BEHAVIOUR OF HIGH STRENGTH CONCRETE FILLED STEEL TUBE INTERMEDIATE LENGTH COLUMNS IN OFFSHORE APPLICATIONS

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by

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NELSON JULIO COSSA

ABSTRACT

The concrete filled steel tubes (CFST) column systems consist of steel tubes filled in concrete. The CFST columns systems have many advantages compared to the reinforced concrete or steel structures. The CSFT have been widely used in construction of tall buildings and bridges in countries located in high seismic activity zones. The application of the CFST has been limited, due to lack of extensive understanding of on the behaviour of the transform section. The main objective of this research is to study the behaviour of intermediate length, CFST columns, filled in with high strength concrete.

In this study, CFST specimens with 30, 60 and 80N/mm^2 concrete compressive strength and external diameter-to-plate thickness (D / t) ratios of 11 and 14 are subjected to concentric axial compression loading. All the columns were 1200mm long. The results obtained are compared with the EC4, BS5400, ACI, AS and AIJ design code predictions. The effect of thickness, grade of concrete and confinement of concrete are examined. Moreover, application of CFST in offshore structures is discussed.

The results indicate that the ultimate compressive strength of the CFST increases as the concrete grade is increased. It also increases when the thickness of the steel section is increased. Although, confinement of concrete increases with thickness of the steel section, it has less effect on the overall failure mode. The intermediate length CFST columns failed largely due to overall elastic buckling. The application of CFST in offshore structures would decrease the costs maintenance and repairs.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Concrete Filled Steel Tubes

Concrete Filled Steel Tube (CFST) refers to the composite structural system based on steel tube in filled with concrete, **Figure 1.1**. Steel and concrete have different stress-strain curves, and distinctly different behaviour. The combination of these two materials provides an ideal contribution of strength, whereby concrete core has the advantages of high compressive strength and stiffness while the steel tube has the advantages of high strength and ductility (Mursi and Uy, 2004).

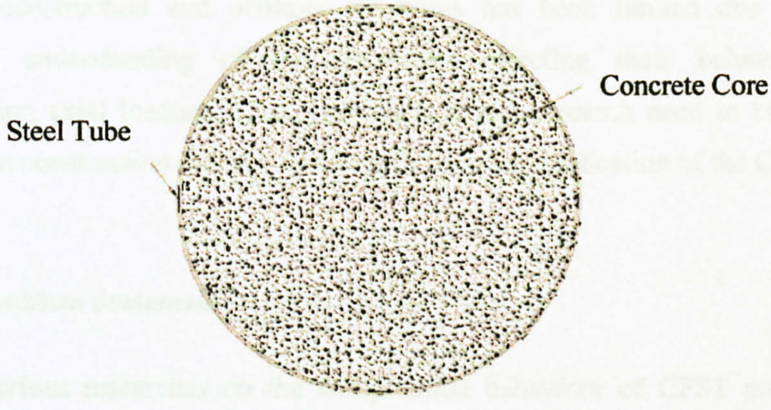

Figure 1.1: Cross section of CFST column

The CFST columns are used as primary axial load carrying members in many structural applications including high-rise buildings, bridges, piles and offshore structures. The structural properties of CFST columns include high strength, high ductility and high energy absorption capacity. The load carrying capacity and behaviour in compression, bending, shear and fatigue resistance under cyclic seismic loading are all superior to reinforced concrete ,reason for they have been widely used in Japan and China (Xiao *et al*, 2005), countries located in earthquake prone zones.

The CFST columns also offer economical advantages during the construction process because:

- Hollow section acts as formwork as well as reinforcement for the concrete;
- The time required for the hardening of concrete does not prevent the progress of the construction. The time for assembly and erection is shorter, compared to the reinforced concrete construction;
- The concrete core increases the fire resistance time compared to a hollow steel section alone;
- There is seldom any problem with respect to the joints due to the highly developed assembly technique in structural engineering today. This permits prefabrication in workshop and a quick assembly on site.

Although, there are many advantages in using the CFST, their application in building construction and offshore structures has been limited due to lack of extensive understanding of the parameter affecting their behaviour under compression axial loading. More investigation and research need to be carried to ensure that construction industry can benefit from the application of the CFST.

1.2 Problem Statement

Various researches on the compression behaviour of CFST columns with ordinary concrete strength steel have been conducted. The use of CFST provides cost saving in construction of high-rise buildings, their application has been significant on the lower storeys of high-rise buildings (Gaikoumelis and Lam, 2004), where stub columns exist. Thus, past research studies have, generally focused on the behaviour of short columns. Aznan (2008) experimented on CFST short columns with concrete strengths of 30, 60 and 80 N/mm^2.

With the need to increase the lettable area in buildings, and reduce the cost, the cross-sections of structural member have to be sacrificed. In circular CFST structural members, this would mean to reduce the diameter, which lead, to increase in the slenderness of the column. In addition, generally, columns with high slenderness ratios are characterized by overall buckling. This study tends to extend the applicability of intermediate length (40 < slenderness ratio < 150) CFST filled with high-strength concrete.

1.3 Objective

The objective of this project is to determine the behavior of intermediate length Concrete Filled Steel Tubes under axial load, to providing a better understanding and practical application of these structural members in the construction industry. Moreover, this project also aims to discuss possible applications of CFST in offshore structures.

1.4 Scope of study

This study is encompasses the following activities:

a. Perform a literature review of CFST and identify hollow structural steel sections commonly used in offshore applications;
b. Develop ordinary concrete mixes, and conduct test to ensure that the mixes achieve the target strength;
c. Determine the theoretical ultimate compression load of the CFST(based on design codes);
d. Carry out axial compression loading tests on CFST;
e. Determine the compression behaviour of CFST, by comparing theoretical predictions and the experimental results;
f. Recommend the application of intermediate length CFST in offshore structures.

1.5 Content of this Report

Apart from this Introduction, this report comprises of four other chapters:

- *Chapter 2* presents the literature review of the CFST under the ordinary loading condition. The behaviour of CFST columns and the factors affecting it are specified. This chapter also provides a brief discussion on the properties of steel and concrete. The related design codes are also discussed in this chapter.
- *Chapter 3* describes the equipments and the methodology for the study. The experimental results are compared with the literature predictions.
- *Chapter 4* provides detailed discussions and on the results obtained.
- *Chapter 5* gives the conclusions and recommendations for further research.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1. Introduction

The use of concrete filled steel tubes (CFST) columns for the construction of various types of buildings and more particularly for high-rise buildings has become increasingly popular in recent years. Some cross-sections representative of CFST columns are indicated in Figure 2.1

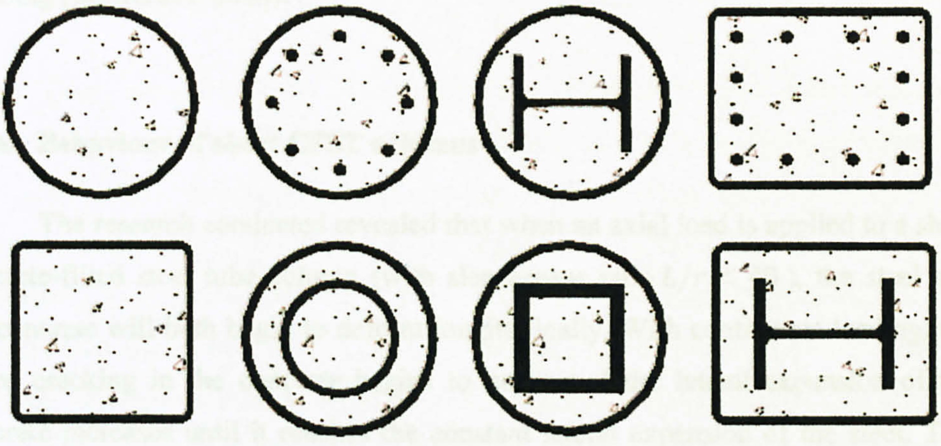

Figure 2.1 Types of CFST column

Source: EUROCODE 4

A number of factors affect the analysis and the design of CFST. A CFST member contains two materials with different stress-strain curves and different behaviour. The interaction of the two materials gives rise to a difficult problem in the determination of combined properties such as moment of inertia and modulus of elasticity. The failure mechanism depends largely on the shape, length, diameter, steel tube thickness, and concrete and steel strengths. Parameters such as bond, concrete confinement, residual stress, creep, shrinkage, and type of loading also have an effect on CFST member behaviour.

