Concrete Filled Steel Tubes
(CFST)

By

AZNAN ISMAIL

Dissertation Report submitted in partial fulfillment of
The requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

JANUARY 2008

Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Concrete Filled Steel Tubes (CFST)

by

Aznan bin Ismail

A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

Approved by,

(Assc. Prof Dr. Narayanan Sambu Potty)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2008

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.

AZNAN BIN ISMAIL
860517-29-5391

ABSTRACT

The Concrete Filled Steel Tube (CFST) Structural System is a completely new system based on filling steel tubes with high-strength concrete. A CFST member contains two materials with different stress-strain curves and distinctly different behavior. The interactions of the two materials give difficult problems in the determination of combined properties such as moment of inertia and modulus of elasticity. The main objective of this research is to determine compression behavior of CFST with ordinary concrete and high strength concrete under axial load and emphasis on identifying behavior of relevance to offshore applications. The CFST specimens were tested under axial load to clarify the effect of the test parameters on the behavior. The tested samples of CFST were observed and discussed in this report.

TABLE OF CONTENTS

CHAPTER 1:	**INTRODUCTION**		
	1.1	Background of Study . . .	1
	1.1	Problem Statement . . .	2
	1.2	Objectives	2
	1.3	Scope of Study . . .	2
CHAPTER 2:	**LITERATURE REVIEW**		
	2.1	Concrete Filled Steel Tubes . .	3
	2.2	Theoretical Values . .	5
	2.3	D/t Ratio . .	6
	2.4	Past Experimental . .	6
CHAPTER 3:	**METHODOLOGY**		
	3.1	Introduction	9
	3.2	Design Mix Composition . .	10
	3.3	Casting Concrete Cubes . .	10
	3.4	Cutting Steel Tubes . . .	11
	3.5	Casting CFST Samples. . .	16
	3.6	Sample Testing . . .	17
	3.7	Load Carrying Capacity Prediction. .	18
	3.8	Hazard Analysis . . .	21
CHAPTER 4:	**RESULTS AND DISCUSSION**		
	4.1	Concrete Compression Test Result .	22
	4.2	Bare Steel Tubes Compression Test Result	24
	4.3	Control Concrete Mix Result .	25
	4.4	CFST Compression Test Result .	25
	4.5	Comparison of Prediction and Experimental Value of CFST .	25
	4.6	Circular CFST . . .	29
	4.7	Square CFST . . .	33
	4.8	CFST for Offshore Applications. .	34

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion 35

5.2 Recommendation . . . 35

REFERENCES 36

APPENDICES 39

LIST OF FIGURES

Figure 2.1	Concrete Filled Square Hollow Section	4
Figure 3.1	Flowchart of Activities	9
Figure 3.2	Circular section	12
Figure 3.3	Square Section	12
Figure 3.4	Circular and Square Hollow Section	13
Figure 3.5	Test setup	17
Figure 3.6	2000kN compression machine	17
Figure 4.1	Compressive strength of Design Mix Concrete	23
Figure 4.2	Comparison of experimental and predicted CFST Value for CHS 40	29
Figure 4.3	Comparison of experimental and predicted CFST Value for CHS 50	29
Figure 4.4	Scale effect diagram	32
Figure 4.5	Scale effect on compressive strength of 30 MPa CHS Column	32
Figure 4.6	Comparison of experimental and predicted CFST Value for SHS 38 x 38 mm	33
Figure 4.7	Comparison of experimental and predicted CFST Value for SHS 50 x 50 mm	33

LIST OF TABLES

Table 3.1	Design Mix for Concrete	10
Table 3.2	Properties of steel	12
Table 3.3	Dimension of Steel Tubes and Properties of Concrete to be used in CFST	12
Table 3.4	Summary of specimen length and dimension	16
Table 3.5	Predicted strength of CFST using EC4 code	18
Table 3.6	Predicted strength of CFST using ACI, AIJ and Australian Standards (AS) code	19
Table 3.7	Predicted strength of CFST using BS5400 method	20
Table 3.8	Summary of predicted load carrying capacity	20
Table 3.9	Hazard Analysis	21
Table 4.1	Grade 30 Compression Test Result	22
Table 4.2	Grade 50 Compression Test Result	22
Table 4.3	Grade 80 Compression Test Result	22
Table 4.4	Bare steel tubes section Compression result	23
Table 4.5	Control Concrete Compressive Strength	25
Table 4.6	Dimensions and Compression Test Result of Square CFST	26
Table 4.7	Dimensions and Compression Test Result of Circular CFST	27
Table 4.8	Comparison of Prediction and Experimental Value of grade 30 MPa CFST	28
Table 4.9	Comparison of Prediction and Experimental Value of grade 60 MPa CFST	28
Table 4.10	Comparison of Prediction and Experimental Value of grade 80 MPa CFST	28
Table 4.11	Mechanical Properties of CHS from BS 1387:1985	30
Table 4.12	Comparison Percentage confinement for Concrete 30 MPa	31
Table 4.12	Comparison Percentage confinement for Concrete 60 MPa	31
Table 4.12	Comparison Percentage confinement for Concrete 80 MPa	31

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The Concrete Filled Steel Tube (CFST) Structural System is a completely new system based on filling steel tubes with high-strength concrete. The CFST Structural System possesses excellent properties such as high strength, high ductility, high lateral stiffness, large energy absorption capacity, high damping against vibration, fire resistance and considerable time saved during the construction due to no need of formwork. A CFST member contains two materials with different stress-strain curves and distinctly different behavior. The interactions of the two materials give difficult problems 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 strengths of concrete and steel. Parameters such as bond, concrete confinement, residual stresses, creep, shrinkage, and type of loading also have an effect on the CFST's behavior. While many advantages exist, the use of CFST in building construction has been limited due in part, to a lack of construction experience and to the complexity of connection detailing. More investigation and research need to be carried out to make sure this technology can be applied in the construction without having problems.

1.2 Problem Statement

It is known that the ultimate strengths of CFST are influenced by its material properties such as the compressive strength of the concrete, the yielding strength of steel, the concrete confining pressure and geometric properties of the tubes. The synergistic interaction of steel tube and the filled concrete using high-strength materials has not been investigated sufficiently. This research focuses on determining the behavior of CFST with different concrete strength and recommendation of CFST on offshore application.

1.3 Objectives

The objective of this project is to determine the behavior of short Concrete Filled Steel Tubes under axial load and emphasis the project related to offshore structures.

1.4 Scope of Study

a) Literature review of CFST and identifying hollow structural steels commonly used for offshore applications.
b) Development of ordinary concrete mixes, high strength mixes and ultra high strength mixes and testing the mixes to make sure that concrete mixes achieved its target strength.
c) Determine the compression behavior of CFST with ordinary concrete, high strength concrete and ultra high strength concrete.
d) Comparison with experimental results and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 Concrete Filled Steel Tubes

Steel members have the advantages of high tensile strength and ductility, while concrete members have the advantages of high compressive strength and stiffness (Ahmed, Atorod 2002). Ahmed and Atorod stated that composite members combine steel and concrete, resulting in a member that has the beneficial qualities of both materials. Concrete filled steel tube (CFST) possesses excellent properties such as high strength, high ductility, high lateral stiffness, large energy absorption capacity, high damping against vibration, fire resistance and considerable time saved during the construction due to the no need for formwork. CFST avoids the brittle failure mode seen in reinforced concrete structures. If CFST is used, the size of members can be reduced thus increasing strength weight ratios. Concrete filled Steel Columns (CFST) has been used widely in structures throughout the world in recent years. This increase in use is due to the significant advantages that CFST offers in comparison to more traditional construction methods. The use of composite columns can result in significant savings in column size, which ultimately can lead to significant economic savings.

A primary deterrent to widespread use of CFST is the limited knowledge regarding their behavior. A CFST member contains two materials and thus poses 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, steel strength. Parameters such as bond, concrete confinement, residual stresses, creep, shrinkage, and type of loading also have an effect on the CFST's behavior. Axially loaded CFST have also been studied. If the strength of the steel exceeds approximately 380 MPa (the stresses corresponding to a longitudinal strain of approximately 0.002), the concrete will likely reach its compressive strength limit and may crush before the steel yields, which is undesirable mode of failure.

In addition, this might cause elastic local buckling of the steel tube. SSRC (1979) thus specifies a steel strength limit of 380 MPa for composite columns. For lower strength steels, the failure of thick walled short columns begins with the yielding of the steel. By filling hollow sections with concrete a composite section is produced (see Figure 2.1), which will increase the section's room temperature load carrying capacity, whilst retaining all the advantageous features of the basic unfilled section. Alternatively, for the same original load capacity, it permits smaller composite sections to be used. Corus Design guide for SHS concrete filled columns (2002) stated that the reduction in section size also gives advantages in subsequent construction processes, including a reduced surface area for painting or fire protection. In the fire condition the presence of the concrete filling acts as a heat sink.

