

JANUARY 2020

Ph.D. in Civil Engineering

HUSSEIN GHANIM HASAN

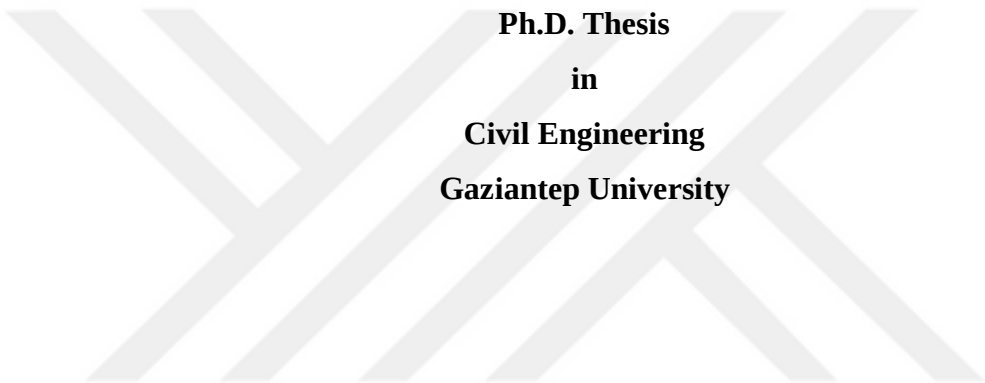
**REPUBLIC OF TURKEY
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES**

**COMPRESSION PERFORMANCE OF CONCRETE FILLED
DOUBLE SKIN STEEL TUBE COLUMNS**

**Ph.D. THESIS
IN
CIVIL ENGINEERING**

**BY
HUSSEIN GHANIM HASAN
JANUARY 2020**

**COMPRESSION PERFORMANCE OF CONCRETE FILLED DOUBLE
SKIN STEEL TUBE COLUMNS**



**Ph.D. Thesis
in
Civil Engineering
Gaziantep University**

**Supervisor
Assoc. Prof. Dr. Talha EKMEKYAPAR**

**by
Hussein Ghanim HASAN
January 2020**



© 2020 [Hussein Ghanim HASAN]

REPUBLIC OF TURKEY
GAZIANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING

Name of the Thesis : Compression Performance of Concrete Filled Double Skin
Steel Tube Columns

Name of the Student : Hussein Ghanim HASAN

Exam Date : 07.01.2020

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. A. Necmeddin YAZICI
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Hanifi ÇANAKCI
Head of Department

This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

Assoc. Prof. Dr. Talha EKMEKYAPAR
Supervisor

Examining Committee Members

Signature

Prof. Dr. Mustafa ÖZAKÇA

.....

Asst. Prof. Dr. Hasan Erhan YÜCEL

.....

Asst. Prof. Dr. Fatih ÇELİK

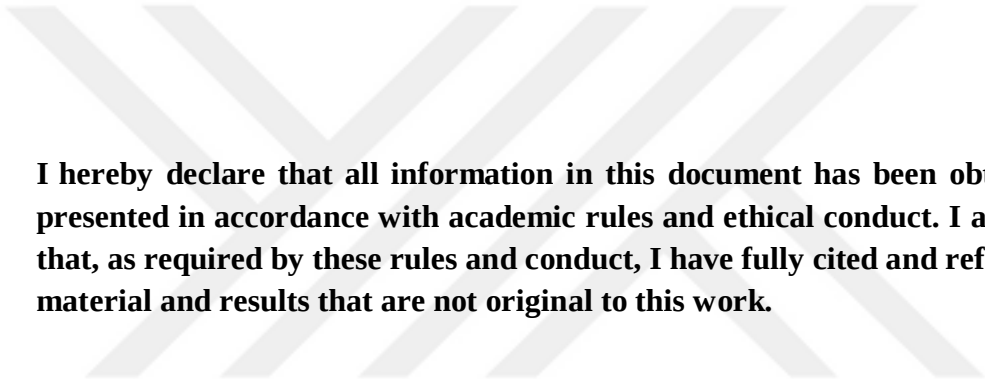
.....

Asst. Prof. Dr. M. Tolga GÖĞÜŞ

.....

Assoc. Prof. Dr. Talha EKMEKYAPAR

.....



I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Hussein Ghanim HASAN

ABSTRACT

COMPRESSION PERFORMANCE OF CONCRETE FILLED DOUBLE SKIN STEEL TUBE COLUMNS

HASAN, Hussein Ghanim

Ph.D. in Civil Engineering

Supervisor: Assoc. Prof. Dr. Talha EKMEKYAPAR

January 2020

191 pages

The inventive novelty of composite members is recognised as Concrete Filled Double Skin Steel Tube (CFDST) columns. CFDST comprises the concrete filled between the two-concentric steel tubes, where the inner tube is empty. The CFDST column could get equal or higher characteristics than the ordinary concrete-filled steel tube (CFST) columns, which the outer tube of CFDST performs as a concrete filled steel tube column, while the inner tube works as an unfilled tube. CFDST columns have been proven to have good characteristics in terms of the ductility, stiffness, strength and fire resistance. The main aim of this thesis is to experimentally explore the mechanical performances of CFDST columns by using the axial compression loads with different parameters. Several experimental procedures were carried out to understand the CFDST column performances. The proposed procedures discuss the topics of ductility, shortening, compression capacity, toughness, buckling, confinement effects, different performance indexes, bond strength, and failure modes. However, some specimens were tested to assess the impact of the parameters, which were used different type of concrete strength, dissimilar D/t ratios, dissimilar patterns of configurations and other variables as the main parameters in this thesis. Finally, methods which could predict the capacity of the CFDST columns were proposed and used versus experimental outcomes to specify appropriate formulation for design purposes.

Keywords: CFDST Columns, Buckling, Confinement, Failure Modes, Bond Strength, Design Methods.

ÖZET

İÇİ BETON DOLDURULMUŞ ÇİFT CİDARLI ÇELİK TÜP KOLONLARIN BASINÇ PERFORMANSI

HASAN, Hussein Ghanim
Doktora Tezi, İnşaat Mühendisliği
Danışman: Doç. Dr. Talha EKMEKYAPAR
Ocak 2020
191 sayfa

İçi beton doldurulmuş çift cidarlı tüp (İBDÇCT) kolonlar kompozit elemanlar içerisinde bir yenilik olarak kabul edilmektedir. İBDÇCT, iç tüpün boş olduğu iki eş merkezli çelik tüp arasına doldurulmuş betondan oluşur. İBDÇCT elemanlarda dış tüp, içi beton doldurulmuş standart bir kolon gibi çalışırken içteki çelik tüp boş bir kolon gibi çalışır ve böylece bu tip kolonlar klasik kompozit kolonlar kadar ya da daha yüksek niteliklere sahip olabilir. İBDÇCT kolonların süneklik, tokluk, mukavemet ve yangına dayanıklılık açısından iyi özelliklere sahip olduğu kanıtlanmıştır.. Bu tezin temel amacı, farklı parametreler kullanarak İBDÇCT kolonlarının mekanik performanslarını aksel basınç altında deneysel olarak incelemektir. Bu anlamda İBDÇCT kolon performanslarını irdelemek için çeşitli deneysel süreçler kullanıldı. Yürütülen deneysel süreçler süneklik, boyuna kısalma, basınç kapasitesi, tokluk, burkulma, sargı etkileri, farklı performans endeksleri, yapışma mukavemeti ve çökme şekilleri konularını tartışmaktadır. Bununla birlikte bu tezde, bazı numuneler farklı tipte beton mukavemeti, farklı D/t oranları, farklı kolon konfigürasyon düzenleri ve diğer değişkenlerin etkilerinin değerlendirilmesi amacı ile test edilmiştir. Son olarak, İBDÇCT kolonlarının kapasitesini tahmin eden yöntemler önerilmiş ve uygun eşitliklerin belirlenmesi amacı ile formüllerinin sonuçları deney sonuçları ile karşılaştırılmıştır.

Anahtar Kelimeler: İBDÇCT Kolonlar, Burkulma, Sargı Etkisi, Çökme Şekilleri, Yapışma Mukavemeti, Tasarım Yöntemleri.

ACKNOWLEDGEMENTS

First of all, I would like to thank **Allah** the Almighty for his blessings that enabled me to achieve such great accomplishment in my life.

Then, I would like to express my special appreciation to my advisor **Dr. Talha EKMEKYAPAR** for his tremendous guidance, kindness, and patience through this study. I would like to thank him for encouraging me to grow as a research scientist.

I would also like to thank the “Iraqi Ministry of Education”, “Iraqi Ministry of Higher Education and Scientific Research” and “University of Gaziantep” for providing this opportunity to finish my PhD study.

I would like to express my sincere gratitude to my friends (PhD Students) for their help and supports in my experimental study.

I leave to the end to people to whom I have heartfelt thankfulness my brother (Ali Ghanim HASAN), and my family for the endless and unconditional support and love.

Special thanks to my wife for accompanying me through the tough times and lighting up my life with her smile, finally to my life candles my children. This work is granted to them with all my love

TABLE OF CONTENTS

	Page
ABSTRACT	v
ÖZET	vi
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	viii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF SYMBOLS	xvii
CHAPTER 1	1
INTRODUCTION	1
1.1 General	1
1.2 Purpose of the Thesis	3
1.3 Layout of Proposal	4
CHAPTER 2	7
LITERATURE REVIEW	7
2.1 General	7
2.2 The Conventional Concrete-Filled Steel Tube (CFST) Columns	9
2.3 Concrete Filled Double-Skin Steel Tube (CFDST) Columns	12
2.4 Effects of Cross-Sectional Geometries on CFDST	27
2.5 Using Stainless Steels and FRP Composites in CFDST Columns	30
2.6 Studies on the Fire Resistance of CFDST	34
CHAPTER 3	41
EXPERIMENTAL WORK AND MATERIAL PROPERTIES	41
3.1 Introduction	41
3.2 Experimental Program	41
3.3 Materials Properties	41
3.3.1 Structural Steel Tubes	41
3.3.2 Concrete and Materials Used for Chemical Admixture	42

3.3.3 Reinforcing Steel.....	47
3.4 Test Instruments and Preparation of CFDST Columns.....	48
CHAPTER 4	50
COLUMN TESTS OF CONCRETE FILLED CLASSICAL, DOUBLE	
SKIN AND DOUBLE SECTION STEEL TUBES.....	50
4.1 General	50
4.2 Experimental Procedures.....	54
4.2.1 Material Properties	54
4.2.2 Double Skin and Double Section Column Specimens.....	56
4.3 Compression Behaviour of Column Specimens.....	60
4.3.1 Specimens with Normal Strength Concrete and Thinner Inner	
Steel Tube	60
4.3.2 Specimens with Normal Strength Concrete and Thicker Inner	
Steel Tube	65
4.3.3 Specimens with High Strength Concrete and Thinner Inner	
Steel Tube	68
4.3.4 Specimens with High Strength Concrete and Thicker Inner	
Steel Tube	71
4.4 Failure Modes	74
4.4.1 Specimens with Normal Strength Concrete and Thinner Inner	
Steel Tube	74
4.4.2 Specimens with Normal Strength Concrete and Thicker Inner	
Steel Tube	76
4.4.3 Specimens with High Strength Concrete and Thinner Inner	
Steel Tube	78
4.4.4 Specimens with High Strength Concrete and Thicker Inner	
Steel Tube	79
4.5 Conclusions	82
CHAPTER 5	85
THE CONTRIBUTION OF THE INNER STEEL TUBE IN THE	
CONCRETE FILLED DOUBLE SKIN (CFDST) COLUMNS.....	85
5.1 General	85
5.2 Aim and Significance of the Study.....	87

5.3 Experimental Tests	90
5.3.1 Material Properties	90
5.3.2 Column Specimens and Compression Testing	91
5.4 Experimental Results and Discussions	97
5.4.1 Specimens with NSC and Thick Outer Steel Tube (Set 1)	98
5.4.2 Specimens with NSC and Thin Outer Steel Tube (Set 2)	100
5.4.3 Specimens with HSC and Thick Outer Steel Tube (Set 3)	101
5.4.4 Specimens with HSC and Thin Outer Steel Tube (Set 4)	103
5.5 Performance Indexes	104
5.5.1 Concrete-Steel Contribution Ratio (CSCR)	105
5.5.2 Strength Index (SI)	106
5.6 Failure Modes	108
5.7 Design Methods Against Test Results	112
5.7.1 AISC-360-16	113
5.7.2 EC4	115
5.7.3 Design Strength by Han <i>et al.</i> [268]	116
5.7.4 Design Strength by Yu <i>et al.</i> [269]	117
5.7.5 Design Strength by Hassanein and Kharoob	118
5.7.6 Results of Strength Predictions	119
5.8 Conclusions	122
CHAPTER 6	126
STIFFENED CONCRETE FILLED DOUBLE SKIN STEEL TUBULAR	
COLUMNS UNDER AXIAL COMPRESSION	126
6.1 General	126
6.2 Research Significance	128
6.3 Experimental Work	128
6.3.1 General	128
6.3.2 Materials Properties	130
6.3.3 Test Setup and Fabrication	133
6.4 Results	137
6.4.1 Compression Loading Versus End Shortening Curves	137
6.4.1.1 Specimens with Thinner Steel Tubes	137
6.4.1.2 Specimens with Thicker Steel Tubes	140

6.4.2 Concrete-Steel Contribution Ratio (CSCR)	143
6.4.3 Compressive Strength Index (SI)	145
6.5 Failure Modes	146
6.6 Comparisons with Design Methods of CFDST Columns	148
6.6.1 AISC-360	150
6.6.2 EC4	151
6.6.3 Design Strength by Han <i>et al.</i> [268]	153
6.6.4 Design Strength by Yu <i>et al.</i> [269]	153
6.6.5 Results of Strength Predictions	154
6.7 Conclusions	157
CHAPTER 7	160
SUMMARY AND CONCLUSIONS	160
7.1 Summary	160
7.2 Conclusions	161
REFERENCES	166
CURRICULUM VITAE	190

LIST OF TABLES

	Page
Table 3.1 SCC limitations [198].....	43
Table 3.2 Physical and chemical properties of cement and fly ash	46
Table 3.3 The properties of superplasticizer	46
Table 3.4 Mix properties	47
Table 3.5 Workability characteristics of self-compacting concrete (SCC).....	47
Table 4.1 Properties of the column specimens.....	61
Table 5.1 Mechanical and geometrical properties of the column specimens	96
Table 5.2 Compression capacities of the specimens	97
Table 5.3 Comparison of the experimental results with strength predictions.....	122
Table 6.1 Details of the Specimens	134
Table 6.2 Experimental N_{exp} , $CSCR$ and SI results	136
Table 6.3 Comparison of Strength Predictions with Test Results	156

LIST OF FIGURES

	Page
Figure 2.1 Different types of concrete filled double skin steel tubes adapted from Han et al. [28]	8
Figure 2.2 Cross-section of a circular: (a) CFST and (b) CFDST column	13
Figure 2.3 Configurations of CFDST and CFST [127]	17
Figure 2.4 Views of the external steel tube and internal PVC-U [129]	18
Figure 2.5 Failure pattern of the tested specimen [130].....	19
Figure 2.6 Types of CFDST column cross-sections [135]	22
Figure 2.7 CFDST columns, (a) specimens after testing, (b) inner tube [31].....	24
Figure 2.8 Arrangement of test specimens [154]	29
Figure 2.9 Cross sections of CFDST columns with different arrangements of stiffeners [182]	36
Figure 3.1 The schematic of tensile coupon specimen	42
Figure 3.2 The schematic of plate used for the slump-test	44
Figure 3.3 The schematic of V-funnel test	44
Figure 3.4 The schematic of L-box test	45
Figure 3.5 The schematic of testing machine	48
Figure 3.6 Displacement transducers	49
Figure 4.1 CFST columns a) classical CFST b) double skin c) double section.....	52
Figure 4.2 Concrete cylinder specimen before and after testing	55
Figure 4.3 Machining process.....	56
Figure 4.4 Preparing and cleaning process	57
Figure 4.5 Curing procedure of specimens.....	58
Figure 4.6 High strength levelling epoxy process	59
Figure 4.7 Compression load vs. end shortening curves of specimens with normal strength concrete and thinner inner steel tube	62
Figure 4.8 Compression load vs. end shortening curves of specimens with normal strength concrete and thicker inner steel tube	66

Figure 4.9 Compression load vs. end shortening curves of specimens with high strength concrete and thinner inner steel tube	69
Figure 4.10 Compression load vs. end shortening curves of specimens with high strength concrete and thicker inner steel tube.....	72
Figure 4.11 Failure modes of the specimens with normal strength concrete and thinner inner steel tube	75
Figure 4.12 Failure modes of the thinner inner steel tubes in double skin specimens with normal strength concrete	76
Figure 4.13 Failure modes of the specimens with normal strength concrete and thicker inner steel tube	77
Figure 4.14 Failure modes of the thicker inner steel tubes in double skin specimens with normal strength concrete	78
Figure 4.15 Failure modes of the specimens with high strength concrete and thinner inner steel tube	79
Figure 4.16 Failure modes of the thinner inner steel tubes in double skin specimens with high strength concrete.....	80
Figure 4.17 Failure modes of the specimens with high strength concrete and thicker inner steel tube	81
Figure 4.18 Failure modes of the thicker inner steel tubes in double skin specimens with high strength concrete.....	81
Figure 5.1 CFDST cross-section details	87
Figure 5.2 CFDST cross-section configurations	88
Figure 5.3 CFDST specimens.....	89
Figure 5.4 Tensile coupon specimens	91
Figure 5.5 The silicone procedure	92
Figure 5.6 Cylinder concrete specimens.....	93
Figure 5.7 Epoxy procedure	94
Figure 5.8 Manufacturing process of the specimen with hollow concrete	95
Figure 5.9 Compression loading vs. end shortening curves of Set 1	98
Figure 5.10 Compression loading vs. end shortening curves of Set 2	100
Figure 5.11 Compression loading vs. end shortening curves in Set 3	102
Figure 5.12 Compression load vs. end shortening curves in Set 4.....	104
Figure 5.13 Concrete-steel contribution ratio in Set 1 and Set 2.....	107

Figure 5.14 Concrete-steel contribution ratio in Set 3 and Set 4.....	107
Figure 5.15 Failure modes of the columns in Set 1.....	109
Figure 5.16 Failure modes of the columns in Set 2.....	110
Figure 5.17 Failure modes of the columns in Set 3.....	111
Figure 5.18 Failure modes of the columns in Set 4.....	112
Figure 5.19 Comparison of experimental results and predictions of design methods	121
Figure 6.1 CFDST cross sections.....	129
Figure 6.2 CFDST columns cross sections.....	130
Figure 6.3 CFDST columns cross sections.....	131
Figure 6.4 Tensile test of deformed steel reinforcing bars.....	132
Figure 6.5 Tensile coupon specimens	132
Figure 6.6 Specimens machining	133
Figure 6.7 Specimens machining	135
Figure 6.8 Compression load vs. end shortening curves for C-1 and 1-W0-0	138
Figure 6.9 Compression load vs. end shortening curves for 1-W60-3 and 1-W114-3	139
Figure 6.10 Compression load vs. end shortening curves for 1-W60-4 and 1-W114-4	139
Figure 6.11 Compression load vs. end shortening curves for 1-W60-6 and 1-W114-6	140
Figure 6.12 Compression load vs. end shortening curves for C-2 and 2-W0-0	141
Figure 6.13 Compression load vs. end shortening curves for 2-W60-3 and 2-W114-3	142
Figure 6.14 Compression load vs. end shortening curves for 2-W60-4 and 2-W114-4	142
Figure 6.15 Compression load vs. end shortening curves for 2-W60-6 and 2-W114-6	143
Figure 6.16 Concrete-steel contribution ratio for (thin-thin tubes) specimens.....	144
Figure 6.17 Concrete-steel contribution ratio for (thick-thick tubes) specimens	145
Figure 6.18 Failure modes of C-1, 1-W0-0, 1-W60-3 and 1-W114-3 specimens.....	147
Figure 6.19 Failure modes of 1-W60-4, 1-W114-4, 1-W60-6 and 1-W114-6 specimens	148

Figure 6.20 Failure modes of C-2, 2-W0-0, 2-W60-3 and 2-W114-3 specimens.....	149
Figure 6.21 Failure modes of 2-W60-4, 2-W114-4, 2-W60-6 and 2-W114-6 specimens	150
Figure 6.22 Comparison of experimental ultimate loads and design methods prediction	157



LIST OF SYMBOLS

A_c	Cross-sectional area of concrete
A_{ce}	Nominal cross-sectional area of concrete
A_s	Cross-sectional area of steel tube
A_{so}	Cross-sectional area of outer steel tube
D_o	Outer diameter of outer steel tube
CFST	Concrete-filled steel tubular
CFDST	Concrete-filled double skin steel tubular
EI_{eff}	The effective flexural rigidity
f_c'	Concrete cylinder strength
f_y	Yield stress of the inner steel
f_{ysb}	Yield stress of the reinforcing bars
ν_e	The Poisson's ratio of the steel tubes with concrete infill
ν_s	The Poisson's ratio of the steel tubes without concrete infill
Ω	Solid proportion, given by $\Omega = A_c / (A_c + A_k)$
χ	The stability reduction factor
λ	The slenderness ratio
SI	Strength index
N_{cr}	The elastic buckling load
η_c	The enhancement factor
η_s	The reduction factor
α	The imperfection factor
ζ	The confinement ratio, $\zeta = (\alpha_s f_{sy} / f_{ck})$
E_c	Concrete modulus of elasticity
E_s	Steel modulus of elasticity
α_n	Nominal steel ratio
f_{rp}	The lateral confining pressure
f_{ck}	Characteristic concrete strength ($f_{ck} = 0.67 f_c$)
RBCR	Reinforcing bars contribution ratio

CHAPTER 1

INTRODUCTION

1.1 General

With the continuing developments in design technology of compression members, composite members provide good mechanical characteristics, since they link the favourable characteristics of constituent materials [1-3]. Accordingly, the research in the composite construction field has been directed towards finding novel composite column configurations which have the potential to circumvent the design challenges of huge structures [4]. The developments in composite column technology intensify around the theme of traditional Concrete Filled Steel (CFST) columns [5]. Although CFST columns have turned out to be one of the most successful composite column systems and provided good mechanical characteristics, the last two decades have seen a growing trend towards the improvement of compression performance of CFST members to challenge the requirements of the state of art engineering projects [6-8].

However, there are four major forms of composite columns can be notable, concrete filled steel tube (CFST) columns, concrete filled double skin steel tube (CFDST) columns, concrete double section steel tube (CFDCST) columns and encased columns [9]. Furthermore, these columns would lead to notable reductions of the cross-sectional dimensions of the composite members for a given load and increment of the useful floor area. CFST columns are recognised as one of the most famous of composite columns [10]. CFST columns have turned out to be one of the most successful composite column systems, particularly with the high-rise buildings, subways, bridges and industrial structures owing to their excessive advantages as ductility, high strength, and good seismic behaviour [11-21]. Generally, the concrete delays or avoids

the steel tube from the buckling, and the tube confines the concrete in the CFST members [22]. Additionally, the steel hollow section acts as the jacket for concrete, accordingly, provides good confinement and enhances the behaviour of the sections. Recently, demand for lighter-weight members widely increased in the world to decrease the dead loads, mainly for multi-story building [23-25].

Besides, the encased columns are the first composite column previously investigated. It was to improve the fire conditions and fire resistance of the steel sections. Generally, in the encased composite columns, the steel core supports loads of the structure during the building process. However, the steel section will be surrounded by cast concrete. The steel and concrete are consolidated in such a mould that the promising properties of two materials are used efficiently in the composite column. The steel properties of higher strength and lighter weight allow the utilization of lighter and smaller foundations. The addition concrete allows the construction to simply limit sways and the lateral deflections [26]. As the encased sections are utilized in seismic regions and buildings, the cyclic behaviour of these types of columns was conducted [27]. Overall, this sort of columns displayed a satisfactory energy dissipation capacity. The energy and deformation capacity of the concrete-encased steel column decreased with the increase of axial load value [28].

On the other hand, the inventive novelty of composite structure is recognised as Concrete Filled Double Skin Steel Tube (CFDST) column. CFDST columns consider the best solution to decrease the foundation loads due to the void inside the inner tube [29, 30]. CFDST comprises concrete sandwiched between the two-concentric steel hollow tubes, where the inner tube is empty. The CFDST column gets equal or higher characteristics than the ordinary CFST column, which the outer tube of CFDST performs as a CFST column, while the inner tube works as an unfilled compact tube [31]. On the other hand, CFDST columns have good performance in terms of fire resistance, bending stiffness, strength and seismic performance [32, 33].

However, steel tubes are directly exposed to fire in CFST column applications, whilst, in CFDST columns the inner tube provides high fire resistance. The external steel tubes and the shell concrete cover the inner steel tube. This configuration delays the temperature increment in the inner steel tube in the fire case. Besides, empty volume in the internal tube serves as a ventilation channel in fire condition [34]. Moreover, the internal steel tube affords additional more ductility and strength [35]. Conversely, strength over weight ratio of the CFDST columns is also significantly higher than the strength over weight ratio of the classical CFST columns. Since the inner skin is not filled with concrete, the dead weight of the member can be significantly reduced. Conversely, the inner tube slightly raises the weight of the Column [36].

Furthermore, some investigators have explored that the constituent member has a higher capacity than the mutual capacity of the components acting alone [37, 38], whereas other investigators determined that the maximum strength of CFDST columns were estimated through the summation of the segment capacities of the concrete, the external steel tube and the internal skin tube [39]. It seems more experiments should be carried out to verify these conclusions. The above-mentioned study has erected a basis for additional investigation of the mechanical properties and design methods of CFDST members. Above-mentioned evidence of CFDST columns meaningfully help engineers to design high-performance structures under static, dynamic and fire loads. However, the underlying mechanics of the CFDST columns have not been specified yet. It is required to perform lots of new experiments with new material and geometric parameters.

1.2 Purpose of the Thesis

The main goal of this thesis is to investigate possible new configurations to improve the mechanical properties of CFDST columns. The proposed campaigns lead to a better understanding of the CFDST column, which discuss the topics of ductility, shortening, strength capacity, toughness, buckling, confinement effects, the bond strength, and failure modes. Overall, several specimens were tested by the impartiality

of assessing the impact of the parameters, which were used different type of concrete strength, different D/t ratios, different patterns of configurations and other parameters as the main parameters in this thesis. Furthermore, to generate detailed knowledge of the strengthened CFDST performance that stiffened by reinforcing bars, the role of steel reinforcing bars in concrete-filled double-skin steel tubes were investigated. On the other hand, the design methods that proposed by several studies were modified to estimate the cross-section capacities of ordinary and stiffened CFDST columns, which were estimated versus the experimental outcomes to suggest the suitable method for design purposes.

1.3 Layout of Proposal

The contents of this study are described as:

- **Chapter One:** This chapter dealing with the introduction to the composite column, encased composite columns, the concrete filled steel tube columns and the concrete-filled double skin steel tube. It also introduces the structural behaviour of CFDST columns and provides an assessment on the behaviour of composite (concrete-steel) columns.
- **Chapter Two:** The literature reviews and previous experimental works of the CFDST columns are offered in this chapter. Furthermore, this chapter presents a literature review of the past researches that deals with composite columns and its behaviour under different load condition and various parameters like: sectional shape, slenderness ratio, L/D ratio, D/t ratio, various strength concrete in-filled tube, cyclic responses, long and short-term sustained loading deformation, fire conditions and fire resistant, thickness of inner and outer tubes, bond-slip behaviour and other parameters.
- **Chapter Three:** In this chapter, the experimental progress for each test is presented. It included the manufacturing of the specimens according to the required properties. Besides, it defines the arrangement of concrete proportions

and all steps from casting, curing and capping up to crushing the concrete specimens. Specimens preparation from fresh concrete to testing is entirely reported. It also presents the concrete types that were used in this thesis and describes their properties as well as the tests required for each type.

- **Chapter Four:** This chapter examines the performances of concrete filled classical, double skin and double section stub columns which have practical ranges of material and geometrical properties. Furthermore, no single study exists on the systematic comparison of the classical, double skin and double section columns which have practical range of material and geometrical properties. To be able to address a wide range of representative discussions, different material and geometrical properties (complying with the field applications) were utilized in the experimental program. Experimental procedures were undertaken for composite columns with normal and high strength self-compacted concrete. Besides, the effect of tube configurations, two types of outer and two types of inner steel tubes with different mechanical and geometrical properties were utilized. In this chapter, the experimental program allows in-depth comparisons between the composite column types.
- **Chapter Five:** This chapter presents the mechanical performance of Double Skin Steel Tube (CFDST) columns stiffened by Welded Reinforcing Bars (WRBs). A series of tests were conducted on sixteen CFDST specimens using dissimilar D/t ratios and different patterns of WRBs as variables. Moreover, the loading versus end shortening relationships, failure pattern, concrete-steel contribution ratio and strength index were studied. Design methods were developed for the calculation of the strength capacity of stiffened CFDST columns and calculated versus the experimental outcomes to suggest the suitable models for this purpose.
- **Chapter Six:** This chapter conveys the findings of an experimental study which was conducted to explore the effect of the inner steel tube on the mechanical response of CFDST columns under axial compression. Two different D/t ratios and the concrete classes (normal strength and high strength) were utilized and in

total sixteen specimens were tested to failure. To be able to analysis the impact of the parameters, failure modes, compression loading versus end shortening curves and the concrete-steel contribution ratios were detailed.

- **Chapter Seven:** This chapter presents a summary of the investigation work described in this thesis and lays out the conclusions drawn from this work.



CHAPTER 2

LITERATURE REVIEW

2.1 General

The literature assessments and previous experimental works of the CFDST columns are focused in this chapter. Furthermore, it presents literature review of the past researches that deal with composite concrete-steel columns and its behaviour under dissimilar load condition and various parameters such as: sectional shape, slenderness ratio, long-term sustained continued loading deformation of CFDST columns, short-term, L/D ratio, D/t ratio, e/D , various strength concrete in-filled tube, cyclic responses, fire conditions and fire resistant, thickness of tube (inner or outer), bond-slip behaviour and other parameters.

A brief review on conventional composite (CFST) columns is presented before CFDST columns so as to enable a better understanding of composite column performance. It may be beneficial for researchers to first have a fundamental understanding of the composite action between the concrete and steel and advantages on CFST and CFDST columns behaviours accordingly. Composite members had been verified to be outstanding columns where they link the favourable characteristics of constituent materials, such as high strength, ductility, stiffness and the large energy absorption capacity [9].

Besides, there is a wide diversity of types of composite column of changing cross-sections as exposed in Figures 2.1, but the circular tubular columns have more benefits than the further sections when they used as compression members [28]. Circular tube columns have a big flexural stiffness in all directions when compared with other sections with the same areas and cross-section. When the skin tube filled with concrete

core, the maximum strength of the construction column will increase without considerable increases in cost. In the thin-walled, the local buckling will be delayed by the concrete and that is the main effect of concrete. In the self-possessed state, it is able to provide higher stresses and strains. It is recognized that the circular conformation sustains the most grounded repression to the concrete core, and the local buckling usually inclined to happen in rectangular or square shape. Though, the in-filled tubes with a rectangular section or a square section are still widely used in construction, because of the easier design in the column -to- beam connection, for high cross-sectional bending stiffness and appealing reasons [28, 40].

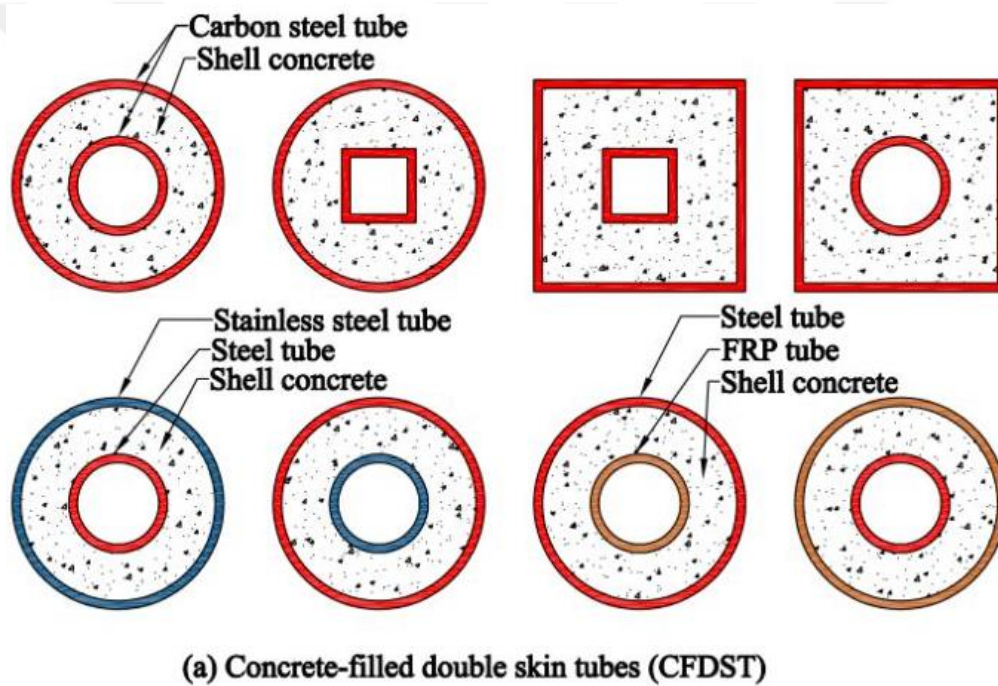


Figure 2.1 Different types of concrete filled double skin steel tubes adapted from Han et al. [28]

Over the last few years, numerous studies concerned about the imperfect bonding that occurs in the CFST and CFDST columns in an elastic stage [41-59]. This phenomenon happens due to the concrete and steel tubes suffer from deformation with dissimilar rates owing to variations in their Poisson's ratio. The Poisson's ratio of steel is higher than that of the concrete, and the lateral expansion of concrete is lesser than the steel's

expansion at this stage (elastic stage). This leads to an unconfined or free concrete behaviour until the concrete cracks occur. This behaviour postpones the confinement effect and decreases the effectiveness of the steel tube [60].

However, it must be ensured that the structural failures should occur in a ductile manner. Hence, the construction will not fail in a brittle manner without notice of a disaster. The seismic philosophy depends on dissipation and load capacity by post-elastic deformation for endurance in the earthquake times. A ductile construction is exposed to over-burdening, it will incline to behave inelastically and responsibility. It will reorganise the extra load to multidimensional of the construction [61, 62]. The use of in-filled columns provides economical solutions because it takes less area compared to the normal reinforced columns. Besides, it provides a larger floor area and does not require the use of frameworks of the construction process, thus reducing construction time and costs. This is an advantage for high-rise building design in some cities where the cost of floor spaces is high [63-73].