This chapter discusses the related researches on the Concrete-Filled Steel Tubular (CFST) Columns; it identifies and provides an analytical description of the factors affecting the behaviour of the CFST under the axial compression loading.

2.2. Behaviour of Concrete Filled Steel Tube columns under axial compression

Columns in axial compression loading will behave in two distinct ways. Columns with a small L/r ratio (short columns) are governed by the strength of the cross-section. These types of column reach their ultimate capacities when both the steel and the concrete reach their ultimate strength, i.e., yielding of steel and crushing of concrete. The second type of behaviour pertains to columns with a large L/r ratio (long columns), which are governed by stability and fail by column buckling (McKenzie, 2004).

a. Behaviour of short CFST columns

The research conducted revealed that when an axial load is applied to a short concrete-filled steel tube column (with slenderness ratio $L/r < 40$), the steel and the concrete will both begin to deform longitudinally. With continuous loading, the micro cracking in the concrete begins to occur and the lateral expansion of the concrete increases until it reaches the constant lateral expansion of the steel. This expansion leads to the confinement (Hajjar, 2000).Therefore; the axial compressive strength of concrete is increased by confinement of steel tube whereas the axial yield strength of steel of the tube is reduced because of tension hoop stresses. With the confinement, the concrete can continue to sustain additional load until the steel tube fails (usually by extensive local buckling) corresponding to the ultimate strength of the section. The confining effect of the steel tube on the concrete core depends on several factors, namely the thickness of the steel tube, slenderness ratio, and cross-sectional shape.

b. Behaviour of long CSFT columns

The long columns often fail by flexural buckling. Overall column buckling will precede strains of sufficient magnitude to allow large volumetric expansion of the concrete to occur. In overall buckling failures, there is little confinement of the concrete and thus little additional strength gain (Hajjar, 2000). Long columns are divided into two: intermediate columns and slender columns. The intermediate columns ($40 < L/r < 150$) will fail by combination of buckling and steel yielding and/or concrete crushing(McKenzie, 2004). The failure mode of slender columns ($L/r > 150$) is characterized by overall elastic buckling of the member.

2.3. Factor affecting the behaviour of Concrete Filled Steel Tube columns

2.3.1. Loading of the section

There are theoretically three basic ways in which concrete filled steel tube (CFST) can be loaded. The first is loading the steel only, second loading the concrete only and the last loading the entire section. Each of these factors influences the behaviour of the CFST. A studied by Johansson and Gylltoft (2002), revealed that the behaviour of the columns was influenced by the bond strength between the steel tube and the concrete core. They observed that loading the concrete alone would be the most efficient method in absence of bond between concrete wall and the steel wall, as the steel would be used to confine the concrete and contain no longitudinal stresses. When load is applied on the concrete core, the axial force is gradually transferred to the steel. Because, the concrete expands creating some bond with the steel wall, hence higher compression strength is achieved (O'Shea and Bridge, 2000). Whereas when the load is applied on the steel section alone, there is significant reduction of the CFST compression strength, as the steel section is longitudinally loaded and the stresses are not distributed to concrete core, thus early buckling occurs. Lastly, even though the efficiency of the steel tube in confining the concrete core is greater when the load is applied only to the concrete section, it does not offer the natural bond strength to get full composite behaviour. Hence, it is ideal to apply load on the entire section to ensure that both material undergo the same longitudinal straining (Bagaber, 2007).

2.3.2. Tube diameter and thickness of the steel plate

The diameter-to-thickness ratio, ***D/t***, provides means for prediction of CFST failure modes. Ellobody et al. (2006) stated that concrete filled steel tube circular columns with a high value of the diameter to thickness ratio provide inadequate confinement for the concrete. This is attributed to the premature failure of the columns due to local buckling of steel tubes. On the other hand, concrete-filled steel tube circular columns with a small value of the diameter to thickness ratio provide remarkable confinement for the concrete. According to Hajjar (2000), in the CFSTs with relatively low diameter to thickness ratios (***D/t < 40***) and low-to-moderate concrete strength, typically, the failure occurs through a combination of yielding of steel, local buckling of steel and crushing of concrete; and flexural buckling of the column may occur if enough length is provided. In this situation, the confinement may occur for columns where concrete is crushed prior to local buckling of steel. Whereas, the CFSTs with thin-walled steel tubes (***D/t > 60)*** or having a high-strength, are very susceptible to local buckling and combined with shear failure of concrete.

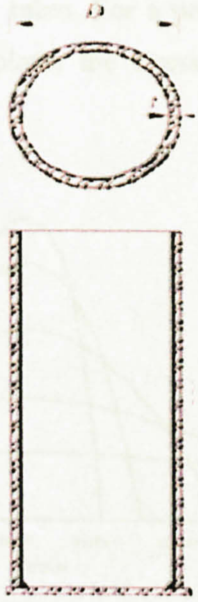

Figure 2.2: Column Details
Source: Baig *et al*, 2002

To avoid local buckling of steel members in composite columns, the design codes provide the minimum thickness of steel to be incorporated in circular CSFT columns. The equations of these design codes and the values are listed in **Table 2.1**

Table 2.1: Limiting Values for the Specimens

Code:	**EC4**	**ACI 318-95 , AS 3600 & BS5400**	**AIJ**
Equation:	$\frac{D}{t} \leq 90 \cdot \frac{235}{f_y}$	$\frac{D}{t} \leq \sqrt{\frac{8E}{f_y}}$	$\frac{D}{t} \leq 1.5 \cdot \frac{23500}{f_y}$
Value: $(f_y = 195N/mm^2)$	108	91	181

2.3.3. Compressive strength and confinement of concrete

The compression strength of concrete applied in CFST columns may vary from 25Mpa to 80Mpa. The concrete compression strength is another parameter, which affects the behaviour of CFST column. The strength of concrete is highly affected by the quality and the casting methods, (Morino and Tsuda, 2003). Formation of creep may cause shading of load to steel; shrinkage may contribute to initial cracking of concrete, (Terry *et al,* 1994). Local buckling of tends to occurs in high strength concrete filled steel tubes. For a premature local buckling of CFST, whereby no confinement takes place, the stress-strain relationship is as follow **(Figure 2.3)**:

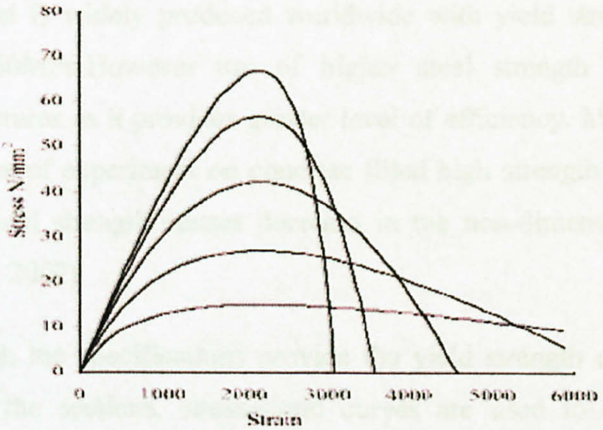

Figure 2.3 Concrete Stress-Strain curves (Unconfined)

Source: Vrcelj & Uy(2002)

Concrete filled steel tubes with compact plate (small D/t), experience high concrete confinement effect. (Hajjar, 2000), the concrete confinement increase with the expansion of concrete, as it begins to crush. The confinement is also affected by the manner the CFST is loaded, concrete triggers confinement. The stress-strain diagram for confined concrete is as follow:

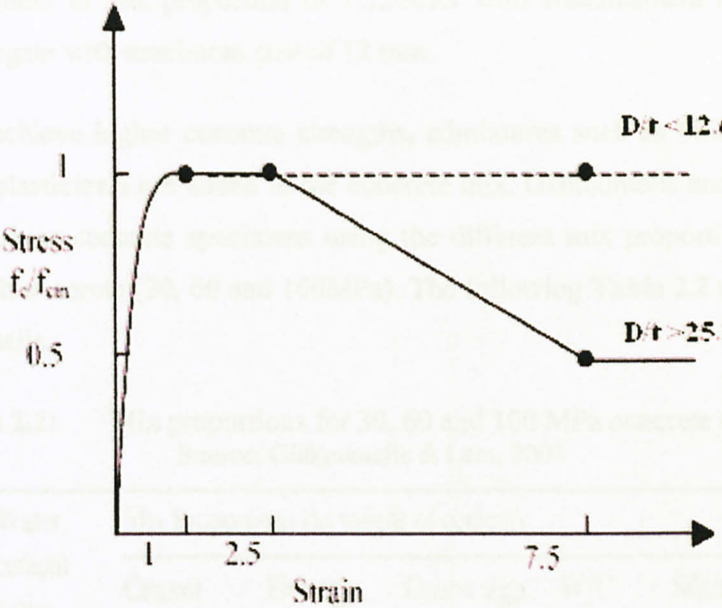

Figure 2.4 Concrete Stress-Strain curves (Confined)
Source: Vrcelj & Uy(2002)

2.3.4. Yield strength of steel

The steel is widely produced worldwide with yield strength ranging from 250MPa to 360MPa.However use of higher steel strength has been used in composite structures as it provides greater level of efficiency. Mursi and Uy (2004) conducted series of experiment on concrete filled high strength steel box columns. Higher steel yield strength causes decrease in the non-dimensional bucking load (Vrcelj and Uy, 2002).

Although the specifications provide the yield strength of the steel used in manufacturing the sections, stress-strain curves are used to observe the strain-hardening pattern, which the ductility of steel can be predicted. Hajjar (2000) stated that ductile yielding of steel generally occurs prior to its local buckling.

2.3.5. Concrete Mixes and Grades

The desired concrete strength is highly dependent on the preparation techniques (vibration, curing) and mixing proportions of cement, sand and coarse aggregate. Different types of cement are available on the market. To achieve concrete grade of 30MPa at the 28-day, Mohanraj and Kandasamy (2008), used Portland cement in mix proportion of 1:1.39:3.1 with water/cement ratio 0.5, and coarse aggregate with maximum size of 12 mm.

To achieve higher concrete strengths, admixtures such as Silica Fume, Fly Ash Super-plasticizers are added to the concrete mix. Giakoumelis and Lam (2004) prepared various concrete specimens using the different mix proportions to obtain high strength concrete (30, 60 and 100MPa). The following **Table 2.2** represents the concrete details.

Table 2.2: Mix proportions for 30, 60 and 100 MPa concrete strength
Source: Giakoumelis & Lam, 2004

Concrete strength N/mm^2	Water/cement ratio	Mix Proportions (to weight of cement)					
		Cement	Fine aggr.	Coarse aggr.	W/C ratio	Silica fumes	Super-plasticiser
30	0.65	1.0	3.0	3.5	0.65	-	-
60	0.42	1.0	2.0	3.25	0.42	-	-
100	0.28	1.0	1.5	2.5	0.28	0.1	2%

2.3.6 Loading Rate

The test loading should be applied in at least five regular increments and the load-deformation behaviour of the test should be recorded, sufficient time should be allowed after each increment for the specimen to reach a stationary equilibrium.(BS5950-1:2000 section 7.3.2).

Giakoumelis and Lam (2004), loaded their specimen at 50KN intervals at the beginning of the test, while the specimen was within the elastic region, and then used 10KN intervals after yielding, in order to have sufficient data points for the stressstain curve. Muhanraj and Kandasamy (2008), applied a pre-load of 5KN to firmly hold the specimen, and then small load increments of 20KN. Deformations are recorded at each load increments until specimen failure. The ideal loading set-up is illustrated in **Figure 2.5**

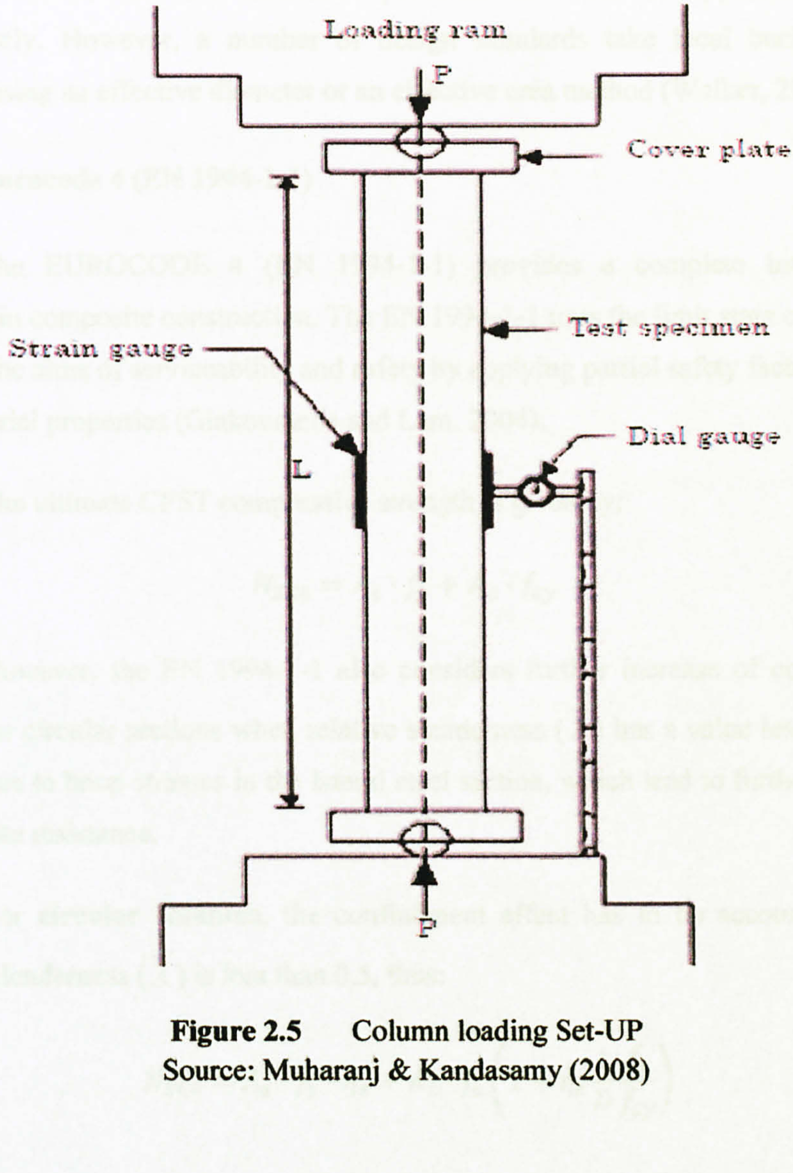

Figure 2.5 Column loading Set-UP
Source: Muharanj & Kandasamy (2008)