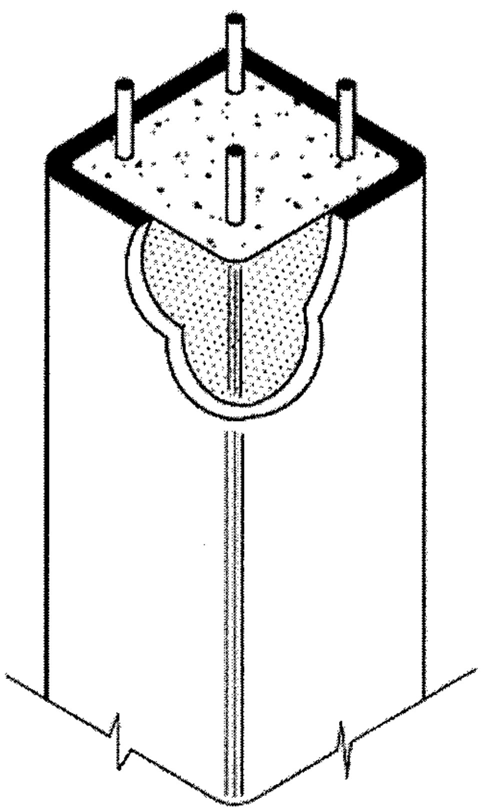

Figure 2.1: Concrete filled square hollow section

(After Corus Design guide for SHS concrete filled columns, 2002)

2.2 Theoretical Values

When a perfectly straight short composite column is loaded axially, its structural components undergo the same strain values, as a result of which of the steel yields before the attainment of the compressive strength of the concrete. For an encased composite column, the surrounding concrete will restrain the yielded steel and prevent it from buckling. Any further increase in the applied axial load will be supported by the concrete encasement until it finally reaches its compressive strength. The final load level is the ultimate strength of an axially loaded short column and referred as Squash load, N_u.

In the case of concrete filled steel tube sections, when the steel tube reaches its yield strength the local buckling of the steel tube is prevented by the outward push of the contained concrete against the tube wall. As a result of this interaction between the steel and the concrete, the axial load acting on a short concrete filled steel tubes section may be increased beyond the load level at which the steel yields. The ultimate load of the column will be reached when the stress in the contained concrete reaches the maximum strength of the concrete.

The theoretical values of the load for different codes were calculated and will be compared to the obtained experimental peak values of compressive loads, which were calculated as the summation of the individual ultimate axial capacities of both the steel tube and concrete and as given by equation 1:

$$N_u = As\,fy + Ac\,fc \qquad (1)$$

Where:

Ac is the cross-sectional area of the concrete core,

As is the cross-sectional area of the steel tube,

fc is the concrete compressive strength

fy is the yield stress of the steel tube.

2.3 D/t Ratio

Uy (1998) tested five square hollow section steel tubes filled with concrete where only the steel tube was subjected to axial load. In study the depth-to-thickness ratios varied from 40 to 100. The experimental results highlighted how the concrete infill can lead to enhanced bearing capacities. The design expression utilized for the calculation of the bearing capacity with large depth-to thickness ratio relied on the effective width method. According to Lanhui et al. (1984) based on the Eurocode 4 design guidelines, limits of depth-to-thickness ratios for rectangular section below which local buckling can be ignored in design are defined as:

$$\frac{D}{t} \leq 52\sqrt{\frac{235}{f_y}} \quad . \qquad (2)$$

According Corus design guide for SHS concrete filled columns (2002) for concrete filled circular hollow section, depth to thickness ratio of steel section in compression must satisfy the following limits:

$$\frac{D}{t} \leq 90\sqrt{\frac{235}{fy}} \qquad (3)$$

2.4 Past Experiment

According to Ahmed and Atorod (2002)

> Experimental studies on rectangular CFT columns subjected to combined flexure and axial loads have been conducted by Furlong (1967), Knowles and Park (1969), Morino et al. (1996) and Fujimoto et al. (1996), among others. Tests on circular CFT columns under combined flexure and axial loads were reported by a number of researchers, including Furlong (1996), Knowles and Park (1969), Neogi et al. (1969), Rangan and Joyce (1992), Boyd et al. (1995), Morino et al. (1996) and Kilpatrick and Rangan (1999). Most of the tested columns had small diameters that ranged from 76 to 152 mm (3 to 6 in.) and only a few columns had a diameter of 203 mm (8 in.) or more. (p. 3)

O'Shea and Bridge (1996) had done a series of tests on the behaviour of circular thin-walled steel tubes. The diameters of the tubes to thickness ratio D/t are from 50 to 200. The tests consist of series of bare steel tubes, tubes with unbounded concrete with only the steel section loaded, tubes with concrete infill with the steel and concrete loaded simultaneously and tubes with concrete infill loaded alone. The result of test strengths were compared to strength models in design standards and specifications. The result showed that the concrete infill for the thin-walled circular steel tubes has little effect on the local buckling strength of the steel tubes.

In another research, O'Shea and Bridge (1997) found that the local buckling strength for rectangular and square sections can be improved with concrete infill. Increased strength due to confinement of high-strength concrete can be obtained if only the concrete is loaded and the steel is not bonded to the concrete. For steel tubes with a D/t ratio greater than 55 and filled with 110–120 MPa high-strength concrete, the steel tube provides insignificant confinement to the concrete when both the steel and concrete are loaded simultaneously. Therefore, they considered that the strength of these sections can be estimated using Eurocode 4 with confinement ignored. The influence of local buckling on behaviour of short circular thin-walled CFTs has been examined by O'Shea and Bridge (1997). Two possible failure modes of the steel tube had been identified, local buckling and yield failure. These were found to be independent of the diameter to wall thickness ratio. Instead, bond between the steel and concrete infill determined the failure mode.

Sakino et al. (1998) proposed design formulas to predict the axial compressive load capacity and ultimate moment of CFT columns with circular or square cross-sections. For circular columns, the extent of confinement was determined from the test results of axially loaded specimens. The same level of confinement was assumed to be applicable to circular columns under bending. The ultimate moment of the section was estimated as the full plastic moment calculated using rectangular stress blocks for both concrete and steel.

Experimental results suggest that circular tubes offer substantial post-yield strength and stiffness not available in most square or rectangular cross-sections (Schneider 1998).However, there is a lack of experimental data on circular CFT columns with large cross sectional dimensions and very few studies have dealt with the behavior of these columns under seismic conditions (Boyd et. al 1995).

Neogi et al. (1969) investigated numerically the elasto-plastic behaviour of pinended, CFT columns, loaded either concentrically or eccentrically about one axis. It was assumed complete interaction between the steel and concrete, triaxial and biaxial effects were not considered. Eighteen eccentric loaded columns were tested, in order to compare the experimental results with the numerical solution. The conclusions were that there was a good agreement between the experimental and theoretical behaviour of columns with L/D ratios greater than 15, inferred that triaxial effects were small for such columns. Where for columns with smaller L/D ratios, it showed some gain in strength due to triaxial effect.

CHAPTER 3
METHODOLOGY

3.1 Introduction

The main objective of this test program is to obtain experimental data on the behavior of CFST column with a variety of material strength, including high strength material of 80 MPa concrete. This project deals with concrete and steel so the test must be done carefully considering safety and hazard seriously. Flow chart of activities that must be followed to complete the project is in figure 3.1 below.

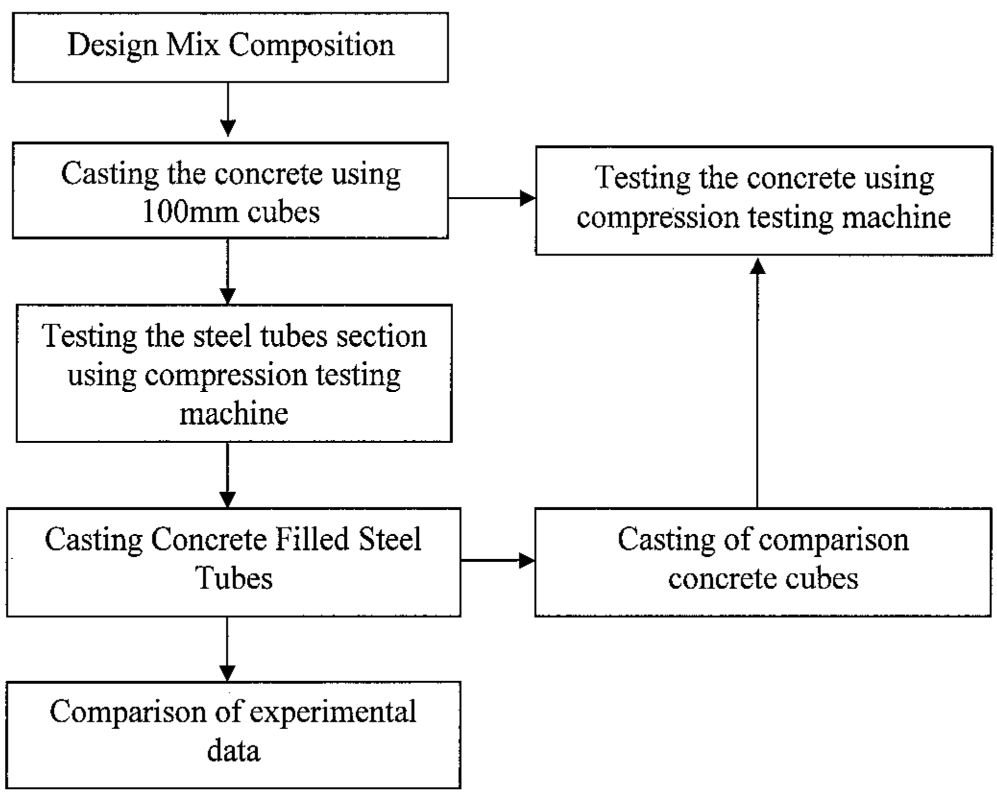

Figure 3.1: Flowchart of activities

3.2 Design Mix Composition

Three different strengths of the concrete normally grade 30 MPa, 60 MPa and 80 MPa were produced with normal mixing and curing techniques. The standard size of cube is 150 mm are used because it is suitable for concrete having a nominal maximum aggregate size more than 20 mm. In this experiment, aggregate less than 10mm are used because the steel tubes samples were small in size. To determine the compressive strength of concrete, 100mm cubes are used in casting the concrete cubes. The three trial mix designs had been prepared before the start of the experiments. The mix designs are shown in Table 3.1.