2.2 The Conventional Concrete-Filled Steel Tube (CFST) Columns

In history around the 1970s in China, many studies were reported about the composite columns. One of the most famous of composite columns are recognised as Concrete-Filled Steel Tube (CFST) columns [10], which have turned out to be one of the most successful composite column systems, particularly with high-rise buildings [60, 74, 75]. Concrete-filled steel tubular columns are composite members that combine the advantages of concrete and steel [76-81]. They are proven to provide efficient and economical applications in industrial buildings, arch bridges, high-rise buildings, subways and offshore applications [82, 83]. Furthermore, the CFSTs are commonly used in regions with high earthquake risk. The steel tube provides lateral confinement for concrete and uses as a permanent formwork, reducing the time and the cost. Besides, the concrete delays or prevents the steel tube from the buckling in the CFST members [84, 85]. In addition, CFST columns can be used as a smaller cross-section compared to the ordinary reinforced concrete columns [86, 87].

On the other hand, the confinement effect is an important feature of the structural behaviour of CFST columns, where is related to the cross-sectional properties as well as the material properties [84, 88]. The confinement effect in the first phase of loading can be neglected, where the Poisson's ratio of the concrete is smaller than that of the steel. Therefore, the steel tube expands faster than the concrete core in the radial direction in the first (elastic) stage. This behaviour leads to an unconfined or free concrete behaviour until the concrete cracks occur. Likewise, this behaviour postpones the confinement effect and decreases the effectiveness of the steel tube in the elastic stage [5]. Micro-cracking of concrete increases under loading and Poisson's ratio of the concrete increases in a lateral direction, hence the confinement of steel develops [88-90].

CFST columns were deliberated by many researchers [91-98], for example, the researches of Goder and Kloppel [99, 100]. However, they recognised minimum and maximum limits to expect the concentrically strength loaded on CFST columns. The minimum limit was articulated as the buckling force of the changed cross-section of the composite column, whilst the maximum limit was found by calculating the buckling force considering an equivalent stiffness as the summation of component parts' stiffnesses. Gardner and Jacobson [101] reported that the steel tube confines the concrete under axial compression until failure. An interior pressure (σ_r) increased between the concrete and steel tube, whereas a hoop stress (tension) (σ_t) was generating in the tube. Consequently, in this stage of compression loading, the concrete strength was increased. O'Shea and Bridge [102], Giakoumelis and Lam [103] and others reported that the CFST columns are appropriate for multi-story buildings in high seismic regions. CFST columns hold both good mechanical properties of the concrete and excellent durability of the steel [104]. Reviewing the previous studies on CFST, it can easily show that numerous experimental studies were focused on the mechanical behaviour of CFST columns.

In the composite structures field, there exist valuable works on the bond behaviour of the classical CFST columns. For instance, concluded that the bond strength between component parts of CFST specimen is influenced by cross section of specimen, age of the concrete, temperature and curing. He also pointed that the reduction in bond strength after one year was around 30% in comparison with the corresponding bond strength at three weeks. Chen *et al.* [104] reported that the interface force between the steel tube and the concrete of CFST columns comprises of the adhesive phase, the sliding phase and the friction phase. They underlined that the interlock friction force is approximately 70% of the bond strength as a shear resistance, whereas the 30% of the bond strength is gained by the force of the chemical adhesive. On the other hand, they reported that the shear resistance continuously decreases by repeating the push-out test, since the mechanical interlocking force and the frictional force between component parts (concrete and a steel tube) progressively decreases. Lutz and Gergely [105] highlighted that the interlock friction force is negligible if the steel surface is smooth or lubricated, and the interface slip occurs when the chemical adhesion ruptures. Hence, the residual bond strength might be attributed to the frictional resistance between the component parts of the specimens [105]. Tao *et al.* [106] showed that the carbon steel of the CFST column had higher bond strength than the stainless steel, and the bond strength decreases noticeably as the cross-sectional dimensions and concrete age increase. Besides, they showed that the embedded ring on the inner surface of the tube is the most effective system to increase the bond strength in classical CFST columns and followed by the shearing stud method. On the other hand, the load transfer between the component parts increases with the increment of the concrete strength [107].

Worth mentioning, a significant bad impact factor on the bond strength of composite members is the shrinkage phenomenon. The shrinkage phenomenon leads to poor adhesion between the steel-concrete interface [108]. A shrinkage does not only lead to serious structural imperfections, but may also compromise the durability performance

of the concrete, which is a major concern in service life [109]. Such a shrinkage problem would not only destroy the load transfer mechanism, but also could degrade the compression performance of the composite column. In order to deal with this problem, many researchers have adapted different types of the concrete. Self-compacting concrete (SCC) may overcome this deficiency, which does not only compensate the shrinkage of the concrete but also eliminates the compaction problem. Furthermore, twenty CFST specimens were tested at the age of twenty-three to fifty-seven days by Roeder *et al.* [110]. The results confirmed that the concrete shrinkage could have an adverse influence on the bond strength of specimens with particularly large cross-sectional dimensions.

On the other hand, Ke *et al.* [111] determined that the bond strength between the component parts of CFST column is enhanced with the increment of the concrete strength. Tao *et al.* [112] found that the fire exposure of the CFST specimens had a major effect on the bond strength between the component parts, and they observed that the bond strength generally reduces after ninety minutes of the fire exposure. However, the bond strength recovered once the time of exposure was increased to 180 minutes. Lu *et al.* [113] carried out 36 CFST with and without steel fibres and observed that the adding of steel fibres advances the bond behaviour with short-term, whereas after 2.5 years of the concrete age, the steel fibres mostly loses its effect. As the load cycle increases, the bond strength in the same direction tends to decrease [114]. However, the steel fibres help the concrete recover the bond strength [109].

2.3 Concrete Filled Double-Skin Steel Tube (CFDST) Columns

The CFDST is a new type of CFST column, had been presented and concerned lots of attention among engineers and researchers. CFDST columns are structures where two steel tubes are placed together concentrically, and the concrete is sandwiched into the void between them, as shown in Figure 2.1. The presence of the shell concrete between outer and inner steel tube was proven to be a great advantage to the CFDST columns since concrete can act as a heat sink and protective layer of the inner tube [115].

Concrete-filled double skin steel tubular was first mentioned by Shakir-Khalil in 1990's [116]. Also, much investigation has been directed on toward behaviour CFDST columns subjected to different load types. Figure 2.2 shows the typical system of CFDST and CFST columns, which shows the cross-section of a circular CFDST column. Generally, once the section modulus is increased by casting a high strength material between the two steel tubes as an annulus filled, the stability of the column would be improved, especially when compared with the ordinary CFST, [117, 118]. The system of sandwich structure uses able to use any filler materials between them. For example: epoxy filler used in vessels [119], concrete used for water construction [120], Cement grout (without fine or coarse aggregate, just cement and water) [116], micro-cement concrete [31] and Polymer concrete used for legs of offshore [38].

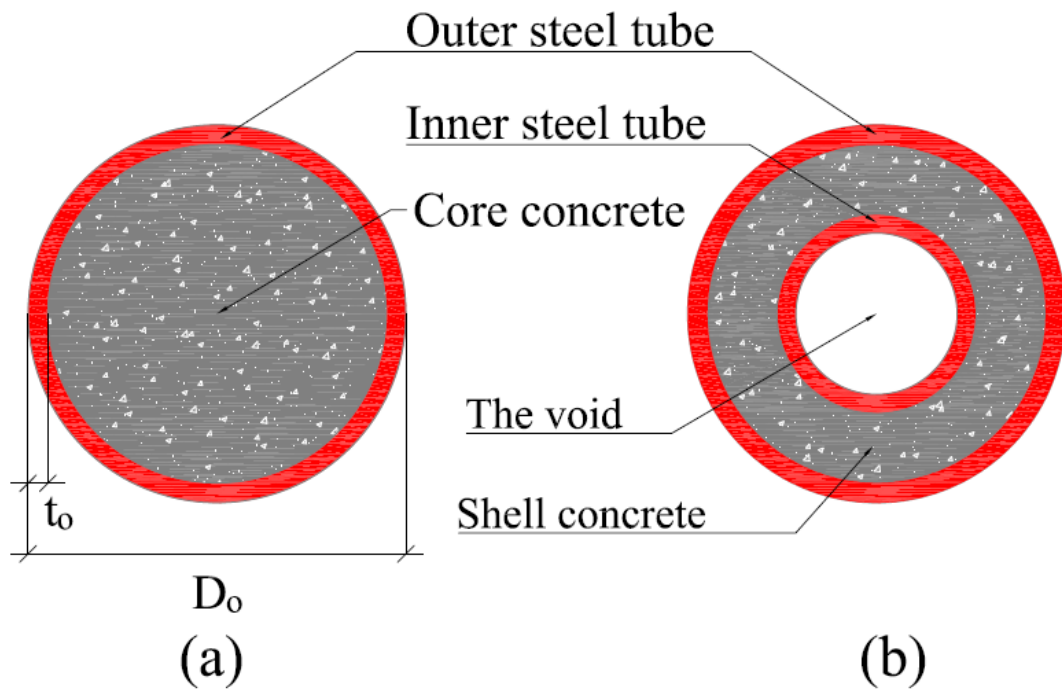


Figure 2.2 Cross-section of a circular: (a) CFST and (b) CFDST column

Both circular and rectangular sections can be used as the inner and outer tubes for the CFDST columns. Besides the previously mentions advantages of ordinary CFST and CFDST, there are some other advantages to CFDST columns. This type of column can be used in offshore structures and very tall buildings. Recently, it has been utilized for

high-rise bridge piers in Japan to reduce the structure's weight while maintaining an acceptable energy absorption capacity [121]. CFDST columns can behave better than the ordinary CFST columns underneath diverse types of loading, because of the structural system of the larger stiffness of the inner tube and superior ratio of strength/weight [122].

In a number of extensive experimental studies [123, 124], a series of both circular and rectangular CFDSTs tested under different types of static loading. Results showed the behaviour of CFDST columns similar to that of traditional CFST columns. For example, Tao *et al.* [124] showed that the performance of the inner tube and its failure can be different according to its D_i/t_i 's ratio. For larger D_i/t_i 's, the inner tube failed with inward local buckling, while for tubes with smaller D_i/t_i 's no local buckling reported from the tests. In terms of the external tube, smaller D_o/t_o 's ratios directed to the additional ductile performance of the column [123].

They also deliberated the impact of the void (hollow) ratio (χ) on the ductility of CFDST columns. The hollow ratio assumed by the equation 2.1 as:

$$\chi = \frac{D_i}{D_o - 2t_o} \quad (2.1)$$

where D_o and D_i are diameters of the outer and inner tubes respectively, and t_o is the outer tube thickness. The ductility of each section was computed using the index of ductility (DI), investigated by Lin and Tsai [37] as the equation 2.2:

$$DI = \frac{\varepsilon_{95\%}}{\varepsilon_y} \quad (2.2)$$

in which $\varepsilon_{95\%}$ is the axial strain at the point where the axial load falls to 95% of the maximum load, and $\varepsilon_{75\%}$ is the axial strain when the load reaches 75% of the

maximum load in the pre-peak stage. The DI values calculated for CFDST columns tested with different void (hollow) ratios and a fixed D_o/t_o of 60. Results showed that the void ratio did not significantly affect the ductility of the CFDST specimens. Furthermore, the data point with ($\chi = 0$) refers to a conventional CFST specimen that was tested as a reference. The results show that the creation of a hollow space in the middle of the section did not negatively affect the overall ductility of the columns [124].

Elchalakani *et al.* [39] showed that a sequence of compression experiments on CFDST columns. In that work, the outer tube was manufactured of circular sections (CHS), whereas the inner tube was manufactured of square sections (SHS). The failure mechanism from the axial loading tests displayed outward buckling for the external tube (similar to what occurs in CFST specimens) and inward local buckling for the inner tube. The failure mode displayed buckling of the external tube to outward. Conversely, the inner tube was played the buckling similar to these empty tubes. Furthermore, they concluded the CFDST stub columns performed satisfactorily up to very huge distortions with failure modes. As well, the performance of CFDST columns was significantly influenced by the slenderness of the outer tube, as long as the inner tube was a completely effective column.

Yagishita *et al.* [125] performed six cyclic tests on CFDST columns made of thin circular mild steel tubes with D/t ratio between 130 to 250 and the annulus was filled with a normal concrete. The resulting tests showed that the new system of specimens (CFDST) had a better behaviour over CFST specimens in terms of toughness, ductility and strength capacities under cyclic loading.

Uenaka *et al.* [62] detected that the failure pattern of CFDSTs and the local buckling of skin tubes associated with shearing failure of the shell concrete. Additionally, the ductility of CFDST specimens were almost same as that of CFST, which the specimens that had the largest D of the internal tube showed a less ductility. The effect of the

confinement stress on the shell concrete was existed. Also, they detected no effect of the inner tube on confinement owing to complex biaxial compression.

Sulthana and Jayachandran [126] concluded that the global buckling of long column samples affected by yielding of the steel tubes. In this stage of yielding, at the mid-height of the specimen in the compression part of the outer skin steel tube, the local swells were formed. Likewise, all specimens displayed linear performance until the range of the buckling load point. This was detected in the curves of the axial load against lateral deflection and the axial load against deformation. Moreover, after the specimen continuing to yield, the behaviour of these specimens depending on the cross-sections type. Correspondingly, it showed that the strength of the inner steel tube had not been used fully at the maximum load point [126].

Li *et al.* [127] offered the two kinds of CFDST columns, which were utilized specimens with circular section (CHS) and square section (CHS), as shown in Figure 2.3. They detected the initial stress and initial deformation were bring by the preload. As well, they concluded that the strength of CFDST column might be reduced once the preload was subjected. Also, it was found that the column slenderness was only slightly affected on the strength index for CFDST columns.

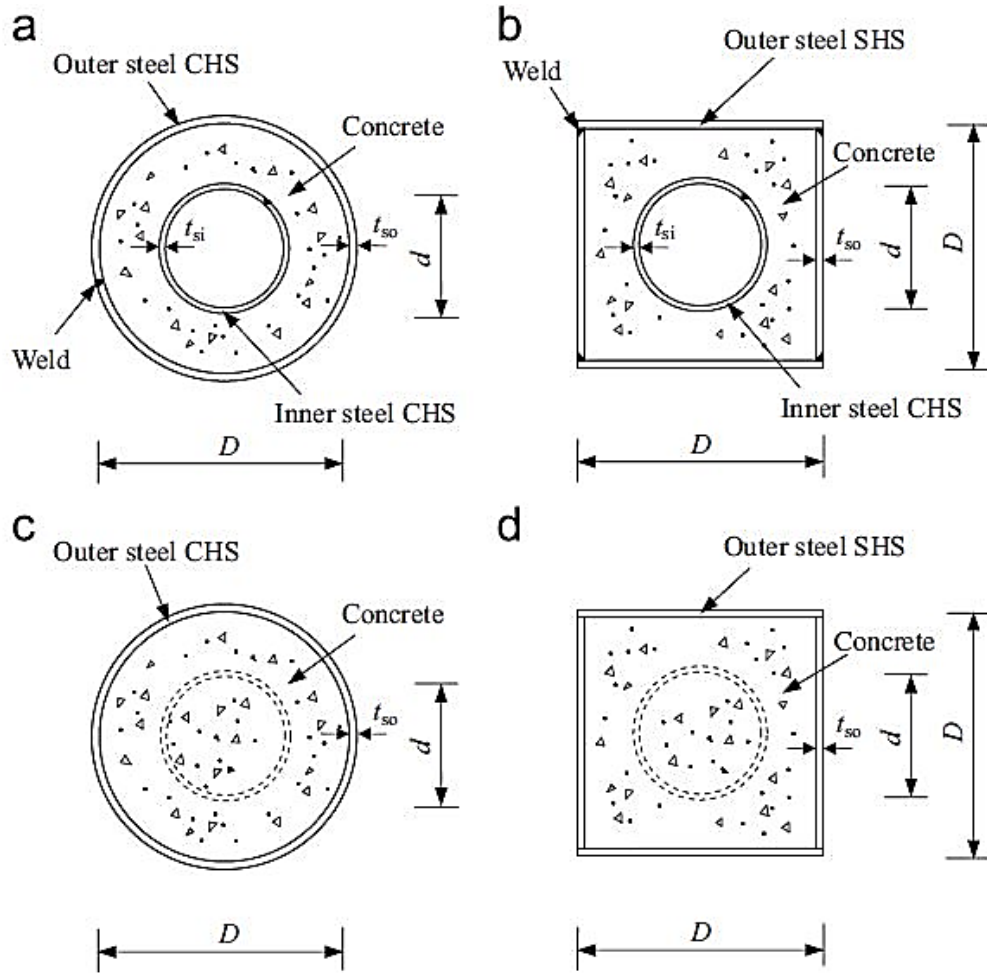


Figure 2.3 Configurations of CFDST and CFST [127]

Yang *et al.* [128] reported that the internal tube acts dependably with the concrete and the external tube can effort with the concrete when the applied loading is lower than 75% of the maximum load. Therefore, the CFDST specimen was keeping the axial loading until the concrete crushed, and at this time, some parts of steel tubes start to yield up to the specimen fail.

Yuan and Yang [129] conducted a research on the performance of CFDST columns under axially compression loads using both experimental and numerical methods. The examined CFDST columns contained an octagonal steel tube as outer tube, besides inner tubes were circle PVC-U pipe. These specimens filled with the high strength concrete as a shell concrete. The researchers investigated that the concrete strength impacts on the maximum capacity of the columns. Additionally, the D/t ratio, the

ratio of hollow section and L/D ratio on the specimens was surveyed. They stated that the load of the CFDST column rises with growing the concrete strength but decreases with either rising D/t ratio or with rising hollow section ratio, Figure 2.4.

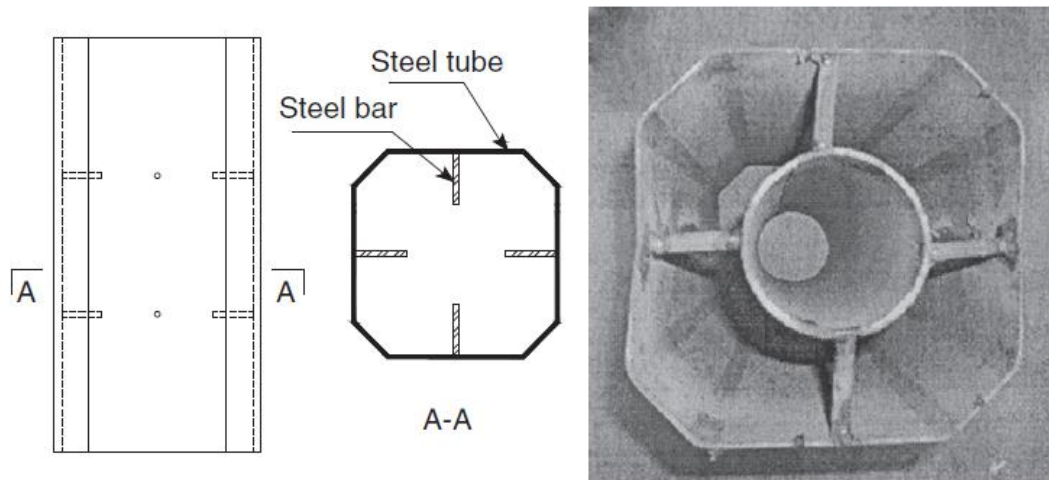


Figure 2.4 Views of the external steel tube and internal PVC-U [129]

Yang *et al.* [130] deliberated the experimental conduct of CFDST columns that exposed to partial compression. The researchers fabricated 14 specimens of circular tube section (CHS) and the 15 samples of square tube section (SHS). All the specimens were tested, as shown in Figure 2.5. The test parameters contained within: hollow section ratio, the thickness of the top endplate, and a ratio of the compression area. The results indicated that the CFDST columns under this condition behaved in a ductile manner. Failure patterns of partially loaded CFDST columns were expressively affected by the deliberated parameters. Finally, the design methods of partially loaded CFDST columns were proposed for predicting their behaviour.

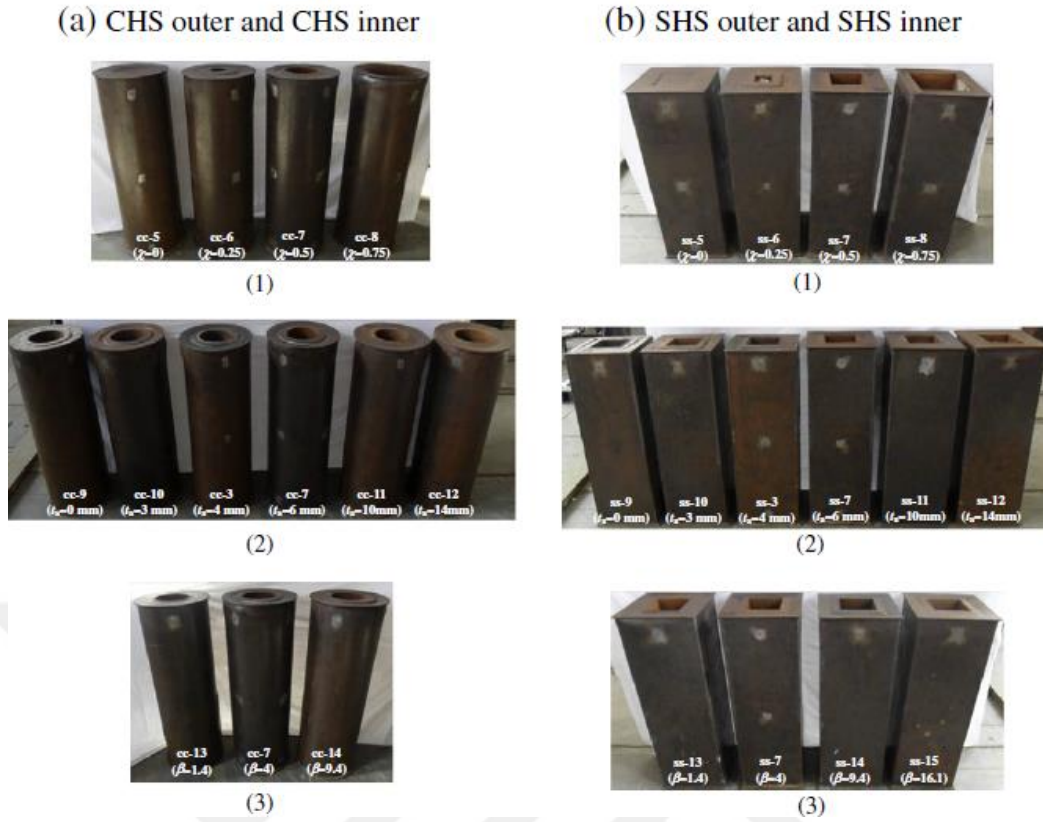


Figure 2.5 Failure pattern of the tested specimen [130]

Hassanein and Kharoob [131] reported that the definition of CFDST slender column is applicable with the slenderness ratio (λ) of 22. On the other hand, the very long CFDST columns that have λ equal or greater than 50, the confinement effect can be neglected from the analysis and designs. The results displayed that the sandwiched concrete of the middle length columns group was fully under compressive stresses which progressively reduced from the compression zone to the opposite zone, whereas stresses of a portion of the sandwiched concrete in very long columns group might contrary from compression to tension. Also, they concluded that the confinement provided by the internal tubes was found to be higher than that provided by the external tubes in intermediate length columns. This is owing to the internal skin widens and shoves outwards under axial compression load. Conversely, there is no confinement provided by both tubes to the shell concrete of very long columns [131].

Chen *et al.* [8] studied the experimental examination and determined the best models for predicting by FEA analysis on the CFDST specimens. The specimens had been worked by cold-method a plane steel plate into a dodecagonal shape, subsequently, the two tops of the skin tubes were cut to a specified length of two meters. The external face of internal tubes and the interior face of the external tubes were treated with a brush to clean and remove any rust. Together, the exterior and interior steel tubes were placed on having the same centre. The seven-dodecagonal section CFDST specimens manufactured in this test. It was presented that D/t value of outer steel tubes had a significant effect on the behaviour of the dodecagonal hollow section specimens, while D/t ratio of inner steel tubes appeared a small effect. As well, the maximum load and flexural stiffness of the dodecagonal section samples decreased with the D/t value of outer steel tube and also decreased with the eccentricity load.

Han *et al.* [132] reported that the CFDST beam–columns presented a good behaviour of the energy dissipation and ductility under high loading. Mostly, the capacities of circular specimen were more than these that had square shapes. Generally, it concluded that the procedure model established for ordinary (CFST) is adequate for the investigation behaviour of CFDST specimens. The prediction capacity against lateral deflection curves for double skin specimens were producing acceptable results with experimental results. On the other hand, the stress studies were shown by using the FE analytical. It was showed the lateral stress increased on the external steel tube through the loading. Additionally, For the CFDST column that fabricated with tapered shape, the diagonal stress differed along the specimens, whereas the stress was normally invariable for the conventional one. This can be attributed to the confinement effect was developed on the smaller section of the tapered CFDST column. Furthermore, they concluded that the compressive strength of tapered CFDST stub column mainly depends on the sectional strength of the smallest section. Besides, in the compressive strength term with the tapered CFDST columns, it chiefly depends on the smallest cross-section along the length of the specimen [133].

Tao *et al.* [124] tested 14 columns and 12 beam-column specimens (CHS inner and CHS outer). A good concordance was gained between the predicted and experimental of result tests. A confinement usually, used to describe the ‘composite action’ between the shell concrete and the surface of steel tube. The established CFDST specimens worked in a comparatively ductile way and the experimental progressed in a simplified manner and controlled mode. The improved mechanical conduct of the columns was described the ‘composite action’ between the concrete and skin tubes. Likewise, the load against strain curves were recognized for CFDST specimens. The results that obtained from load against deflection curves was very acceptable with experimental values.

Hassanein and Kharoob [134] developed formulations for guessing the capacity of the CFDST columns. Those numerous formulations were compared with the experimental outcomes in the lab from former researches on this type of columns [62, 124, 133]. The available test results were written by Hassanein and Kharoob [134], it assessed according to the D/t_e ratio. This study separated the D/t_e of the CFDST into three ranges; $D/t_e \leq 47$, $47 < D/t_e \leq 150$, $D/t_e > 150$. Furthermore, the (FE) models have been created to recompense for the lack in the existing studies. However, no effect of the D/t_i ratio was found on the strength of the CFDST short specimens. This may attribute to the internal skin tube contributes moderately slight to the strength of the column. Alternatively, it was shown that the load values of the CFDST columns rely on the confinement effect of the outer skin than that of the internal skin. Besides, the most important variables affecting of the capacity of CFDST short columns is the D/t_e ratio of the external skin tubes [134].

Hassanein *et al.* [135] defined the axial load performance of slender and short of the (CFDST) columns with circular internal tubes as shown in Figure 2.6. The new formulas were proposed to explore the influence of a grade of the concrete and a local slenderness on the CFDST columns. The results showed that the proposed formulas [136, 137] provided acceptable estimates compared to the FE strengths. However, the

AISC mostly predict respectable strength capacity of the CFDST specimens, whereas EC4 predicts conservative strength capacity for the same specimens especially with slender cross-sections.

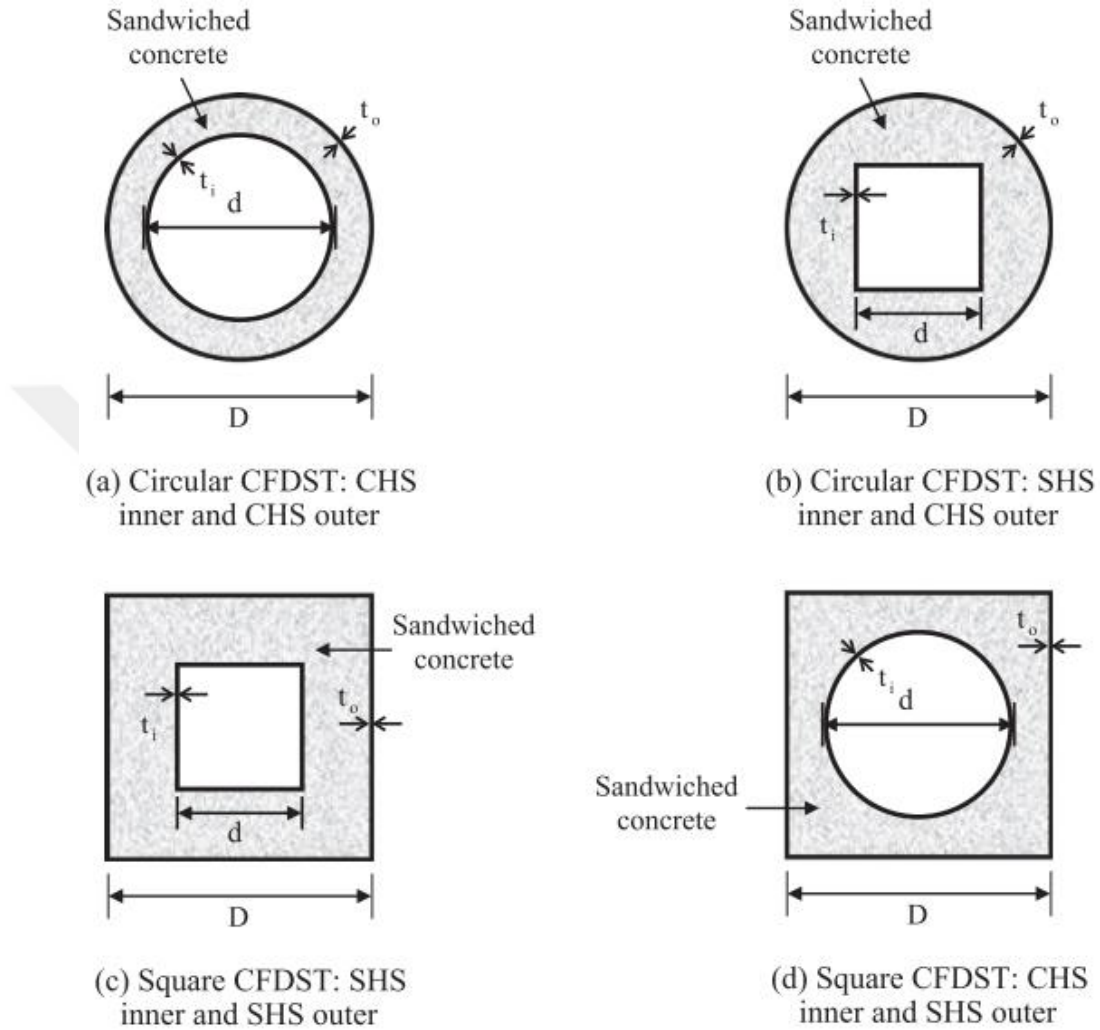


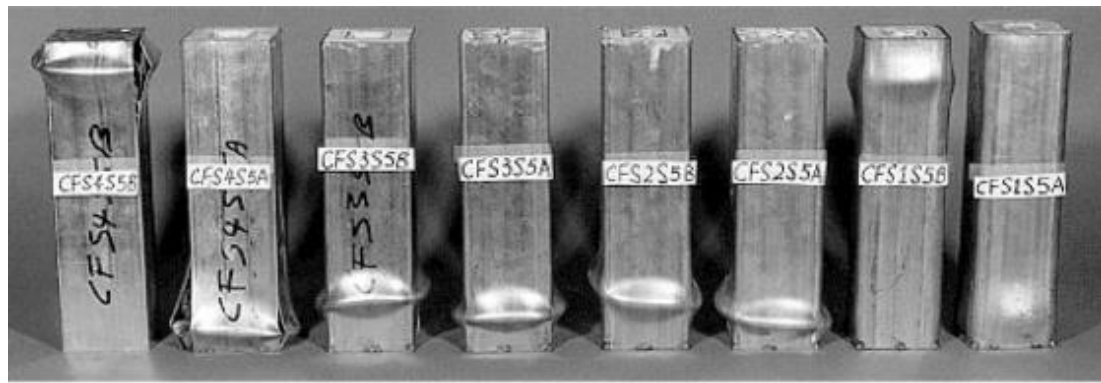
Figure 2.6 Types of CFDST column cross-sections [135]

Han *et al.* [138] studied the long-term deformation of CFDST columns. The researchers presented that the long-term distortion and distortion of CFDST columns rises comparatively fast at a primary phase, at the same time as the procedure had a tendency to stabilise after approximately 100 days. They concluded the long-term sustained loading effects on the maximum capacity and distortion of the CFST and CFDST specimens. The long-term continued loading reduces the maximum capacity of the CFDST specimen, whereas rises in the deformation.

Through the long-term continued loading phase, the load supported by the shell concrete, where the load was transported between the external and internal steel tubes by the shell concrete. Moreover, they found that the varying steel grade and D/t ratio of the internal tube slightly affected on the index of strength capacity (SI) of specimens that exposed to long-term continual loading. Whilst, SI of CFDST columns were increased with more value of the hollow ratio [138].

Zhao and Grzebieta [31] tested the number of series of CFDST specimens. They investigated that the responses of the external tubes were similar to that showed for ordinary CFST columns, whereas the response of the internal skins were similar to that showed for the empty tubes. Actually, the concept of CFDST is obtained to increase the ductility and energy absorption using. It had been clinched that the external skin steel works like a tube entirely full of concrete, while the internal skin steel works like an unfilled one, Figure 2.7.

The usage of high strength materials in the building of the new composite system for instance CFSTs and CFDSTs is mostly good-looking because the grouping of those high-strength materials results in high-performance structural members as was demonstrated in Refs. [139-144]. Generally, the cross-section of the CFDST columns reduces when used the high strength materials, whereas the member slenderness is increasing, consequently, the buckling problems will be presented. Therefore, newly advanced explanations are needed to guarantee that these combination of columns (with high strength) produces the suitable constructional response.



(a)



(b)

Figure 2.7 CFST columns, (a) specimens after testing, (b) inner tube [31]

One purpose of this part is increasing the knowledge of effect of high strength concrete (HSC) on CFST columns. Recently, the usage of the high strength concrete has turned out to be more common owing to the developments in technology, mostly these affecting essentials exposed to high compression. Many techniques are designed to be suitable for applications in columns with high structures, and also to achieve a significant reduction in section of the columns. Nevertheless, the effect of the different strength concrete has focused chiefly on short specimens more than specimens that were fabricated as slender columns. Besides, if the CFST columns filled with HSC, the columns are offering larger buckling more than if that filled with NSC [144]. The

fact of the high strength concrete has low response, it is not produced a large confinement in the experiments. Nevertheless, some researchers do not entirely approve with this view because the confinement effect depends on the post-peak performance and the increment of the maximum load [145]. On the other hand, many studies were investigated that the use of HSC or ultra-strength in CFDST columns does not give the same enhancement as the use of normal strength concrete with the same columns [146].

Romero *et al.* [147] examined the influence of two types of strength concrete (30 MPa and 150 MPa) on CFDST columns, which were tested 12 CFDST columns and 2 CFST columns. They observed the specimens that filled with NSC outer ring and the thick inner tube reached almost the same buckling load with the others specimens. Moreover, they detected that the small effect of the samples that filled with the ultra-strength in assessment with the specimens that filled with normal strength concrete.