2.4. Design Codes

The European Committee for Standardization (Eurocode 4), the American Concrete Institute (ACI), Architectural Instituted of Japan (AIJ), Australian Standards (AS) and British Standards (BS 5400) provide guidance for the design of CFST columns. These design codes, are based on different theories and produce different results, and the assistance provided in terms of application varies significantly. However, a number of design standards take local buckling into account using an effective diameter or an effective area method (Walker, 2006).

2.4.1 Eurocode 4 (EN 1994-1-1)

The EUROCODE 4 (EN 1994-1-1) provides a complete international standard in composite construction. The EN 1994-1-1 uses the limit state concepts to achieve the aims of serviceability and safety by applying partial safety factors to load and material properties (Giakoumelis and Lam, 2004).

The ultimate CFST compressive strength is given by:

$$N_{EC4} = A_s \cdot f_y + A_c \cdot f_{cy}$$

However, the EN 1994-1-1 also considers further increase of confinement effects for circular sections when relative slenderness ($\bar{\lambda}$) has a value less than 0.5. This is due to hoop stresses in the lateral steel section, which lead to further increase in concrete resistance.

For **circular columns**, the confinement effect has to be accounted if the relative slenderness ($\bar{\lambda}$) is less than 0.5, thus:

$$N_{EC4} = A_s \cdot f_y \cdot \eta_s + A_c \cdot f_c \left(1 + \eta_c \frac{t}{D} \frac{f_y}{f_{cy}}\right)$$

Where:

- A_s and A_c : the areas of steel and concrete, respectively
- η_s and η_c : the coefficients of confinement for concrete and steel, when the column is axially loaded(zero eccentricity):

- $\eta_s = 0.25(3 + 2\bar{\lambda}) \leq 1$ and $\eta_c = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2) \geq 0$

- Relative slenderness $\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}$ where N_{cr} –Euler Elastic Bucking Equation and $N_{pl,Rk}$ –Plastic Strength of the section
- f_{cy} :is the cylinder compressive strength of concrete ($0.85f_c$)

2.4.2 American Concrete Institute (ACI 318-95) and Australian Standards (AS 3600 & AS4100) Codes

The ACI and the AS apply the same formula to determine the squash load (Mohanraj and Kandasamy, 2008). They both use the similar method as for the reinforced concrete columns, whereby the 0.85 coefficient is included in the concrete cylinder strength to account for the long term and size effects (Liu & Gho, 2005). However, this formula does not consider the confinement of effect. The squash load is determined by:

$$N_{ACI/AS} = A_s \cdot f_y + 0.85A_c \cdot f_c$$

Giakoumelis and Lam (2004), proposed a modified equation, which takes into account the effect of concrete confinement on the axial load capacity for circular columns. The proposed equation is as follow:

$$N_{ACI/AS} = A_s \cdot f_y + 1.30A_c \cdot f_c$$

Where:

- A_s *and* A_c : areas of steel and concrete, respectively;
- f_y *and* f_c : steel and concrete strength, respectively

2.4.3 Architectural Institute of Japan (AIJ) Code

Morino and Tsuda (2003), provide recommendations for design of concrete steel tubes under compression loading, for the AIJ. The recommendation considers the ultimate compressive strength for $L/_D > 12$, to be governed by bucking strength, thus:

$$N_{AIJ} = A_s \cdot f_y\{1 + 0.545(\lambda_s' - 0.3)\} + 0.85A_c \cdot f_c\left(\frac{2}{1 + \sqrt{(\lambda_c')^4 + 1}}\right)$$

This formula applies for $0.3 \leq \lambda_s' < 1.3$ and $\lambda_c' \leq 1.0$

Where:

- $\lambda_s' = \frac{\lambda_s}{\pi}\sqrt{\frac{f_y}{E_s}}$ and $\lambda_c' = \frac{\lambda_c}{\pi}\sqrt{0.93(0.85f_c)^{\frac{1}{4}} \times 10^{-3}}$
- λ_s *and* λ_c : the slenderness ratios of steel and concrete, respectively
- E_s : Young's modulus of steel tube

2.4.4 British Standards BSI 5400 Part 5

The BSI 5400 Part 5, gives a design method for concrete filled steel tubes, which takes account of the composite action between the elements forming the cross section. The clause 11.3.7 provides a formula for determining the ultimate strength of axially loaded CFST.

$$N_{BS} = 0.91A_s \cdot f_y' + 0.45A_c \cdot f_{cc}$$

Where:

- f_{cc} is the enhanced characteristic strength of triaxially contained concrete under axial load given by : $f_{cc} = f_{cu} + C_1\frac{t}{D}f_y$
- f_y' is the reduced nominal yield strength of steel casing given by $f_y' = C_2f_y$
- C_1 *and* C_2 Are constants in *Table 12* (BSI 5400 Part 5) and are function of $L/_D$ *ratio.*

2.5 Summary

Although of the current available research draws similar conclusions on the behaviour of CFST columns, there are a number of conflicting views being documented. Currently there is no comprehensive design standard that can be used for the design high strength CFST intermediate length columns and further investigation is required to ensure safe and reliable application of the technology in the market.

Methods of analysis, similar to some of those mentioned in this chapter, will be utilised in this dissertation to investigate the behaviour of the high strength CSFT intermediate columns.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes methodology used in this research project. The main objective of the project is to obtain experimental data on the behaviour of CFST column with a variety of material strength.

3.2 Analytical Methods

In order to perform theoretical analysis on the behaviour of the intermediate length CFST, design codes were used. Each of the codes recommends design equations based on parameters which have been discussed on the literature review section. The equations are used to determine the axial load capacity of the selected cross-section.

3.3 Experimental Work

The second step is experimental work. Hot-rolled welded steel pipes Class Light BS 1387:1985 were selected to conduct series of axial compression tests. The steel tubes were cut to a length of 1200mm, in order to fit in to the Compression Loading Machine. four (4) samples of bare steel hollow section will be tested to determine the ultimate strength of steel(control), and sixteen (16) will be filled in with concrete of different strengths, namely 30, 60, 80Mpa. Only circular sections were tested.