Table 3.1: Design Mix for Concrete

Mix	Grade 30 (kg/m^3)	Grade 60 (kg/m^3)	Grade 80 (kg/m^3)
Ordinary Portland Cement	313	490	600
Water	158	141	178
Fine Aggregate (sand)	619	471	650
Coarse Aggregate	1313	1310	1090
Silica Fume	-	-	60
Superplasticizers	-	-	24
Water/Cement Ratio	0.50	0.29	0.27

3.3 Casting Concrete Cubes

Before casting the concrete cubes, precautions must be taken into consideration to make sure that the work done smoothly. The inside of the concrete mould must be oiled to prevent the concrete from sticking to it. The two sections must be bolted firmly together, and the moulds held down firmly on the base plates. After the sample has been mixed it must be filled immediately into the cube moulds and the concrete must be compacted with, either by hand or poker vibrator. Any air trapped in the concrete will reduce the strength of the cube. Hence, the cubes must be fully compacted. However, care must also be taken not to over compact the concrete as this may cause segregation of the aggregates and cement paste in the mix. This may also reduce the final compressive strength.

100 mm moulds filled in two approximately equal layers (50 mm deep). A compacting bar is provided for compaction of the concrete. During the compaction of each layer with the compacting bar, the strokes should be distributed in a uniform manner over the surface of the concrete and each layer should be compacted to its full depth. After the top layer has been compacted, a trowel should be used to finish off the surface level with the top of the mould, and the outside of the mould should be wiped clean. *Refer Appendix 1.*

Test cubes should be demoulded between 16 and 24 hours after casting. If after this period of time the concrete has not achieved sufficient strength to enable demoulding without damaging the cube then the demoulding should be delayed for a further 24 hours. After demoulding, each cube should be marked with a legible identification on the top or bottom using a waterproof crayon or ink. The mould must be thoroughly cleaned after demoulding the cube. Ensure that grease or dirt does not collect between the faces of the flanges, otherwise the two halves will not fit together properly and there will be leakage through the joint and an irregularly shaped cube may result. Cubes must be cured before they are tested. The cubes were tested at the age of 7, 14 and 28 days.

3.4 Cutting Steel Tubes

Steel tubes were cut into length before casting of CFST can be done. *Refer Appendix 2.* Four types of hollow steel section were tested in the research. Two hot-rolled welded steel pipes Class Light BS 1387:1985 and two cold rolled Square Hollow Section (Grade A) ASTM A 500 were used in a series of test (see Figure 3.4). It should be noted that the hollow sections are not assumed to have sharp corners and that the effect of the corner is not ignored. So, before testing the short tubes, the value of the cross-sectional areas (As) of the steel was evaluated. First the steel tubes were weighed and the length of each specimen was measured. This gave the actual cross sectional area of steel of each specimen which was later used in the relevant calculations of the different columns.

The material properties of steel are shown in Table 3.2 and the dimensions of steel used in the experiment are listed in Table 3.3.

Table 3.2: Properties of steel

Standard Specification		**Mechanical Properties**	
	Standard Grading	Tensile Strength (MPa) min.	Yield Strength (MPa) min.
BS 1387	Light Grade	320-460	195
ASTM A-500	Grade A SHS	310	269

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

Parameters, Section Size (mm)	Thickness (mm)	Yield Stress (MPa)	Ordinary Concrete 30 MPa	High Strength Concrete 60 MPa	Ultra High Strength Concrete 80 MPa
Circular					
40	2.9	195	✓	✓	✓
50	3.3	195	✓	✓	✓
Square					
38 x 38	1.2	269	✓	✓	✓
50 x 50	1.5	269	✓	✓	✓

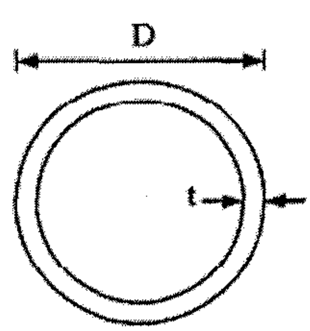

Figure 3.2: Circular section

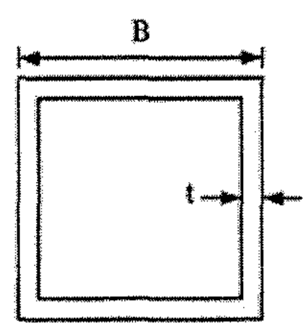

Figure 3.3: Square section

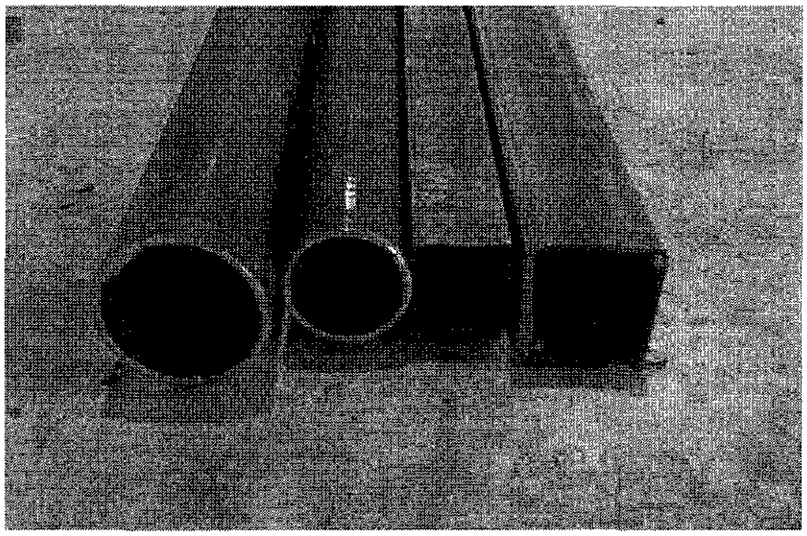

Figure 3.4: Circular and Square Hollow Section

3.4.1 Limiting slenderness for short struts

Before cutting steel tubes into size, the slenderness ratio of the steel must be calculated to prevent overall buckling of the sections. Slenderness ratio, λ is the ratio of the effective length of a column to the least radius of gyration of its cross section. This ratio affords a means of classifying columns. A short steel column is one has slenderness ratio does not exceed 50. An intermediate length steel column has a slenderness ratio ranging from 50 to 200, while a long steel column may be assumed to have a slenderness ratio greater than 200. To make sure that our sample is short, it is very important to calculate maximum length for short struts which has a slenderness ratio less than 50.

The equation of limiting slenderness for axial compression is below:

$$\lambda_o = 0.2\left[\frac{\pi^2 E}{Py}\right]^{0.5} \tag{4}$$

3.4.1.1 Calculation for Circular Section

For CHS which has yield strength of 195 MPa

$$\lambda_o = 0.2\left[\frac{\pi^2 \times 205000}{195}\right]^{0.5} = 20.37$$

where $\lambda_o = \frac{\lambda}{\gamma}$ and $\gamma = \sqrt{\frac{I}{A}}$

Moment of Inertia = 0.0491 (D^4- d^4)

where D^4 is outer diameter and d^4 is inner diameter

i. Nominal Size 40 mm, thickness, t = 2.9 mm

A= 4.14 cm^2, I = 10.77 cm^4

γ = 1.61

$\lambda_o = 20.37 = \frac{\lambda}{\gamma}$

λ= 20.37 x 1.61 = 32.8 cm

≈ 32 cm @ 320 mm

ii. Nominal Size 50 mm, thickness, t = 3.2 mm

A= 5.74 cm^2, I = 23.5 cm^4

γ = 2.02

$\lambda_o = 20.37 = \frac{\lambda}{\gamma}$

λ= 20.37 x 2.02 = 41.14 cm

≈ 41cm @ 410 mm

3.4.1.2 Calculation for Square Section

For SHS which has yield strength of 269 MPa

$$\lambda_o = 0.2\left[\frac{\pi^2 \times 205000}{269}\right]^{0.5} = 17.34$$

i. 38 mm x 38 mm (CR), thickness, t = 1.2 mm

A= 1.729 cm^2, I = 3.99 cm^4

$\gamma = 1.51$

$$\lambda_o = 17.34 = \frac{\lambda}{\gamma}$$

λ= 17.34 x 1.51 = 26.18 cm

≈ 26 cm @ 260 mm

ii. 50 mm x 50 mm (CR), thickness, t = 1.5 mm

A= 2.851 cm^2, I = 11.42 cm^4

$\gamma = 2.0$

$$\lambda_o = 17.34 = \frac{\lambda}{\gamma}$$

λ= 17.34 x 2.0 = 34.68 cm

≈ 34 cm @ 340 mm

The summary of sample length to be cut into length is shown in Table 3.4

Table 3.4: Summary of specimen length and dimension

Type of Specimen	Length (mm)	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)
CHS 40	250	48.0	42.2	2.9
CHS 50	300	60.2	54.4	2.9
SHS 38	250	38.2	35.6	1.2
SHS 50	300	50.1	47.1	1.5

3.5 Casting CFST samples

36 Hot Rolled circular and cold rolled square steel tubes were used in the construction of the specimen. Three types of concrete, with the compressive cube strength at 28 days of 30 MPa, 50 MPa and 80 MPa were designed earlier and tested before. The concrete will be filled in layers and compacted using compacting bar (*refer Appendix 3*). Comparison cubes will be cast again for comparison purpose. All specimens were cast from one batch of concrete. The specimens were placed into the testing machine and the loads were applied on the specimens axially. In order to investigate the behaviour of the composite CFT column, 36 specimens were tested with various concrete strength and wall thickness.