Portolés *et al.* [144] described thirty-seven experiments on slender specimens with NSC and HSC that were loaded to eccentric load, to found the suitability of the use of HSC as opposed to that of NSC. The experiment variables were the type concrete (30, 70 and 90 MPa), D/t , e/D and L/D . The experimental results have been compared to the predicted load that estimated by the design code of EC4, which the strength of concrete is not more than 50 MPa. Furthermore, the outcomes presented that the use of HSC of the slender specimen tube was exciting, notwithstanding the capacities of specimens were not significantly improved [144].

De oliveira *et al.* [148] conducted tests of the effect of confinement in the CFST concerning two limitations: the strength of concrete and the slenderness ratio of the column. A sixteen specimen columns with circular shape were experienced under compressive loading. The specimens were cast with different grade of f_c (30, 60, 80, and 100 MPa). The experimental results had been compared to the predicted load that estimated by the design codes of CAN/CSA [149], the Brazilian Code NBR,

AINSI/AISC 360, and Eurocode 4 [150]. The axial compressive load of specimens improved with rising the concrete strength and reduced with growing L/D ratio. Additionally, the Brazilian Code was the most conservative, while Eurocode 4 offered the values closest to the test results.

Giakoumelis and Lam [103] examined the actions of CFST under axial load with several different parameters such as grade of concrete, the thickness effect of the specimen tube, the bond strength between the component parts of the specimen, and the confinement index. In which the experiments values compared with USA Codes, EC 4, and Australian Standards. The diameters of the specimen's columns were 114 mm and the lengths were 300 mm for all specimens. After testing, all the experiments values had higher than the three codes predicted values.

Zeghiche and Chaoui [87] tested 27 CFST columns with the numerous parameters. The different parameters were the L/D ratio of the specimen, the eccentricity load and single or double curvature bending loaded of specimen columns, and the concrete grade. The experiment results confirmed the effect of those limitations on the behaviour of CFST specimens. On the other hand, testing results of specimens equated with the predicted outcomes that estimated in accordance with EC 4. EC4 predicted values showed the accuracy and acceptability for eccentrically and axially subjected columns with elementary curvature bending, whereas those predictions were very unconservative and risky for specimens that subjected to double curvature bending [87].

On the other hand, high-strength steel is gradually used in multi-story structures, bridges and other structures because of its benefits of saving materials and increasing building space. The problem of the high type-strength steel is vulnerable to the buckling because of the thin wall of steel plates. Many researchers examined the effect of the high strength steel type on local buckling, failure modes, axial compressive

behaviours, SI, ductile behaviours, local buckling performances, load-strain curve and lateral/longitudinal deformation relationship which were reported and determined.

Commonly, in engineering studies the level of the high strength of material is overall structural requests, structural steel members are famous for their adequate ductility, whereas the concrete sections take gain of compressive strength. The service of composite sections made-up from materials (both steel and concrete) in the building is a hopeful way to take good properties of both the high capacity of deformation for steel and the strength capacity of concrete. The steel walls put in the CFDST section as skins to confine the concrete infill and improve its compressive behaviour. It presented that the usage of ultra-strength steel in the manufacture of composite specimens has promising effects on the structural behaviour of these sections. Additionally, the usage of high strength steel (HSS) or ultra-high strength (UHS) can increase the capacity of axial load of CFDST [151, 152].

Farahi *et al.* [152] reported the experiment marks of static compression. The CFDST specimens containing ultra-high strength UHS steel tubes and corner mild steel (MS) were reported. They reported that the usage of corner manufactured by steel can growth the maximum axial load of CFDST columns. Furthermore, a yielding plateau was detected in the performance of the sections with UHS tubes corner, in another meaning that the non-ductile compressive behaviour experiential for the specimen with MS corner tubes.

2.4 Effects of Cross- Sectional Geometries on CFDST

New styles of the building structures are the hollow steel member (CHS), rectangular (RHS) and square (SHS) which are frequently cast by concrete to make composite columns. The good properties of composite columns had been discovered in recent studies of their capacity, fast of implementation, small space, and good fire resistance. Conferring to the previous study on the performance of CFDST specimens, it was detected that the strength capacity of CFDST sections is significantly affected by the

cross section of the tube, and the form of the section's area. The square form sections demonstration just a small increment in strength capacity owing to the tri-axial effects. However, a confining effect could be predictable in specimen CFDST columns. Then again, the load-deformation relationship of specimens is influenced by the specimen's cross-section area, the D/t of the skin tube, and the concrete grade. The load against the deformation curve for specimens presented the strain-hardening or elastic-perfectly plastic performance after yielding, whereas square columns showed a debasing type load-deformation behaviour.

Muhammad *et al.* [153] concluded that the circular columns have better properties than other geometric shapes. They found that the strength and mechanical properties of the columns with different cross sections will increase significantly if other determinants were maintained. The shape geometries expressively influence on the axial behaviour of specimens. Actually, after the tube thickness increases, positively the factor of enhancement is increasing. However, circular shape columns performed in a ductile method as compared to another shape, especially the square ones. In this case of the filled concrete can postpone the local buckling, since the skin tube enhances the confinement of composite columns [153].

The tapered CFDST columns were tested by Li *et al.* [133]. They described that all specimens were worked as a ductile way. Likewise, they investigated that the failure pattern of the external tube of the tapered CFDST specimen was outward buckling while the inward buckling happened in the internal tube with the destruction of the annulus concrete wherever the tubes buckled. They showed that the failure happened close to the section had the smallest cross-section, which was similar to that of the normal and constant dimension of CFDST column. Then again, their results discovered that the annulus concrete and the tubes might also act composed well even with the tapered angle.

The characteristics of the CFDST specimens were studied by Uenaka [36]. Those specimens were consisting of circular outer tubes and square inner tubes with the shell concrete that filled between them. He detected that the shape of the failure was separated into two collections: (i) local buckling related to the shear failure of the concrete and (ii) buckling related to the yield strength of the both tubes. These shapes of failure effected by the ratio of the width of the internal tube to the diameter of the external tube. Take into consideration, the elephant-foot buckling occurred through using thinner steel with those specimens.

Han *et al.* [154] tested double-skin tubular (CFDST) columns. They found that the typical shapes of failure of CFDST specimens were the inward buckling on the internal tubes and the outward local buckling on the external tubes. Furthermore, for tilted CFDST columns, the tilt angle had a slight effect on the strength capability. At the same time, for the tapered CFDST column, the capacity was significantly reduced as the taper angle increases. The strength of specimen reduced by 11.2%, 11.4%, 7.1% and 6.0% for the elliptical, round-end rectangular, square and circular when the angle varied from 0° to 1° , respectively. [154], Figure 2.8.

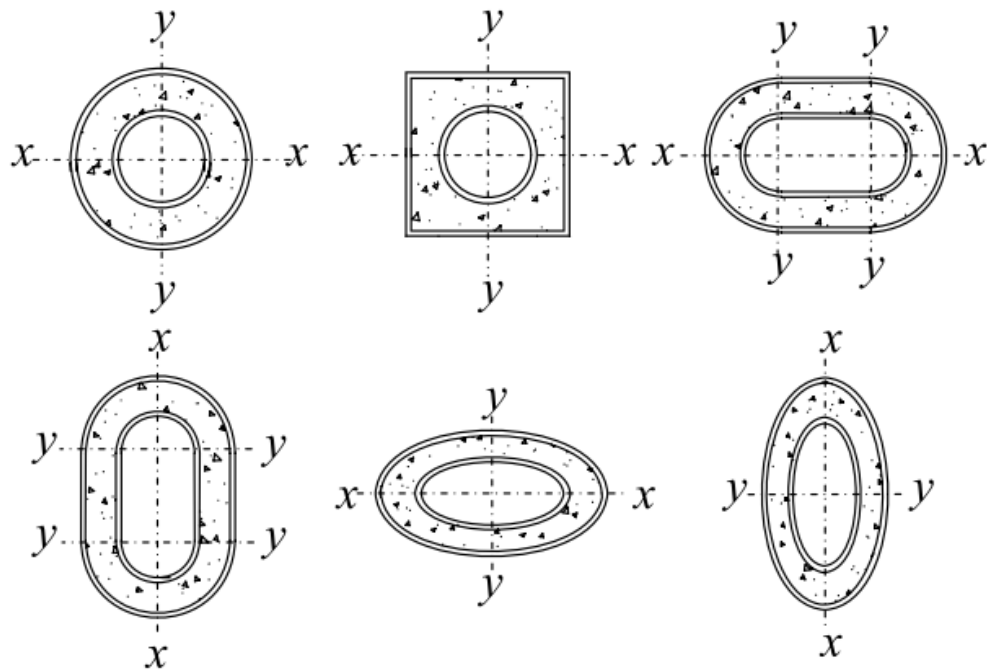


Figure 2.8 Arrangement of test specimens [154]

2.5 Using Stainless Steels and FRP Composites in CFDST Columns

The stainless steels have higher durability and fire resistance than carbon steels that augmented their requests in new constructions [155]. The stainless steel was used as an inner or outer tube within a CFDST tube with several configurations [131, 155-163]. Traditionally, stainless steel is a regarded solution to buildings and constructions problems. So, the use of stainless steel as the main mechanical material for ordinary structures is still quite limited. Beforehand, the use of stainless steel had many disadvantages, including limited structural codes, limited partial availability, and absence of good understanding of the benefits of stainless steel within the constructions [164].

However, a CFDST column consisting of either inner stainless-steel tube or external stainless-steel skin with the shell concrete. The strength capacity and behaviour of the slender circular CFDST specimens was studied by Hassanein *et al.* [146]. Specimens were collected of an internal carbon steel skin and an external stainless-steel tube with filling by the shell concrete. From results, they indicated that the intermediate length CFDST columns failed by elastic-plastic buckling, while the long double skin columns failed by elastic buckling. Conversely, the slenderness limit (λr) which exhibition the outlines between the middle and long length of the CFDST columns. The outer steel tubes' confinement differ between long and intermediate length of CFDST columns. Hassanein *et al.* [146] reported that the confinement effect can be neglected with long CFDST columns.

An 80 stainless-carbon CFDST columns had been presented by Han *et al.* [154] to explore their performance. They showed that the samples behaved in a ductile way and the DI improved with the rise of the hollow ratio (χ).

Zhou and Xu [159] presented a test program on CFDST under cyclic loading which (CHS internal and SHS external) stainless steel tube beam-columns. Two dissimilar sizes of cross-section SHS specimens calculated inclusive ratios of width/thickness

(B/t_o), reaching between (32.6-42.3) and two other sizes of section CHS sections with calculated the ratio of (d/t_i) fluctuating between (9.3-18.9) was measured. The length of 700 mm saved constant for all their specimens in order to avoid overall buckling. The observation according to the parameters study reported that the CFDST (SHS outer and CHS inner) stainless specimens displayed good deformation capacity and energy dissipation. Largely, the level of axial compressive load and external tubes' thickness had a main act on the behaviour of specimens, whereas the concrete strength and hollow ratio had a slight influence when the level of the axial load was little.

Zheng *et al.* [156] tested eight CFDST columns, which were content circular internal carbon tubes and external stainless-steel tubes. In comparison with the double-section columns, the CFDST columns exhibited lower lateral ultimate capacity, energy dissipation, elastic stiffness and ductility. Likewise, the strength capacity was increased with the yield strength of outer stainless-steel tubs increased, whereas the ductility decreased with growing the strength capacity of the shell concrete.

Wang *et al.* [157] concerned about CFDST columns with outer stainless and inner carbon steel skin tubes. Furthermore, they presented finite element analysis and estimated capacity of square and circular CFDST columns under axial compression. In this study, performances of outer stainless steels within CFDTs columns were compared with the specimens that had outer carbon steel tubes. They reported that the ductility and capacity of the CFDST columns enhanced once the outer stainless-steel tube was used compared to outer carbon steel tubes.

Recently, Li *et al.* [158] presented sea sand and seawater with CFDST-stainless tubes under axial compression. They investigated that the capacity of CFDST specimens was mainly affected by confinement. Likewise, the behaviour of post-peak depends on the slenderness of the inner tube and the confinement factor. Furthermore, the prediction cross-sectional strengths were predicted to evaluate the ultimate load of CFDST specimens with seawater and sea sand.

Hassanein *et al.* [146] presented the strength capacity and performance of the slender CFDST columns under compression loading. Those specimens collected of the outer stainless tube and an inner carbon tube with shell concrete that filled between them. The researchers found that HSC and UHSC in CFDST slender columns was not useful as their effect on the strengths of the columns was insignificant. The predicted strengths that proposed by FE model had been compared with predicted capacities that calculated by EC4 code. It was found that the EC4 provided unconservative predictions for the CFDST slender specimens.

The fibre reinforced polymers (FRP), measured as a comparatively new construction material, had been gradually used in the new building along with the retrofit of the present buildings. The FRP contains fibre reinforcements entrenched in an epoxy environment. The expensive cost of FRP compared to ordinary materials is counterbalanced by considerable savings in labour and overall project life cycle prices because of their greater characterizes as the ratio of strength-weight, the comfort of application, and durability.

The famous purpose application of FRP composites as concrete's confinement with superficially FRP has acknowledged a great agreement of consideration over the last periods. The new kind of composite sections investigated extensively, whilst the FRP used in the construction as the form of concrete-filled FRP (CFFT) tubes. This arrangement of these sections consists of two tubes, the internal one is a steel tube while the external tube is an FRP and filled the concrete between them. The good properties of these combines achieved and a high-performance mechanical member. The advantages of all three materials came as a result from these combines. The test results of axial compression conducted by several researchers and studies to inspect the behaviour of FRP columns [165-176].

Ozbakkloglu and Fanggi [177] offered the partial outcomes of the experimental research on the compressive performance of fibre reinforced polymers–CFDST

columns. From the test results determined that the increasing of the diameter of an inner tube leads to rise in the capacity of CFDST. Besides, they reported that the yield strength of the internal steel tube doesn't influence on the strength capacity and strain of CFDST columns.

Zhou *et al.* [172] used a new method of consuming FRP as a cover to enhance the structural performance with lightweight concrete type. They had first inspected the compressive behaviour of the normal carbon FRP (CFRP)-confined lightweight aggregate concrete type and proved that CFRP-confined LWAC considerably increases the deformation capacity and strength of LWAC. It found that the enhancement in both strength and the deformation capacity owing to the FRP with the normal concrete was lower confinement compared with LWAC, and the lower value of the strength of LWAC type caused to the significant enhancement for LWAC than that for ordinary type concrete. Those marks of results made a good provision to the possibility of the usage of the lightweight aggregate type of concrete in DSTC composite sections.

Zhou *et al.* [178] investigated by experimentally study the performance of FRP-CFDST columns with full lightweight aggregate concrete (FLAC), which were content the hundred percent of the lightweight aggregate under axial load. They determined the FRP-CFDST columns and steel tubes causes of the lateral confinements. The axial maximum load of the FLAC that filled CFDST was considerably bigger than the axial loads of the free FLAC. The growth ranges 40–55% for the strength performance of the carbon steel (reinforcement fibre polymer) FRP – CFRP confined FLAC sections and 52–65% for CFDST sections. Both the deformation capacity and strength of the confined FLAC were enhanced considerably. The maximum strength was 70% more than that the free FLAC and the strain was increased about 300%. Likewise, the hollow ratio of the hybrid member had a slight effect on the strength of the FLAC-filled CFDST columns, consequently, can be ignored, while it considerably effects to the value of the strain of the FLAC-filled CFDST columns. Hence, the strength model

increased by CFRP-confined LWAC by Zhou *et al.* [172], which was used the FLAC in the CFDST to explore the maximum value of strength. Furthermore, the maximum value of the strain of CFRP-confined FLAC was improved by seeing the acts of the hollow ratio to forecast the maximum value of the strain of the FLAC in the CFDST [178].

Yu *et al.* [179] offered an experimental study on the compressive behaviour of hybrid CFDSTs with a huge rupture strain FRP tube (i.e. polyethene terephthalate PET-FRP tube). The experimental parameters contained the section shape, the wall thicknesses of the FRP column, and the normal steel tube. The CFDSTs with a PET-FRP tube procedure a high-level ductility of the established specimens. Likewise, the buckling of the tube happened in PET-FRP CFDSTs before the crack of FRP, because of the huge crack strain of PET-FRP [179].

2.6 Studies on the Fire Resistance of CFDST

The upgraded kind of ordinary CFST is labelled as CFDST columns, which were established to enhance their performance under fire conditions. The fire behaviour of CFDST columns and their performance at ambient temperature were studied by several researches [40, 115, 124, 139, 180-189].

This characteristic of concrete decelerates heat transfer from the external tubes to the internal tubes acting to accumulation of heat in the outer tube which in turn causes rapid degradation of strength in the outer tube.

The external tube of the CFDST column is straightway exposed to the fire, which is increasing quickly, whereas the internal tube is covered and protected by the shell concrete. Previous studies have shown that CFDST columns can maintain virtually all fire resistance properties after exposure to fire [187]. Furthermore, it found that the thickness of outer tubes of CFDST column do not significantly effect on the compression capacity of composite members when the specimen was subjected to fire

[186]. Conversely, the inner tube can be considered effective on the compression capacity when its thickness was changed.

Mohd Zuki *et al.* [115] concluded that at 600°C the strength reduction was 14.5% for 90 minutes and 7.8% for 60 minutes of fire exposed CFDST columns. The secant stiffness was decreased for sixty- and ninety-minutes by about 11.3% and 36.9% under exposure to fire at 600°C, correspondingly the existence of concrete between the external and the internal steel specimen was confirmed to be useful to the double skin columns since concrete can performance as a protective layer to the internal tube [115].

Shekastehband *et al.* [182] conducted several patterns of the stiffened CFDST columns as well as different parameters such as stiffeners yield strength and f_c of concrete that were studied under fire exposure. They concluded that the stiffeners which were welded onto steel tubes worked to enhance the fire behaviour of CFDST columns, as shown in Figure 2.9. They also reported that the stiffeners that embedded on the interior face of the external tube or exterior face of the internal tube significantly absorbed heat. This technique (the stiffened CFDST column) was further operative than growing the steel tube's thickness of specimens. Furthermore, they measured the effect of strength of concrete and yield strength of stiffeners on the fire endurance of the CFDST columns. In which, the yield strength of stiffeners had an unimportant effect on the fire resistance of specimens, whereas the fire resistance of the stiffened columns decreases with the rise of the concrete strength. Besides, in term of bond strength, they concluded that the fire resistance increases owing to rise the bond between stiffeners and the concrete within the tube [182].

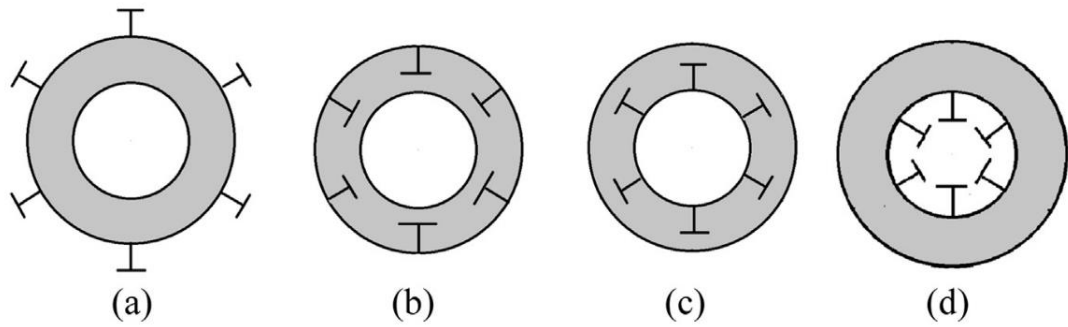


Figure 2.9 Cross sections of CFDST columns with different arrangements of stiffeners [182]

Largely, associating with the ordinary CFST tube, the CFDST has good temperature endurance, better fire resistance and sturdier preventive temperature. Wan *et al.* [183] clinched that the degree of the temperature of an internal tube with the similar thickness rises with the ratio of steel. At the same time as, the loading ratio had a superior effect on the fire resistance. They showed that the superior load ratio can result in a significant decrease in the fire resistance and poor ductility performance, while the influence of the cover thickness and the steel ratio effect was limited. In which, the load ratio and the steel ratio had no evident difference between the results of the solid and hollow CFDST columns [183].

Romero *et al.* [139] investigated some results from tests on the CFDST columns at room temperature, it was found that the CFDST specimens with the thicker-inner tube can achieve just about the same buckling load with those had a thicker-outer tube. Based on the comparison between HSC and NSC, they presented that the effect of NSC was more significant as compared to those for HSC. From the outcomes, in the fire condition term, they reported that the outcomes depend on the combinations of the CFDST columns. In which, the thinner-inner tube slightly affected on the fire resistance in comparison with the other combinations, whereas the thicker-inner tube was significant affecting in the fire resistance.

Yao *et al.* [184] proposed a new model to guess the fire resistance of CFDST columns. Furthermore, they proposed new formulations to estimate the fire resistance of the same specimens. The outcomes of the formulations and design method were reasonable accuracy compared with their experimental laboratory testing results.

Won *et al.* [185] investigated formulations to estimate the performance of the CFDST column under the ISO-834 standard fire with different parameters such as the hollow ratio, thicknesses of the tubes. They reported the relationship between the components of CFDST specimens and the fire resistance, considering the confining effect. The improved performance of fire resistance related with increasing of the thickness of the inner tube. Whilst, regardless of the influence of the thickness of the external tube to the residual strength of the restricted concrete.

Imani *et al.* [186] proposed new methods to assess the capacity of the CFDST columns that were exposed to fire by using tables or require complex FE method. The estimated prediction results of the temperature value by formulations were sufficiently accurate in comparison with the experimental and FEM results. On the other hand, they reported that the thickness value of the outer tube had no significant influence on the strength of the specimen after fire exposing. Whilst, the thickness of the inner tubes can be significantly effective on the strength capacity of CFDST columns after fire exposing.

Lu *et al.* [40] used polypropylene fibre and steel fibre within the shell concrete of the CFDST column. They Investigated that the thickness the shell concrete in CFDST reduced the temperature distribution, while the steel fibre had no significant effect on the temperature distribution. Besides, the steel fibre that added to the shell concrete of CFDST stub columns rises the fire endurance. Moreover, they concluded that when the load decreases, the fire endurance of CFDST columns increases.

For the fire tests, six full scale of CFDST columns were fabricated by Lu *et al.* [181]. It was found that the composite action between component parts of CFDST was very

important during fire exposure. Moreover, they concluded that the outer steel tubes of CFDST columns had a larger value of temperatures than conventional CFST columns. This indicates that the CFDST columns have a better fire resistance than traditional CFST and unfilled columns [181].

Yang and Han [188] concerned with the behaviour of CFDST columns that were exposed to a standard fire (ISO-834). The design methods and FEM were employed for the calculation of temperature distributions in the CFDST specimens. From the results, the design methods presented to examine the effects of more than a few key parameters on the fire endurance, which the hollow ratio, the external diameter, and the L/D ratio had noteworthy affect the fire resistance of CFDST columns. While, the inner tubes' thickness, the load eccentricity ratio, the steel ratio and the shell concrete strength, had slightly affected the fire resistance.

Besides, other studies of CFDST columns had been conducted, for example Li *et al.* [190] offered an experimental work of the compressive and flexural performance of the grout-filled double skin steel tubular (GCFDST) columns. An overall of fourteen samples experiment, with eight steel columns, four of beam-columns and two just beams. For the axial load of columns, the chief parameter of the test was the hollow ratio of the specimen, and the equivalent hollow steel corresponding item was considered to learning the influence of the grout sandwich. The grout was being made up of cement and water only, lacking any fine or coarse aggregate adding to this mix.

Habitually, the ability of the grout to flow was super and there was no need for any vibration. It was distinguished that no separation was found between the steel and the grout shell after the hardening of grout. Generally, the grout operated well with the steel tubes, no hole was found between the tubes and grout out the district of the failure area. It can be understood that some cracks found in the grout around the crinkled region after the test, and they were technologically advanced along the longitudinal path owing to the brittleness of grout property [190]. Only inward buckling was

detected for GFDST tubes with a small value of the hollow ratio, as the more thickness of annulus grout possibly will offer high strength to the tubes.

The grout in tube operated well with both internal and external tubes and reformed the failure mode of the CFDST and the outward buckling may perhaps also happen in the internal tube when the GCFDST had a big hollow ratio. Also, the grout could improve the strength and stiffness of GCFDST sections. In the meantime, the DI of GCFDST section was improved when compared to the normal hollow steel.

A FEM was suggested by Yao *et al.* [184] to estimate the fire performance of CFDST members. The typical model was compared with experimental work marks and displays good trustworthiness. The failure mechanism of the CFDST columns was calculated to depend on the numerical model. An analytical study absorbed on the concrete and steel, load eccentricity, load level and relative slenderness ratio that was achieved to explore the effects on fire behaviour of CFDST specimens. Engineering design approvals were proposed to promote the fire endurance of CFDST columns. The ordinary Rankine approach was lengthy to estimate the fire endurance of the exposed CFDST specimens to an axial load. The forecasts show reasonable accuracy-related to both the simulations and experimental data [184].

Li *et al.* [191] established the new method of FE for CFDST columns under cross impact. They presented that the data of the results of the simulation and laboratory experiments was very reliable. As the impact height rises, the loading time and peak point of impact force upsurge, but the impact stage value was moderately steady and had a slight change through full-range analysis, the full procedure can be separated into three phases: peak value phase, platform phase and unloading phase. There was a link deformation of local distortion and essential deformation during the second stage [191].

Kuranovas and Kvedaras [192] described the theoretic and experimental investigations. It can be displayed that performance of CFDST sections was more

complex than that of traditional CFST sections. The triaxial stress state for single-layered CFST sections was reached only at the interaction face between the steel and shell concrete. The core concrete of CFDST elements had the same stress state with comparison with that in the CFST members [192, 193]. The performance of one- or multi-layered CFST parts varies principally. Multi-layered parts of CFSTs improve strength capacity, ductility and Young's modulus (E). Furthermore, the failure mechanism of the CFDST specimens was more ductile, hence the constructions from such parts may be used more securely.

Wan *et al.* [183] proposed new unified methods (3D FEA model) that was established to compute the temperature field of the CFDST specimens. The effects of significant parameters on the temperature conditions of the CFDST were inspected. The investigation presented that the temperature of the external tube decreases when the external tube's wall thickness increases. Obviously, the thickness effect of the annulus concrete and the thickness of the internal tube on the temperature was very high. The unified methods for calculating the value of temperatures of CFDST columns were validated through comparisons with existing experimental results [183].

Liang [194] presented a new FEM for estimating the structural performance of CFDST columns under axial load. Additionally, outcomes displayed that the use high level of the steel strength favourably increases the initial axial stiffness of CFDST specimens. On the other hand, a design formula was proposed to estimate the capacity of CFDST columns. It had been shown that the FE method can accurately capture the complete P - ϵ curves of CFDST specimens under compression.

CHAPTER 3

EXPERIMENTAL WORK AND MATERIAL PROPERTIES

3.1 Introduction

The aim of the experimental work that addressed in this thesis was to explore the mechanical performance of composite columns under axial compression. This chapter presents the experimental procedure, specimen preparation, material properties and testing setup.

3.2 Experimental Program

In this thesis, the experimental process was separated into four chapters. Numerous modes were conducted to explore the composite column's behaviour. Moreover, the compressive loading versus displacement curves, failure pattern, strength index and reinforcing bars *RBs* contribution ratio were investigated in each chapter.

3.3 Materials Properties

3.3.1 Structural Steel Tubes

Hollow steel sections could be manufactured welded or seamless. Seamless hollow sections are completed in two stages, the first stage comprises of an ingot piercing process. The second one is elongate this hollow section into the desired shape. Besides, a hollow section with a longitudinal weld is generally made with an induction welding procedure or with electrical resistance welding procedures. The plate is welded longitudinally after being formed by rollers into a cylindrical shape. By using the electrical resistance, plate edges were heated while being pushed together by rollers, resulting in a pressure weld. After the welding process finished, all external remaining

parts were trimmed. By deforming the circular hollow sections through forming rollers, the rectangular hollow sections are made. The previous process could be made in the cold or hot procedure, and longitudinally welded or seamless can be used. Seamless sections would be reasonable for thicker sections and special applications, otherwise, it is ordinary performed to use longitudinally welded hollow sections which are cost value effective [195]. For the larger circular hollow sections, they could be prepared by rolling a strip through a U-O press process. On the other hand, the large tubular sections are applied to weld the edges together which required to use the wide and continuous strip at a specific angle to form the spiral circular section [195].

Worth mentioning that all the steel tubes in this thesis were cold-formed tubes which were produced according to EN 10219-1 [196]. Coupon specimens were cut from each tube to measure the actual yield strength of steel tubes (f_y) by coupon test according to [197], Figure 3.1.

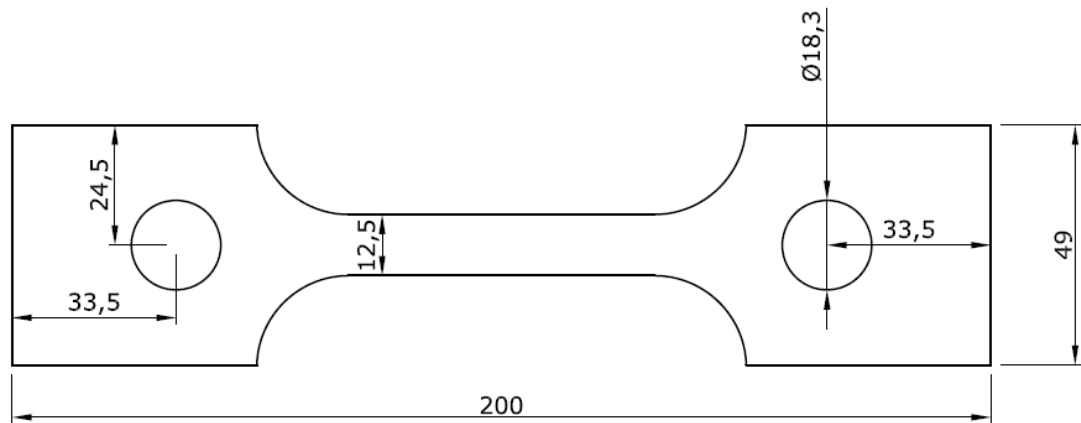


Figure 3.1 The schematic of tensile coupon specimen (mm)

3.3.2 Concrete and Materials Used for Chemical Admixture

In Japan in the late 1980s, Self-compacted concrete (SCC) technology was proposed which is utilized in several submissions in the civil engineering field. This new proposed technology depends on increasing the fine material, such as superplasticizer and cementitious materials, to attain the required workability without changing the

water content. There are several practical conditions for the concrete to be considered SCC: resistance to segregation, passing ability and filling ability.

The features of SCC in the fresh state are: passing ability, flowability, segregation, and viscosity. However, these characteristics can define by one or more test methods:

- 1- Passing ability: L-box test, Figure 3.4.
- 2- Flowability: slump-flow test, Figure 3.3.
- 3- Segregation: Segregation resistance (sieve) test.
- 4- Viscosity: T_{500} slump-flow test or V-funnel test, Figure 3.2.

In addition, the fresh features of SCC are specified by the classifications of Table 4.1 according to EFNARC [198].

Table 3.1 SCC limitations [198]

Characteristic	Test	Class	Limitations
Flowability	Slump-flow (SFL)	SF1	$550 \text{ mm} \leq \text{SF1} \leq 650 \text{ mm}$
		SF2	$660 \text{ mm} \leq \text{SF1} \leq 750 \text{ mm}$
		SF3	$670 \text{ mm} \leq \text{SF1} \leq 850 \text{ mm}$
Viscosity (V)	V-funnel (VF): T_{500}	V1	$\text{VF} < 8 \text{ s}; T_{500} \leq 2 \text{ s}$
		V2	$9 \text{ s} < \text{VF} \leq 25 \text{ s}; T_{500} > 2 \text{ s}$
Passing ability (PA)	L-box	PA1	$\text{PA} \geq 0.8 \text{ s}$: two bars
		PA2	$\text{PA} \geq 0.8 \text{ s}$: three bars
Segregation resistance (SR)	Sieve segregation	SR1	$\text{SR1} \leq 20\%$
		SR2	$\text{SR1} \leq 15\%$

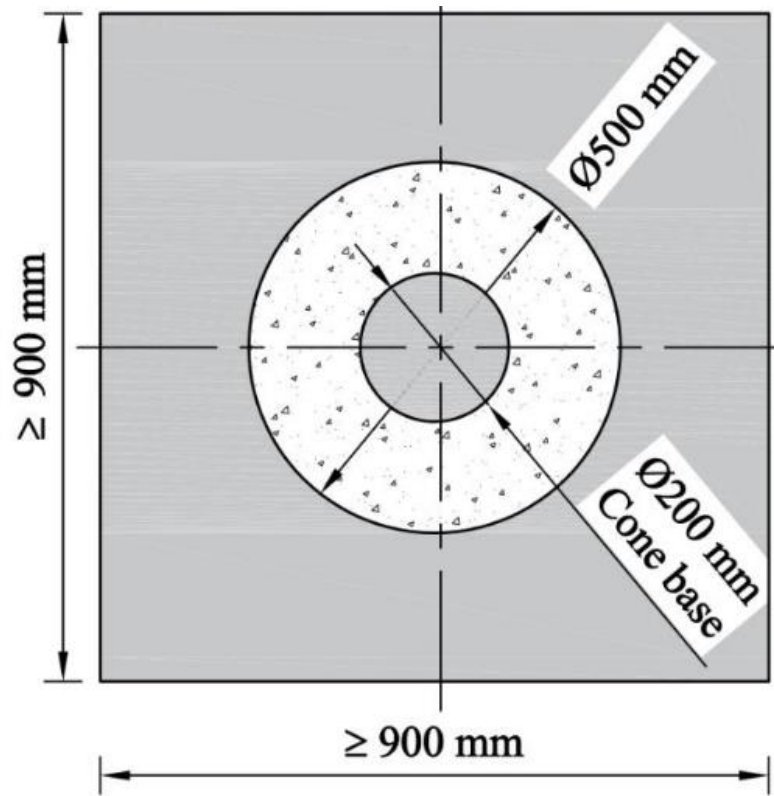


Figure 3.2 The schematic of plate used for the slump-test

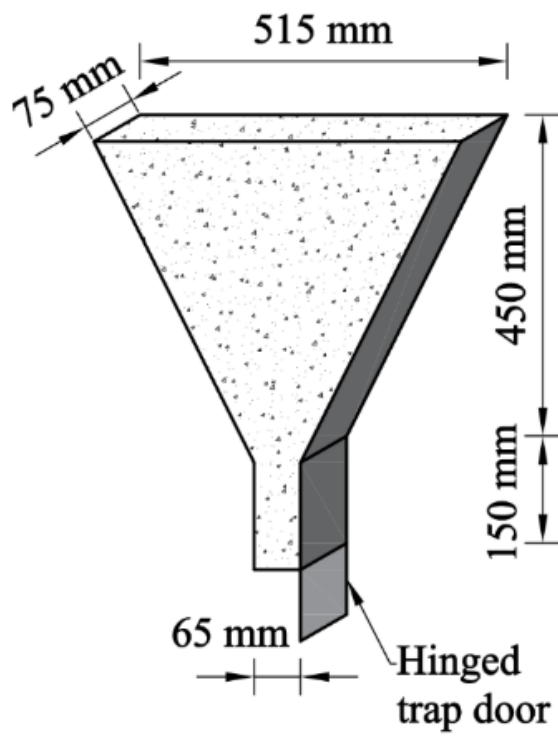


Figure 3.3 The schematic of V-funnel test

Table 3.2 Physical and chemical properties of cement and fly ash

Chemical analysis (%)	FA	Cement
CaO	2.2	62.6
SiO ₂	57.2	20.2
Al ₂ O ₃	24.4	5.3
Fe ₂ O ₃	7.1	4.0
MgO	2.4	2.8
SO ₃	0.3	2.7
K ₂ O	3.4	0.9
Na ₂ O	0.4	0.2
Loss of ignition	1.5	3.0
Specific gravity (g/cm ³)	2.25	2.88
Blaine Fineness (m ² /kg)	379	326

Table 3.3 The properties of superplasticizer

Property	Superplasticizer
Structure of a material	Polycarboxylic ether based
Colour	Dark Brown
State	Liquid
Specific Gravity [kg/cm ³]	10.7
Freezing Point	-4

Table 3.4 Mix properties

A grade of the concrete	NSC	HSC
Cement (kg/m ³)	285	592
Fly ash (kg/m ³)	285	0
Water (kg/m ³)	188.1	188.1
River sand (kg/m ³)	650.68	668.4
Coarse aggregate (kg/m ³)	709.83	835.5
Crushed sand (kg/m ³)	216.89	167.1
Super-plasticizer (kg/m ³)	285	592

Table 3.5 Workability characteristics of self-compacting concrete (SCC)

Tests	Result	Workability classes
Slump flow diameter (DF) (mm)	650	SF1 (550–650)
Slump flow time (T ₅₀) (seconds)	2.5	VS2/VF2 (>2)
V-funnel flow time (V _f) (seconds)	8.5	VS2/VF2 (> 8)

3.3.3 Reinforcing Steel

Steel reinforcing bars have a wide use in civil engineering structures. The strength and unity provided in reinforced concrete members are the results of using steel reinforcing bars. Reinforcing bars have the further benefits of eliminating the adverse effects of time-dependent behaviour of the concrete. The shrinkage and creep behaviour of the concrete could minimize by employing steel bar reinforcements. The application of steel reinforcing bars in civil engineering structures is conventional and a basic routine. The cost of the steel bar reinforcement is very low compared to the additional benefits of such reinforcement. The benefits of longitudinal reinforcing bars could be maximized since the core concrete of CFST columns is also supported by the outer steel tube. Typically, the steel reinforcing bars are used to improve composite member resistances without change of a column section [26]. The yield strength of deformed steel reinforcing bars was tested by ASTM-A615/A615M [200].