3.3.1 Design Mix Composition for Concrete.

The concrete mix design is based on BS 1881 and tested as per prescribed by the test procedures. The strengths 30, 60, and 80 MPa were obtained were obtained from conventional mixing and curing techniques. The trial mixes prepared and used for this experiment are shown on the following **Table 3.1**:

Table 3.1: Mix proportion for 30, 60 and 100 MPa concrete strength

Mix Elements	Grade 30 (Kg/m^3)	Grade 60 (Kg/m^3)	Grade 80 (Kg/m^3)
OPC	313	490	600
Water	158	141	178
Fine Aggregate	619	471	650
Coarse Aggregate	1313	1310	1090
Silica Fume	-	-	60
Superplasticizer	-	-	24
W/C Ratio	0.50	0.29	0.27

After the samples were mixed, the concrete if carefully poured into the hollow steel tubes. In the pouring process, the concrete must be well compacted by steel rod air traps, which reduce the overall concrete strength. However, over compaction must also be avoided to prevent the segregation of the mix. The CFST specimens were let to cure at a room temperature, for at least 28 days.

The same mix design is used to obtain the actual ultimate strength of concrete. This process consists pouring the concrete in to the standard 150 mm moulds, at approximately equal layers (50 mm deep). A vibrator is used for compaction of the concrete to allow a uniform distribution of concrete on the mould, and avoid air traps, which may affect the overall compression strength.

Test cubes were removed from the mould 24 hours after casting, marked and placed in the curing tank for a period of at least 28 days. The concrete cubes were tested at the age of 7, 14 and 28 days.

3.3.2 Preparation of steel tubes

Steel tubes were cut in 1200mm length, to fit into the Compression Testing Machine. Six (6) meters steel tubes were cut to the desired length using the Chop Saw Steel Cutter. Then the both ends of the tubes were trimmed and leveled, with aid of grinder and level, this is to ensure that the specimen will be loaded evenly across the whole cross section area. The steel thickness was measured to find the cross steel cross section area (A_S).The material properties of steel and dimensions are shown on **Table 3.2** and **Table 3.3**, respectively:

Table 3.2: Steel properties

Standard Specification		**Mechanical Properties**	
	Standard Grading	Tensile Strength (MPa) min.	Yield Strength (MPa) min.
BS 1387:1985	Light Grade	320-460	195

Table 3.3: Dimension of Steel Tubes and Properties of Concrete to be used in CFST

Diameter (mm)	**Thickness (mm)**		Yield Strength (MPa)
	Nominal	Measured	
50	4.00	3.60	195
50	5.00	4.50	195
100	4.00	3.60	195
100	5.00	4.50	195

Although the 1200mm length was selected, not only, due to the limitation of the equipment, but it selected based on the slenderness ratio (L/r) parameter, which provides means for classification of column. In this research, the slenderness ratio was also used as scale factor for the specimen, with which the column where scaled to represent the real situation. The equation to calculate the slenderness of columns is as follow:

$$\frac{L}{r} = \frac{L}{\sqrt{\frac{I_S}{A_S}}}$$

Where:

- L – the length of the column.
- I_s – second moment of inertia of the steel section, $I_s = \frac{\pi(D^4-d^4)}{64}$
- A_s –area of steel section.

Table 3.4: Slenderness ration and column classification

D (mm)	t (mm)	A_s	I_s	L	L/r	Classification
50	3.6	525	142077	1200	73	Intermediate
50	4	578	154051	1200	74	Intermediate
100	3.6	1090	1268232	1200	35	Intermediate*
100	4	1206	1392153	1200	35	Intermediate*

(*) Although the slenderness ration of the 100mm diameter specimens, is less that 40, they were still considered as relatively intermediate length columns,

3.3.2 Axial Compression Loading Diagram

The axial compression test were carried out in both 500KN and 1500KN capacity loading frame. After placing the CFST columns on the machine, the applied loading rate was 5KN/s. Strain gauges where used to measure the deformation of the column. Due to the complexity and safety concerns on fabrication of fully pinned end connections, the columns were placed in plates, as illustrated on the Figure 3.1. This modification introduced some restrains on the columns. However for theoretical load calculation, the effective length was considered as total length of the column.

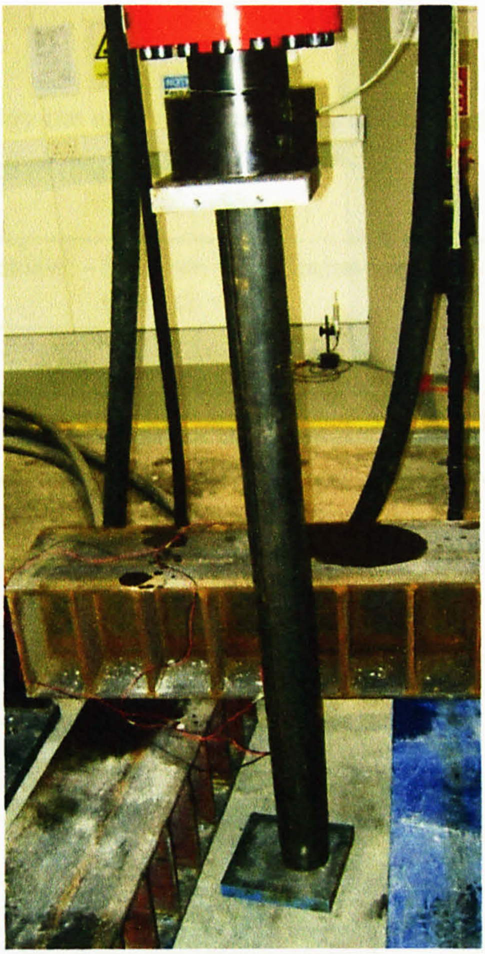

Figure 3.1: Test set-up

3.4 Summary

The methodology the applied to carry out this research work is summarized on the following flowchart (**Figure 3.2**):