3.6 Sample Testing

All specimens for concrete cube, steel section and concrete filled steel tubes will be tested using 3000kN compression testing machine at the age of 7, 14, and 28 days *(Refer Appendix 4)*. All data will be recorded. The experimental set-up and instrumentation is illustrated in Figure 3.5. The experiments were conducted using a 2000 KN capacity compression machine. The 2000 KN compression machine is shown in the figure 3.6.

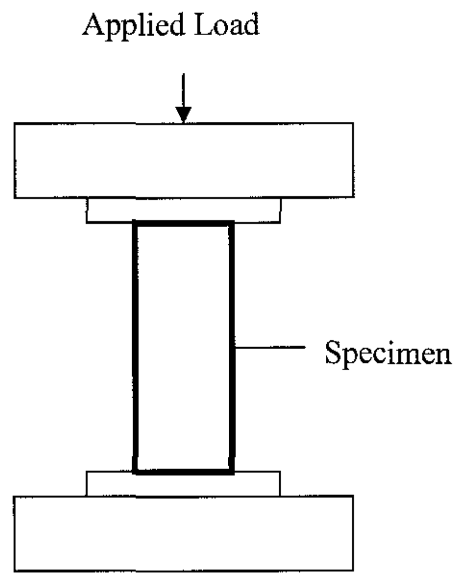

Figure 3.5: Test setup

Figure 3.6: 2000 KN compression machine

3.7 Load Carrying Capacity Prediction

There are many widely used design codes to calculate the capacity of CFST such as ACI [18], AIJ [19], Australian Standard (AS), BS5400 [20], EC4 [21]. This theoretical or prediction value calculated were compared with experimental data for composite section of CFST. The design codes above are applied to calculate section capacities of adequately stiffened CFST.

3.7.1 Eurocode 4 (EC4) method

The nominal strength for composite compression members is given same as equation 4:

$$N_{EC4} = As\,fy + Ac\,fc \qquad (5)$$

The calculated prediction value using EC4 are tabulated in table 3.5.

Table 3.5: Predicted strength of CFST using EC4 code

	CHS 40 mm (KN)	CHS 50 mm (KN)	SHS 38 x 38 mm (KN)	SHS 50 x 50 mm (KN)
fcu 30	123.6	184.2	89.8	156.2
fcu 50	152.10	218.0	118.7	208.1
fcu 80	194.9	287.7	162.0	208.1

3.7.2 ACI, AIJ and Australian Standards (AS) method

The ACI, AIJ and Australian Standards (AS) method use the same formula for calculating the squash load. Neither code takes into consideration to concrete confinement. The squash load for square, rectangular, and circular columns is determined by equation 6:

$$N_{ACI,AIJ,AS} = As\,fy + 0.85\,Ac\,fc \qquad (6)$$

The calculated prediction value using codes above are tabulated in table 3.6.

Table 3.6: Predicted strength of CFST using ACI, AIJ and Australian Standards (AS) code

	CHS 40 mm (KN)	**CHS 50 mm (KN)**	**SHS 38 x 38 mm (KN)**	**SHS 50 x 50 mm (KN)**
fcu 30	117.2	175.2	83.3	144.5
fcu 50	141.1	214.8	107.8	188.6
fcu 80	177.8	274.0	144.7	231.4

3.7.3 BS5400 method

The squash load of composite cross section given by equation below:

$$N_{BS5400} = As\,fy + 0.675\,Ac\,fc \qquad \textbf{(7)}$$

The predicted value in Table 3.7 is compared with the experimental values.

Table 3.7: Predicted strength of CFST using BS5400 method

	CHS 40 mm (KN)	CHS 50 mm (KN)	SHS 38 x 38 mm (KN)	SHS 50 x 50 mm (KN)
fcu 30	109.7	180.2	95.2	165.9
fcu 50	129.0	180.2	95.2	165.9
fcu 80	157.8	227.2	124.4	199.9

Below are the summaries of Theoretical Load Carrying Capacity which already calculated earlier.

Table 3.8: Summary of predicted load carrying capacity

	fc 30			**fc 50**			**fc 80**		
	N_{EC4}	$N_{ACI,AIJ,AS}$	N_{BS5400}	N_{EC4}	$N_{ACI,AIJ,AS}$	N_{BS5400}	N_{EC4}	$N_{ACI,AIJ,AS}$	N_{BS5400}
CHS 40 mm	152.1	141.4	129.0	152.1	141.4	129.0	194.9	177.8	157.8
CHS 50 mm	218.0	214.8	180.2	218.0	214.8	180.2	287.7	274.0	227.2
SHS 38 x 38 mm	118.7	107.8	95.2	118.7	107.8	95.2	162.0	144.7	124.4
SHS 50 x 50 mm	208.1	188.6	165.9	208.1	188.6	165.9	258.4	231.4	199.9

*All units in KN

3.8 Hazard Analysis

A hazard analysis is a review of the procedures used within the laboratory to discover all hazards to personnel and property, and to define control methods to prevent exposures. The step-by-step review analyzes the procedures for potential hazards, and determining risks. The waste produced by all experiments must be classified for proper disposal.

Table 3.9: Hazard Analysis

ACTIVITY	POTENTIAL HAZARD	RECOMMENDED CONTROLS
Handling and pouring the concrete into mould and	Materials in eyes	Wear eye protection equipment.
Mixing the concrete	Materials in hands	Wear hand protection
Handling Concrete Cubes	Cubes may drop while handling	Wear safety boots
Testing the Concrete and Steel	i. Equipment hazard and place of working ii. Loading Steel drop iii. Could injured user hands iv. Chips of concrete flying hitting body parts	i. Wear proper protective safety shoes ii. Wear proper protective safety shoes iii. Close the cover and lock it iv. Wear proper lab coats / Safety protective body guard

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Concrete Compression Test Result

The results for Compression Test Result for Trial Mix of three mixes are shown in the table below.

Table 4.1: Grade 30 Compression Test Result

	Compressive Strength (N/mm^2)			
days	1	2	3	Average
7	16.3	28.5	29.4	24.7
14	28.4	34.1	33.2	31.9
28	33.6	34.1	29.9	32.5

Table 4.2: Grade 50 Compression Test Result

	Compressive Strength (N/mm^2)			
days	1	2	3	Average
7	42.3	41.3	38.3	40.6
14	44.4	42.3	41.2	42.6
28	53.2	51.7	52.0	52.3

Table 4.3: Grade 80 Compression Test Result

	Compressive Strength (N/mm^2)			
days	1	2	3	Average
7	42.8	46.0	42.0	43.6
14	55.3	60.2	58.2	57.9
28	77.3	72.3	75.2	74.9

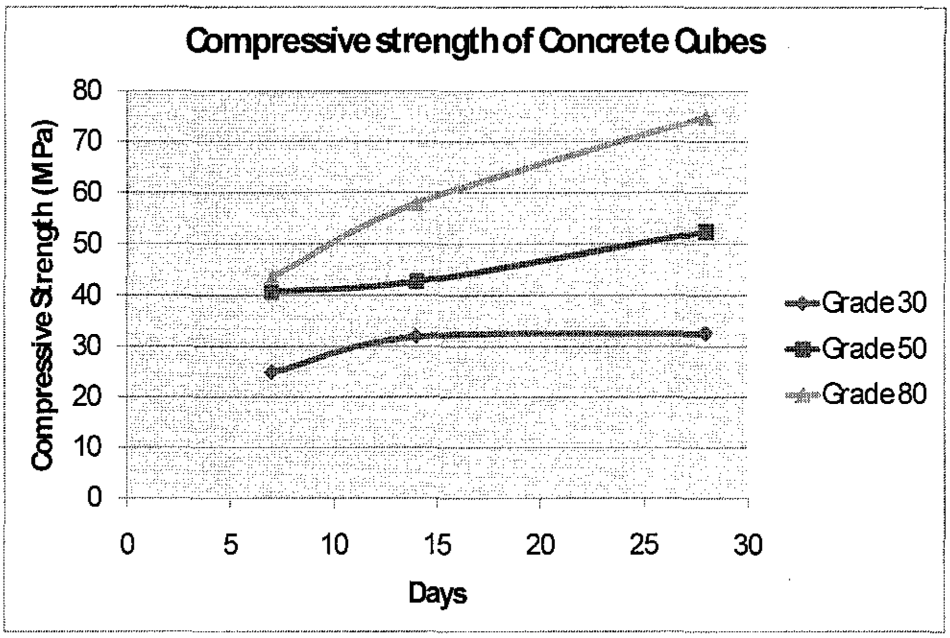

Figure 4.1: Compressive strength of Design Mix Concrete

It was observed that compressive strength for mix 3 (grade 80) in Figure 4.1 did not achieve 80 MPa for 28 days. Some modification was made to the mix to make sure that concrete will achieved its compressive strength. Grade 80 concrete does not achieve its compressive strength at 28 days for the trial mix because the effect of aggregate size used in concrete. Because the sample of CFST is small, smaller aggregate size (less than 10 mm) must be used in concrete mixing. These smaller aggregate sizes affect the concrete compressive strength. Fracture surfaces in concrete with smaller aggregate size exhibit low roughness than that for larger aggregate sizes. Modification to the design mix were done by adding more cement content and percentage of silica fume to increase the strength of the concrete and make sure that it achieve target compressive strength of 80 MPa at 28 days. The concrete then were used in the CFST samples.