3.4 Test Instruments and Preparation of CFDST Columns

All tests in this thesis were completed with a universal testing machine with a capacity of 3000 kN, Figure 3.5. Moreover, two linear variable differential transformers (LVDTs) were located at two points in order to measure the shortening, Figure 3.6. The average values of the two LVDTs were used to draw the compression load-end shortening curves. Column specimens were tested by following a slow rate of displacement-controlled loading procedure.

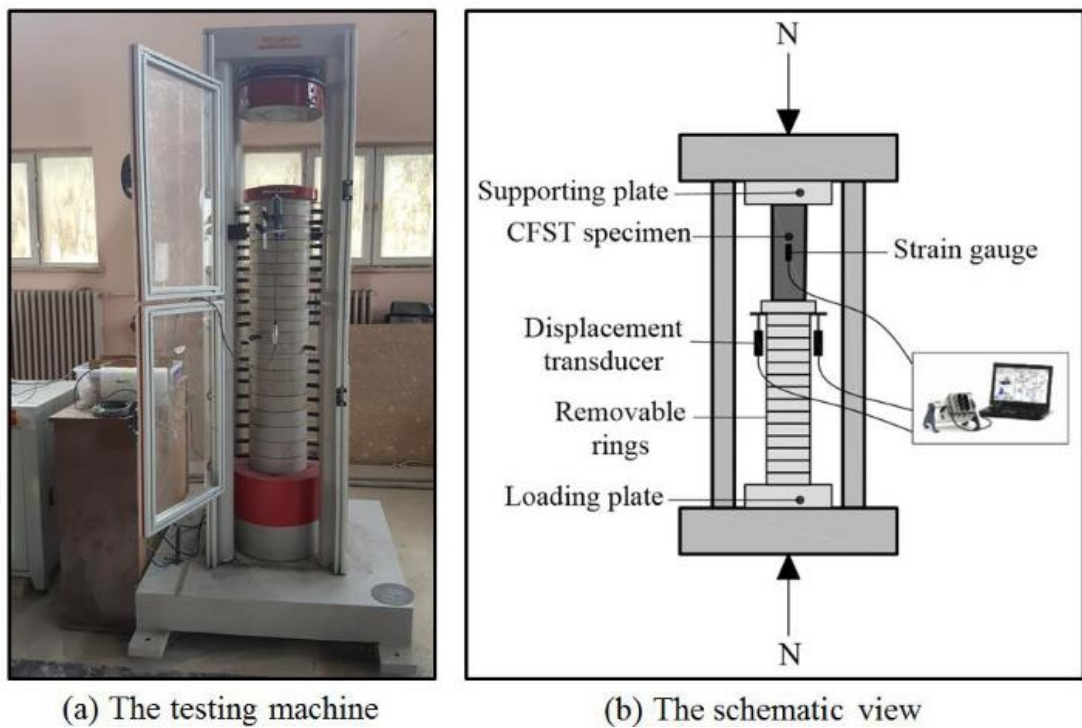


Figure 3.5 The schematic of testing machine

Worth mentioning, the overall behaviours of the small-scale units were quite similar to the full-scale specimen during testing [201]. Such a machining process was undertaken to obtain flat ends which are perpendicular to the axis of the tube. Prior to concrete casting, to obtain suitable interaction between the concrete and the steel tubes, steel tube surfaces were cleaned carefully. Afterwards, to be able to keep the fresh concrete in filling process, the lower ends of the outer tubes were closed with flat glass plates using silicon. Following, the self-compacted concrete (SCC) mixes were used

to cast the steel tubes. The top last 3-4 mm of the steel tube were left empty for levelling purpose. After completion of the curing of the concrete, the attached glass plates were removed. The glass plates provided flat and levelled lower ends of the composite columns. However, it is also crucial for compression testing to obtain flat upper ends. The upper ends of specimens were flattened by using flattening epoxy. To eliminate the eccentricity and related bending effect, the composite columns were carefully centred in the testing device.



Figure 3.6 Displacement transducers

CHAPTER 4

COLUMN TESTS OF CONCRETE FILLED CLASSICAL, DOUBLE SKIN AND DOUBLE SECTION STEEL TUBES

4.1 General

In the field of steel and concrete composite construction, Concrete Filled Steel Tube (CFST) columns were recognised to be outstanding members, since they link the favourable characteristics of constituent materials. The mechanical properties of the materials are exploited efficiently in CFST columns. The steel is internally supported by the core concrete which leads to greater compression performance of the tube against local buckling [202-210]. The location of tube section in the CFST cross section allows the steel to fully serve its bending capacity [28]. Furthermore, the steel tube could be considered as a permanent formwork for concrete, thus construction cost could be reduced. In circular CFST columns, due to confinement effect concrete is stressed in triaxial state and this allows the concrete to exhibit greater compression performance compared to unconfined condition [4]. In addition, the existence of the steel tube motivates the use of high strength concrete by suppressing the explosive behaviour of such concrete [211-223]. The combination of above characteristics gives rise to a robust structural member which could be utilized in severe loading scenarios to provide high strength, stiffness and ductility [6, 7].

Although CFST compression members provide good mechanical characteristics, the last two decades have seen a growing trend towards the improvement of compression performance of such members to challenge the requirements of the state of art engineering projects [224-234]. Recently, a considerable literature has grown up around the theme of Concrete Filled Double Skin Tube (CFDST) columns. CFDST column cross section consists of two concentric steel tubes and the shell concrete

between them. CFDST columns provide lighter weight, larger bending stiffness and better cyclic behaviour [123, 126]. The fire behaviour of CFDST columns is also superior to CFST counterpart since the inner steel tube is protected by the outer steel tube and shell concrete [126, 209, 235]. The presence of the internal tube also suppresses the brittle type of rupture failures which could happen when ultra-high strength materials are used [235]. Moreover, building services, such as cables and lines, could be placed in the hollow region of CFDST members to eliminate any inconvenient appearance [159]. Due to superior engineering properties, CFDST columns have been the main subject of many numerical and experimental investigations [52, 88, 161, 162, 183, 202, 236-246].

A novel member of CFST family which shares the most of the promising properties of CFDST columns and offers additional benefits, has been receiving increasing attention in recent years. This composite member is referred as Concrete Filled Double Circular Steel Tube (CFDCST) column [146]. Considering the term “double skin”, this novel composite member could be referred as double section. Compared to the double skin columns, double section columns additionally include the core concrete in the inner steel tube. Figure 4.1 shows the relative sights of the ordinary CFST, double skin and double section ideas. Further favourable characteristics of double section columns could be detailed as follows: Since the double section columns includes core concrete, the inner steel tube is braced both externally and internally. This condition leads to minimization of local buckling risk of the inner tube and allows the use of compression capacity of this thin-walled tube completely. Also, suppressing the local buckling of the inner steel tube by providing internal support would significantly improve the compression performance of the shell concrete. The limited lateral distortion behaviour of the inner tube could supply additional confinement to the shell concrete and increase its compression performance. Furthermore, the core concrete itself has significant potential to contribute to column compression capacity. Considering the field applications of the classical CFST columns with diameters up to 1600 mm [144,

147], underlined characteristics of the double section members would lead to notable reductions of the cross sectional dimensions of the composite columns for a given load and increment of the useful floor area.

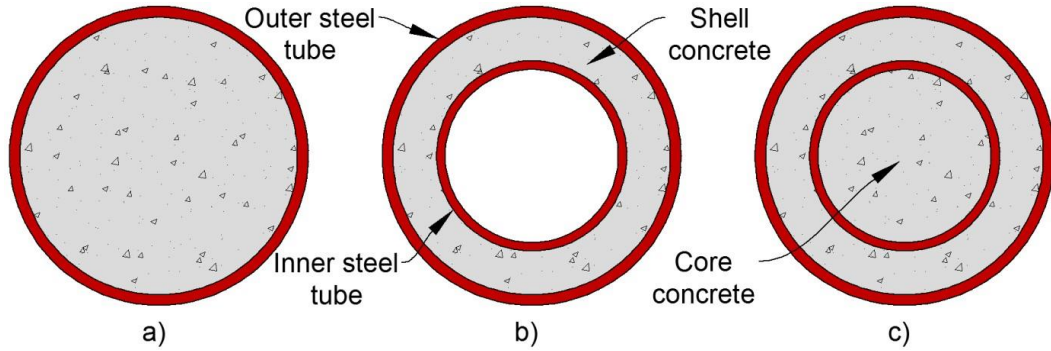


Figure 4.1 CFST columns a) classical CFST b) double skin c) double section

A concern in classical CFST column research which is related to the performance of the columns in elastic stage was revealed lately [247, 248]. Since the Poisson's ratio of the steel is larger than that of concrete, in the elastic stage the lateral expansion of the steel is greater than the expansion of the concrete. This behaviour results in the delamination of the steel and concrete interface in the elastic stage. As a result, unconfined concrete behaviour arises until the development of initial cracks in concrete and the lateral expansion of the concrete becomes larger than that of the steel tube. In case of employing thin-walled steel tube and high strength concrete, this behaviour could be more critical. The double section composite columns also offer a superior interaction between the materials and increases the interface area after each concrete layer.

Herein, it is necessary to detail the precautions which were undertaken between steel and concrete. Consequently, the performance of the composite column could be significantly improved in elastic stage. Although double skin columns offer superior fire performance compared to classical CFST columns, double section concept could increase the fire resistance of the columns to further levels in two aspects. A deficiency of the double skin columns in fire exposure was specified to be the inadequate steel

and concrete interface bonding which leads to delamination of the materials at elevated temperatures and triggers the buckling failure of the column [249]. The presence of core concrete in double section columns increases the interface area between the steel and concrete and precludes the risk of delamination. Also, in double section columns the core concrete is protected by the outer steel tube, shell concrete and inner steel tube. This geometric nature of the double section columns is an additional benefit against fire exposure. As a further matter, double section concept allows the use of two different concrete kinds in core and shell regions. A concrete type which has thermal insulation properties, could be employed in the shell region to provide a better protection of the inner tube and core concrete. Obviously, longitudinal steel bar reinforcements with spiral stirrups could improve the load and fire resistances of the composite columns. However, this option would significantly increase the required labour and would not allow using different concrete types in the column. In addition, the use of bar reinforcements always requires further precautions for compaction concerns.

Although the double section columns provide crucial benefits for composite construction, there has been little quantitative analysis of these members in the literature [146, 197, 250]. In addition, most of the existing work on double section columns do not account for the comparison of the compression performances of double skin and double section columns. Furthermore, the works which undertake comparative analyses of double skin and double section members focused on long slender columns with ultra-high strength materials [196, 197, 251]. However, much uncertainty still exists about the performance assessment of CFDST and CFDCST stub or medium specimens which are manufactured using a practical range of material properties. Although the distinctive characteristics of the double section concept are obvious, the nature of these columns have not been well documented for design purposes. The main goal of this study is to systematically explore the compression features of double skin and double section circular composite stub columns in a

comparative way for a range of geometrical and material properties. To be able to address the research gaps and advance the understanding of double skin and double section concepts an in-depth experimental work was undertaken. Material properties and geometrical characteristics of the specimens were selected in such a way to represent field applications. Two different external steel tube, two different internal steel tube and two different concrete classes were utilized to delve into the compression behaviour of double skin and double section columns. In total, 24 columns were carried out concentrically and the behaviours of the test specimens in pre-collapse, collapse and post-collapse regions were monitored. A longitudinal experimental assessment of double skin and double section columns would contribute new insights to this growing area of steel and concrete composite structures.

4.2 Experimental Procedures

4.2.1 Material Properties

The material characteristics of the laboratory specimens should cover a range of properties to remove any uncertainty in the behaviours and draw accurate discussions which would be highly representative for general field applications. Towards this aim, two concrete classes were produced. Concrete mixes were prepared with the objective of obtaining self-compacted concrete classes. Self-compacted concrete eliminates the need for extreme precautions in compaction process and minimizes the risk of inappropriate contact between the tube and concrete [3, 252]. The first self-compacted mix was designed with the objective of producing a normal strength concrete. On the other hand, the second self-compacted mix was prepared to obtain a high strength concrete class. For each mix design cylinder moulds of 100×200 mm dimensions were filled with the concrete. Since the concrete mixes were self-compacted, just small shaking efforts were made after filling the moulds. Concrete specimens were crushed in accordance with ASTM C39/C39M [253] after the completion of the curing stages, Figure 4.2. Average compressive strengths of the two different mixes were measured to be 42.87 MPa and 71.02 MPa. These magnitudes of the compressive

strengths are highly representative for normal and high strength concrete classes and field applications of composite columns. Two different types of inner steel tubes were employed in the experimental work to specify the influence of this tube properties on the performance of the columns. Both of the inner steel tubes have outer diameters of 60.3 mm. However, the thickness of the tubes are 2.52 mm and 4.77 mm for the thinner and thicker inner tubes, respectively.



Figure 4.2 Concrete cylinder specimen before and after testing

In order to assess the performance of the outer tube properties, two different outer steel tubes were also used in the experimental work. Both of the outer steel tubes have outer diameters of 114.3 mm. However, the first tube has a thickness of 2.74 mm and the second one has a thickness of 6.11 mm. All of the steel tubes in the present study are cold-formed tubes which were produced according to EN 10219-1 [254] and EN 10219-2 regulations [255]. During the preparation of double skin and double section columns, also a number of tensile coupon specimens were sectioned from the tubes to

measure the mechanical properties. The dimensional details and the testing procedure of the tensile specimens comply with ASTM E8/E8M [256]. The yield strengths of the inner tubes were measured to be 396 MPa and 310 MPa for the 60.3×2.52 mm and 60.3×5.77 mm steel hollow sections, respectively. On the other hand, for the outer tubes the yield strengths were 355 MPa and 535 MPa for the 114.3×2.74 and 114.3×6.11 mm sections, respectively.

4.2.2 Double Skin and Double Section Column Specimens

Considering the diameters of the outer steel tubes an L/D ratio of 3.0 was selected for double skin and double section specimens. An L/D ratio of 3.0 has been widely utilized in the literature to examine the behaviour of stub columns [103]. According to this L/D ratio and considering a further machining process, all hollow steel tubes were cut to lengths which are slightly greater than 343 mm. Afterwards, the upper and lower ends of the steel tubes were machined flat and perpendicular to the tube axis to ensure that uniform compression load could be applied, Figure 4.3. The machining process reduced the steel tubes to a final exact length of 343 mm.



Figure 4.3 Machining process



Figure 4.4 Preparing and cleaning process

To remove the dust and residues and provide an appropriate interaction between the steel tubes and the concrete, the inner and outer surfaces of the tubes were carefully cleaned, Figure 4.4. Thick and flat glass plates were employed at the lower ends of the hollow sections to hold the fresh concrete during the casting process. Glass plates were connected to the steel tubes using silicon. The flat glass plates also allowed having levelled surfaces for the concrete at the lower ends. Following, the column specimens were filled with concrete in five layers. The concrete mixes were self-compacted. However, considering the narrow shell regions between the inner and outer steel tubes, to ensure about the compaction column specimens were gently hammered to eliminate any possible compaction problem in narrow shell and core regions. First, the highly flowable nature of the self-compacted concrete significantly helped in this process. Furthermore, the concrete mixes were prepared by using river material (fine and coarse aggregates) which have rounded shapes. Also, the maximum size of the coarse aggregate was limited to be 10 mm to eliminate any possible compaction risk in the narrow shell regions. To be able to have reliable test results, the concrete must also be levelled at the upper ends of the columns. To this end, the top last 3-4 mm of the steel tubes were left empty. Once the curing process was completed (Figure 4.5), the upper empty ends of the specimens were filled and levelled using high strength levelling epoxy which is highly stable and does not experience shrinkage effect, Figure 4.6.

Also, to be able to address the contributions of individual parts of the columns and assess the composite action thoroughly, classical CFST columns were produced. That is to say, in addition to CFDST and CFDCST specimens, CFST specimens which have a single steel tube of 114.3 mm outer diameter and 60.3 mm outer diameter were manufactured. The capacity of the classical CFST specimens which have 114.3 mm outer diameter could reveal the contribution of the inner steel tube of double section columns. Besides, the performance of the CFST specimens which have 60.3 mm outer diameter could specify the contribution of the shell concrete plus outer steel tube of double section columns.



Figure 4.5 Curing procedure of specimens

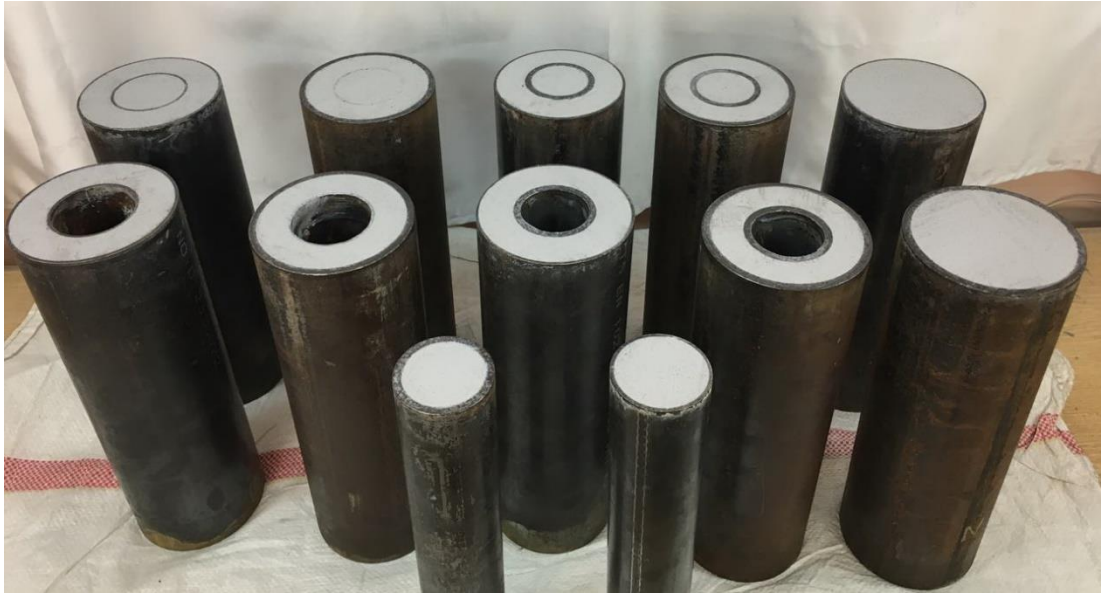


Figure 4.6 High strength levelling epoxy process

Before the compression testing of the columns, the glass plates at the lower ends of the specimens were detached and the silicon remains were cleaned. With the objective of eliminating any possible bending action which could be a result of eccentric loading, column specimens were carefully centred in the testing machine. Calibrated displacement transducers were used to automatically measure the end-shortenings of the specimens at specified intervals. The displacement transducers are strain gauge type which have high fidelity measuring capability. The columns were tested to failure using a slow rate displacement-controlled loading procedure.

The geometrical and mechanical characteristics of the test columns are presented in Table 4.1. The labelling convention of the specimens in Table 4.1 is based on the cross-sectional details. For example, the specimen 1-2-1-2 refers the double section column with NSC-core, thicker internal steel tube, NSC-shell and thicker outer tube. Therefore, the numbers 1 and 2 in the labelling system denote the weaker and stronger properties, respectively. The labelling for double skin columns starts with “0”, since there is no core concrete in this type of columns. Furthermore, the classical CFST columns were labelled using a three levels system. As an example, the specimen 1-2-I refers the classical CFST column with NSC and thicker steel tube. The suffix “I”

shows that the CFST specimen was produced using the steel tube of 60.3 mm which is the inner tube diameter in double skin and double section columns. For the CFST columns with 114.3 mm outer diameter a suffix of “O” is used in Table 4.1.

4.3 Compression Behaviour of Column Specimens

Assessments of column performances are based on compression loading versus end-shortening curves. Compression loading versus end-shortening curves of the columns could be exploited in addressing the stiffness, compression capacity, ductility and toughness.

4.3.1 Specimens with Normal Strength Concrete and Thinner Inner Steel Tube

Figure 4.7 illustrates compression loading against end shortening relationships of the specimens which have normal strength concrete and thinner internal steel tube. The curves with solid lines represent the behaviour of classical CFST columns. Besides, the curves with dotted lines and dashed lines show the behaviours of double skin and double section specimens, respectively. The CFST specimen 1-1-I reached a compression capacity of 351.30 kN with low initial stiffness but high ductility. Since this CFST specimen was produced using smaller diameter tube, the L/D ratio of this column is greater than the other specimens. The performance of this specimen could not be directly compared to others, but it could be a useful sense to understand the efficiency of double skin and double section concepts.

Table 4.1 Properties of the column specimens

Column (ID)	Core f_c (MPa)	Inner tube (t) (mm)	Inner tube D (mm)	Inner tube f_y (MPa)	Shell f_c	Outer tube D (mm)	Outer tube t (mm)	Outer tube f_y (MPa)
0-1-1-1	-	2.52	60.3	396	42.87	114.3	2.74	355
0-1-1-2	-	2.52	60.3	396	42.87	114.3	6.11	535
0-2-1-1	-	5.77	60.3	310	42.87	114.3	2.74	355
0-2-1-2	-	5.77	60.3	310	42.87	114.3	6.11	535
1-1-1-1	42.87	2.52	60.3	396	42.87	114.3	2.74	355
1-1-1-2	42.87	2.52	60.3	396	42.87	114.3	6.11	535
1-2-1-1	42.87	5.77	60.3	310	42.87	114.3	2.74	355
1-2-1-2	42.87	5.77	60.3	310	42.87	114.3	6.11	535
1-1-I	42.87	—	—	—	—	60.3	2.52	396
1-2-I	42.87	—	—	—	—	60.3	5.77	310
1-1-O	42.87	—	—	—	—	114.3	2.74	355
1-2-O	42.87	—	—	—	—	114.3	6.11	535
0-1-2-1	—	60.3	60.3	396	71.02	114.3	2.74	355
0-1-2-2	—	60.3	60.3	396	71.02	114.3	6.11	535
0-2-2-1	—	60.3	60.3	310	71.02	114.3	2.74	355
0-2-2-2	—	60.3	60.3	310	71.02	114.3	6.11	535
2-1-2-1	71.02	60.3	60.3	396	71.02	114.3	2.74	355
2-1-2-2	71.02	60.3	60.3	396	71.02	114.3	6.11	535
2-2-2-1	71.02	60.3	60.3	310	71.02	114.3	2.74	355
2-2-2-2	71.02	60.3	60.3	310	71.02	114.3	6.11	535
2-1-I	71.02	—	—	—	—	60.3	2.52	396
2-2-I	71.02	—	—	—	—	60.3	5.77	310
2-1-O	71.02	—	—	—	—	114.3	2.74	355
2-2-O	71.02	—	—	—	—	114.3	6.11	535

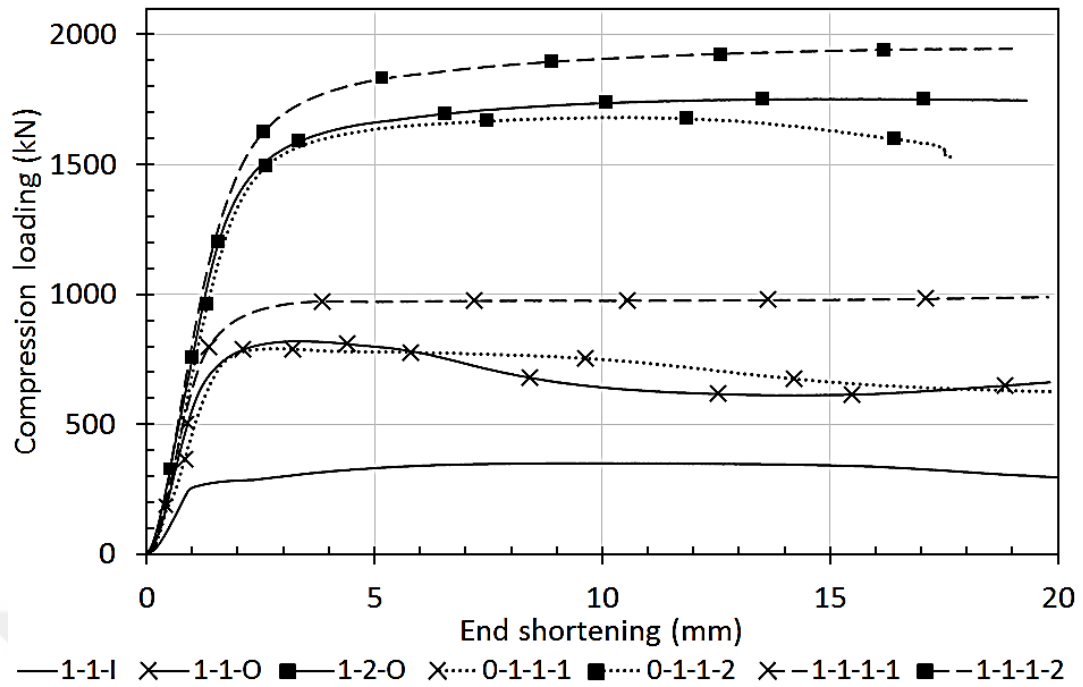


Figure 4.7 Compression load vs. end shortening curves of specimens with normal strength concrete and thinner inner steel tube

The CFST specimen 1-1-O, double skin specimen 0-1-1-1 and double section specimen 1-1-1-1 achieved compression capacities of 820.29 kN, 789.42 kN and 989.12 kN, respectively. It is interesting here to observe that the classical CFST specimen exhibits a greater performance over double skin counterpart. This behaviour conveys important details about double skin columns with thinner inner steel tubes and could be explained by the absence of the core concrete in this specimen. As a result of absence of the core concrete in the double skin column, the thinner internal steel tube could not be provided. Consequently, the thin-walled inner steel tube stemmed from early inward local buckling before experiencing the yield performance. Furthermore, the lack of interior support for the thinner internal steel tube compromised the performance of the shell concrete. The lateral extension of the shell concrete could not be precluded sufficiently and as the early local buckling of the thinner inner tube developed, the loss of lateral restraint allowed to a lower capacity of the shell concrete.

On the other hand, comparison of the capacities of the double skin and double section columns reveals a crucial and compelling conclusion. Specimen 1-1-1-1 developed

199.70 kN greater (25.30 %) capacity compared to double skin counterpart 0-1-1-1. As is known, the specimen 1- 1-1-1 only differ from the specimen 0-1-1-1 in the presence of core concrete. However, the performance difference between the specimens is almost twice the crushing load of the normal strength core concrete alone which is 102.82 kN. The additional 96.88 kN (94.22 %) performance increment could be obtained due to proper internal support for the internal steel tube which allowed the thinner inner tube to eliminate the occurrence of early local buckling and exhibit greater compression performance. Accordingly, an appropriate confinement effect could be provided for both the shell and core concretes which also contributed to capacity improvement.

Comparison of the performances of the double section and classical CFST columns has the potential to specify if the cross-sectional area of the inner steel tube could be used effectively in double section columns. Specimen 1-1-1-1 has 168.83 kN greater compression capacity compared to that of specimen 1-1-O. This load level is very close to the squash load of the inner steel tube which is equal to 181.14 kN. In addition, considering the effect of the removed concrete area (is equal to the cross-sectional area of the inner steel tube) to place the inner steel tube, it can be deduced that the squash load of the thinner internal tube could be exploited efficiently in the double section column. The ability to consume the capacity of the internal tube is a very promising characteristic of double section columns. To be able undertake a complete assessment, the ductility performance of the specimens should also be addressed. Although double section specimen 0-1-1-1 experience slightly lower compression performance over 1-1-O, it has a superior ductility behaviour, Figure 4.7. This is due to the greater steel area in the double skin column. However, as can be observed in Figure 4.7, the double section specimen 1-1-1-1 develops significantly higher ductility compared to the classical CFST and double section counterparts. The effective use of the inner steel tube properties in double section configuration has a big role in this ductility performance.

The compression capacities of the specimens 1-2-O, 0-1-1-2 and 1-1-1-2 were recorded to be 1752.60 kN, 1681.98 kN and 1943.40 kN, respectively. The use of the thicker outer steel tube with greater yield strength significantly improved compression resistance. A comparison of the capacities of the columns with thicker outer tubes and thinner outer tubes introduces performance improvements in the range from 96.48 % to 113.07 %. This improvement range underlines the governing role of the thicker outer steel tube with higher yield strength. It could be again seen that classical CFST specimen performs slightly better than double skin counterpart. This behaviour could again be attributed to the insufficient support of the inner steel tube in the double skin specimen 0-1-1-2. Double section column 1-1-1-2 has 15.54 % greater capacity compared to double skin specimen 0-1-1-2. This capacity improvement is smaller than the capacity improvement provided with the double section column with thinner outer tube (comparison of 0-1-1-1 and 1-1-1-1), due to the dominating role of thicker outer tube. However, 15.54 % improvement corresponds to 261.42 kN which is greater than the capacity improvement obtained in double section column 1-1-1-1 (199.70 kN). This level of 261.42 kN increment is significantly higher (154.25 %) than the crushing load of the core concrete alone. Therefore, the capacity improvement of 261.42 kN suggests that the thicker outer tube with higher yield strength significantly improves the confinement effect which allows obtaining greater performances from core and shell concretes. Also, as a result of the superior confinement effect, the thinner inner steel tube performs better. Examining the performances of the classical CFST column and double section counterpart, it can be observed that double section column has 190.80 kN greater capacity which is already higher than the squash load of the thinner inner steel tube. Besides, consideration of the possible performance of the removed concrete area to place the inner tube could enhance this improvement to a further level. Accordingly, the greater confinement effect of the thicker outer steel tube with higher yield strength could be emphasized here again. Since the thicker outer tube has a dominant role in the performance of the specimens, the behaviour of ductility of the classical CFST column is better than that of the double skin column. Although double

skin column has greater steel area, the insufficient support for the inner steel tube compromised a possible ductility contribution of this tube. Furthermore, it could be also deduced that the lack of interior provision for the internal steel tube consequentially effected the ductility performance of the outer steel tube. Besides, the double section column here again exhibited surpassing ductility behaviour.

4.3.2 Specimens with Normal Strength Concrete and Thicker Inner Steel Tube

Figure 4.8 presents compression loading versus end shortening of columns with normal strength concrete and thicker inner steel tube. The curves of the specimens 1-1-O and 1-2-O which are shown in Figure 4.7 are plotted in Figure 4.8 again to be able to perform appropriate comparisons. The employment of the thicker inner steel tube has a profound useful effect on the performance of the composite columns. First, the thicker smaller diameter tube significantly increased compressive strength and ductility performance of the classical CFST column, Figure 4.8. Although the yield strength of this smaller diameter tube is smaller than the yield strength of thinner counterpart, the greater thickness played a significant role and led the specimen 1-2-I to reach 448.21 kN compression capacity.

The compression capacity of column 1-1-O is 820.29 kN as stated in previous subsection. The specimens 0-2-1-1 and 1-2-1-1 achieved capacities of 969.16 kN and 1076.18 kN, respectively. It is worth here noting that, unlike the double skin column with thinner inner steel tube, the double skin column with thicker inner tube exhibited a greater compression capacity compared to classical CFST counterpart, Figure 4.8. This result implies a very important characteristic of double skin columns. Since the thicker inner steel tube is less susceptible to local buckling compared to the thinner inner tube, the lack of internal support for thicker tube has a less adverse effect in double skin columns. Therefore, the cross sectional capacity of the thicker inner steel tube could be exploited more efficiently and the thicker inner steel tube allows the double skin column to create a distinct difference over the classical CFST column.