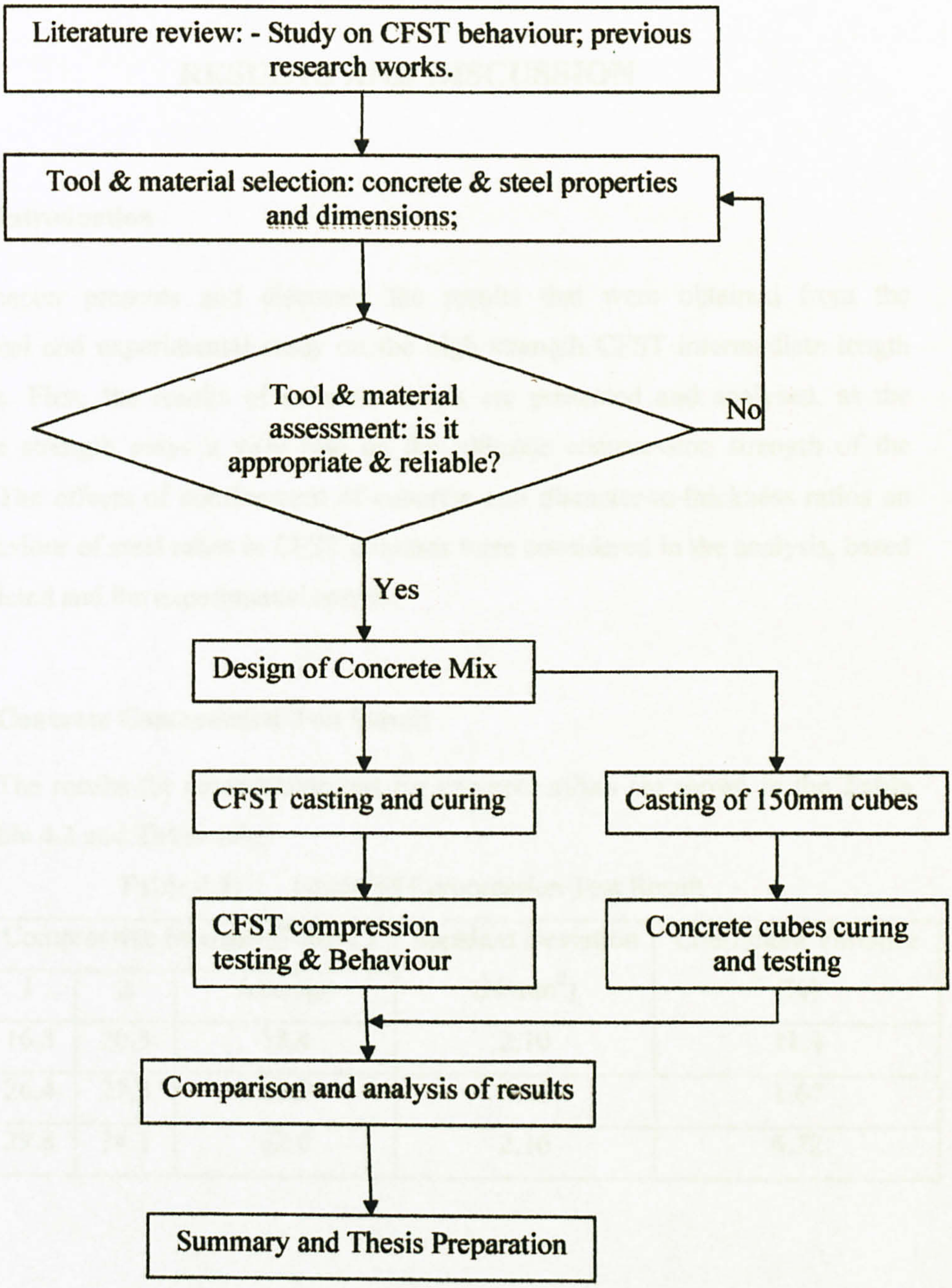

Figure 3.2: Flow chart of the research

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results that were obtained from the theoretical and experimental study on the high strength CFST intermediate length columns. First, the results of concrete mixes are presented and analysed, as the concrete strength plays a vital role on the ultimate compression strength of the CFST. The effects of confinement of concrete and diameter-to-thickness ratios on the behaviour of steel tubes in CFST columns were considered in the analysis, based on predicted and the experimental results.

4.2 Concrete Compression Test Result

The results for compression test for concrete mixes are shown in the **Table 4.1, Table 4.2** and **Table 4.3.**

Table 4.1: Grade 30 Compression Test Result

Days	Compressive Strength (N/mm^2)			Standard Deviation (N/mm^2)	Coefficient Variance (%)
	1	2	Average		
7	16.3	20.5	18.4	2.10	11.4
14	26.4	27.3	26.9	0.45	1.67
28	29.8	34.1	32.0	2.16	6.72

Table 4.2: Grade 60 Compression Test Result

Days	Compressive Strength (N/mm^2)			Standard Deviation (N/mm^2)	Coefficient Variance (%)
	1	2	Average		
7	39.3	40.3	39.8	0.50	1.25
14	56.6	53.5	55.1	1.55	2.81
28	61.6	63.4	62.5	0.9	1.44

Table 4.3: Grade 80 Compression Test Result

Days	Compressive Strength (N/mm^2)			Standard Deviation (N/mm^2)	Coefficient Variance (%)
	1	2	Average		
7	42.5	45.0	43.8	1.25	2.85
14	67.3	68.2	67.8	0.45	0.66
28	79.3	77.8	78.6	0.75	0.95

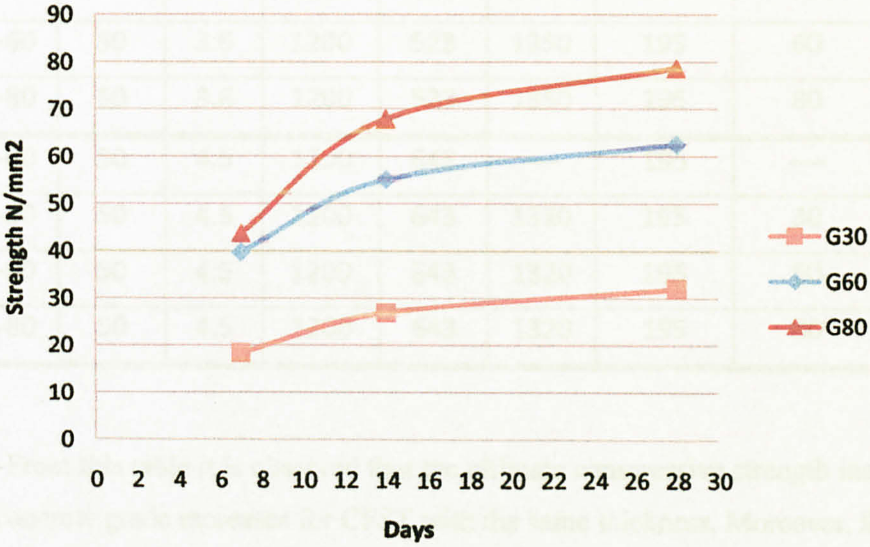

Figure 4.1: Compressive strength of concrete design mix

These results show that from the concrete design mix adopted, it was possible to achieve the desired concrete strength at the 28th day. However, for the compressive strength for concrete Grade 80 the strength achieved was 78.6MPa, instead of

80MPa. Although, the required strength, for Grade 80, was not achieved, no further modifications were conducted, because the CFST were let to cure beyond the 28th day, thus allowing the concrete to mature. These were not used for prediction of ultimate load, but are important because ensure that concrete mix used in CFTS achieves the nominal strength used.

4.3 CFST Compression Test Result

The CFST were tested 28 days after the curing process, all specimens were tested in compression machine and the data were recorded. The data recorded is presented on the **Table 4.4.**

Table 4.4: Dimensions and CFST experimental results

Sample No	D (mm)	t (mm)	L (mm)	As (mm^2)	Ac (mm^2)	fc (N/mm^2)	fc (N/mm^2)	N_{exp} (KN)
C50-4-00	50	3.6	1200	523	----	195	----	123
C50-4-30	50	3.6	1200	523	1350	195	30	153
C50-4-60	50	3.6	1200	523	1350	195	60	166
C50-4-80	50	3.6	1200	523	1350	195	80	189
C50-5-00	50	4.5	1200	643	----	195	----	150
C50-5-30	50	4.5	1200	643	1320	195	30	166
C50-5-60	50	4.5	1200	643	1320	195	60	181
C50-5-80	50	4.5	1200	643	1320	195	80	207

From this table it is observed that the ultimate compressive strength increases as the concrete grade increases for CFST with the same thickness. Moreover, there is a significant increase of ultimate compressive with the thickness of the tube is greater. It was also observed that all the specimens exhibited same behaviour of load versus deformation as illustrated on **Figure 4.2** and **Figure 4.3**:

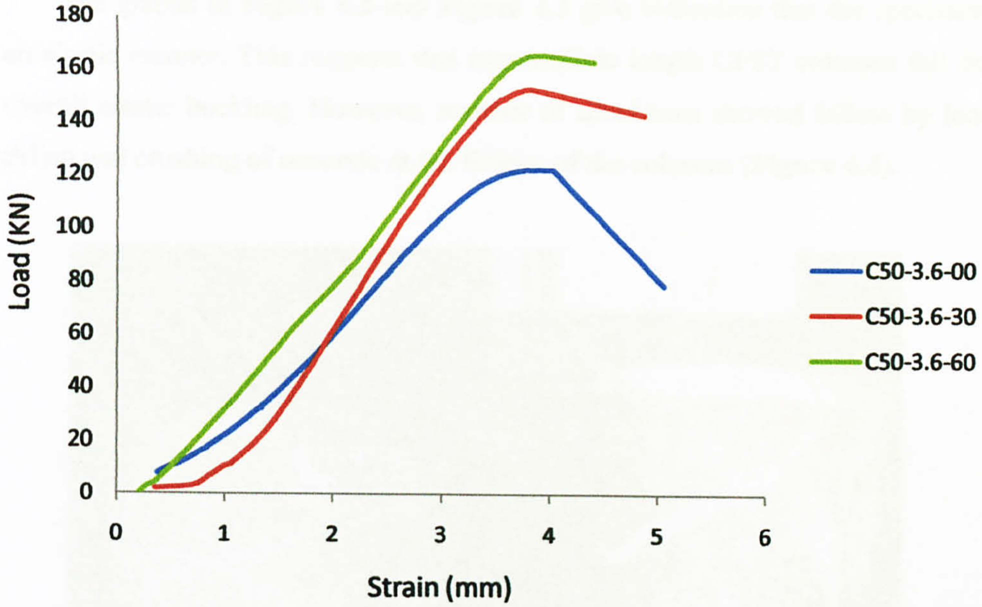

Figure 4.2: Load-deformation relationship for C50-3.6 (D/t =14) CFST

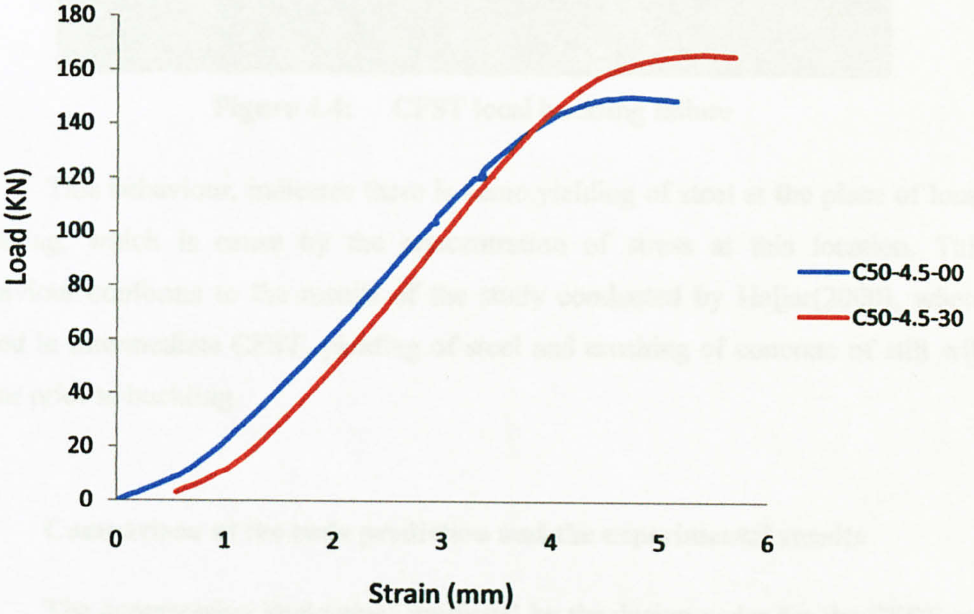

Figure 4.3: Load-deformation relationship for C50-4.5(D/t =11) CFST

The graphs in **Figure 4.2** and **Figure 4.3** give indication that the specimens in an elastic manner. This suggests that intermediate length CFST columns fail due to overall elastic buckling. However, number of specimens showed failure by local buckling and crushing of concrete at the fixities of the columns (**Figure 4.4**).

Figure 4.4: CFST local buckling failure

This behaviour, indicates there is some yielding of steel at the place of local buckling, which is cause by the concentration of stress at this location. This behaviour conforms to the results of the study conducted by Hajjar(2000), where stated in intermediate CFST, yielding of steel and crushing of concrete of still will occur prior to buckling.

4.4 Comparison of the code prediction and the experimental results

The compression load values predicted by the design codes for the CSFT are compared with the experimental results in **Table 4.5**, **Figure 4.5** and **Figure 4.6.**

Table 4.5: Comparison of Prediction and Experimental

Sample No	N_{Exp} (KN)	N_{EC4}			N_{BS5400}			N_{AIJ}			$N_{AS/ACI}$		
		N_u (KN)	N_{Exp}/N_{EC4}	Δ (%)	N_u (KN))	N_{Exp}/N_{BS5400} Ratio	Δ (%)	N_u (KN))	N_{Exp}/N_{AIJ}	Δ (%)	N_u (KN))	$N_{Exp}/N_{AS/ACI}$ Ratio	Δ (%)
C50-4-00	123	102	1.20	17	89	1.38	28	102	1.20	17	102	1.20	17
C50-4-30	153	145	1.05	5	113	1.35	26	139	1.10	9	139	1.10	9
C50-4-60	166	189	0.88	-14	132	1.25	20	176	0.94	-6	176	0.94	-6
C50-4-80	189	217	0.87	-15	145	1.30	23	200	0.94	-6	200	0.94	-6
C50-5-00	150	125	1.20	17	109	1.37	27	125	1.20	17	125	1.20	17
C50-5-30	166	165	1.01	1	132	1.26	20	159	1.04	4	159	1.04	4
C50-5-60	181	205	0.88	-13	150	1.21	17	193	0.94	-7	193	0.94	-7
C50-5-80	207	231	0.90	-12	162	1.28	22	215	0.96	-4	215	0.96	-4