4.2 Bare Steel Tubes Compression Test Result

All bare steel tubes section was tested under compression machine to get its compressive strength. The results of the tests are listed below in Table 4.4.

Table 4.4: Bare steel tubes section Compression result

	Length (mm)	**Outer diameter (mm)**	**Sample 1 (KN)**	**Sample 2 (KN)**	**Sample 3 (KN)**	**Average (KN)**
CHS 40 mm	250	48.0	220.5	183.7	199.6	**201.26**
CHS 50 mm	300	60.2	260.8	274.9	265.4	**267.03**
SHS 38x38 mm	250	38.2	43.8	45.6	44.8	**44.73**
SHS 50x50 mm	300	50.1	88.9	91.7	96.5	**92.36**

From the result, Circular Hollow Section (CHS 50) with outer diameter of 60.2 and length of 300 mm give the highest compressive strength compare to other section. CHS 40 compressive strength is slightly lower than CHS 50 result. From the result, it is observed that steel tube section with large outer diameter give higher compressive strength compare to the smaller diameter. This showed that the design strength was affected by the length and diameter of the tubes.

For Square Hollow Section (SHS), the compressive strength of both sections is very small compare to CHS section. The failure of the tested specimen was accompanied by a slow drop of the load as indicated by the test machine readings and sudden fail to the specimen was observed. The steel section experienced local buckling caused the capacity reduction of compressive strength. This result showed that steel section having local buckling give lower compressive strength.

4.3 Control Concrete Mix Result

Control Concrete Mix cubes were casted during casting of CFST samples. The concrete were taken from the same mix of concrete to be poured into steel tubes. After 28 days of curing, the concrete cubes were tested under compression machine to get its compressive strength. The data of compressive strength of CFST were used in the calculation of predicted squash load of CSFT using different codes. The results of Concrete Compressive strength are in Table 4.5.

Table 4.5: Control Concrete Compressive Strength

	Cube 1 (MPa)	**Cube 2 (MPa)**	**Cube 3 (MPa)**	**Average (MPa)**
Mix 30	35.63	36.34	33.26	**35.07**
Mix 50	56.42	57.37	61.57	**58.45**
Mix 80	78.98	81.12	83.32	**81.14**

4.4 CFST Compression Test Result

After 28 days of curing process, all CFST specimens were tested under compression machine to get its compressive strength. All data were recorded and used for comparison and discussion. All result of the test was recorded in Table 4.6 and Table 4.7.

4.5 Comparison of Prediction and Experimental Value of CFST

The predicted value of squash load of CFST was calculated earlier and compared with the experimental value of CFST compressive load. The comparisons of data are listed in Table 4.8, Table 4.9 and Table 4.10.

Table 4.6: Dimensions and Compression Test Result of Square CFST

Series	No	Name	D (mm)	t (mm)	L (mm)	D/t	fck (N/mm2)	fy (N/mm2)	**Ne (kN)**
1	1	S1-38-C1-1	38.2	1.2	80	31.6	30	269	**90.8**
	2	S1-38-C1-2	38.2	1.2	80	31.6	30	269	**92.4**
	3	S1-38-C1-3	38.2	1.2	80	31.6	30	269	**89.6**
1	4	S1-38-C2-1	38.2	1.2	80	31.6	60	269	**11.8**
	5	S1-38-C2-2	38.2	1.2	80	31.6	60	269	**110.2**
	6	S1-38-C2-3	38.2	1.2	80	31.6	60	269	**112.4**
1	7	S1-38-C3-1	38.2	1.2	80	31.6	80	269	**119.0**
	8	S1-38-C3-2	38.2	1.2	80	31.6	80	269	**125.3**
	9	S1-38-C3-3	38.2	1.2	80	31.6	80	269	**121.1**
2	10	S2-50-C1-1	50.1	1.5	100	33.3	30	269	**147.7**
	11	S2-50-C1-2	50.1	1.5	100	33.3	30	269	**166.5**
	12	S2-50-C1-3	50.1	1.5	100	33.3	30	269	**154.3**
2	13	S2-50-C2-1	50.1	1.5	100	33.3	60	269	**192.5**
	14	S2-50-C2-2	50.1	1.5	100	33.3	60	269	**190.3**
	15	S2-50-C2-3	50.1	1.5	100	33.3	60	269	**188.4**
2	16	S2-50-C3-1	50.1	1.5	100	33.3	80	269	**314.7**
	17	S2-50-C3-2	50.1	1.5	100	33.3	80	269	**325.8**
	18	S2-50-C3-3	50.1	1.5	100	33.3	80	269	**319.5**

* Ne is Experimental Ultimate Load

Table 4.7: Dimensions and Compression Test Result of Circular CFST

Series	No	Name	D (mm)	t (mm)	L (mm)	D/t	fck (N/mm2)	fy (N/mm2)	**Ne (kN)**
3	1	S3-40-C1-1	48.0	2.9	100	24.2	30	195	**317.4**
	2	S3-40-C1-2	48.0	2.9	100	24.2	30	195	**315.3**
	3	S3-40-C1-3	48.0	2.9	100	24.2	30	195	**310.4**
3	4	S3-40-C2-1	48.0	2.9	100	24.2	60	195	**390.9**
	5	S3-40-C2-2	48.0	2.9	100	24.2	60	195	**392.3**
	6	S3-40-C2-3	48.0	2.9	100	24.2	60	195	**387.4**
3	7	S3-40-C3-1	48.0	2.9	100	24.2	80	195	**423.6**
	8	S3-40-C3-2	48.0	2.9	100	24.2	80	195	**425.3**
	9	S3-40-C3-3	48.0	2.9	100	24.2	80	195	**422.1**
4	10	S4-50-C1-1	60.2	3.2	120	18.8	30	195	**405.4**
	11	S4-50-C1-2	60.2	3.2	120	18.8	30	195	**403.2**
	12	S4-50-C1-3	60.2	3.2	120	18.8	30	195	**399.6**
4	13	S4-50-C2-1	60.2	3.2	120	18.8	60	195	**504.8**
	14	S4-50-C2-2	60.2	3.2	120	18.8	60	195	**496.7**
	15	S4-50-C2-3	60.2	3.2	120	18.8	60	195	**505.2**
4	16	S4-50-C3-1	60.2	3.2	120	18.8	80	195	**624.8**
	17	S4-50-C3-2	60.2	3.2	120	18.8	80	195	**611.3**
	18	S4-50-C3-3	60.2	3.2	120	18.8	80	195	**616.6**

* Ne is Experimental Ultimate Load

Table 4.8: Comparison of Prediction and Experimental Value of grade 30 MPa CFST

	Concrete 30 Mpa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	N_{EXP}/N_{EC4}	$N_{EXP}/N_{ACI,AIJ,AS}$	N_{EXP}/N_{BS5400}
CHS 40 mm	123.6	117.2	109.7	314.3	2.53	2.66	2.88
CHS 50 mm	184.2	175.2	148.8	402.7	2.18	2.35	2.71
SHS 38x38 mm	89.8	83.3	75.7	90.9	1.01	1.09	1.2
SHS 50x50 mm	156.2	144.5	130.9	156.1	0.99	1.08	1.19

Table 4.9: Comparison of Prediction and Experimental Value of grade 60 MPa CFST

	Concrete 50 MPa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	N_{EXP}/N_{EC4}	$N_{EXP}/N_{ACI,AIJ,AS}$	N_{EXP}/N_{BS5400}
CHS 40 mm	152.1	141.4	129.0	390.0	2.56	2.76	3.02
CHS 50 mm	218.0	214.8	180.2	502.2	2.30	2.34	2.78
SHS 38x38 mm	118.7	107.8	95.2	111.4	0.96	1.06	1.20
SHS 50x50 mm	208.1	188.6	165.9	190.4	0.91	1.00	1.14

Table 4.10: Comparison of Prediction and Experimental Value of grade 80 MPa CFST

	Concrete 80 Mpa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	N_{EXP}/N_{EC4}	$N_{EXP}/N_{ACI,AIJ,AS}$	N_{EXP}/N_{BS5400}
CHS 40 mm	194.9	177.8	157.8	423.6	2.18	2.38	2.69
CHS 50 mm	287.7	274.0	227.2	617.5	2.14	2.25	2.71
SHS 38x38 mm	162.0	144.7	124.4	145.8	0.89	1.00	1.16
SHS 50x50 mm	258.4	231.4	199.9	320.0	1.24	1.38	1.60

4.6 Circular CFST

From comparison of compression test result of CFST, a comparison chart of CFST for experimental and theoretical value can be drawn. Figure 4.2 and Figure 4.3 shows the comparison of predicted value and experimental value of CFST. *Refer Appendix 5* for the picture of CFST samples after compression test.