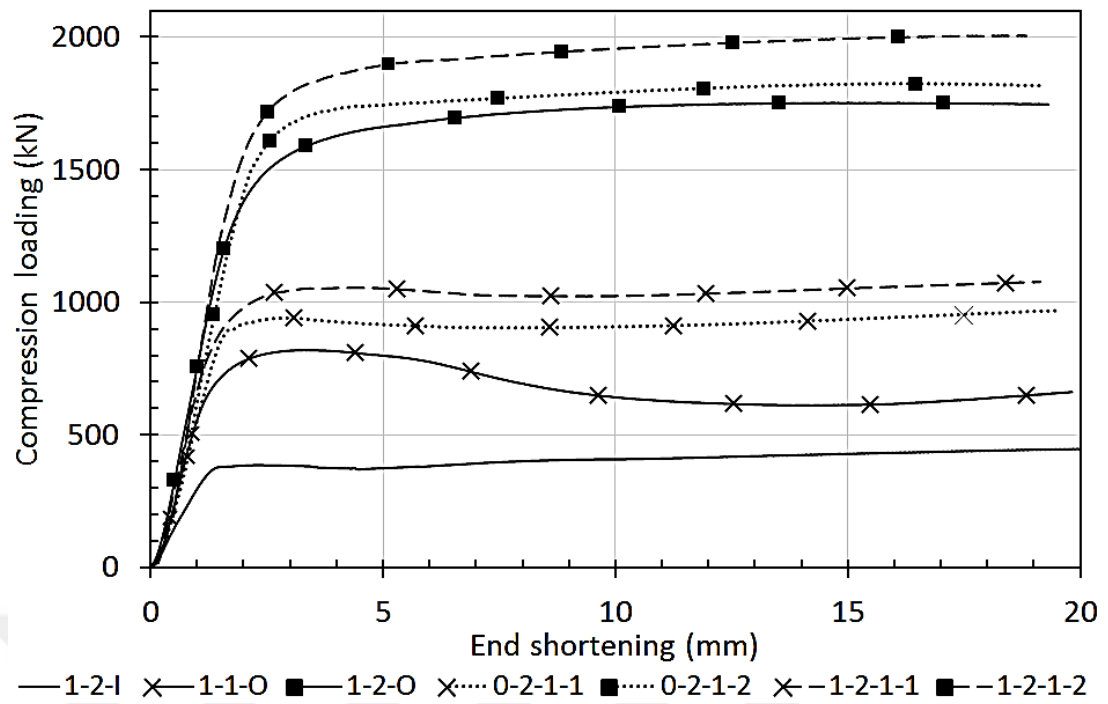


Figure 4.8 Compression load vs. end shortening curves of specimens with normal strength concrete and thicker inner steel tube

The double section column 1-2-1-1 has 107.02 kN (11.04 %) greater performance compared to double skin specimen. The contribution of the core concrete to column capacity is not high as it was (25.30 %) with the double section column with thinner internal steel tube. Since the properties of the thicker inner steel tube could be used effectively in CFDST column, the internal support effect of the core concrete could not contribute much. However, 107.2 kN contribution is still greater than the crushing load of the core concrete alone (33.69 %). This indicates again that double section configuration could develop an additional confinement effect. Another evaluation between classical CFST column and double section column reveals that the double section column develops 255.89 kN greater capacity over the CFST counterpart. Considering the potential effect of the removed concrete area on this load level, it can be concluded that f_y of the inner steel tube could be utilized appropriately in double section column 1-2-1-1.

Double skin column 0-2-1-2 which has a thicker outer tube achieved 1823.35 kN capacity which is greater than the compression capacity of classical CFST counterpart 1-2-O. On the other hand, as discussed in a previous subsection, the double skin column with thinner inner steel tube exhibited lower performance compared to CFST counterpart. Here, the smaller D/t ratio for the thicker inner tube developed a robust section which is less susceptible to local buckling and the detrimental effect of the absence of the core concrete was suppressed. Examining the compression behaviour of the double section column 1-2-1-2, it can be specified that this specimen reached a capacity of 2005.03 kN which is 181.68 kN (9.96 %) greater than the capacity of double skin column 0-2-1-2. Considering the crushing load of the core concrete, this performance increment is more than the twice of the crushing load which corresponds to a 126.95 % greater performance. This level of higher increment could be attributed to two main improvements. The first is the additional confinement triggered by the presence of the internal support. Secondly, the presence of the internal support also improved the compression performance of the inner steel tube.

Furthermore, comparison of the effect of the core concretes in columns with thinner and thicker outer tubes, it can be deduced that thicker external tube has the ability to exploit the benefits of the core concrete more efficiently. Assessment of the contribution of the inner tube to the column capacity reveals that double section column improves the column capacity 252.43 kN compared to the classical CFST column. This load level plus the effect of the removed concrete area, which is used to place the inner steel tube, suggest that the yield level of the inner steel tube could be efficiently utilized in double section column.

In order to address the contribution of the thicker outer steel tube over thinner outer steel tube, the capacities of the double section specimens 0-2-1-1 and 0-2-1-2 could be compared to each other. Also, the capacities of the 1-2-1-1 and 1-2-1-2 could be compared to each other to specify the contribution of the thicker outer tube for double section configuration. Unlike the specimens with thinner inner tube, the contribution

of the thicker outer tube for the specimens which have thicker inner tube is smaller. In double skin specimen configuration thicker outer tube improves the capacity by 88.14 % and in double section configuration this improvement is equal to 86.31%. The robust nature of the thicker inner tube plays an important role in this response, resulting in a relative reduction in the contribution of the thicker outer steel tube.

As opposed to the ductility of the double skin columns with thinner inner steel tubes, the ductility of the corresponding double skin columns with thicker inner tubes are significantly higher, Figures 4.7 and 4.8. This result implies that thicker inner steel tube does not only improve the compression capacity of the double skin columns, but also allows the column to develop remarkable ductility performance. On the other hand, double section columns with thicker inner tubes again exhibited favourable ductility behaviours like the double section columns with thinner inner tubes.

4.3.3 Specimens with High Strength Concrete and Thinner Inner Steel Tube

The compression loading versus end shortening of the specimens with high strength concrete and thinner inner tube are depicted in Figure 4.9. The capacity of the specimen 2-1-I was measured to be 389.14 kN. Based on the performance of the specimen 1-1-I with NSC, HSC contributed to the capacity just 37.84 kN. This improvement level is smaller than the expected contribution of the nominal crushing load of the high strength concrete. This behaviour is due to the long column effect which governs the behaviour of the classical CFST specimens manufactured by using inner tubes.

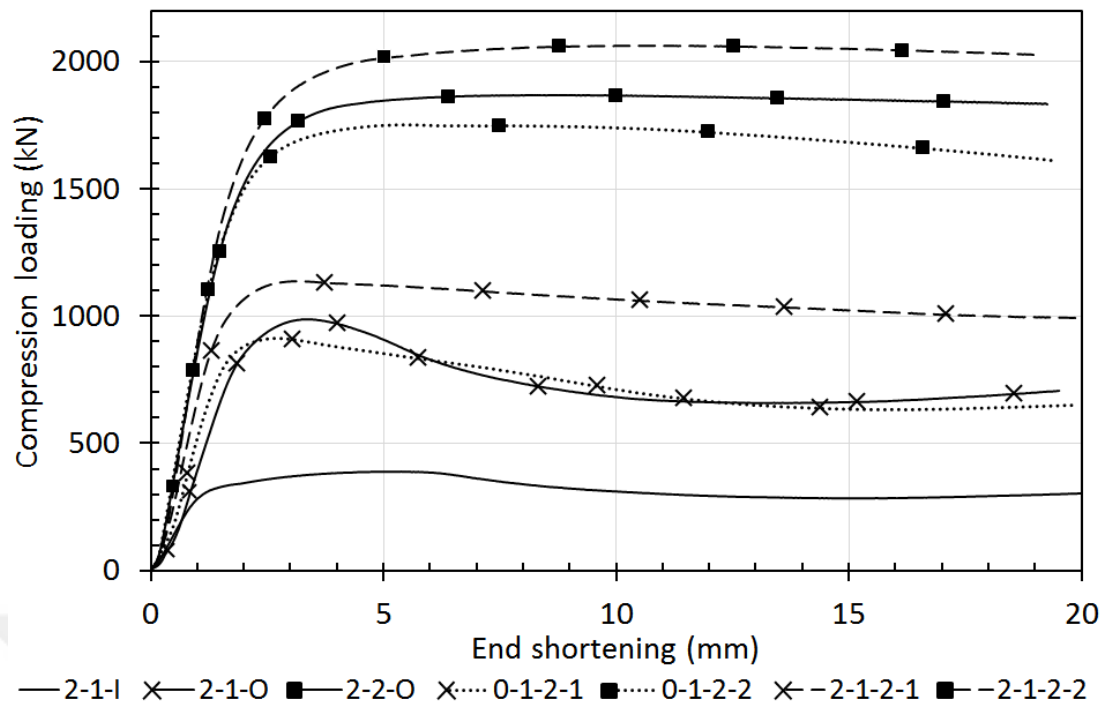


Figure 4.9 Compression load vs. end shortening curves of specimens with high strength concrete and thinner inner steel tube

The compression capacities of the specimens 2-1-O, 0-1-2-1 and 2-1-2-1 were achieved at 987.49 kN, 914.32 kN and 1138.44 kN, respectively. The detrimental local buckling effect of the thinner inner steel tube again led double skin specimen 0-1-2-1 to experience lower capacity performance compared to the classical CFST counterpart 2-1-O. Double section column 2-1-2-1 developed 224.12 kN (24.51 %) greater capacity over double skin counterpart 0-1-2-1.

However, this level of contribution of the core concrete is just 31.58 % greater than the crushing load of the core concrete alone. The level of the core concrete contribution in double section column with normal strength concrete was 94.22 % greater than the crushing load of the core concrete (comparison of 1-1-1-1 and 0-1-1-1). Therefore, this observation conveys crucial information about the nature of the high strength concrete.

The confinement effect could not be efficiently developed for the high strength concrete. The less confinement effect on the high strength concrete is mainly due to the low dilatation of this concrete type. The confinement could be developed after the

occurrence of the micro cracks in concrete which allows the concrete to expand and experience lateral stresses due to the existence of the steel tube. The increment of the compressive strength of the concrete increases the stiffness of the concrete and leads to less lateral expansion which does not allow the high strength concrete to attain confinement effectively [48, 49]. The double section specimen 2-1-2-1 performs 150.95 kN greater capacity over classical CFST counterpart 2-1-O. This loading level is less than the squash load of the internal tube. However, consideration of the effect of the removed concrete area to place the inner steel tube reveals that the yield strength capacity of the inner steel tube was completely exploited in the double section column.

The column specimens 2-2-O, 0-1-2-2 and 2-1-2-2 developed 1868.99 kN, 1752.89 kN and 2061.89 kN compression capacities, respectively. The early local buckling of the thinner inner steel tube which was not internally supported again caused an unfavourable effect on the double skin column and as a result, the specimen 2-2-O attained 116.1 kN (6.63 %) greater compression capacity compared to the double skin specimen 0-1-2-2. Examining the performance of the double section column over double skin counterpart, it could be seen that specimen 2-1-2-2 achieved 309.0 kN (17.62%) greater capacity. This capacity increment is 81.41 % greater than the crushing load of the core concrete. This level of the improvement could not just be attributed to the confinement effect. The existence of the internal support for the inner steel tube also improves the performance of this tube. However, it is a good implication for the confinement assessments. Although this level of increment is remarkable, it is less than the percent contribution of the normal strength core concrete which was 154.25 % greater than the crushing load of core concrete (comparison of 0-1-1-2 and 1-1-1-2). The decrease in the level of the core concrete contribution could again be explained by the ineffective confinement of the high strength concrete. The double section specimen 2-1-2-2 develops 192.90 kN (10.32 %) greater capacity over classical CFST specimen 2-2-O. This level of loading is already greater than the squash load of the thinner inner steel tube. In addition, consideration of the removed concrete area

suggests that the influence of the inner tube is even greater than 192.90 kN. The thicker outer tube with greater yield strength provides additional confinement effect and leads to higher performance.

The employment of the thicker outer steel tube instead of the thinner outer steel tube provides improvements in the compression capacities in the range of 81.12 % to 91.71 %. This rate of improvement is less than the improvement rate provided in columns with normal strength concrete (96.48 % to 113.07 %). Hence, the compromising effect of the high strength concrete in providing confinement should be underlined here again.

Assessments of the ductility of the columns with HSC against the specimens with normal strength concrete raise a crucial inference. It can be obviously observed that the ductility of the specimens with HSC are distinctly less than that of the specimens with normal strength concrete, Figures 4.7 and 4.9. As is well known, HSC is more brittle compared to normal strength concrete [32, 50]. Although high strength concrete enhances the compression capacity significantly, it decreases the ductility performance of the columns. Even though the ductility performance of the double section columns was influenced by the presence of high strength concrete, they perform superior ductility behaviours over classical CFST and double skin counterparts, Figure 4.9.

4.3.4 Specimens with High Strength Concrete and Thicker Inner Steel Tube

The compression performance of the column specimens with high strength concrete and thicker inner steel tubes are presented in Figure 4.10. The classical CFST specimen 2-2-I with smaller diameter tube reached a capacity of 457.46 kN which is just 9.25 kN greater than the capacity of column with normal strength (1-2-I). The high strength concrete could not improve the column capacity efficiently, due to the long column effect.

The double skin 0-2-2-1 and double section 2-2-2-1 specimens developed compression capacities of 1068.06 kN and 1226.19 kN, respectively. The use of the thicker inner

tube in CFDST column circumvents the detrimental local buckling effect of the unsupported tube and double skin specimen develops 80.57 kN greater compression capacity. Nevertheless, the presence of the core concrete in double section 2-2-2-1 column allowed this column to exhibit 158.13 kN greater capacity compared to double skin specimen 0-2-2-1. This capacity improvement is 19.24 % greater than the crushing load of the core concrete and smaller than the improvement obtained with normal strength concrete (33.69 %). The less effective confinement effect on high strength concrete showed itself here again. The double section specimen 2-2-2-1 achieves 238.70 kN (19.47%) greater performance compared to the capacity of classical CFST 2-1-O. This load improvement is smaller than the squash load of the thicker inner tube. However, consideration of the effect of the removed concrete area in double section specimen upgrades this load level up to the yield performance of the inner steel tube. Thus, it could be underlined again that yield performance of the thicker inner steel tube could be effectively utilized in double section columns even with high strength concrete.

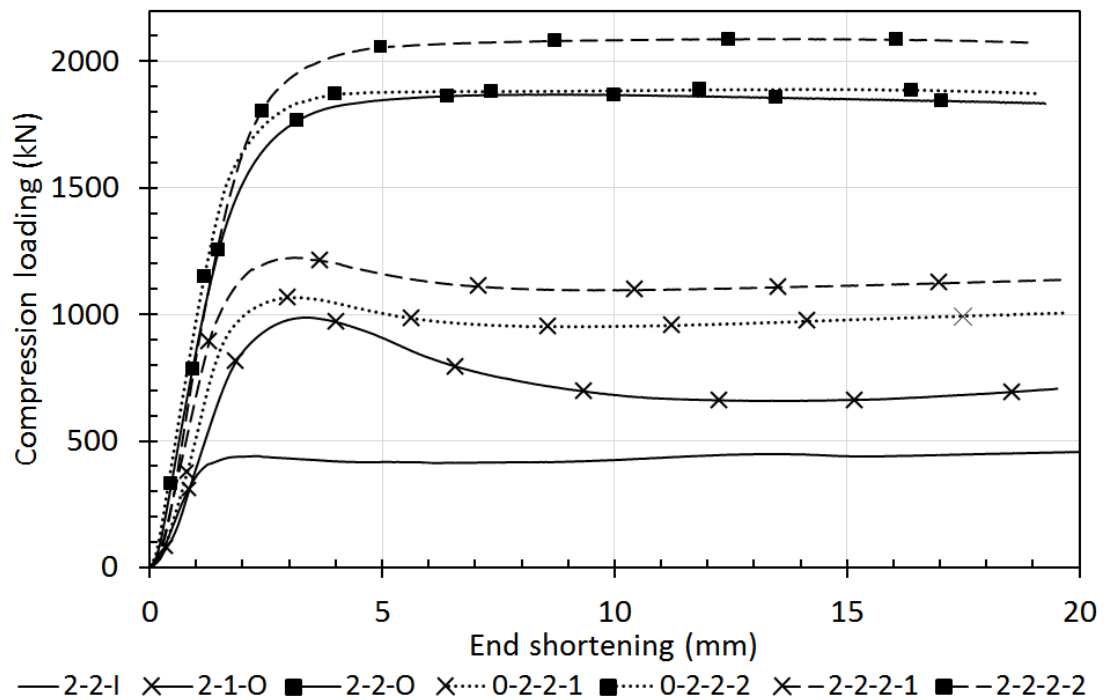


Figure 4.10 Compression load vs. end shortening curves of specimens with high strength concrete and thicker inner steel tube

The compression capacities of the specimens with thicker outer tube 0-2-2-2 and 2-2-2-2 were recorded to be 1889.69 kN and 2088.11 kN, respectively. The performance of the double skin specimen 0-2-2-2 is just 20.70 kN greater than the classical CFST specimen 2-2-O. The thicker internal tube enhanced the performance of the double skin column. However, this enhancement is not sufficient to develop a remarkable difference over classical CFST column. Double section specimen achieved 198.42 kN (10.50%) greater capacity compared to double skin specimen. This level of capacity difference is 49.62 % greater than the crushing load of the core concrete. It could again be noted that the contribution of the core concrete in double section column with thicker outer tube is significantly greater than that of the core concrete in double section column with thinner outer tube (19.24 %). The performance difference of 219.13 kN between the double section and classical CFST column is lesser than the squash load of the internal tube. However, considering the potential contribution of the removed concrete area to place the inner steel tube, it can be deduced that the yield performance of the inner tube could be effectively utilized in double section column 2-2-2-2.

The employment of the thicker tube for the double skin specimen improved the performance by 76.93 %. Besides, the thicker steel tube contributed to the compression performance by 70.29 % for the double section column. Comparing the contributions of the thicker outer tube for the columns with HSC against that of the specimens with NSC (88.14 % and 86.31 %), it could be concluded that the high strength concrete led the steel tubes to develop less confinement effect. The ductility behaviour of the specimens with thicker inner tube is obviously superior than that of the columns with thinner inner steel tube, Figures 4.9 and 4.10. However, the specimens with normal strength concrete perform better ductility behaviour compared to the specimens with high strength concrete, Figures 4.8 and 4.10. Therefore, the brittle nature of the high strength concrete shows itself in developing less confinement and ductility.

4.4 Failure Modes

The failure pattern of the columns could reveal the individual physical behaviour of constituent parts of the columns and the composite action. The comparison of the failure modes of the column specimens are based on the type of the inner tube and concrete again.

4.4.1 Specimens with Normal Strength Concrete and Thinner Inner Steel Tube

The failure modes of the specimens with normal strength concrete and thinner inner steel tube are depicted in Figure 4.11. Specimen 1-1-I which was manufactured using smaller diameter steel tube experienced a global mode of failure due to greater L/D ratio as shown in Figure 4.11. On the other hand, all other columns exhibited yielding of the steel tube which was followed by crushing of the concrete. Therefore, due to the smaller L/D ratios these columns attained local modes of failure. It is crucial here to note that the specimens with thinner outer tube also showed evidence of shear cracks in concrete (specimens 1-1-O, 0-1-1-1 and 1-1-1-1). However, the thicker outer tube governed the compression behaviour of the columns and did not allow the specimens to exhibit shear failure modes. This dominating nature of the thicker outer tube is another benefit for the composite columns. Furthermore, it is also obvious in Figure 4.11 that the specimens with thicker outer steel tube exhibit significantly fewer lateral deformations compared to the specimens with thinner outer tube. This implies that the thicker outer tube provides an appropriate composite action which allows the concrete and steel tube to serve together properly. It is important in composite structural members to satisfy this harmony.

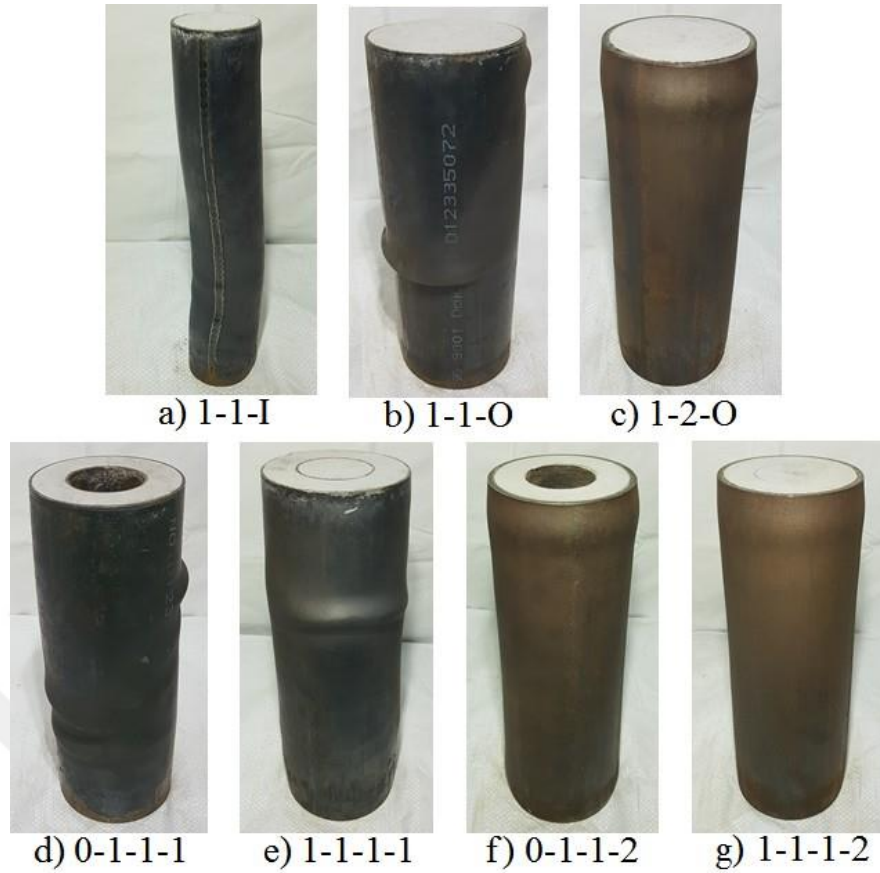


Figure 4.11 Failure modes of the specimens with normal strength concrete and thinner inner steel tube

To be able to address the behaviour of the CFDST columns, it is also necessary to observe the failure shape of the inner steel tube. Figure 4.12 shows the failure shape of the thinner inner steel tubes in double skin columns 0-1-1-1 and 0-1-1-2. The thinner inner steel tube in specimen 0-1-1-1 experienced excessive level of inward local buckling as shown in Figure 4.12. This type of inward local buckling is the result of lack of internal support for the inner steel tube. Therefore, it could be verified that the use of the thinner internal steel tube raises a significant compromising effect in double skin columns. It is not possible to exploit the yield performance of the inner steel tube which stems from this level of excessive local buckling. Furthermore, this level of local buckling would compromise the performance of the shell concrete. That is to say, the shell concrete and the inner steel tube could not serve together properly under this circumstance. The thinner inner steel tube in double skin specimen 0-1-1-2 also

exhibits inward local buckling. However, the level of the local buckling in this specimen is not severe and intense as it was with 0-1-1-1, Figure 4.12. This behaviour could be explained by the presence of the thicker outer tube in specimen 0-1-1-2. The thicker outer tube supports the shell concrete appropriately and provides a good interaction. Thus, it could preclude the severe local buckling in the thinner inner steel tube.

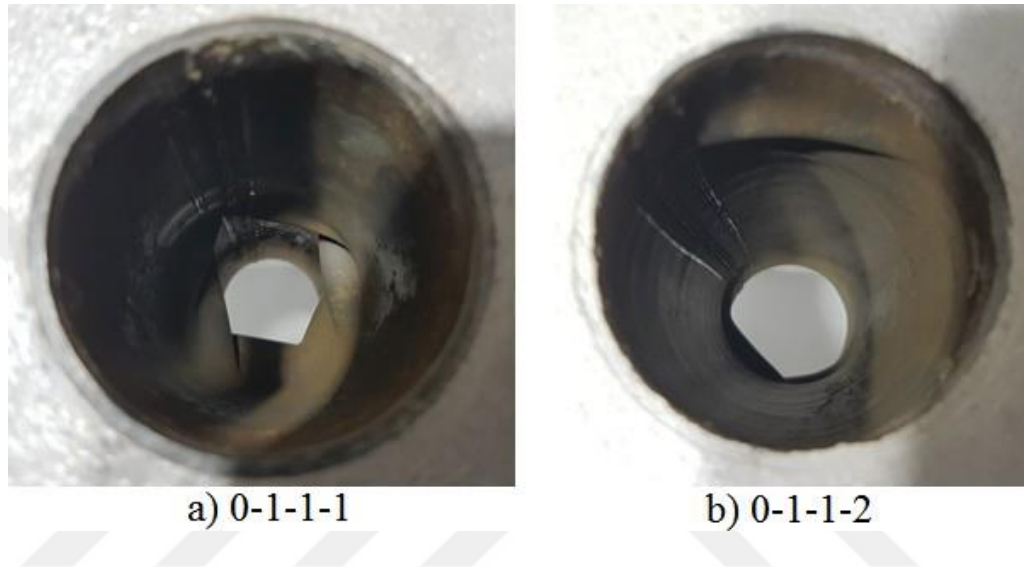


Figure 4.12 Failure modes of the thinner inner steel tubes in double skin specimens with normal strength concrete

4.4.2 Specimens with Normal Strength Concrete and Thicker Inner Steel Tube

The failure modes of the specimens with normal strength concrete and thicker inner tube are presented in Figure 4.13. The failure modes of the specimens 1-1-O and 1-2-O are shown in Figure 4.13 again for comparison purposes. Specimen 1-2-I attained a global mode of failure with no interaction with local mode. The greater L/D ratio for this specimen is the reason of global failure mode. The detrimental effect of the thinner outer tubes led to the intensified local buckling of these tubes, Figure 4.13. On the other hand, the specimens with thicker outer tube performed plausible composite action and developed convenient failure modes.



Figure 4.13 Failure modes of the specimens with normal strength concrete and thicker inner steel tube

It is important here to examine the failure modes of the inner steel tubes of double skin specimens, Figure 4.14. The failure modes of the thicker inner steel tubes are extremely different compared to the failure modes of the thinner inner steel tubes. Unlike thinner inner steel tubes shown in Figure 4.12, the thicker inner steel tubes did not experience harsh and intense local failure modes. Instead, thicker inner tubes showed evidence of smooth and moderate level of local buckling. This kind of behaviour implies that the thicker inner steel tube is strong enough to eliminate adverse effects of early local buckling and appropriate to fulfil the performance requirements of double skin columns. However, it could be observed that the thicker inner tube is apt to perform better in double skin column with thicker outer tube and experiences less distortions, Figure 4.14 (b). It is also possible to obtain superior performance from the shell concrete thanks to the robust nature of the thicker inner steel tube. Therefore,

it is worth noting that to be able to provide a desired level of composite action thicker inner tubes should be used in double skin columns.

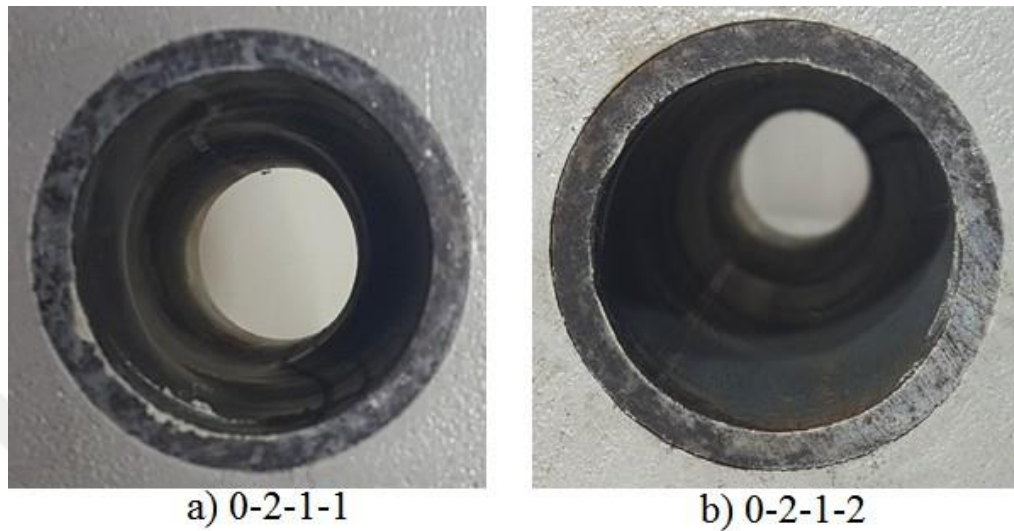


Figure 4.14 Failure modes of the thicker inner steel tubes in double skin specimens with normal strength concrete

4.4.3 Specimens with High Strength Concrete and Thinner Inner Steel Tube

Figure 4.15 displays the failure modes of the specimens with high strength concrete and thinner internal tube. Although the specimen 2-1-I has a greater L/D ratio, the global failure mode of this column is highly interacted with local buckling of the steel tube. On the other hand, the case was completely different with the column with normal strength concrete (1-1-I), Figure 4.11. The late response of the high strength concrete to the lateral expansion led the steel tube to exhibit early local buckling. Other specimens with thinner outer tubes showed severe local buckling distortions as illustrated in Figure 4.15. Besides, the specimens with thicker outer tube performed good composite action and showed less local buckling distortions.

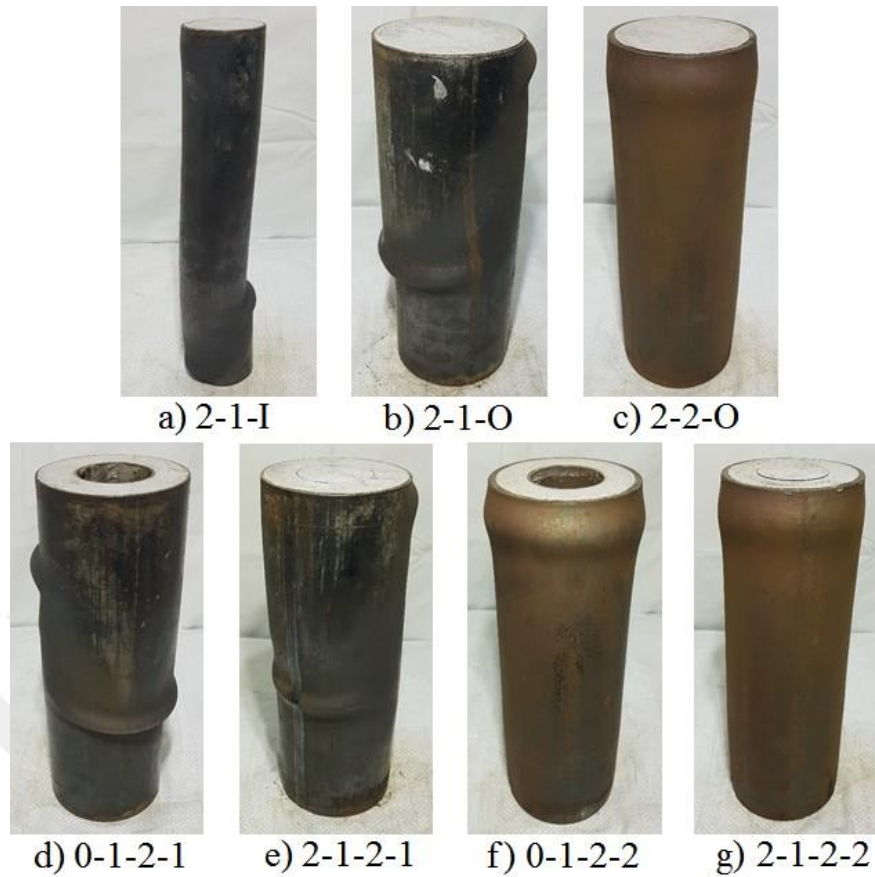


Figure 4.15 Failure modes of the specimens with high strength concrete and thinner inner steel tube

The lack of the internal support again caused excessive amount of distortions in thinner inner steel tubes in CFDST columns as seen in Figure 4.16. Nevertheless, the thinner inner steel tube in the double skin column with a thicker outer tube has fewer lateral distortions. This again shows that in double skin columns thinner inner steel tubes could gain greater performance when used with thicker outer steel tubes. However, it is obvious that the useful capacity of the thinner inner steel tube cross section could not be exploited efficiently due to local buckling.

4.4.4 Specimens with High Strength Concrete and Thicker Inner Steel Tube

The failure behaviour of the columns with high strength concrete and thicker inner steel tubes are presented in Figure 4.17. It is important here to show that the specimen 2-2-I attained a global mode of failure without any interaction with local modes, as

opposed to the column with high strength concrete and thinner tube (2-1-I). Therefore, this result implies that the thicker tube eliminates the detrimental effect of the high strength concrete and provides better configuration. The columns with thinner outer tubes attained severe local failure modes as shown in Figure 4.17. The performance of the columns with thicker outer tubes are again superior to that of the columns with thinner outer steel tubes.

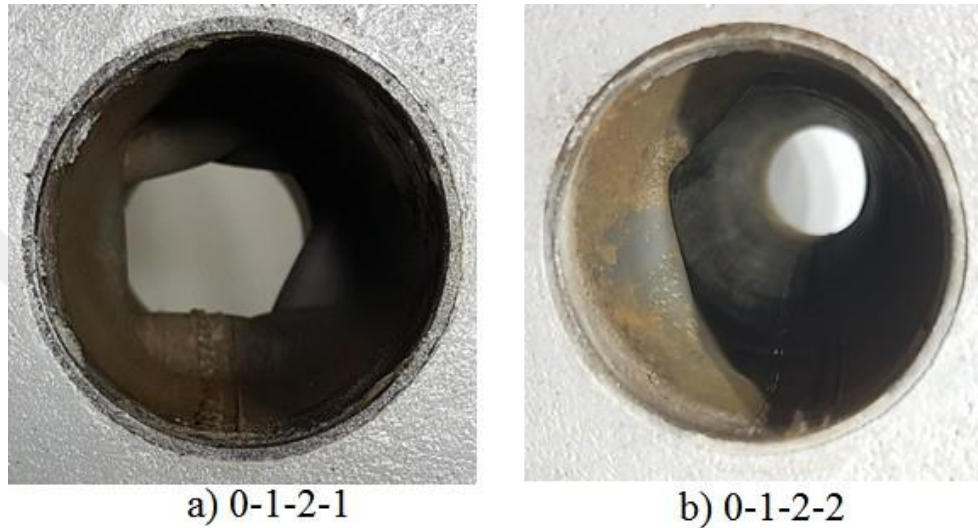


Figure 4.16 Failure modes of the thinner inner steel tubes in double skin specimens with high strength concrete

Thicker inner steel tubes developed good interaction behaviour in double skin columns again and exhibited significantly fewer inward distortions compared to the thinner inner steel tubes, Figures 4.16 and 4.18. This means that the thicker inner tube serves the cross-sectional capacity efficiently. Furthermore, the thicker inner steel tube in the column with a thicker outer tube has a very promising performance and attained very small inward distortions as can be observed in Figure 4.18. Therefore, the thicker inner tube is able to develop good composite action even with HSC. This behaviour is very important to be able to exploit the strength capacity of high strength concrete in composite columns.

