance of concrete encased composite column is given by equation 3.22

$$P_{Code} = \quad 3809.16 \quad MPa$$

6.3. Comparisons

For validation $P_{Analytical}$ and P_{Code} are compared with P_{Test}

$$P_{Test}/P_{Analytical} = \quad 0.999$$

$$P_{Test}/P_{Code} = \quad 1.108$$

The result showed that the analytical model 99.9% approximately represent the test result and the code estimate the compression resistance of concrete encased composite column by 10.8% lower value than the earlier experimental result.