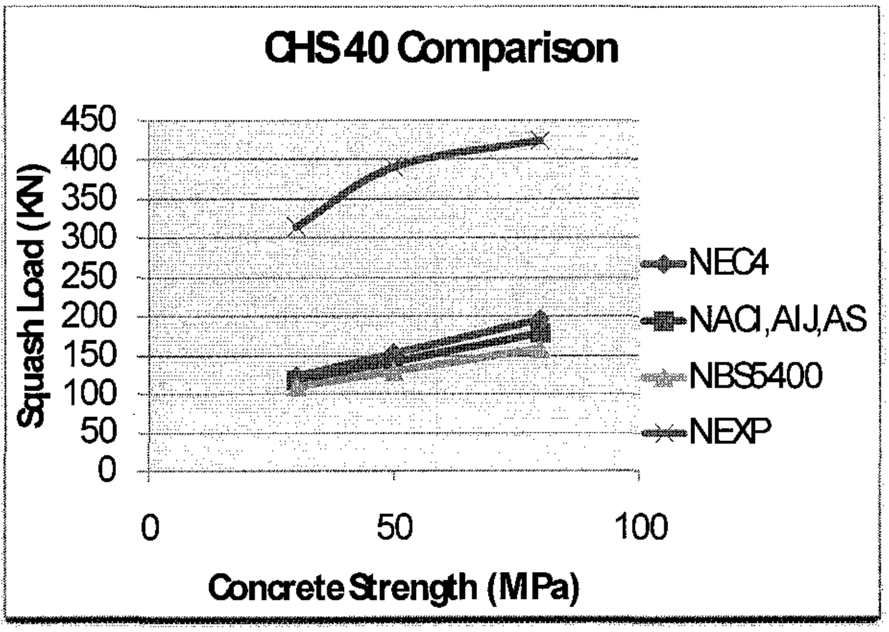

Figure 4.2: Comparison of experimental and predicted CFST Value for CHS 40

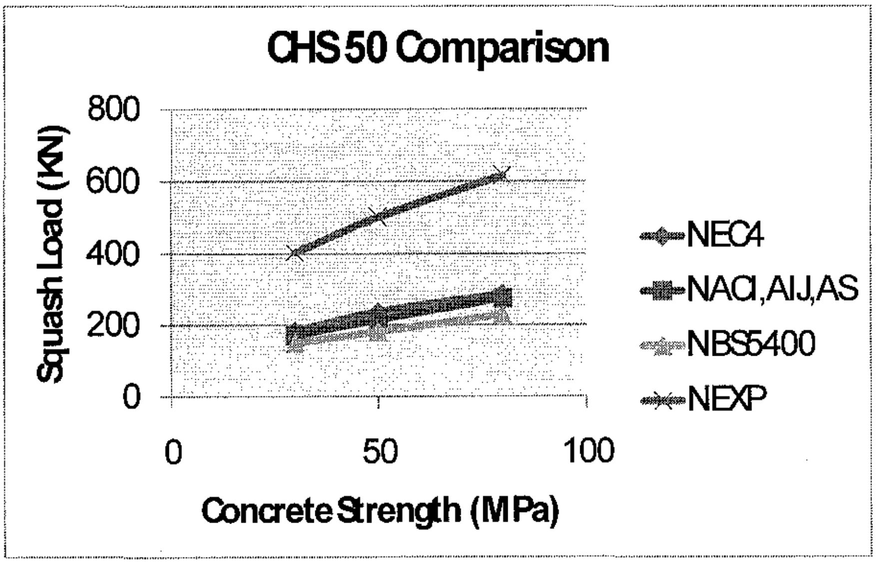

Figure 4.3: Comparison of experimental and predicted CFST Value for CHS 50

From the chart, it is observed that experimental value of compressive strength of CFST is very high compared to calculated value of CSFT using codes. There are many factors that lead to very high relative compressive strength of CFST. The factors are discussed below:

4.6.1 Steel Yield Strength

The yield strength of CHS is lower that actual value because the yield strength used in the calculation is from manufacturer's standard of BS 1387:1985. Table 4.11 shows the mechanical properties of the circular steel tubes from manufacturer's standard. The actual yield strength of the steel tubes is higher than the manufacturer's standard of yield stress. This will affect the value of predicted squash load from codes. If the actual yield stress of the steel tubes is slightly the same from standard, then relative compressive strength will be small. As long as the experimental value is higher than predicted value, it is safe for design of CFST column using yield strength from manufacturer's standard.

Table 4.11: Mechanical Properties of CHS from BS 1387:1985

The mechanical properties at room temperature shall be as given in the table below:

Tensile strength (N/mm2):	320 to 460
Yield strength (N/mm2):	195 min.
Elongation on gauge length Lo = 5.65√So(%):	20 min.

4.6.2 Confinement effect

Maximum experimental axial load is greater than the predicted nominal squash load in all of the circular CFT columns. A main reason for this augmentation of axial load capacity is attributed to the confinement effect of the steel tube on the filled concrete. This is due to increase in the strength of the concrete by the confinement effect produced due to the presence of the external steel tubes. The ratio of the load carrying capacity values of experimental to theoretical one were obtained and tabulated. The percentage confinement was calculated by the ratio of the difference in values between the experimental and theoretical ones to the theoretical values and reported in table 4.12, table 4.13 and table 4.14. Also the steel tube carries higher load because of stiffening of steel by concrete.

Table 4.12: Comparison Percentage confinement for Concrete 30 MPa

	Concrete 30 Mpa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	Percentage Confinement N_{EC4}	Percentage Confinement $N_{ACI,AIJ,AS}$	Percentage Confinement N_{BS5400}
CHS 40 mm	123.6	117.2	109.7	314.3	154	168	186
CHS 50 mm	184.2	175.2	148.8	402.7	118	129	170

Table 4.13: Comparison Percentage confinement for Concrete 60 MPa

	Concrete 50 MPa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	Percentage Confinement N_{EC4}	Percentage Confinement $N_{ACI,AIJ,AS}$	Percentage Confinement N_{BS5400}
CHS 40 mm	152.	141.4	129.0	390.0	155	175	202
CHS 50 mm	218.	214.8	180.2	502.2	130	132	178

Table 4.14: Comparison Percentage confinement for Concrete 80 MPa

	Concrete 80 Mpa						
	N_{EC4} (KN)	$N_{ACI,AIJ,AS}$ (KN)	N_{BS5400} (KN)	N_{EXP} (KN)	N_{EXP}/N_{EC4}	$N_{EXP}/N_{ACI,AIJ,AS}$	N_{EXP}/N_{BS5400}
CHS 40 mm	194.9	177.8	157.8	423.6	117	138	168
CHS 50 mm	287.7	274.0	227.2	617.5	114	125	171

4.6.3 Scale effect

One of the most important parameters in the experimental program is the D/t or B/t ratio of the steel tubes. The value of D/t (B/t) ratio was controlled by outside diameter of circular steel tubes if thickness is same. As expected, it seemed to be necessary to consider scale effect on the compressive strength of concrete. This resulted in the great differences in diameter or width of specimens as shown in Fig. 4.4. From Figure 4.4, it is observed that as the CFST become smaller, the relative compressive strength is increasing. Referring to Figure 4.5, a comparison of experimental of Circular CFST was made with CFST experimental from P.K Gupta et.al. The chart shows that smaller diameter tubes with same thickness having high relative compressive strength compare to tubes with larger diameter.