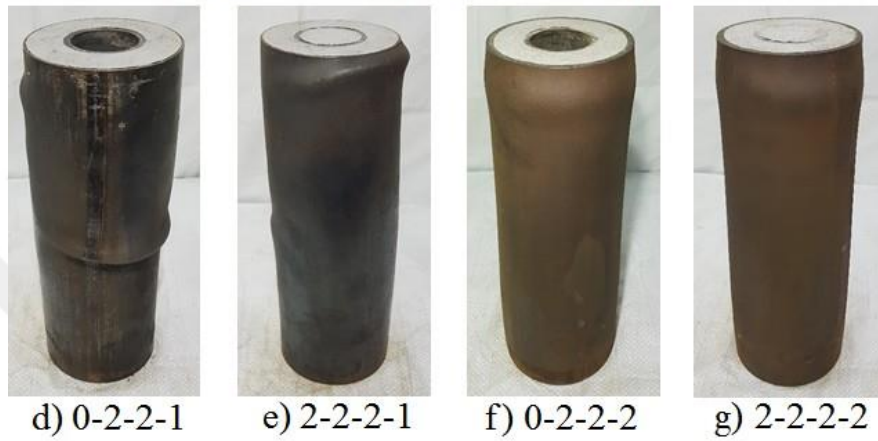


Figure 4.17 Failure modes of the specimens with high strength concrete and thicker inner steel tube

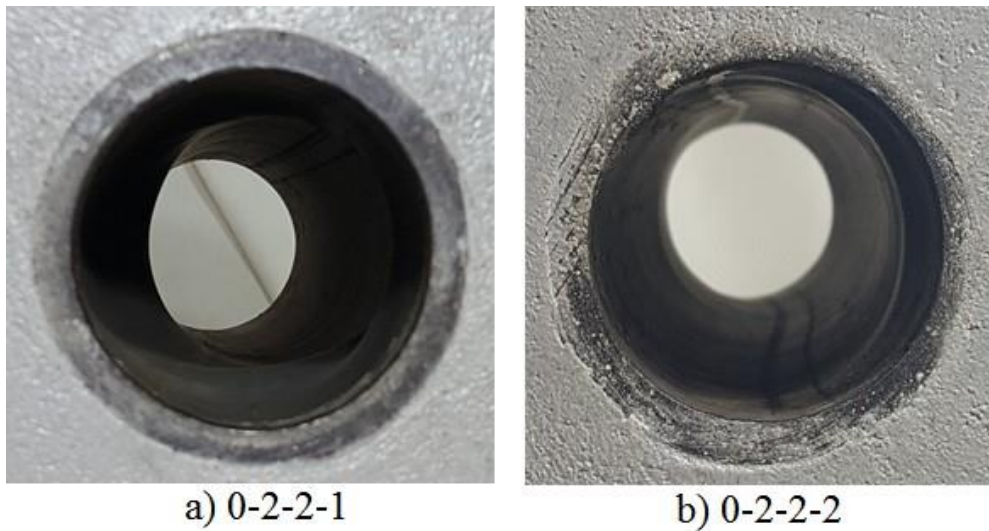


Figure 4.18 Failure modes of the thicker inner steel tubes in double skin specimens with high strength concrete

4.5 Conclusions

The design of high-rise buildings, deep underground tunnels, huge towers and long span bridges is on the rise due to the intensified actions of the cities. Given these circumstances, it would appear desirable and crucial to develop robust structural members which could be stressed and deformed to extreme levels without any failure. CFST columns have the ability to resist significant level of compression forces. However, the current developments in the civil engineering projects challenge the classical CFST column configurations. Concrete filled double skin columns have been the main focus of many papers to propose efficient structural component which could potentially replace the classical CFST compression members in difficult design scenarios. On the other hand, concrete filled double section columns offer distinctive advantages and could circumvent many more design concerns of huge structures simultaneously. However, to date far too little attention has been paid to the concrete filled double section columns. Besides, no research has been found that surveyed the compression behaviour of ordinary, CFDST and CFDCST columns in a comparative form. This work presents the results of an in-depth experimental program which was undertaken to address the performances of the classical, double skin and double section columns. A systematic way was traced to manufacture the column specimens. Furthermore, different levels of material and geometrical properties were employed to reveal discussions which would be highly representative for the composite construction field. Following, the developed formulations of the EC4 and AISC 360–16 prediction methods were deployed versus the test results to trace the suitable prediction method for double skin and double section columns. Based on the results of the experimental program and design formulation assessments, following conclusions could be underlined;

The primary complication with using the thinner inner steel tube ($D/t = 23.93$) in double skin columns is the early local buckling which leads to smaller compression performances compared to classical CFST counterparts. Besides, the double skin

columns with thicker inner tube ($D/t = 10.45$) attained greater performances over classical CFST counterparts. Thicker inner tubes also improved the ductility of the columns.

- However, in all cases, double section columns always exhibited significantly greater compression performances compared to classical CFST and double skin specimens. Also, double section columns always experienced superior ductility behaviour.
- Double section column configuration allows a complete utilization of the yield capacity of the inner steel tube and crushing capacity of the core concrete. In addition, a further level of confinement could be obtained in this type of column.
- Although high strength concrete improves the capacity of the columns, it adversely effects the confinement effect and ductility due to lower dilatation. Moreover, it was shown that lower dilatation of the high strength concrete causes the column to attain early local buckling.
- In double skin columns which have thinner inner steel tubes, the effect of the high D/t ratio led to harsh inward local buckling behaviours. On the other hand, the thicker inner steel tubes did not show any evidence of harsh inward local buckling which significantly improved the column capacity and confinement.
- For classical CFST columns EC4 has a superior prediction ability over AISC 360–16 and on average the discrepancy is 6.5% for the tested specimens.
- Among four modified methods, AISC 360–16 reinforcement approach performs very well for the double skin columns and on average the predictions diverge 4.7% from the test results. This response verifies the potential of the modified formulations for design purposes. On the other hand, for double section columns EC4 two columns approach has the predictions which agree very well with the test results with 5.9% discrepancy on average.

- It is shown that the divergences N10% for the EC4 format are mainly due to the excessive confinement effect attributed to the thinner outer tubes in the standard formulations. However, for the AISC 360–16 format this type of divergence arises due to the ignorance of the higher confinement effect of the thicker outer tube in standard formulations. It is quite possible to obtain predictions with higher fidelity by calibrating the effect of confinement in both design specifications.



CHAPTER 5

THE CONTRIBUTION OF THE INNER STEEL TUBE IN THE CONCRETE FILLED DOUBLE SKIN (CFDST) COLUMNS

5.1 General

Concrete filled steel tube (CFST) columns have been commonly utilized in marine structures, bridges, offshore applications and high-rise buildings owing to their distinctive advantages as high ductility, high strength, and good seismic behaviour [60, 74, 75, 123, 138, 257-259]. The crucial benefit of a CFST column configuration is the provided confinement effect with the use of circular steel tubes. The circular steel tube leads the infill concrete to be stressed in triaxial state and as a result confined concrete attains greater compression performance over the performance of the same concrete in unconfined condition. Such a confinement effect could not be efficiently provided in square or rectangular sections, since the walls in these tubes withstand the lateral expansion of the concrete by plate bending, instead of the developed hoop stresses in circular sections.

In addition, the steel tube allows the utilization of high and ultra-high strength concrete by precluding the extremely brittle and explosive failure of these concrete classes [139, 147, 152, 247, 260]. Also, the infill concrete improves the compression characteristics of the steel tube by suppressing inward local buckling [248]. This allows the utilization of the steel tubes with greater D/t ratios for design purposes to provide cost effective solutions. Additional cost reductions could be acquired with the use of CFST members, since the steel tube serves as a constant formwork for the fresh concrete [261, 262]. Furthermore, bending strength of the steel tubes could be exploited completely in CFST configuration, since the steel tube is at the greatest distance from the column centroid (bending stresses are maximum at the outer fibres).

This nature of CFST members is compelling and gives rise to the employment of these members as highly stressed beam columns in moment resisting structures. Combination of above merits develops a high standard structural member which could serve under serious loading actions. The anatomy of the CFST members; their use, composite action between the materials, design concerns, failure behaviours under different loading scenarios and real field applications were comprehensively reviewed by Han *et al.* [28].

Concrete Filled Double Skin Steel Tube (CFDST) column which is an engineered form of composite structural member, draw great attention in the literature. Figure 5.1 and 5.2 depict the cross-sectional details of a CDST column. With the objective of replacing classical CFST counterparts, a great number of works were undertaken on CFDST members. It has been shown that the CFDST columns have desired properties in static and dynamic loading cases [184]. The fundamental benefits expected from a CFDST column design are the higher strength to weight ratio and bending stiffness compared to the classical CFST member [39, 152]. Since the inner steel tube is empty, the own weight of the member could be noticeably reduced [122]. The section of the inner steel tube is also located to distance away from the column centroid and has remarkable potential to improve the bending stiffness. Furthermore, in a fire scenario a CFDST column would perform superior in two aspects. First, the shell concrete and outer steel tube mitigate the tremendous temperature increment in the inner steel tube, thus the column could sustain the loading longer before the collapse. Also, the hollow inner steel tube could serve as a ventilation channel in fire case [139, 181]. The attractive engineering properties of CFDST columns directed many works in which the main target was the investigation of column parameters. D/t ratios of the steel tubes (outer and inner), L/D ratio and the hollow ratio have been the main research parameters in experimental and numerical investigations on CFDST columns [31, 62, 129, 138, 194, 237, 263].

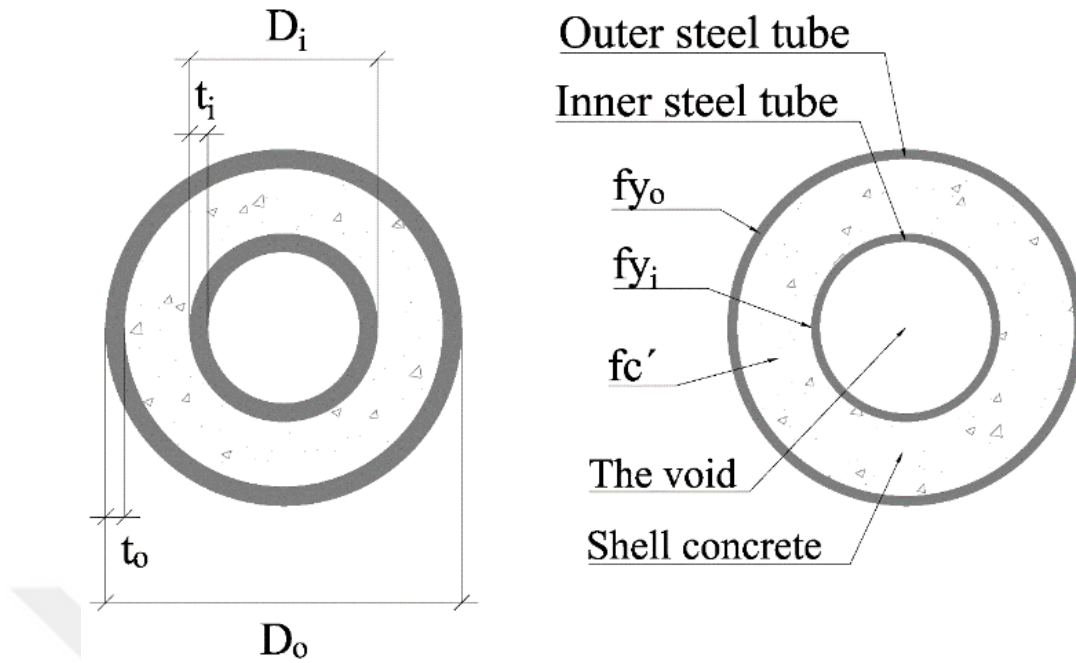


Figure 5.1 CFDST cross-section details

5.2 Aim and Significance of the Study

The past decades have seen increasingly rapid advances in composite construction. In this manner, CFDST columns have been specified to be strong members which could potentially replace the standard CFST counterparts in several aspects. Although the benefits of a CFDST column lie in the presence of the inner steel tube, the research to date has tended to focus on the general performance of such columns rather than the characterization of the inner steel tube. With the objective of addressing the influence of the inner steel tube on the compression characteristics of the CFDST columns, this chapter reveals the results and key findings of a comprehensive experimental work. Mechanical and geometrical properties of the test specimens were specified in such a way that would represent a wide range of real field constructions. To this end, two different D/t ratios for the inner and outer steel tubes and two concrete classes were utilized. To be able to characterize the influence of the inner steel tube in detail, the existence of the inner tube in CFDST columns was considered to be another parameter.

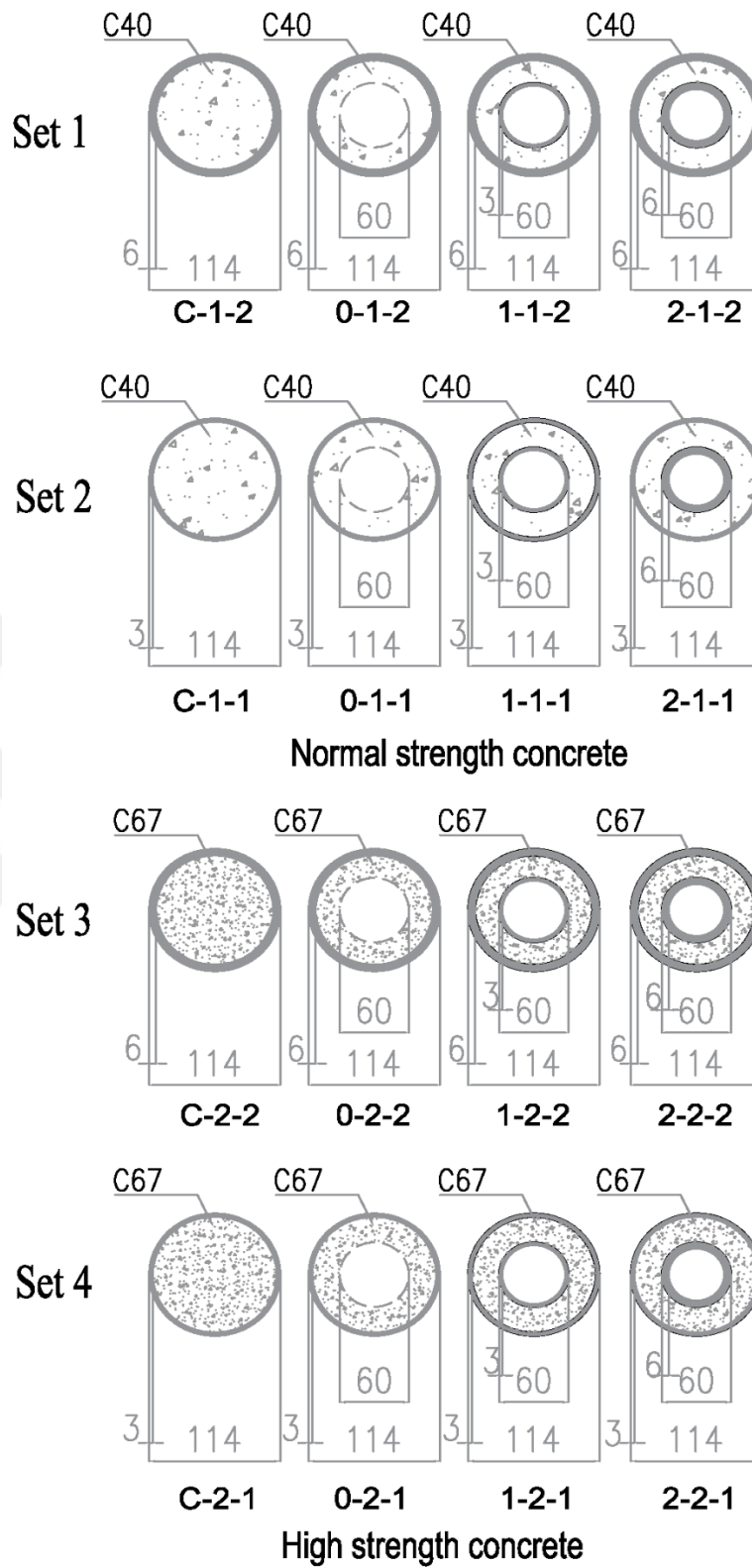


Figure 5.2 CFDST cross-section configurations



Figure 5.3 CFDST specimens

That is to say, while CFDST specimens include the inner steel tube in the experimental sets, some additional specimens which have the outer tube and shell concrete, but without inner steel tubes were produced. The concrete sections in these specimens have the hollow shapes identical to that of the shapes of the shell concrete in CFDST specimens, but there is no inner steel tube. To be able to address the performance of the specimens it is required to designate some reference behaviours. Towards this aim, classical CFST columns were also manufactured. In total, sixteen specimens were experimentally tested under concentric compression to delve into the behaviour of the CFDST columns. Finally, design specification prediction methods and some additional design formulations proposed by several authors were used against the test results to assess the ability of the existing formulations. The findings in this study will provide a new understanding of CFDST columns and extend the knowledge on the contribution of the inner steel tubes.

5.3 Experimental Tests

5.3.1 Material Properties

In present experimental investigation, two different concrete grades (normal strength and high strength) were adapted in filling the composite columns. The concrete mix designs for both grades were produced with the aim of having Self Compacted Concrete (SCC). SCC has been confirmed to be a very promising way of concrete construction, especially in formidable fields [91, 264, 265]. Such a concrete eliminates compaction problems which could jeopardize the performance of the structure by leading inappropriate interaction between the materials. There is no need to follow extreme precautions to be satisfied about suitable compaction by using SCC. It is also plausible to employ this concrete type in CFST column construction, since the concrete is filled in hollow tubes and a possible compaction problem because of low workability of normal concrete could not be detected in these closed members. During the concrete casting of composite columns, to measure the compressive strengths, cylinder moulds with the dimensions of 100×200 mm were also cast with concrete, Figure 5.6. Following the curing process, ASTM C39/C39M [253], regulations were followed in concrete specimens crushing. The recorded average compressive strengths of the normal strength and high strength SCC mixes are 40.24 MPa and 67.32 MPa, respectively.

Two different outer steel tubes and two different inner steel tubes were used in the experimental study to determine the impact of tube parameters on the behaviour of the composite columns, Figure 5.2 and 5.3. While the outer diameters of the different outer tubes are identical and equal to 114.3 mm, the thicknesses of the thinner and thicker tubes are 2.73 mm and 5.85 mm, respectively. The thicknesses of two different inner steel tubes are equal to 2.52 mm and 5.77 mm. Also, two different inner steel tubes have identical outer diameters of 60.3 mm. Corresponding D/t ratios for the thinner and thicker outer tubes are 41.87 and 19.54, respectively. In this manner, the D/t ratio for the thinner inner steel tube is 23.93, while this ratio for the thicker inner steel tube

is equal to 10.45. The D/t ratios used in the present study are highly representative of practical CFDST columns in the construction field. Along with the manufacturing of the columns, tensile specimens were cut from the steel tubes. Coupon specimens were sectioned and tested following the procedures of ASTM E8/E8M [197], Figure 5.4. The yield strengths of the 114.3×2.73 mm, 114.3×5.85 mm, 60.3×2.52 mm and 60.3×5.77 mm steel tubes were measured to be 285 MPa, 455 MPa, 396 MPa and 310 MPa, respectively.



Figure 5.4 Tensile coupon specimens

5.3.2 Column Specimens and Compression Testing

The current campaign focuses on the experimental behaviour of stub CFDST columns. A stub column configuration eliminates the global buckling failure and enables clear observation of the impact of the material and cross-sectional properties on the compression behaviour of the columns [265]. For this purpose, $L/D = 3$ was specified for the composite columns. L/D of 3 has been generally used in the investigations to

explore the performance of CFST stub columns [3, 201]. Considering the machining process of the specimen ends, the tubes were cut to lengths which are somewhat longer than 343 mm. Subsequently, all member ends were machined to obtain final exact tube lengths of 343 mm. Such a machining process was undertaken to obtain flat ends which are perpendicular to the axis of the tube. Prior to concrete casting, to obtain suitable interaction between the concrete and steel tubes, steel tube surfaces were cleaned carefully. Afterwards, to be able to keep the fresh concrete in filling process, the lower ends of the outer tubes were closed with flat glass plates using silicon, Figure 5.5.

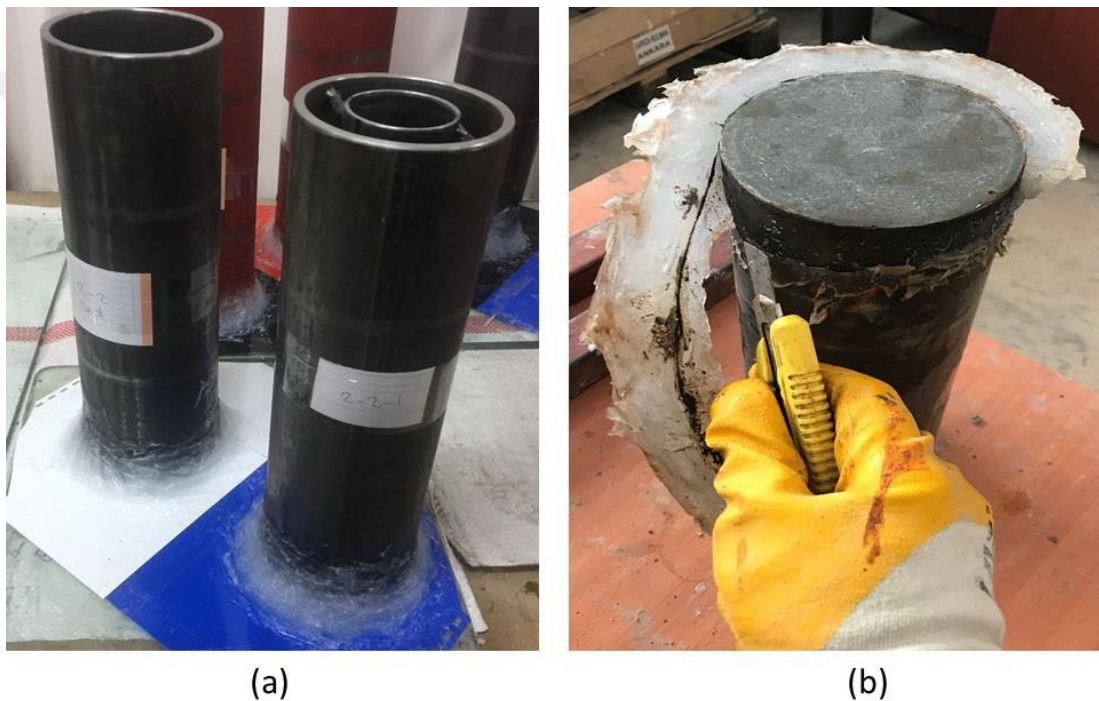


Figure 5.5 The silicone procedure

Following, the SCC mixes were used to cast the steel tubes. The top last 3-4 mm of the steel tube were left empty for levelling purpose. After completion of the curing of the concrete, the attached glass plates were removed. The glass plates provided flat and levelled lower ends for the composite columns. However, it is also crucial for compression testing to obtain flat upper ends. The specimens' upper ends were levelled by using levelling epoxy, Figure 5.7. Herein, it is also important to detail the manufacturing process of the columns which have hollow shell concrete without an

inner tube. To produce the shape of hollow concrete, inner steel tubes of 60.3 mm diameter which are much longer than the 343 mm were used as moulds. Very thin oiled papers were rolled to the outer surfaces of these moulds. After the setting of the shell concrete, these inner steel tubes were pulled out slowly in such a way that would not harm the concrete. Figure 5.8 shows the details of such a specimen which has shell concrete without an inner steel tube.



Figure 5.6 Cylinder concrete specimens

To eliminate the eccentricity and related bending effect, the composite columns were carefully centred in the testing device. Strain gauge type displacement transducers which have sensitive measuring ability were attached to test setup to record the end shortening of the specimens during the compression testing continuously.



Figure 5.7 Epoxy procedure

Column specimens were tested by following a slow rate of displacement-controlled loading procedure. Table 1 presents the properties of the column specimens. The naming convention of the specimens in the present study is built on the column cross-sectional properties. The numbers 0, 1, and 2 are used to represent properties of the constituent materials. 0 is used to imply the absence of the inner steel tube (specimens with hollow concrete without inner steel tube). 1 and 2 stands for the weaker and

stronger properties, respectively. For example, 1-2-1 represents the specimen which has a thinner inner tube ($D/t = 23.93$), high strength shell concrete and thinner outer tube ($D/t = 41.87$). The letter C refers the classical CFST column which is considered to be control specimen for the experimental set. For instance, C-1-2 represents the classical CFST column which has normal strength concrete and thicker outer tube.



Figure 5.8 Manufacturing process of the specimen with hollow concrete

Table 5.1 Mechanical and geometrical properties of the column specimens

Column (ID)	Do/t	Shell f_c (MPa)	Inner tube			Outer tube		
			D	t	f_{yi}	D	t	f_{yo}
			(mm)	(mm)	(MPa)	(mm)	(mm)	(MPa)
Set 1								
C-1-2	19.53	40.24	—	—	—	114.3	5.85	455
0-1-2	19.53	40.24	—	—	—	114.3	5.85	455
1-1-2	19.53	40.24	60.3	2.52	396	114.3	5.85	455
2-1-2	19.53	40.24	60.3	5.77	310	114.3	5.85	455
Set 2								
C-1-1	41.86	40.24	—	—	—	114.3	2.73	285
0-1-1	41.86	40.24	—	—	—	114.3	2.73	285
1-1-1	41.86	40.24	60.3	2.52	396	114.3	2.73	285
2-1-1	41.86	40.24	60.3	5.77	310	114.3	2.73	285
Set 3								
C-2-2	19.53	67.32	—	—	—	114.3	5.85	455
0-2-2	19.53	67.32	—	—	—	114.3	5.85	455
1-2-2	19.53	67.32	60.3	2.52	396	114.3	5.85	455
2-2-2	19.53	67.32	60.3	5.77	310	114.3	5.85	455
Set 4								
C-2-1	41.86	67.32	—	—	—	114.3	2.73	285
0-2-1	41.86	67.32	—	—	—	114.3	2.73	285
1-2-1	41.86	67.32	60.3	2.52	396	114.3	2.73	285
2-2-1	41.86	67.32	60.3	5.77	310	114.3	2.73	285

Table 5.2 Compression capacities of the specimens

Column (ID)	N_{exp} (kN)	CSCR	SI
C-1-2	1461.95	1	1.23
0-1-2	1099.61	0.75	0.93
1-1-2	1421.54	0.97	1.12
2-1-2	1574.26	1.08	1.13
C-1-1	684.13	1	1.16
0-1-1	551.92	0.81	0.94
1-1-1	734.60	1.07	1.09
2-1-1	913.07	1.33	1.14
C-2-2	1683.19	1	1.22
0-2-2	1265.80	0.75	0.92
1-2-2	1505.67	0.89	1.08
2-2-2	1666.41	0.99	1.09
C-2-1	1024.75	1	1.28
0-2-1	713.44	0.70	0.89
1-2-1	899.21	0.88	1.09
2-2-1	1088.06	1.06	1.15

5.4 Experimental Results and Discussions

The experimental ultimate compression loads of the column specimens are given in Table 2. In this section, the compression behaviours of the specimens are discussed considering the load versus end shortening curves. Such curves could reveal the capacities of the columns and their ductility behaviours in a comparative form. In each experimental set, the standard CFST column is set to be the control specimens and the

performances of the double skin columns are assessed considering the behaviour of the control specimen. Also, the specimens with hollow concrete could be suitable base references for the other columns.

5.4.1 Specimens with NSC and Thick Outer Steel Tube (Set 1)

The control specimen C-1-2 exhibited a high ductile behaviour as shown in Figure 5.8. Although the steel cross-sectional area is greater in double skin specimen 1-1-2 compared to the control specimen C-1-2, the double skin specimen 1-1-2 experienced a performance loss of -2.76 % based on the performance of the specimen C-1-2. Also, this specimen developed less ductile behaviour over the control specimen C-1-2. The degradations in compression capacity and ductility of the specimen 1-1-2 could be attributed to the characteristics of the inner tube.

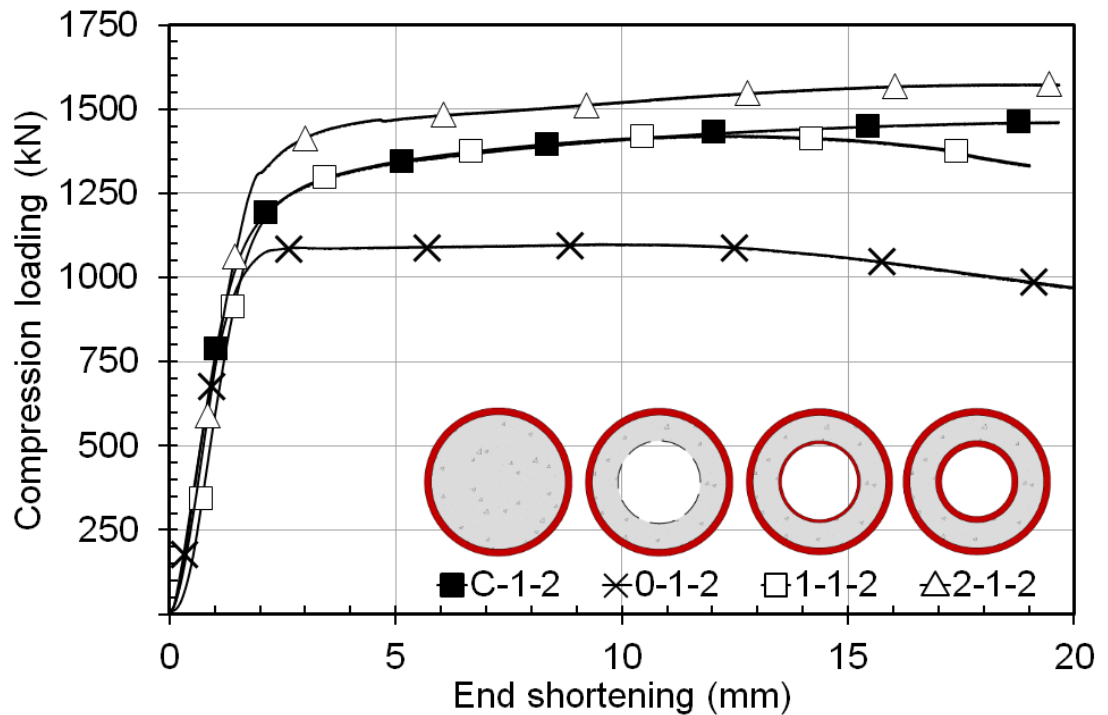


Figure 5.9 Compression loading vs. end shortening curves of Set 1

Since, the inner tube has a higher D/t ratio ($D/t = 23.93$), it suffers due to early inward local buckling and the compression capacity of the inner steel section cannot be exploited efficiently. While this is the case, the double skin specimen 2-1-2 which has

a thicker inner steel tube developed + 7.68 % greater compression capacity over the specimen C-1-2. As opposed to the specimen 1-1-2, the presence of the thicker inner steel tube eliminated the early local buckling behaviour and led the specimen 2-1-2 to exhibit superior compression performance and a good ductility behaviour.

It is also important to discuss the behaviour of the specimens considering the capacity of the column 0-1-2 which has hollow concrete without inner steel tube. Classical CFST specimen developed + 32.95 % greater compression capacity and better ductility characteristic over the specimen 0-1-2. This improvement rate corresponds to 362.34 kN and is + 215.30 % higher than the crushing capacity of the removed concrete of 60.3 mm diameter (crushing load of this removed concrete is 114.92 kN). This result ensures the existence of the provided confinement effect with the circular tube. Since the normal strength concrete is confined properly in the specimen C-1-2, the concrete in this specimen performs better than its crushing load. On the other hand, due to hollow concrete, steel tube could not generate hoop stresses to confine the concrete efficiently in specimen 0-1-2. Furthermore, the inner steel tubes in the CFST specimens 1-1-2 and 2-1-2 led these columns to experience + 29.28 % and + 43.16 % higher compression capacities compared to the specimen 0-2-2. These improvement rates are greater than the yield loads of the inner steel tubes. It is not possible for the thinner inner steel tube to utilize its complete yield capacity because of the early local buckling. Therefore, it could be deduced that in addition to the contribution of the inner steel tubes to the ultimate compression load of the columns, the confinement effect on shell concrete has an important role on such great enhancements. The lateral expansion of the inner steel tubes during the compression loading, restricts the lateral behaviour of the shell concrete in inward direction and leads to additional confinement effect which improves the performance of the concrete. It can be captured that thicker inner steel tube provides much more improvement compared to the improvement provided with the thinner inner tube. Moreover, it is crucial to note that the specimen 0-1-2 with hollow concrete attains the compression capacity at a very early stage of end

shortening. However, classical CFST and the double skin specimens achieved compression capacities at very high level of end shortenings. This behaviour confirms less ductile characteristic of the columns with hollow concrete. This noticeably less ductile behaviour of the specimen with hollow concrete shows itself also in further sets (Sets 2, 3 and 4).

5.4.2 Specimens with NSC and Thin Outer Steel Tube (Set 2)

The specimens which have thinner outer tube ($D/t = 41.87$) developed less ductile behaviours over the specimens with thicker outer tubes, Figures 5.9 and 5.10. In this experimental set both CFDST specimens 1-1-1 and 2-1-1 provided higher compression performances over the control specimen C-1-1. Since the contribution of the thinner outer steel tube on the column performance is not dominant as that of thicker outer steel tube, the thinner inner tube section played a crucial role in improving the capacity.