Note: $\Delta = \frac{N_{Exp}-N_u}{N_{Exp}} \cdot 100\%$

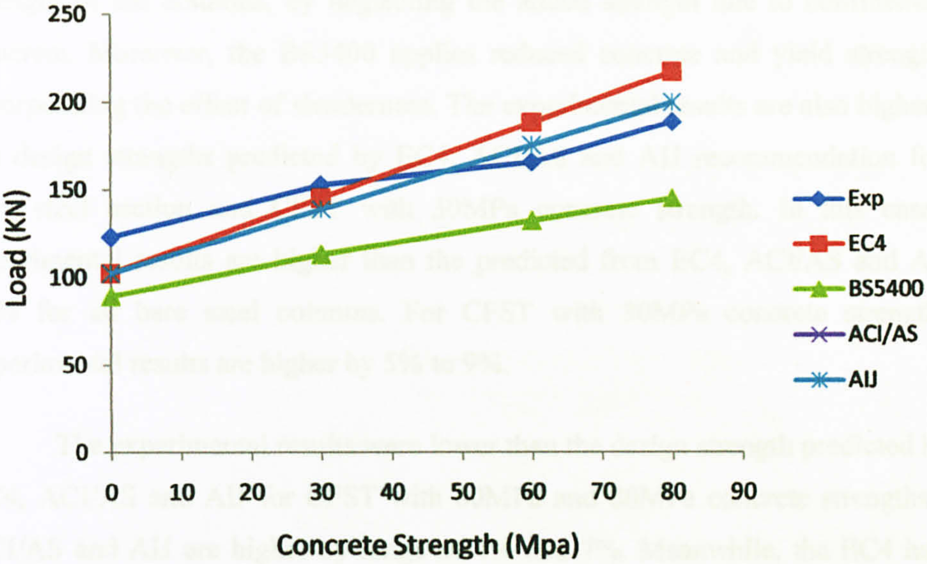

Figure 4.5: Comparison of experimental and predicted results C50-3.6

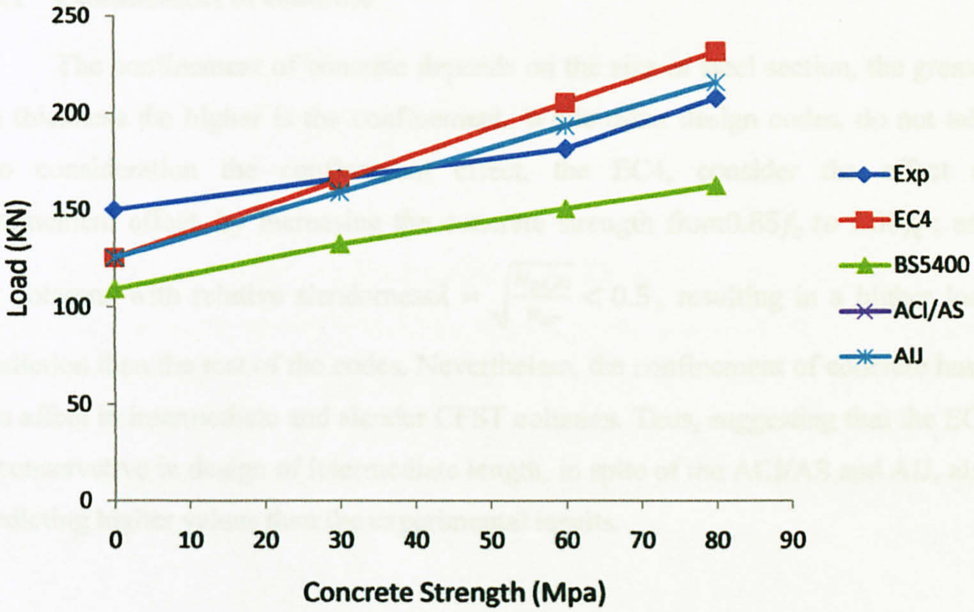

Figure 4.6: Comparison of experimental and predicted results C50-4.5

From these comparisons, it is observed that, the experimental results are relatively higher than the values predicted by the BS5400, as it should be. The reason is that the BS400 uses a more conservative approach in calculating the design strength of the columns, by neglecting the added strength due to confinement of concrete. Moreover, the BS5400 applies reduced concrete and yield strength, by incorporating the effect of slenderness. The experimental results are also higher than the design strengths predicted by EC4, ACI/AS and AIJ recommendation for the bare steel section and CFST with 30MPa concrete strength. In this case, the experimental results are higher than the predicted from EC4, ACI/AS and AIJ by 17% for all bare steel columns. For CFST with 30MPa concrete strength the experimental results are higher by 5% to 9%.

The experimental results were lower than the design strength predicted by the EC4, ACI/AS and AIJ for CFST with 60MPa and 80MPa concrete strengths. The ACI/AS and AIJ are higher by range of 4% and 7%. Meanwhile, the EC4 had the highest overprediction of 12% to 15%. The reason is that the EC4 takes into consideration the confinement of concrete by the steel tube.

4.4.1 Confinement of concrete

The confinement of concrete depends on the size of steel section, the greater the thickness the higher is the confinement. While other design codes, do not take into consideration the confinement effect, the EC4, consider the effect of confinement effect, by increasing the concrete strength from$0.85f_c$ to $1.00f_c$; and for columns with relative slenderness$\bar{\lambda} = \sqrt{\frac{N_{pl,Rl}}{N_{cr}}} < 0.5$, resulting in a higher load prediction than the rest of the codes. Nevertheless, the confinement of concrete has a less affect in intermediate and slender CFST columns. Thus, suggesting that the EC4 unconservative in design of intermediate length, in spite of the ACI/AS and AIJ, also predicting higher values than the experimental results.

4.4.2 Diameter to thickness ratio

The diameter-to-thickness ratio plays a vital role in determining the compressive strength of the CSFT tubes. The D/t ratios of the selected specimen are presented in **Table 4.6:**

Table 4.6 Diameter-to-thickness ratio

Sample No	D/t Ratio	N_{Exp} (KN)
C50-4-00	14	123
C50-4-30	14	153
C50-4-60	14	166
C50-4-80	14	189
C50-5-00	11	150
C50-5-30	11	166
C50-5-60	11	181
C50-5-80	11	207

As predicted in the literature review the smaller the D/t ratio greater is the compressing strength of the CFST, as shown in the table above. For example, specimen **C50-5-60** ($D/t = 11$) has higher load resistance than **C50-4-60** ($D/t =$ 14). The reason is that, the smaller D/t ratio provides a better confinement of concrete. However, in this research, the confinement of concrete was not significant in overall CSFT behaviour, as the length of the column dictated the failure mode.

4.5 CFST for Offshore Application

Circular hollow steel section, have been widely used in offshore structures, because of its numerous structural advantages over other materials. However, they also are susceptible to operational and environmental damage, and difficult to repair. The concrete filled steel tubes (CFST) technology, which has been widely used in tall building, bridges construction, and coastal structures, would enhance the steel usage in offshore structures. Filling in concrete will increase increase the ultimate strength of members without significant increase in cost, by increasing the floor area, while decreasing the steel cross section area. CFST can also be used for repair of damaged offshore structural member, by filling in grout or concrete in to the hollow steel.

CHAPTER 5

CONCLUSIONS and RECOMMENDATIONS

5.1 Conclusions

The project consists of literature review, experimental work and analysis of behaviour of CFST under axial compression loading. The literature review and experimental results obtained of the selected cross sections reveal that:

- Buckling of the column depends on the slenderness of the columns
- The mode of failure of the specimens was largely due to overall elastic buckling despite of some specimens showing a local buckling at the fixities.
- The BS5400 predicted values were 17% to 28% lower than the experimental results, as it neglected the added concrete strength due to confinement.
- The ACI, AS and the AIJ, showed same trend of results, and the predicted strength was 1% to 5% lower than the experimental results for concrete of 30Mpa.
- Although, the diameter-to-thickness ratios are low (11 and 14), the confinement of concrete had less effect on the specimens; justified by the fact the experimental result had lower values than the predicted by the EC4 that takes consideration of confinement.

Overall, the behaviour of the high strength CFST intermediate length columns, is characterized by elastic buckling, and although there is no confinement, the strength of concrete add compression capacity of the column.

5.2 Recommendations

For future research, some recommendations are made to make sure that the CFST research is well investigated. In future research, more studies on parameters such as material bonding, residual stress, creep, shrinkage, and type of loading, are needed to provide a detailed comprehension on the behavior of intermediate length CFST. It is also recommended the usage of self compacting concrete (SCC) as concrete infill for CFST. SCC has many advantages like no need compaction to the samples during casting process. Furthermore, research should focus more on the added implication of applying CFT in offshore structures.

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APPENDICES

Appendix 1

Concrete strength after testing

CFST C50-4-60 after testing