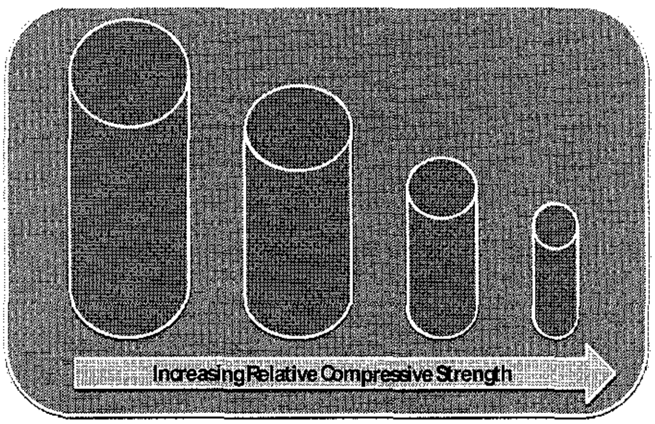

Figure 4.4: Scale effect diagram

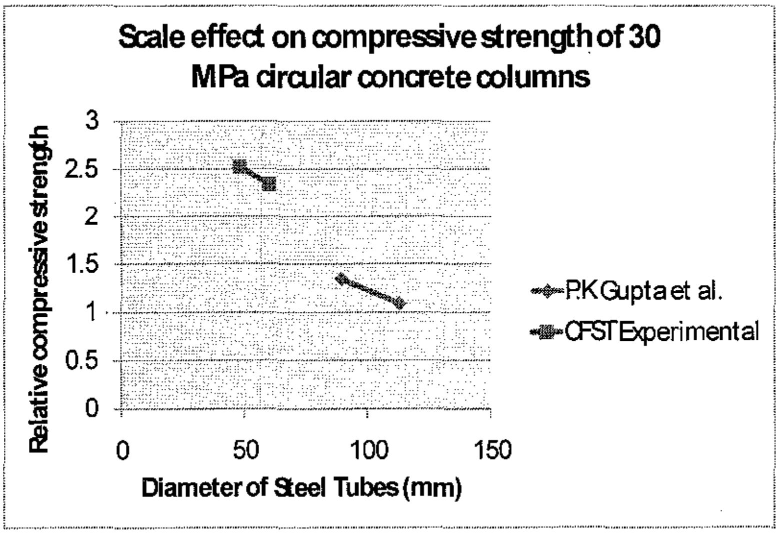

Figure 4.5: Scale effect on compressive strength of 30 MPa CHS Column

4.7 Square CFST

From comparison of compression test result of Square CFST, a comparison chart of CFST for experimental and theoretical value were drawn and Figure 4.6 and Figure 4.7 shows the comparison of predicted value and experimental value of CFST. *Refer Appendix 6* for the picture of CFST samples after compression test.

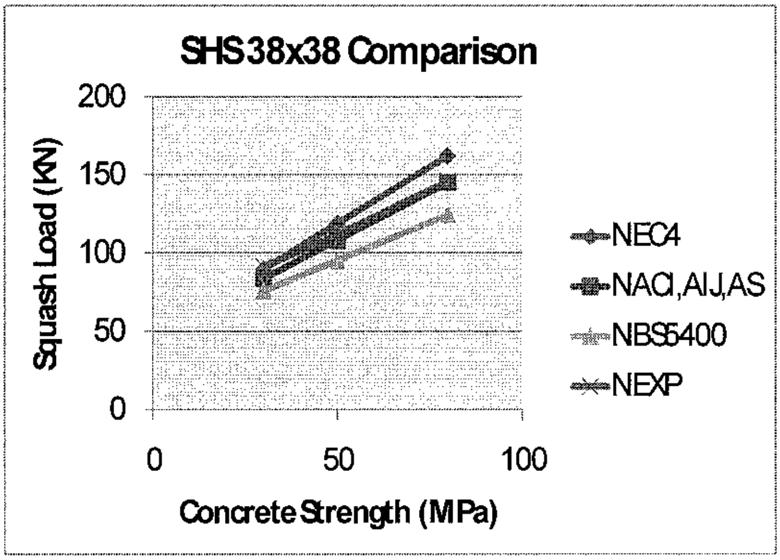

Figure 4.6: Comparison of experimental and predicted CFST Value for SHS 38 x 38 mm

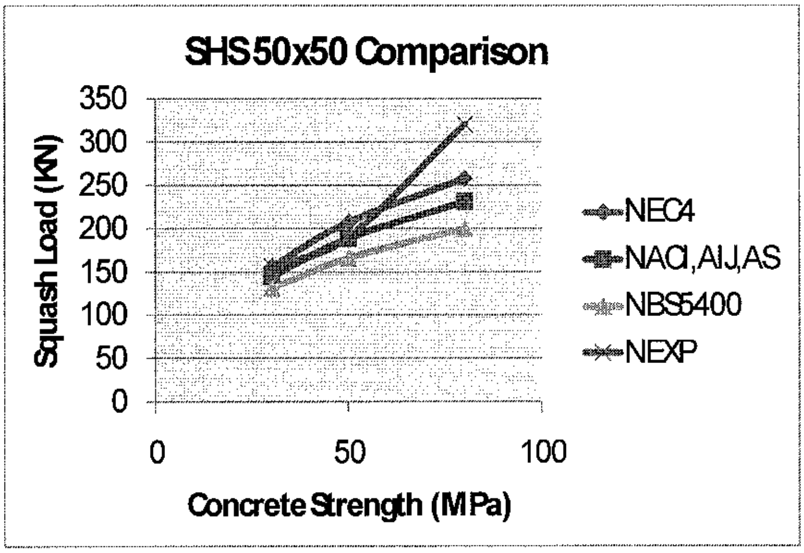

Figure 4.7: Comparison of experimental and predicted CFST Value for SHS 50 x 50 mm

From the experimental of Square CFST, it was observed that experimental value of CFST were slightly lower than predicted value using Eurocode 4 (EC4) except for SHS 50x50 concrete 90 MPa. For other two codes, the experimental value gives slightly same value to predicted value. Local buckling was observed in all Circular CFST samples after tested under compression machine.

Although B/t for square CFST satisfy EC4 code for square Section, small local buckling of the tube wall still occurred. The calculated value using EC4 code shows that for SHS 38 x 38 mm, the calculated value, 31.8 is less than 48.51 and for the SHS 50 x 50 mm calculated value, 33.4 is less than 48.51. Steel tubes with large B/t ratio provide inadequate confinement for the concrete.

In the case of square columns, it is necessary to take into consideration a capacity reduction due to local buckling of the steel tube wall of the column with large B/t ratio rather than the confinement effect of the steel tube. A main reason for this reduction of axial load capacity is attributed to the local buckling of steel tube wall. The local buckling that occurs during compressive test reduces the compressive strength of square CFST.

4.8 CFST for Offshore Application

Circular CFST is found to be very suitable for offshore platform application especially jacket for oil platform. Circular CFST have a large uniform flexural stiffness in all directions. Filling the tube with concrete will increase the ultimate strength of members without significant increase in cost. Saving in cost can be done by increasing lettable floor area by a reduction in the required cross section size. CFST application can be used for jacket repair. Common offshore jacket is using hollow circular section. By filling concrete into the section will improve its compressive strength properties.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Conclusion

With the experiment of Concrete, Steel and Concrete Filled Steel Tubes, a comparison of compression behavior of CFST with ordinary concrete and high strength concrete under axial load were investigated. High Strength Concrete combined with High Steel Column will give more excellent properties. Small circular CFST are largely affected with steel confinement effect and scale effect. It was seen that for smaller D/t ratio, a steel tubes provides good confinement effect to concrete. For Square CFST, it is necessary to take into consideration a capacity reduction due to local buckling of the steel tube wall of the column with large *B/t ratio*. Comparison of Theoretical and Experimental load capacities of CFST were investigated and Eurocode 4 code provides a good prediction of axial strength of CFST. Some modification must be done to the code by considering confinement effect of the steel to make sure that the predicted value of squash load is correct.

5.2 Recommendation

For future research, some recommendations are made to make sure that the CFST research is well investigated. In future research, it is 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. This will make process of casting CFST easy without compaction. Steel tubes yield stress must be determined experimentally to get the actual value of yield stress. So the predicted value for CFST using codes will be more accurate. Recommendation of CFST using larger diameter size for future research can be done to determine the behaviour of CFST with larger diameter.

REFERENCES

1. Ahmed Elremaily, Atorod Azizinamini Behavior and strength of circular concrete-filled tube columns. *Journal of Constructional Steel Research 58* (2002) 1567–1591.

2. Bowlin, W.F., Renner, C.J., and Rives, J.M. (2003) A DEA study of gender equity in executive compensation. *Journal of the Operation Research Society*, 54(7), pp.751-7.

3. Boyd FP, Cofer WF, McLean DI. Seismic performance of steel-encased concrete columns under flexural loading. *ACI Struct J* 1995;(May–June):355–64.

4.Design guide for SHS concrete filled columns. *Corus Tubes Structural & Conveyance Business*

5. Fujimoto T, Nishiyama I, Mukai A, Baba T. Test results of concrete filled steel tubular beam– columns. *US–Japan Cooperative Earthquake Engineering Research on Composite and Hybrid Structures, 3rd JTCC Meeting, Hong Kong*, 12–14 December 1996.

6. Furlong RW. Strength of steel-encased concrete beam columns. *J. Struct. Div., ACSE* 1967;93(ST5):113–24.

7. Kilpatrick A, Rangan V. Tests on high-strength concrete-filled steel tubular columns. *ACI Struct J* 1999;(March–April):268–74.

8. Knowles B, Park R. Strength of concrete filled steel tubular columns. *J. Struct. Div., ACSE* 1969;95(ST12):2565–87.

9. Lanhui Guoa, Sumei Zhanga, Wha-Jung Kimb, Gianluca Ranzic. Behavior of square hollow steel tubes and steel tubes filled with concrete. *Journal of Thin-Walled Structures 45* (2007) 961–973

10. Morino S, Sakino K, Mukai A, Yoshioka K. US–Japan Cooperative Earthquake Research Program on CFT column systems. *Proceedings of the 5th International Colloquium on Stability of Metal Structures, Chicago*, 1996. pp. 83–92.

11. Neogi PK, Sen HK, Chapman JC. Concrete-filled tubular steel columns under eccentric loading. *Struct Eng 1969*;47(5):195–7.

12. O'Shea M, Bridge R. Circular thin-walled tubes with high strength concrete infill. *Composite construction in steel and concrete II. Irsee (Germany): ASCE*;1996, p.780-93.