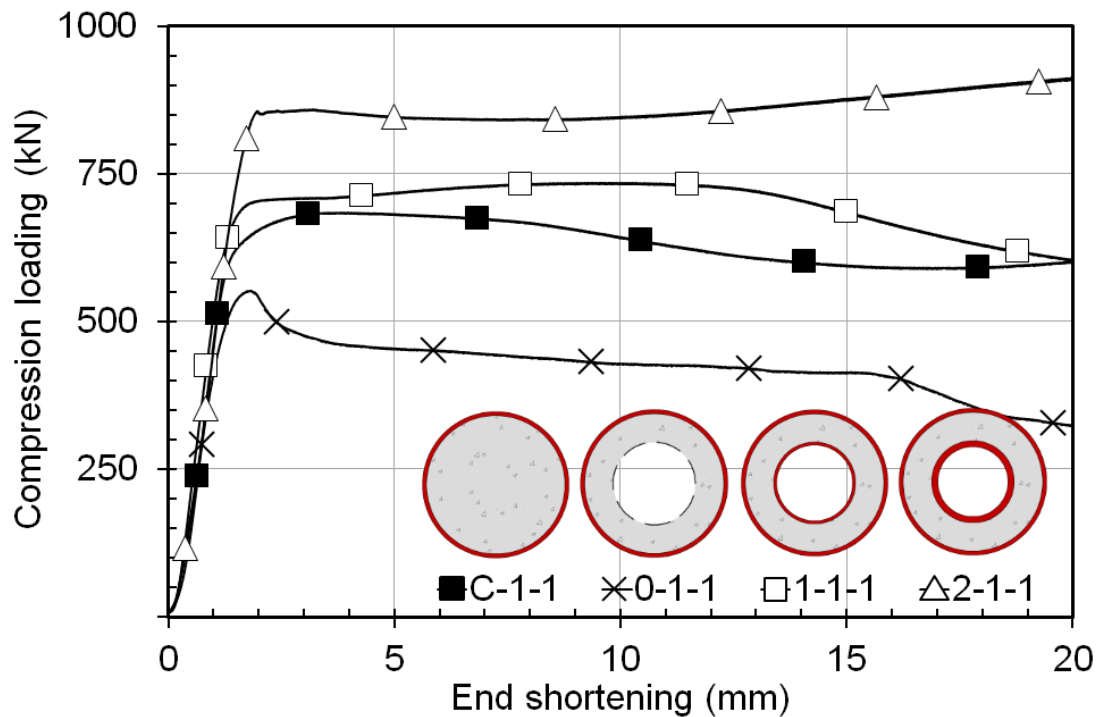


Figure 5.10 Compression loading vs. end shortening curves of Set 2

The improvements provided by the double skin specimens are + 7.38 % and + 33.46 % for specimens 1-1-1 and 2-1-1, respectively. It is also worth noting that, both double

skin specimens exhibited more ductile behaviours over the classical CFST specimen C-1-1, Figure 5.9. Examining the behaviour of the specimen with hollow concrete, it could be observed that the classical CFST column C-1-1 has + 23.95 % greater capacity over the specimen 0-1-1. This rate corresponds to 132.21 kN. Considering the improvement provided in Set 1 with thicker outer tube (+ 32.95 %), this improvement rate is remarkably small, but slightly higher than the crushing capacity of the removed concrete. Thus, it could be concluded that thinner outer tube ($D/t = 41.87$) provides the confinement effect, although it is not efficient as the confinement provided with the thicker outer tube ($D/t = 19.54$). The CFDST specimens 1-1-1 and 2-1-1 in this set developed + 33.10 % and + 65.43 % compression capacities over the specimen 0-2-2 with hollow tube, respectively. These improvements are greater than the improvements provided in the previous set with a thicker outer tube. It is possible to explain this by the behaviour of the thinner outer tube. Since the thinner outer tube could not contribute much to the compression capacity of the column and develops less confinement effect, the impact of the inner steel tubes is more visible and dominant.

5.4.3 Specimens with HSC and Thick Outer Steel Tube (Set 3)

The specimens in this set differ from the specimens of Set 1 in having HSC. The HSC led to significant changes in the compression behaviour of the columns compared to the behaviour of the columns with NSC, Figures 5.9 and 5.11. In this set, the CFDST columns 1-2-2 and 2-2-2 attained less compression capacities over the classical CFST specimen C-2-2. The capacity losses are – 10.55 % and – 1.0 % for the specimens 1-2-2 and 2-2-2, respectively. It is expected for the specimen 1-2-2 to achieve less compression performance over the specimen C-2-2 due to the early inward local buckling of the thinner inner steel tube. However, it is interesting to observe degradation in the performance of the specimen 2-2-2. This result could be attributed to the characteristics of the HSC. It is possible for the steel tube to develop an efficient confinement effect only after development of the micro cracks in concrete that allow

the concrete to experience lateral expansion and trigger the hoop stresses in the steel tube. The increment of the concrete strength leads to higher stiffness and as a result of high stiffness, lateral deformation of the concrete delays [266]. Therefore, as opposed to NSC the HSC could not be efficiently confined by the steel tube. Furthermore, such an adverse late response of the HSC causes inappropriate supporting for the steel tube. Thus, it has the potential to trigger early buckling of the steel tube [144, 194]. It is also important to observe the ductility behaviours of the specimens. The brittle nature of the HSC led the specimens in this set to attain less ductility over the specimens in the Set 1.

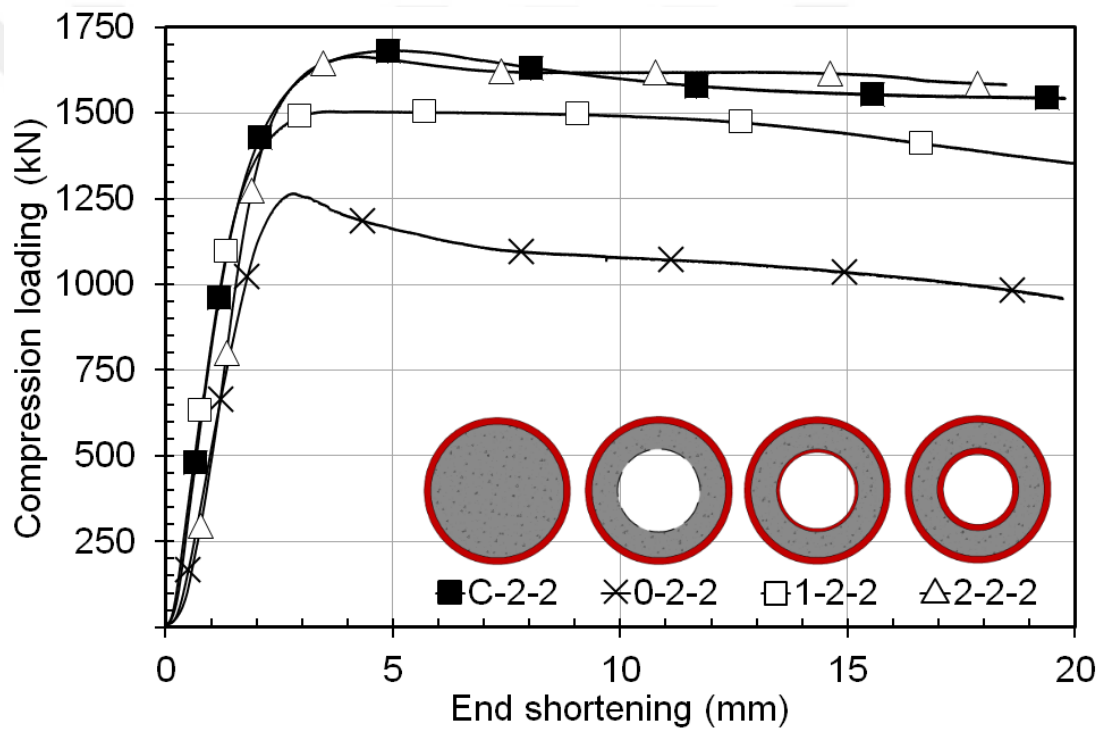


Figure 5.11 Compression loading vs. end shortening curves in Set 3

Classical CFST column C-2-2 developed + 32.97 % higher capacity compared to the specimen 0-2-2. This performance increment is 417.39 kN. This increment is higher than the crushing performance of the removed HSC with 60.3 mm diameter (crushing load of HSC with 60.3 mm diameter is 192.25 kN). However, considering the enhancement rate over the crushing load provided with normal strength concrete in Set 1 (+ 215.30 %), this rate provided with HSC corresponds to + 117.11 % greater than

the crushing load and is not so efficient. This result again underlines the inefficient confinement of the HSC compared to the NSC. Nevertheless, the result suggests that although it is not promising as it is with NSC, there exists confinement effect with HSC. The inner steel tubes of the CFDST specimens 1-2-2 and 2-2-2 improved the compression capacity by + 18.95 % and + 31.65 % over the specimen 0-2-2 with hollow concrete. These improvement rates provided with the inner steel tubes are substantially smaller than the improvements provided with the same tubes in the specimens with NSC. The compression capacity of the HSC has an important contribution to the column performance, thus influences of the steel tubes in terms of percent contribution get smaller. Also, the adverse effect of the HSC does not allow the steel tubes to provide superior confinement effect. Nevertheless, in addition to compression performance increment, the existence of the inner steel tubes remarkably enhances the ductility behaviour, Figure 5.11.

5.4.4 Specimens with HSC and Thin Outer Steel Tube (Set 4)

The use of the thinner outer steel tubes with HSC led to significant differences in the compression and ductility characteristics. The ductility behaviours of the columns with thinner outer tubes are quite lower than that of the columns with thicker outer tubes, Figure 5.12. Furthermore, it could be deduced that apart from the thinner outer steel tube, the HSC itself also is responsible for such ductility degradations. Comparison of the ductility of the specimens with NSC and HSC confirms this phenomenon, Figures 5.10 and 5.12. Although the double skin specimen 1-1-1 with thinner inner tube in Set 2 developed higher performance than that of classical CFST column C-1-1 due to higher confinement rate of the NSC, the nature HSC caused the double skin specimen 1-2-1 to experience – 12.25 % performance loss over the specimen C-2-1. On the other hand, the specimen 2-2-1 with thicker inner steel tube attained + 6.17 % greater performance over the C-2-1. This rate of performance increment is also smaller than the increment provided with NSC (+ 33.46 %).

The classical CFST column C-2-1 developed + 43.63 % greater capacity compared to the specimen 0-2-1 with hollow concrete. Such a capacity improvement corresponds to a compression load which is + 61.93 % higher than the crushing performance of the removed concrete. Such an enhancement is much smaller than the enhancement provided with a thicker outer tube (+ 117.11 %). The existence of the inner steel tubes generated + 26.04 % and + 52.51 % higher compression capacities for the specimens 1-2-1 and 2-2-1, respectively. While these enhancement rates are less than that of provided with NSC, they are greater than the improvements provided in the specimens with thicker outer tube.

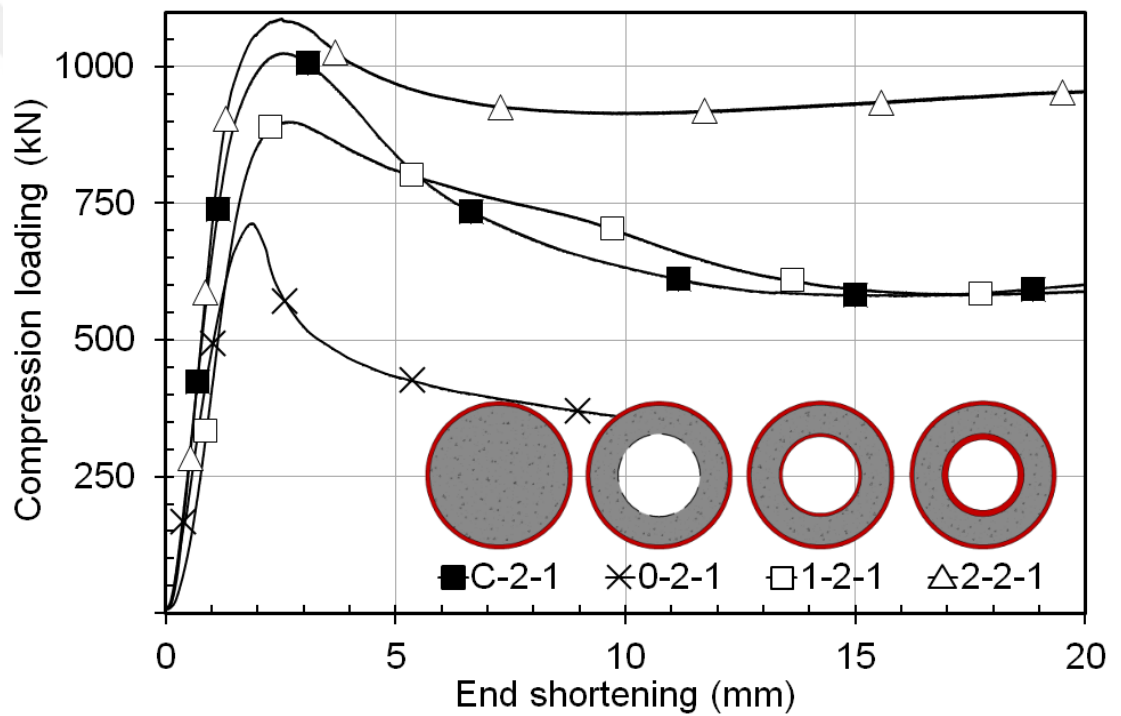


Figure 5.12 Compression load vs. end shortening curves in Set 4

5.5 Performance Indexes

Performances of the composite columns were discussed in the previous section in a comparative way and impact of each column parameter was elaborated. Since the number of column parameters in the present study is high, it is also required to utilize some practical measures to gain an inclusive sense for design purposes. In this manner, Concrete Steel Contribution Ratio (CSCR) and Strength Index (SI) are appropriate

measures and already used in the literature. The CSCR and SI values of the specimens are presented in Table 2.

5.5.1 Concrete-Steel Contribution Ratio (CSCR)

CSCR is used to assess the performance of double skin columns against classical CFST columns [147]. It could be specified as the ratio of the compression performance of the CFDST column to that of performance of the classical CFST column, Equation 5.1.

$$CSCR = \frac{N_{exp,CFDST}}{N_{exp,CFST}} \quad (5.1)$$

Examining the CSCR values in Table 2, it can be concluded that the columns with hollow concrete could gain a maximum performance of 81 % of the corresponding classical CFST column. CSCR values for the rest of the specimens with hollow concrete drops down to 0.7 which corresponds 70 % performance of CFST column. Herein, it is important to observe that 0.81 CSCR value is obtained with the configuration of NSC plus thinner outer tube. Since the impacts of the thinner outer tube and NSC on the compression capacity of the columns are not prominent and the provided confinement with the thinner outer tube is not robust, the specimen 0-1-1 could develop such a performance.

The maximum CSCR values for the CFDST columns with thinner and thicker inner steel tubes could be again achieved with thinner outer tube plus NSC configuration. The CSCR values for these specimens are 1.07 and 1.33, respectively as could be observed in Table 2. Again, due to the unsatisfactory strength properties of the thinner outer tube and NSC, the contribution of the inner steel tubes became highly influential. A CSCR value of 1.33 is impressive and could be very functional for design purposes, Figures 5.13 and 5.14.

5.5.2 Strength Index (SI)

The SI parameter has been widely used in the CFST column research to assess the confinement performance of the columns [260, 264, 267]. This parameter could be measured as the ratio of the composite column compression capacity to the squash load of the column section, Equation 5.2. In calculation of the squash load of the column, the coefficient of 0.85 is used to compensate uncertain defects inherent in the concrete properties.

$$SI = \frac{N_{exp}}{A_{so}f_{yo} + 0.85 A_c f_c + A_{si}f_{yi}} \quad (5.2)$$

where A_{so} , A_{si} and A_c are the cross-sectional areas of the outer steel tube, inner steel tube and the concrete, respectively. f_{yo} refers the yield strength of the outer tube, f_{yi} represents the yield strength of the inner tube and f_c is the compressive strength of the concrete.

It is expected that the column C-1-2 to attain the maximum SI value because of the promising characteristics of the NSC and thicker outer steel tube in triggering higher confinement effect. However, the hardening performance of the compression loading versus end shortening curve of this specimen did not allow the specimen to achieve such a maximum SI value. Due to safety reasons the specimens' compression tests were terminated at an end shortening value of approximately 20 mm. However, as can be observed in Figure 5.9, the high ductile behaviour of the specimen C-1-2 led the loading to increase up to end of the test. For a possible further end shortening level, this specimen could resist greater loading magnitude which would increase the SI value. Specimen 2-1-2 also exhibits the same behaviour, Figure 5.9.

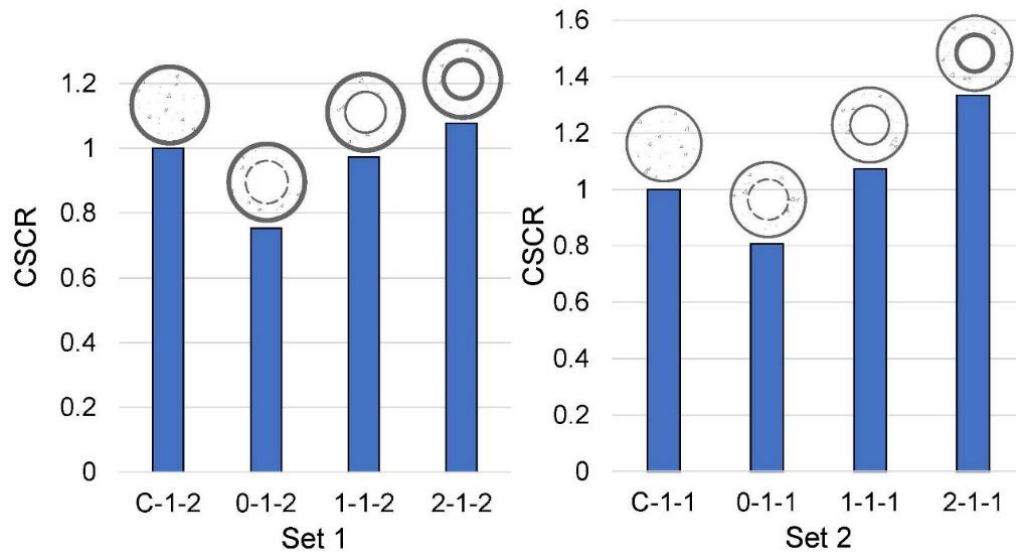


Figure 5.13 Concrete-steel contribution ratio in Set 1 and Set 2

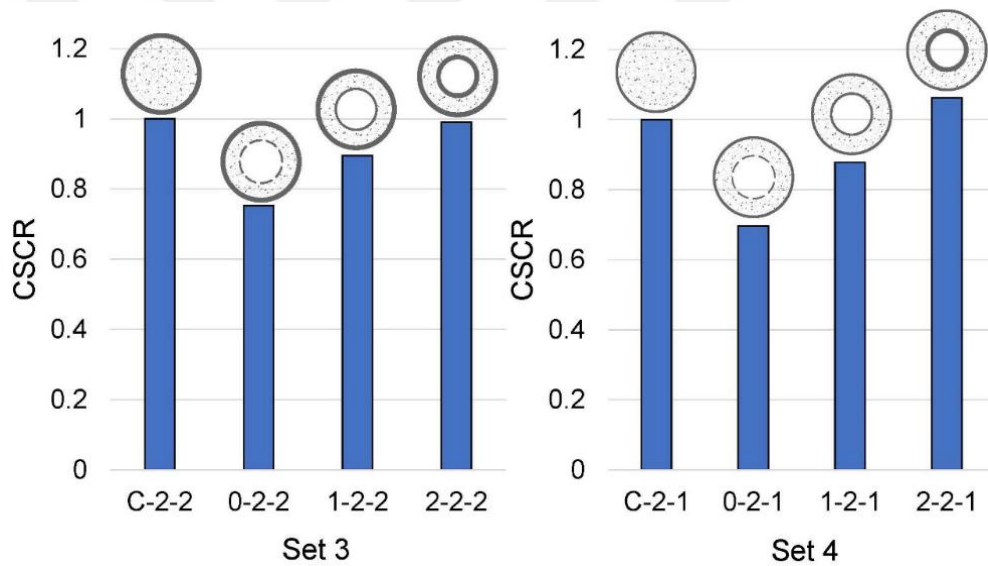


Figure 5.14 Concrete-steel contribution ratio in Set 3 and Set 4

Nevertheless, it is possible to gain a general sense by observing the SI values. The SI values of the CFDST specimens which have thicker inner tubes are greater than the values of the specimens with thinner inner tubes, thus the confinement effect provided with the thicker inner steel tubes could be verified. Furthermore, it is significant to note that none of the specimens with hollow concrete could reach the squash load of the cross section. The maximum SI value for these specimens is 0.94. Such a result underlines the importance of the inner steel tube in performing high resistance.

5.6 Failure Modes

Failure shapes of the columns are presented in Figures 5.15-5.18. The expected failure mode of a stub column is the crushing of the concrete plus yielding of the steel under compression. However, the characteristics of the outer and inner steel tubes, absence of the inner tube and the compressive strength of the concrete changed the failure behaviours. It is necessary first noting that the columns which have thinner outer tube experienced excessive levels of lateral deformations in the form of local buckling. Moreover, the concrete in those columns failed in the shape of shear failure, Figures 5.15 and 5.17. On the other hand, most of the specimens which have thicker outer tube exhibited compression dominant failure and the lateral deformations in these columns are less visible. Therefore, the weaker confining properties of the thinner outer tube could not restrict lateral deformation behaviour of the concrete efficiently and the failure shapes of the specimens are governed by the failure of the concrete. However, the thicker outer tube has stronger confining properties and is able to limit the lateral deformation behaviour of the concrete. It is interesting to see that the existence of the thinner tubes did not change the shear failure behaviour of the concrete which implies that the failure of the column is highly dependent on the outer tube instead of the inner tube.

In order to capture the mechanism of the internal elements of the columns, it is required to understand the failure behaviours of the hollow concrete and inner tubes. The failure of the concrete in the specimens with hollow concrete are depicted in Figures 5.15b, 5.16b, 5.17b and 5.18b. It is crucial to capture that in the specimens which have thinner outer tubes, the failure cracks in the hollow concrete are diagonal and the failure paths are accompanied by outward local buckling of the tubes. In pure concrete specimens the failure cracks are likely to occur vertically. This finding suggests that although there is no inner steel tube in these specimens, the outer tube and the hollow concrete interact, and composite action arises between these members.

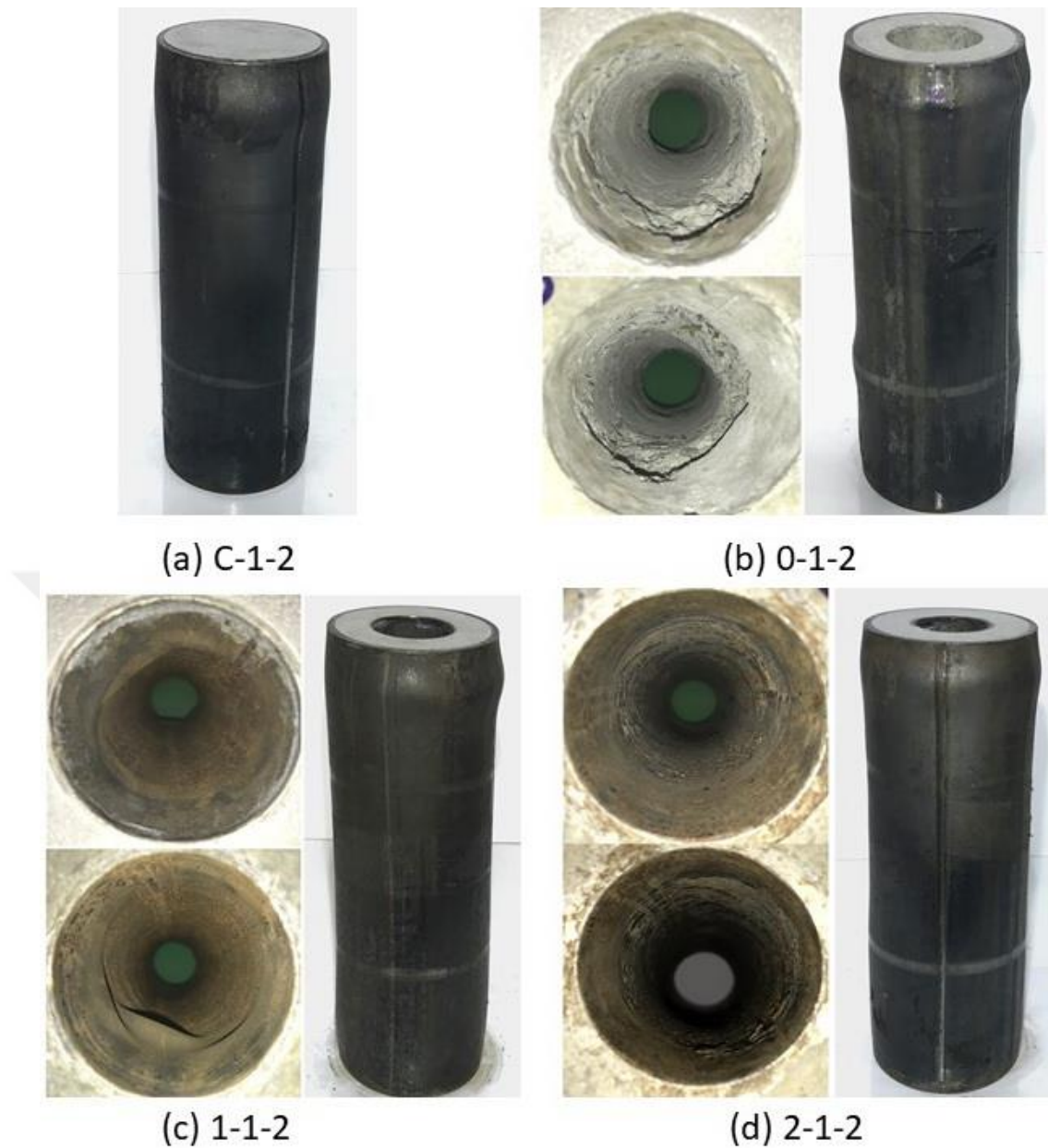


Figure 5.15 Failure modes of the columns in Set 1

In the specimens which have thicker outer tube, since the failure of the column is dominated by compression, vertical deep cracks arise in addition to diagonal shear cracks. This behaviour again implies the available composite action between the materials, even it is not strong as it is with the classical and double skin columns.

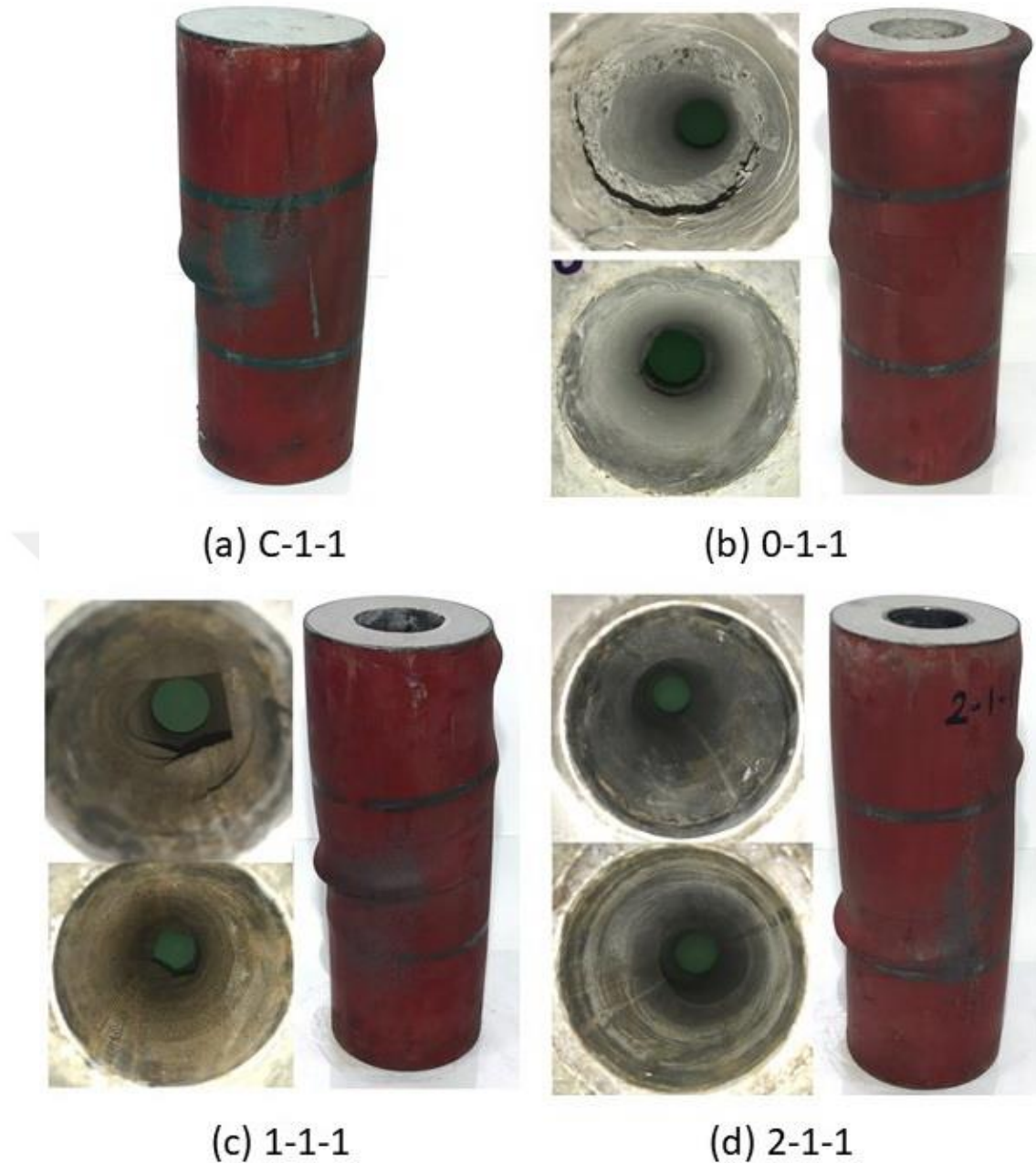


Figure 5.16 Failure modes of the columns in Set 2

Examination of the failure behaviours of the inner steel tubes in CFDST specimens reveals that while the thinner inner steel tubes develop a harsh and intensified form of inward local buckling, the failure characteristics of the thicker inner steel tubes are quite different. Instead, the thicker inner steel tubes developed compression yielding plus smooth global failures in addition to slight inward deformations. Such a failure behaviour implies that the thicker inner steel tubes could upgrade the composite action between the materials and

the associated confinement. It is also important noting that the inward local buckling of the thinner inner steel tubes is more intensified in the specimens with thinner outer tubes. Therefore, the interaction of the inner and the outer tubes could be underlined.

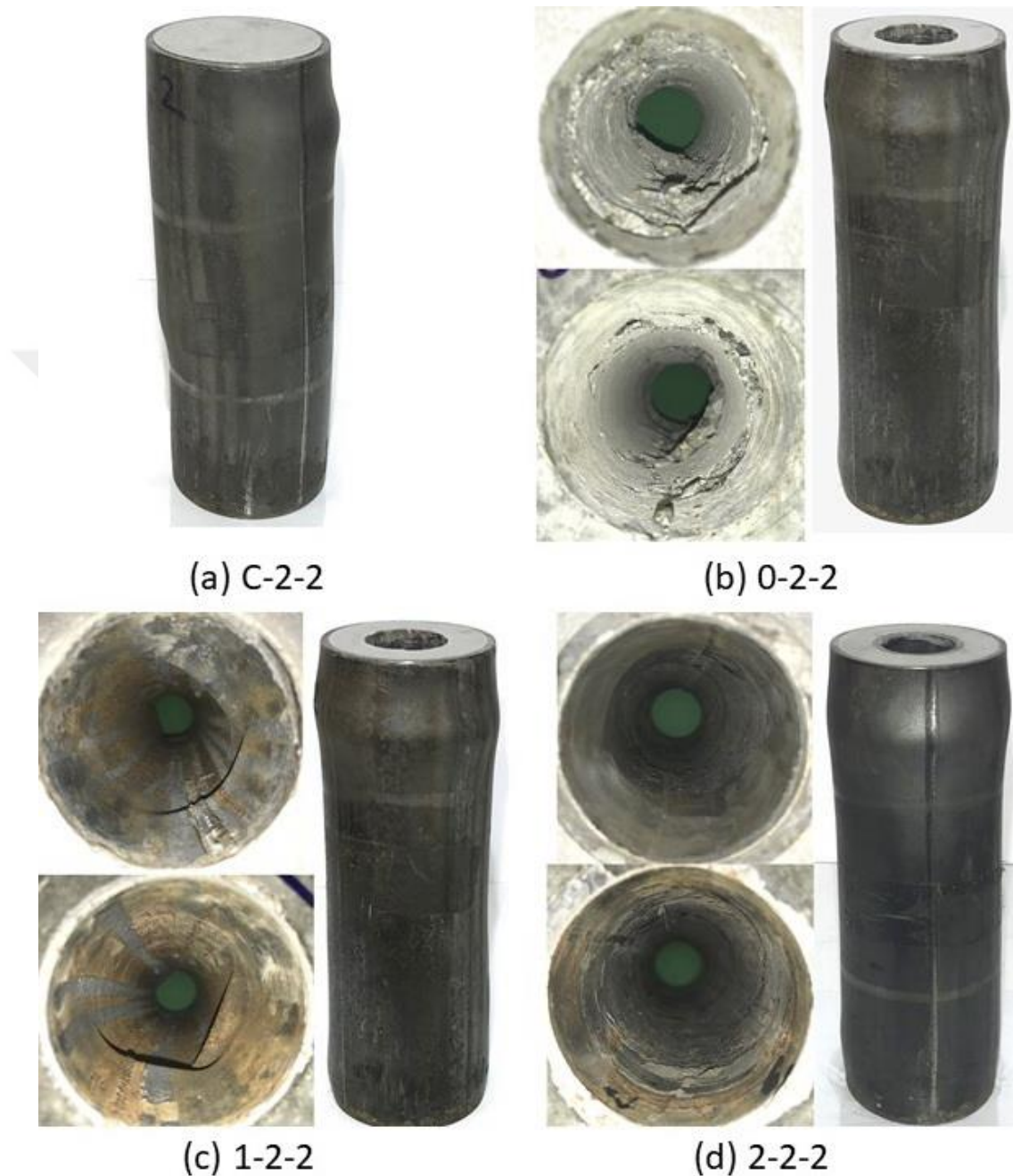


Figure 5.17 Failure modes of the columns in Set 3



Figure 5.18 Failure modes of the columns in Set 4

5.7 Design Methods Against Test Results

Structural design is a matter of extreme relevance to the prediction of members' bearing capacities. If the failure is to be avoided, accurate and realistic prediction approaches must be deployed with a consistent reliability and sensitivity framework. In this manner, design specifications step in and with the objective of providing standard methods, they offer capacity prediction formulations based on the different background theories. The AISC-360-16 and EC4 are the most prominent composite

member design specifications which have been widely utilized for research purposes. AISC 360-16 which is built on the structural steel design, enables the employment of allowable stress or limit state design. On the other hand, EC4 procedures are built on the limit state design and employ factors of safety to load and material properties to satisfy safety and serviceability conditions. However, as is well known, neither AISC 360-16 nor EC4 accommodate any specific formulation for double skin columns. Yet, by imposing some material and geometrical limitations they provide capacity prediction formulations for classical CFST columns. Nevertheless, the composite member technology advances continuously and new forms of compression driven sections arise. Therefore, it is compulsory to develop some other technical approaches to satisfy the needs of composite construction field. Towards this aim, the modified formulations of the AISC 360-16 and EC4 are employed in this section for double skin columns to assess the prediction capabilities. Furthermore, additional methods which have been developed by the researchers are used compare the reliability of these methods against the test results. These methods are proposed by the researchers based on the undertaken experiments. Prior to comparing the results, it is necessary to understand the fundamentals of the methods and underlying theories.