13. O'Shea M, Bridge R. The Design for local buckling of concrete filled steel tubes. In: Composite Construction Conventional and Innovate, Innsbruck, Austria;1997, p.319-24.

14. Rangan V, Joyce M. Strength of eccentrically loaded slender steel tubular columns filled with high strength concrete. *ACI Struct J* 1992;(November–December):676–81.

15. Sakino K, Ninakawa T, Nakahara H, Morino S. Experimental studies and design recommendations on concrete filled steel tubular columns—US–Japan Cooperative Earthquake Research Program. *Structural engineering worldwide 1998. Oxford: Elsevier Science Ltd,* 1998. Paper T169-3.

16. Schneider SP. Axially loaded concrete-filled steel tubes. *Journal of Structural Enginering, ASCE* 1998;124(10):1125–38.

17. Uy B. Local and post-local buckling of concrete filled steel welded box columns. *J Construct Steel Res* 1998;47(1):47–72.

18. ACI Committee 318. *Building code requirements for reinforced concrete (ACI 318-99) and commentary (ACI 318R-99).* Detroit: American Concrete Institute; 1999.

19. Architectural Institute of Japan. *Recommendations for design and construction of concrete filled steel tubular structures*. October 1997

20. AISC-LRFD. *Load and resistance factor design specification for structural steel buildings*. Chicago: American Institute of Steel Construction, Inc.; 1999.

21. BS5400.*Steel, concrete and composite bridges, Part 5, Code of practice for design of composite bridges*. London: British Standards Institution; 1979.

22. Eurocode 4.*Design of steel and concrete structures, Part1.1, General rules and rules for building.* DD ENV 1994-1-1: 1996. London W1A2BS: British Standards Institution; 1994

APPENDICES

Appendix 1

Figure A-1: During Casting of Concrete Cubes

Figure A-2: Concrete Cubes after casting

Appendix 2

Figure A-3: Cutting Steel Tubes using Steel Cutter

Appendix 3

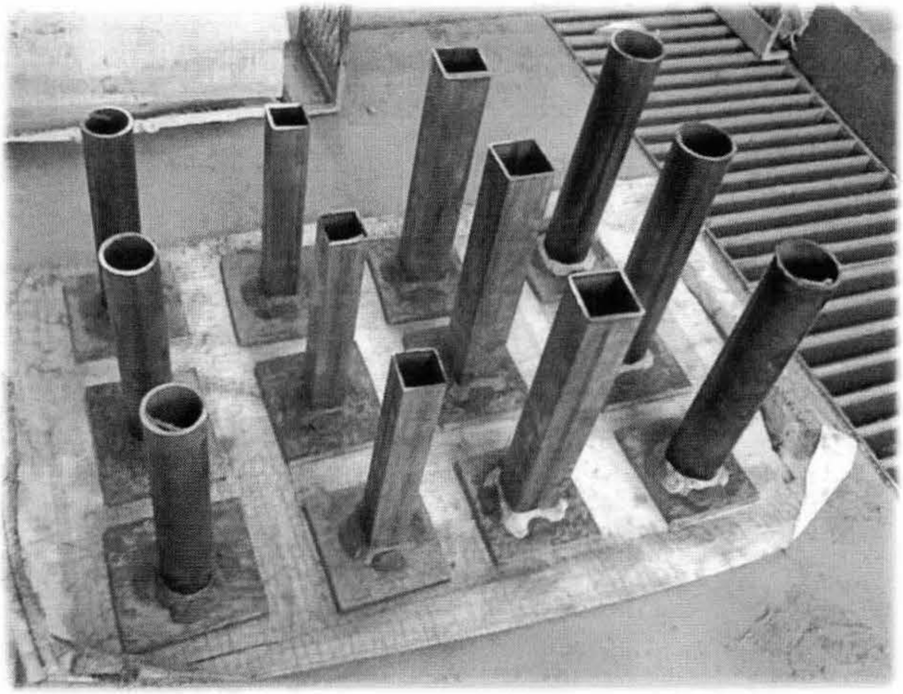

Figure A-4: Steel Tubes before filled with concrete

Figure A-5: Compaction of concrete using Compacting bar

Appendix 4

Figure A-6: CFST samples before testing

Appendix 5

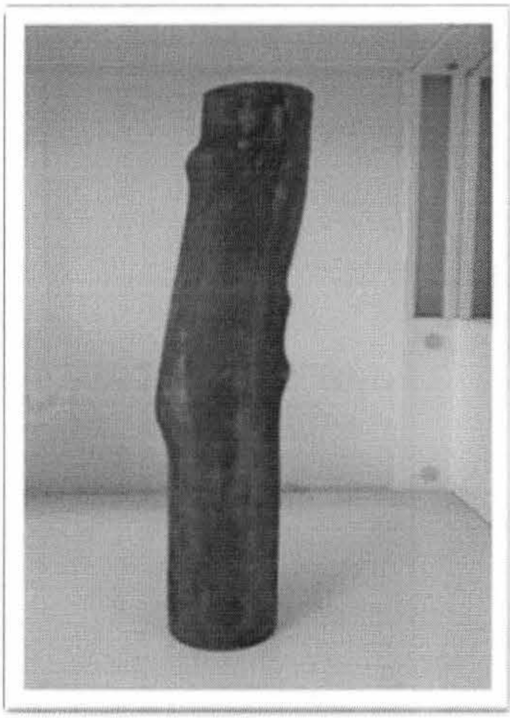

Figure A-7: Circular CFST CHS 40 after testing

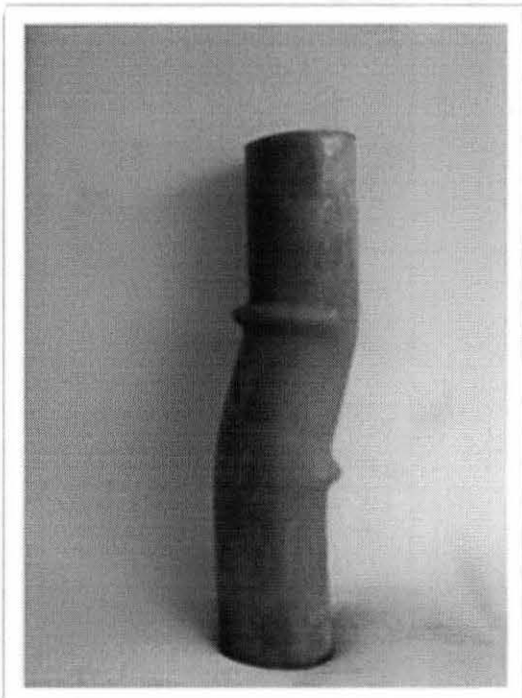

Figure A-8: Circular CFST CHS 50 after testing

Appendix 6

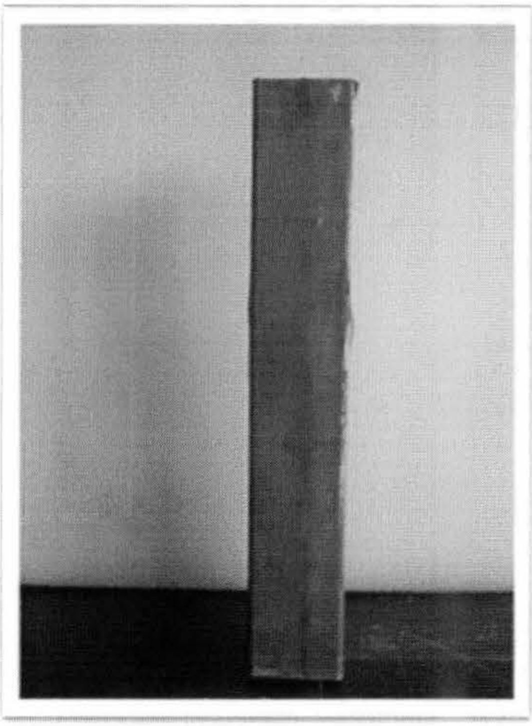

Figure A-9: Square CFST SHS 38 x 38 mm after testing

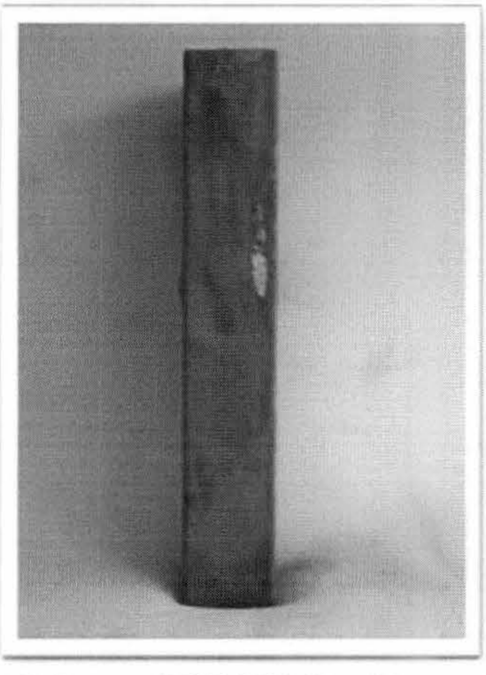

Figure A-10: Square CFST SHS 50 x 50 mm after testing