5.7.1 AISC-360-16

AISC 360-16 utilizes the equation below to determine the plastic resistance of the column with compact circular steel tubes.

$$P_p = A_s f_y + 0.95 f_c \left(A_c + A_{sr} \frac{E_s}{E_c} \right) \quad (5.3)$$

where A_{sr} is the cross-sectional area of the longitudinal reinforcement, E_s and E_c represent the elastic modulus for steel and concrete, respectively. It is worth to note that AISC 360-16 uses a constant confinement for the columns with circular steel tubes by utilizing the coefficient 0.95, with ignoring the effect of the D/t ratio. For the composite columns with square or rectangular tubes 0.85 replaces the coefficient 0.95.

The nominal capacity of the column section is set to be equal to the cross-sectional plastic resistance.

$$P_{no} = P_p \quad (5.4)$$

Following, to evaluate the compression capacity of the CFST column Equations 5.4 and 5.5 is employed.

$$P_n = P_{no} \left[0.658^{\frac{P_{no}}{P_e}} \right] \quad \frac{P_{no}}{P_e} \leq 2.25 \quad (5.5)$$

$$P_n = 0.877 P_e \quad \frac{P_{no}}{P_e} > 2.25$$

in which P_e is the critical buckling load for the CFST column and could be calculated using the effective flexural rigidity of the cross section:

$$EI_{eff} = E_{so}I_{so} + E_{sr}I_{sr} + C_3E_cI_c \quad (5.6)$$

$$C_3 = 0.6 + 2 \left(\frac{A_{so} + A_{sr}}{A_{so} + A_{sr} + A_c} \right) \leq 0.9 \quad (5.7)$$

However, it must be underlined that AISC 360-16 ignores the yield strength of the longitudinal reinforcement. Instead, it uses an equivalent area approach and transforms the reinforcement area into concrete area by employing Equation (5.3). In the present thesis, the inner tube cross-sectional area is considered to be reinforcement. Therefore, in addition to the area of the inner tube, its yield strength is also important for the column capacity. According to this approach, the modified version of the AISC-360-16 formulation which is given in Equation (5.8) is used for double skin columns. For the classical CFST columns the standard AISC 360-16 procedure is adapted.

$$P_p = A_s f_y + 0.95 A_c f_c + A_{sr} f_{sr} \quad (5.8)$$

5.7.2 EC4

To evaluate the plastic resistance of the composite CFST column, EC4 employs the following equation which includes the confinement effect by considering D/t effect.

$$N_{pl,Rd} = \eta_a A_a f_y + A_c f_c \left(1 + \eta_c \frac{t}{D} \frac{f_y}{f_c} \right) + A_s f_s \quad (5.9)$$

in which η_a is the reduction factor for steel and η_c is the enhancement factor for concrete. The cross-sectional areas of the steel tube, concrete and the longitudinal reinforcement are represented by A_a , A_c , and A_s , respectively. f_y , f_c , and f_s refer yield strength of the steel tube, compressive strength of the concrete and the yield strength of the reinforcement, respectively. For the CFDST columns, the cross-sectional area of the inner tube is set to be equal to reinforcement area. A reduction factor (χ) is multiplied by the column's plastic resistance to determine the compression capacity. The reduction factor (χ) is utilized to include the effect of the imperfections which might present in the column.

$$N_{EC4} = \chi N_{pl,Rd} \quad (5.10)$$

$$\chi = \frac{1}{\emptyset + [\emptyset^2 - \bar{\lambda}^2]^{0.5}} \leq 1.0 \quad (5.11)$$

where, $\bar{\lambda}$ refers the relative slenderness of the column. The relative slenderness and $\emptyset$, are evaluated as follows:

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}} \quad (5.12)$$

$$\phi = 0.5[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2] \quad (5.13)$$

$N_{pl,Rd}$ in Equation (5.12) is the cross-section plastic resistance which could be determined by using Equation (5.14) for circular CFST sections. EC4 defines an imperfection factor α , which is equal to 0.21 up to reinforcement ratio of 3%. For the reinforcement ratios between 3 and 6% it is equal to 0.34.

$$N_{pl,Rd} = A_a f_y + A_c f_c + A_s f_s \quad (5.14)$$

The critical buckling load of the column N_{cr} is calculated by using effective flexural rigidity which is given below:

$$EI_{eff} = E_a I_a + 0.6 E_c I_c + E_s I_s \quad (5.15)$$

5.7.3 Design Strength by Han *et al.* [268]

Han *et al.* [268] suggested new formulations to calculate the cross-section capacity of CFDST columns, where the effect of the confinement for the shell concrete was taken into account. The maximum cross-section performance of the CFDST column is measured as follows:

$$N_{Han} = N_{i,u} + N_{osc,u} \quad (5.16)$$

where, $N_{i,u} = A_{si} f_{syi}$ and $N_{osc,u} = f_{scy} A_{sco}$. In the formulations A_{si} and f_{syi} are the area and the yield strength of the inner steel tube, respectively. Here, it must be captured that this formulation considers the inner steel tube to be a separate bare steel column and the shell concrete is just confined by the outer tube. The effect of confinement and the performance of the shell and the outer steel tube are implemented in the following equation.

$$f_{scy} = k_1 C_1 \chi^2 f_{syo} + C_2 (1.14 + 1.02 \xi) f_{ck} \quad (5.17)$$

The parameters in Equations 5.18 are given below:

$$\begin{aligned} \chi &= \frac{d}{D-2t_o}; & \alpha &= \frac{A_{so}}{A_c}; \\ \alpha_n &= \frac{A_{so}}{A_{ce}}; & C_1 &= \frac{\alpha}{(1+\alpha)}; \\ \xi &= \alpha_n \frac{f_{syo}}{f_{ck}}; & C_2 &= \frac{(1+\alpha_n)}{(1+\alpha)}; \\ A_{ce} &= \frac{\pi}{4} (D - 2t_o)^2; & A_{sco} &= A_{so} + A_c; \\ f_{ck} &= \frac{f'_c}{1.5} \end{aligned} \quad (5.18)$$

where, χ is a hollowness ratio and ξ is a confinement ratio factor. The diameters of the inner and outer tubes are represented by d and D , respectively and t_o stands for the thickness of the outer tube. The parameter $k_1 = 1$ when the tube has a thickness less than 16 mm. Furthermore, C_1 and C_2 are the factors which are based on the area of components (area of concrete and steel).

5.7.4 Design Strength by Yu *et al.* [269]

Yu *et al.* [269] proposed the equation below to determine the capacity of a CFST column.

$$N_{Yu} = \left(1 + 0.5 \left(\frac{\xi}{1 + \xi}\right) \Omega\right) (f_{sy} A_s + f_{ck} A_c) \quad (5.19)$$

where, $\xi = (\alpha f_{sy}/f_{ck})$, $\alpha = (A_s/A_c)$, the solid ratio $\Omega = A_c / (A_c + A_k)$, A_s is the outer steel tube area, A_c is the concrete area, and A_k is the hollow part area. Besides, the strength capacity formulas of the CFST column suggested by Yu *et al.* [269] was modified by Hassanein and Kharoob [134] to include the effect of the inner steel tube. Hence, the modified form of the formulation for the CFDST columns is given as:

$$N_{Yu,mod} = \left(1 + 0.5 \left(\xi / 1 + \xi\right) \Omega\right) (f_{sy0} A_{so} + f_{ck} A_c) + N_{i,u} \quad (5.20)$$

in which $N_{i,u} = f_{syi} A_{si}$.

5.7.5 Design Strength by Hassanein and Kharoob

A novel strength capacity of the circular CFDST column was suggested by Hassanein and Kharoob [134] as follows:

$$N_{Hassanein} = \gamma_{so} f_{sy0} A_{so} + \gamma_{si} f_{syi} A_{si} + f'_{cc} A_{sc} \quad (5.21)$$

$$f'_{cc} = \gamma_c f'_c + 4.1 f'_{rp,so} \quad (5.22)$$

$$f'_{rp,so} = \begin{cases} 0.7(\nu_e - \nu_s) \frac{2t_o}{D - 2t_o} f_{sy0} & \text{for } \frac{D}{t_o} \leq 47 \\ \left(0.006241 - 0.0000357 \frac{D}{t_o}\right) f_{sy0} & \text{for } 47 < \frac{D}{t_o} \leq 150 \end{cases} \quad (5.23)$$

where, ν_s and ν_e are the Poisson's ratios of the tubes without and with concrete infill, respectively and ν_s is assumed as 0.5 at the ultimate strength. However, ν_e was calculated by Tang *et al.* [270] as given in Eqs. 5.26 and 5.27. A_{sc} is the area of the shell concrete and the factors γ_{so} , γ_{si} and γ_c are given below:

$$\gamma_{so} = 1.458 \left[\frac{D}{t_o} \right]^{-0.1} \text{ and } \gamma_{si} = 1.458 \left[\frac{d}{t_i} \right]^{-0.1} \quad (0.9 \leq \gamma_s \leq 1.1) \quad (5.24)$$

$$\gamma_c = 1.85 D_c^{-0.135} \quad \text{with } D_c = D - 2t_o \text{ and } (0.85 \leq \gamma_c \leq 1.0) \quad (5.25)$$

However, the lateral confining pressure $f'_{rp,so}$ of the steel tube on the concrete can be provided when the D/t is between 47 and 150 as shown in Equation (5.23). On the other hand, confinement could not be provided for the concrete for columns with $D/t > 150$ [134].

$$v'_e = 0.881 \times 10^{-6} (D/t)^3 - 2.58 \times 10^{-6} (D/t)^2 + 1.953 \times 10^{-2} (D/t) + 0.4011 \quad (5.26)$$

$$v_e = 0.2312 + 0.3582 v'_e - 0.1524 \left(\frac{f'_c}{f_{sy}} \right) + 4.843 v'_e \left(\frac{f'_c}{f_{sy}} \right) - 9.169 \left(\frac{f'_c}{f_{sy}} \right)^2 \quad (5.27)$$

5.7.6 Results of Strength Predictions

The ratios of the predictions to the experimental results are presented in Table 3. All of the EC4 predictions are unconservative and the average of the EC4 prediction to test result ratio is 1.088. It could be deduced that the greater discrepancies between the predictions and the test results for EC4 belong to classical CFST columns and the columns with hollow concrete. It is expected for the EC4 to present unconservative results for the columns with hollow concrete, since such a concrete is not confined properly. However, the overpredictions for the classical columns could be explained by the excessive confinement considered for the steel tubes by the EC4 formulations. On the other hand, the EC4 format is very successful in predicting the capacities of double skin columns. Especially, the prediction to experimental result ratios for the CFDST columns with thicker inner tubes are very close to unity. Considering the AISC 360-16 calculations, it could be observed that except for one specimen all the

predictions are conservative. This is because the AISC 360-16 considers a constant confinement effect regardless of the D/t ratio of the steel tube as shown in Equation (5.8). Also, AISC 360-16 format has generally better predictions for the CF DST columns compared to the predictions for the classical CFST columns and the columns with hollow concrete.

Examination of the prediction methods which were proposed by Hassanein and Kharoob [134], Han *et al.* [268] and Yu *et al.* [269] shows that these methods could be utilized for design purposes. The average ratios of these prediction results to the experimental capacities are very close to the unity and superior than the ratios obtained for EC4 and AISC 360-16. Among these three methods the method proposed by Hassanein and Kharoob performs better with an average ratio of 1.006 and a standard deviation of 0.07. On the other hand, it must be underlined that these three prediction methods were developed for stub columns, while the standard EC4 and AISC 360-16 methods could be applied for stub, medium and long columns. That is to say, these three methods do not consider the length effect and associated critical buckling loads. With proper modifications and high-fidelity calibrations, it would be possible to adapt these methods to general composite column design processes. To visually implement the behaviours of the prediction methods, Figure 5.19 depicts the relations of the methods with the experimental results.

In the last decades, design and construction of huge and formidable engineering structures have been on the rise. Such robust structures which are designed for different purposes and promise much more service life are required across the world to provide sustainable solutions. In this manner, composite structures could optimize the costs and mitigate the concerns, since they couple the favourable engineering properties of the materials.

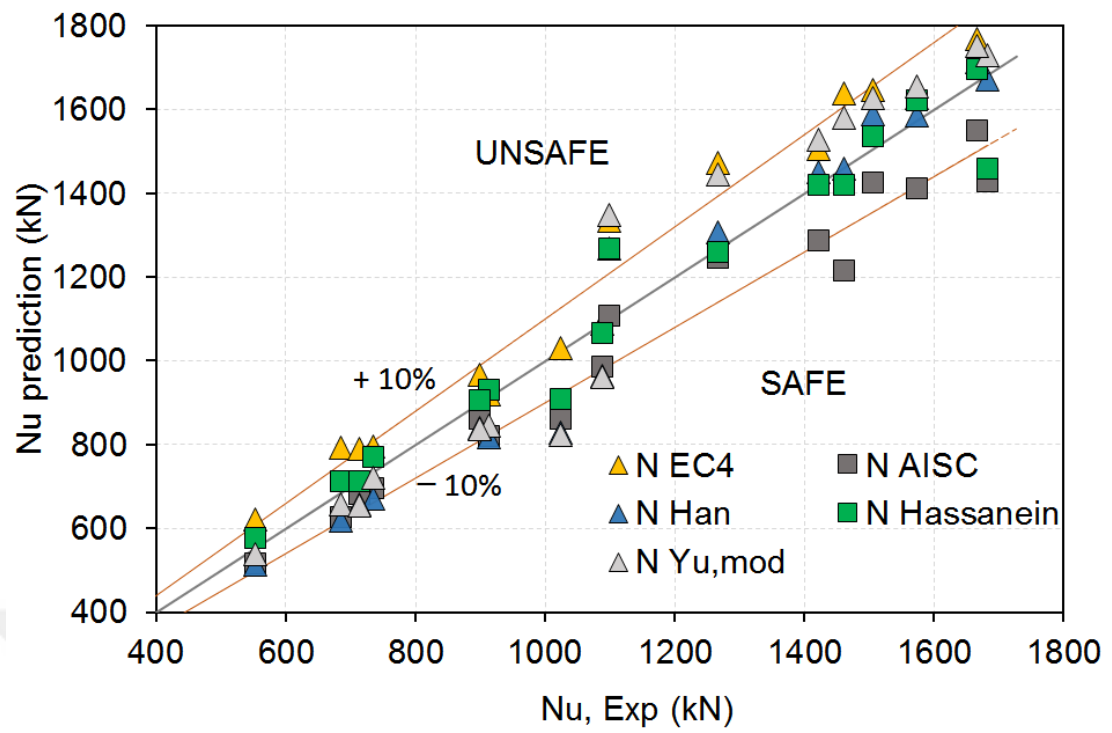


Figure 5.19 Comparison of experimental results and predictions of design methods

Table 5.3 Comparison of the experimental results with strength predictions

	Specimen	N_{exp}	N_{EC4}/N_{exp}	N_{AISC}/N_{exp}	N_{Han}/N_{exp}	$N_{Hassanein}/N_{exp}$	$N_{Yu,mod}/N_{exp}$
Set1	C-1-2	1461.95	1.122	0.832	0.999	0.972	1.082
	0-1-2	1099.61	1.213	1.008	1.155	1.154	1.226
	1-1-2	1421.54	1.059	0.906	1.020	0.999	1.076
	2-1-2	1574.26	1.034	0.897	1.008	1.030	1.051
Set 2	C-1-1	684.13	1.158	0.914	0.904	1.042	0.960
	0-1-1	551.92	1.126	0.937	0.930	1.049	0.978
	1-1-1	734.60	1.084	0.949	0.913	1.049	0.981
	2-1-1	913.07	1.006	0.900	0.897	1.020	0.926
Set 3	C-2-2	1683.19	1.095	0.848	0.993	0.867	1.027
	0-2-2	1265.80	1.163	0.985	1.033	0.997	1.142
	1-2-2	1505.67	1.093	0.947	1.055	1.020	1.081
	2-2-2	1666.41	1.061	0.930	1.028	1.018	1.051
Set 4	C-2-1	1024.75	1.006	0.842	0.810	0.887	0.805
	0-2-1	713.44	1.107	0.956	0.923	1.001	0.919
	1-2-1	899.21	1.074	0.958	0.934	1.008	0.930
	2-2-1	1088.06	1.001	0.906	0.887	0.981	0.884
Mean			1.088	0.920	0.968	1.006	1.007
Standard Dev.			0.09	0.05	0.08	0.07	0.11
Coefficient of Var.			0.08	0.05	0.09	0.06	0.10

5.8 Conclusions

CFST compression dominant members are very attractive and robust forms of composite construction. The investigations and the associated developments on the CFST columns are continuous and highly efficient forms of members are being proposed in the literature. In this regard, CFDST members have the potential to increase the efficiency of the composite construction. However, it is necessary to delve

into the major aspects of such members by assessing the compression characteristics of each cross-sectional element to provide reliable design guides. Based on the performance of the classical CFST columns and the columns with steel tube plus hollow concrete, the current study experimentally investigates the contribution of all CFDST column cross-sectional elements under compressive loading. The test program comprises sixteen composite columns. Two different D/t ratios for the inner and also for the outer tubes, presence of the inner tube and two different strength grades for concrete were used as parameters to allow a better anticipation of the performance of the parameters and especially characterize the inner steel tube in CFDST columns. Towards this aim, the compressive loading vs. end shortening curves, failure modes, concrete-steel contribution ratio and concrete strength contribution were analysed. Furthermore, to evaluate the applicability of the design methods of CFDST columns, five design capacity prediction procedures were compared against the experimental results. Based on the results, the conclusions below can be deployed within the scope of present study:

- The presence of the inner steel tube has a vital role on the performance of CFDST columns. Inner tubes provided compression capacity increments in the range of 18.95–65.44 %. However, it is important noting that the thinner inner tubes ($D/t = 23.93$) suffer from early local buckling which prevents cross sectional-area of such a tube to be exploited efficiently and causes less confinement for the shell concrete.
- For “composite action” between the shell concrete and steel tubes, the inner steel tube helps the concrete to be entirely confined by limiting its expansion in inward direction during the loading process. It can be concluded that when the hollow concrete is used without inner steel tube, the outer tube cannot develop the proper confinement for the concrete.
- The results confirmed that the thin inner tube ($D/t = 23.93$) cannot improve the compression capacity of CFDST with high strength concrete (HSC). However,

such a tube could provide remarkable performance with normal strength concrete (NSC) compared to the performance of classical CFST counterpart. In contrast, the thick inner tube ($D/t = 10.45$) can develop good “composite action” even with HSC. The CSCR values and the compression loading versus end shortening curves support these findings.

- The compression loading vs. end shortening curves of CFDSTs indicate that the compression performance, toughness and ductility increase with increasing the thickness of the inner tube. Furthermore, the absence of the inner tube (columns with hollow concrete) leads the columns to reach the compression capacity at a very early level of end shortening which implies a poor ductility behaviour.
- The results corroborate that the contribution of the shell concrete strength is less important with the thick outer tube ($D/t = 19.45$) in CFDST column. However, the effect of the shell concrete strength is more significant with thin-outer tubes ($D/t = 41.87$).
- Likewise, the SI ratios of the specimens indicate that the effect of confinement increases when the thickness of the inner tube increases. Therefore, in CFDST columns, the confinement effect of the inner tube must be considered in design calculations.
- The failure shape mostly is dependent on the D/t ratio of the outer tube. On the other hand, the thinner inner tubes experience intensive level of inward early local buckling which compromise the performance of the column. The thicker inner steel tubes could contribute cross sectional capacities efficiently and do not exhibit harsh local buckling.
- Examining the performance of standard prediction methods (with modified versions), it could be concluded that EC4 has better predictions for CFDST columns compared to the predictions of this method for the classical CFST columns. The conservative predictions of the AISC 360-16 showed itself for

classical and double skin columns. However, for the CFDST columns it has also better predictions compared to the predictions for classical CFST columns.

- The capacity methods provided by Hassanein and Kharoob [134] and Yu *et al.* [269] perform very well in predicting the capacity of the double skin columns. Nevertheless, it is worth noting that these methods were formulated for stub columns and do not consider L/D effect.



CHAPTER 6

STIFFENED CONCRETE FILLED DOUBLE SKIN STEEL TUBULAR COLUMNS UNDER AXIAL COMPRESSION

6.1 General

Concrete filled steel tube (CFST) columns have been commonly utilized in the high-rise buildings, subways, bridges and industrial structures owing to their excessive advantages as ductility, high strength, and good seismic behaviour [11-14, 257]. Generally, the concrete delays or avoids the steel tube from the buckling, and the tube confines the concrete in the CFST members [22, 84, 85, 248]. Additionally, the steel hollow section acts as the jacket for concrete, accordingly, provides good confinement and enhances the behaviour. Recently, demand for lighter-weight members widely increased in the world to decrease the dead loads, mainly for multi-story building [23, 24, 39, 85]. The inventive novelty of composite structure is recognised as Concrete Filled Double Skin Steel Tube (CFDST) column. CFDSTs consider the best solution to decrease the foundation loads due to the void inside the inner tube [29, 30, 39, 147]. CFDST comprises concrete infill between the two-concentric steel hollow tubes, where the inner tube is empty as shown in Figure 6.1. The CFDST column gets equal or higher characteristics than the ordinary CFST column, which the outer tube of CFDST performs as a CFST column, while the inner tube works as an unfilled compact tube [31].

Over the last few years, numerous studies concerned about the imperfect bonding that occurs in the CFST and CFDST columns within an elastic stage [5, 88]. This phenomenon happens due to the concrete and steel tubes suffer from deformation with dissimilar rates owing to variations in their Poisson's ratio. The Poisson's ratio of steel is higher than that of the concrete, and the lateral expansion of concrete is lesser than

the steel's expansion at this stage. This leads to an unconfined or free the concrete behaviour until the concrete cracks occur. This behaviour postpones the confinement effect and decreases the effectiveness of the steel tube [271-280]. Therefore, the late researches in the literature tend to improve the performance of such columns in the elastic stage by considering different configurations [29, 30, 147]. Moreover, some researches [18, 259, 281-283] have demonstrated the effectiveness of stiffening members to enhance the performance of CFST members, such as longitudinal stiffeners and reinforcing bars. In general, the stiffening can be achieved by using cold-formed stiffeners or welded stiffening members [237]. However, the effect of stiffening members in delaying the local buckling of steel tubes have been confirmed by tests [284, 285]. In addition, the stiffening members were welded with the steel tube act to enhance the ductility and strength of the CFST columns due to the additional interaction provided [286-294]. Besides, it is found that the role of the stiffening members is dramatically improving the fire resistance of the composite columns [118, 295-302]. Correspondingly, the welding of the internal stiffening members is possible only with a large diameter of steel tubes, whereas, they are difficult to weld with the steel tubes that have a small diameter [28, 243].

Moreover, Tao *et al.* [284] concluded that the strength and ductility of CFST can be increased with increasing the number of the stiffening members on tube surface and/or adding fibres to concrete. Ge and Usami [281] reported that the CFST columns behaviour can be improved by either welding longitudinal strips on the inner surface of the tube or welding shear studs. Shekastehband *et al.* [182] experimentally investigated that the longitudinal steel-stiffening members embedded in the surfaces of tubes of CFDST column improving steel-concrete contact, consequently, improve the fire resistance of the columns [303-309].

6.2 Research Significance

Above-mentioned evidence, the studies in the field of stiffening haven't dealt with the CFDST columns but only focused on the ordinary CFST columns. Leading to the behaviours of the stiffened CFDST columns are still obscure. In this context, the aim of the current work is experimentally to explore the mechanical performance of CFDST columns stiffened by an innovative type of stiffening members, which is described as "welded reinforcing bar" (WRBs). 16 specimens have been tested to assess the impact of the parameters. The main parameters of this work were (i) two different patterns of WRBs. The first pattern is included the reinforcing bars which welded on the external surface of the inner steel tube, whereas, the second pattern is included the reinforcing bars which welded on the internal surface of the outer tubes. The innovative patterns were altered to find out the best position of WRBs within CFDST column, which in turn helps to delay the buckling of tubes and to enhance the confinement effect on sandwiched concrete. Moreover, each pattern is included a different number of WRBs (6, 4 and 3). (ii) To be able to explore the effect of tube thicknesses, two different thicknesses of steel tubes were utilized. Finally, the design methods that proposed by several researchers for unstiffened CFDST columns were modified to estimate the cross-section capacities of stiffened CFDST columns. It is shown here that the modified design methods have the potential to be utilized for stiffened CFDST columns.

6.3 Experimental Work

6.3.1 General

Two ordinary CFST specimens and two unstiffened CFDST columns fabricated without WRBs as the references. Moreover, twelve-CFDST column specimens have been fabricated with WRBs. The specimens' geometry can be observed in Figures 6.1-6.3. Likewise, an overview of the parameters that used in the current work and the rest of the details listed in Table 6.1.

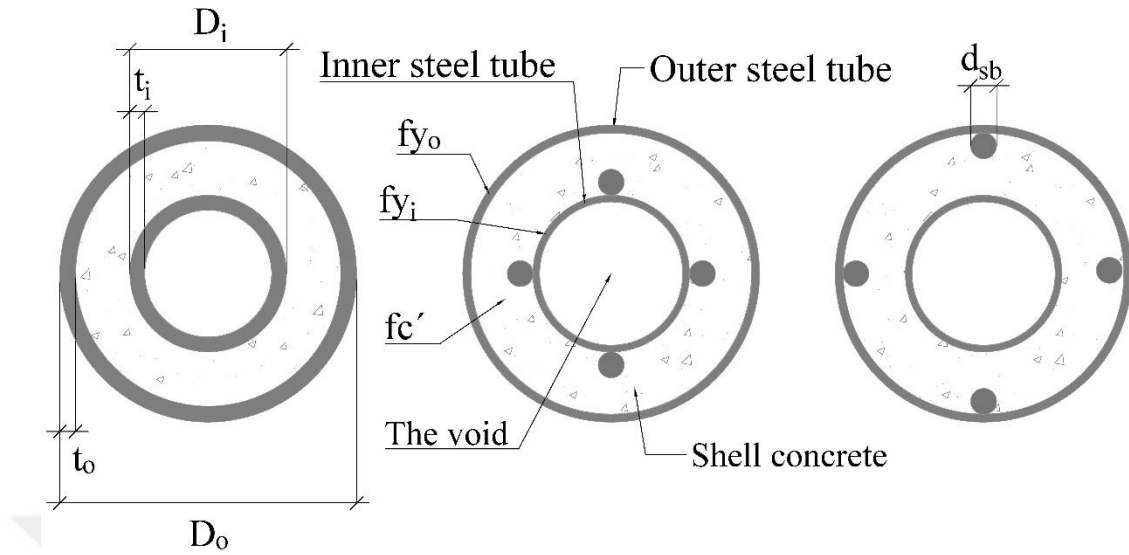


Figure 6.1 CFDST cross sections

The labelling of specimens included the numbers 1 and 2, which the number 1 refers to thinner thicknesses of both the inner and outer tubes, whereas the number 2 refers to thicker thicknesses of both tubes. Therefore, the labelling system includes the thickness of both tubes, position of WRBs, and the number of the WRBs, respectively. Besides, W60 represents that reinforcing bars embedded with an inner steel tube, while, W114 represents the reinforcing bars embedded with outer steel tube. For example, 1-W60-3 represents the CFDST column as, thicknesses of both steel tubes are thinner (thin-thin), the reinforcing bars welded on the external surface of the inner steel tube, finally the number 3 represents the number of the welded reinforcing bars. On the other hand, the specimen 2-W0-0 represents the CFDST column has thicker thicknesses of both tubes (thick-thick), and no WRB embedded in this specimen. Moreover, the character “C” represents CFST columns as a reference or control. As an example, C-2 means CFST specimen with a thicker thickness of the outer steel tube, whereas, C-1 means CFST specimen with a thinner thickness of the outer steel tube, as illustrated in Figure 6.2.



Figure 6.2 CFDST columns cross sections

6.3.2 Materials Properties

All of the steel tubes in the present study are cold-formed tubes which were produced according to EN 10219-1 [196]. Two coupon specimens were cut from each tube to measure the actual yield strength of steel tubes (f_y) by coupon test according to [197]. $\phi 10$ mm diameter of deformed steel reinforcing bars was used with a yield strength of 430 MPa [197], Figure 6.4. Besides, one concrete class was produced. The concrete mix was prepared with the objective of obtaining normal self-compacted concrete class (C42 MPa). Four 100×200 mm cylinder moulds were cast with concrete to obtain the actual compressive strength (f_c), Figure 6.7. After completing the curing process, concrete samples were tested according to ASTM [199].

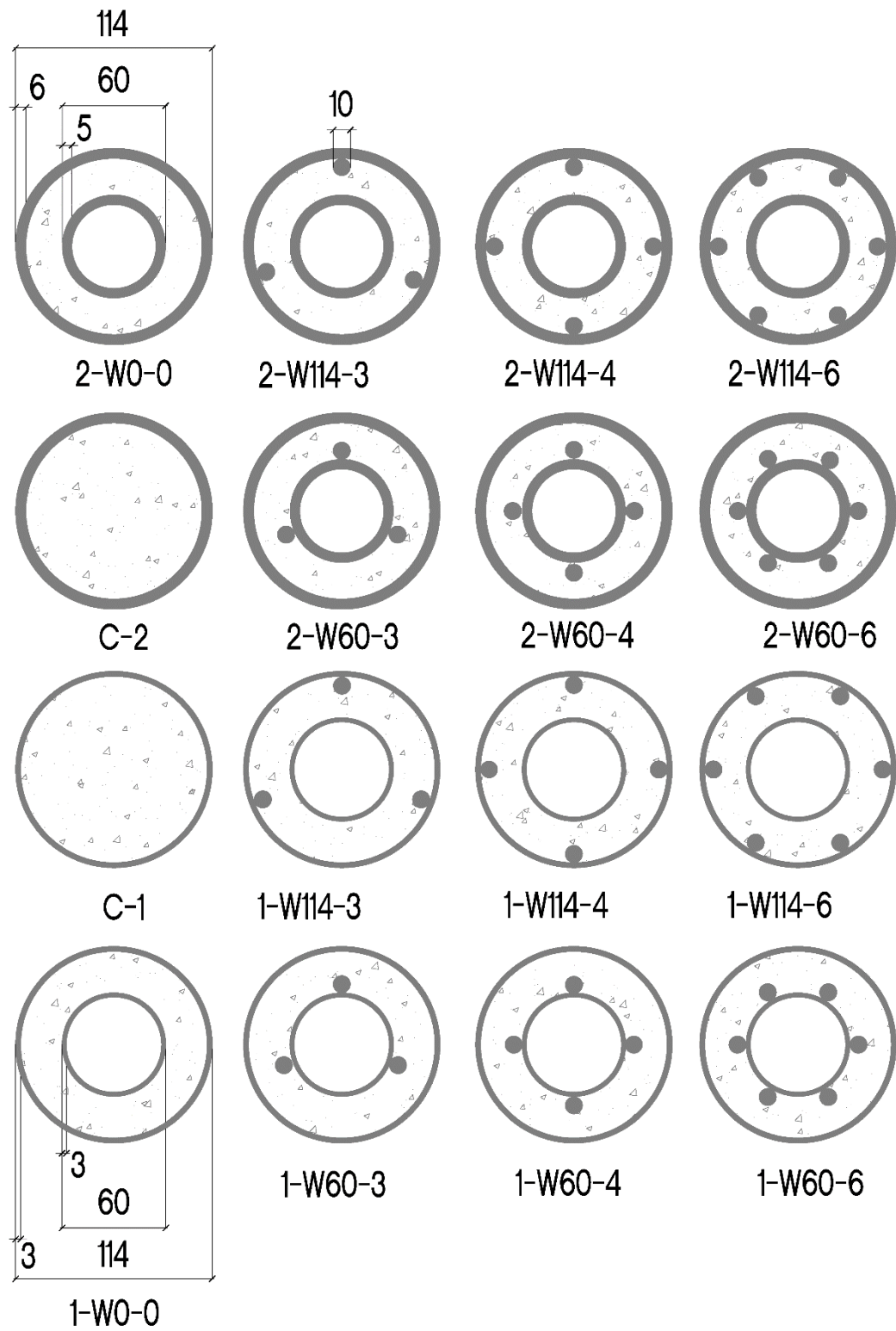


Figure 6.3 CFDST columns cross sections

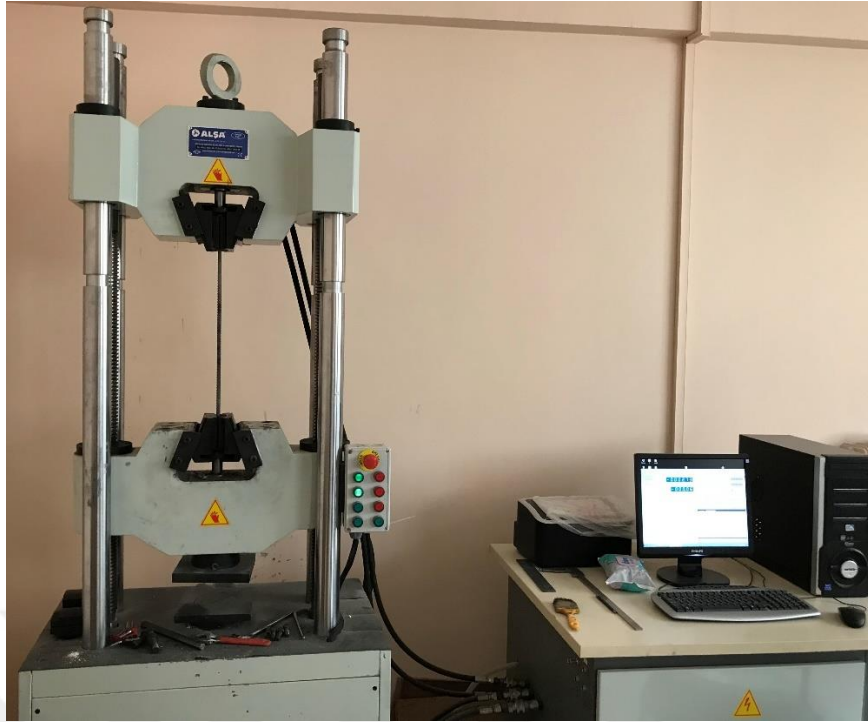


Figure 6.4 Tensile test of deformed steel reinforcing bars



Figure 6.5 Tensile coupon specimens

6.3.3 Test Setup and Fabrication

An L/D ratio of 3.0 was designated for all specimens, this ratio has been extensively used in the literature to examine the behaviour of stub columns [201]. According to this L/D ratio and considering a further machining process, all hollow steel tubes were cut to lengths which are slightly greater than 343 mm. Afterwards, the upper and lower tube ends were machined to be flat and perpendicular to the tube axis, hence, to ensure that the uniform compressive load applied properly. The flat ends are important in column testing to gain authoritative results [256]. The machining process reduced both the steel tubes and WRBs to a final exact length of 343 mm, Figure 6.6.

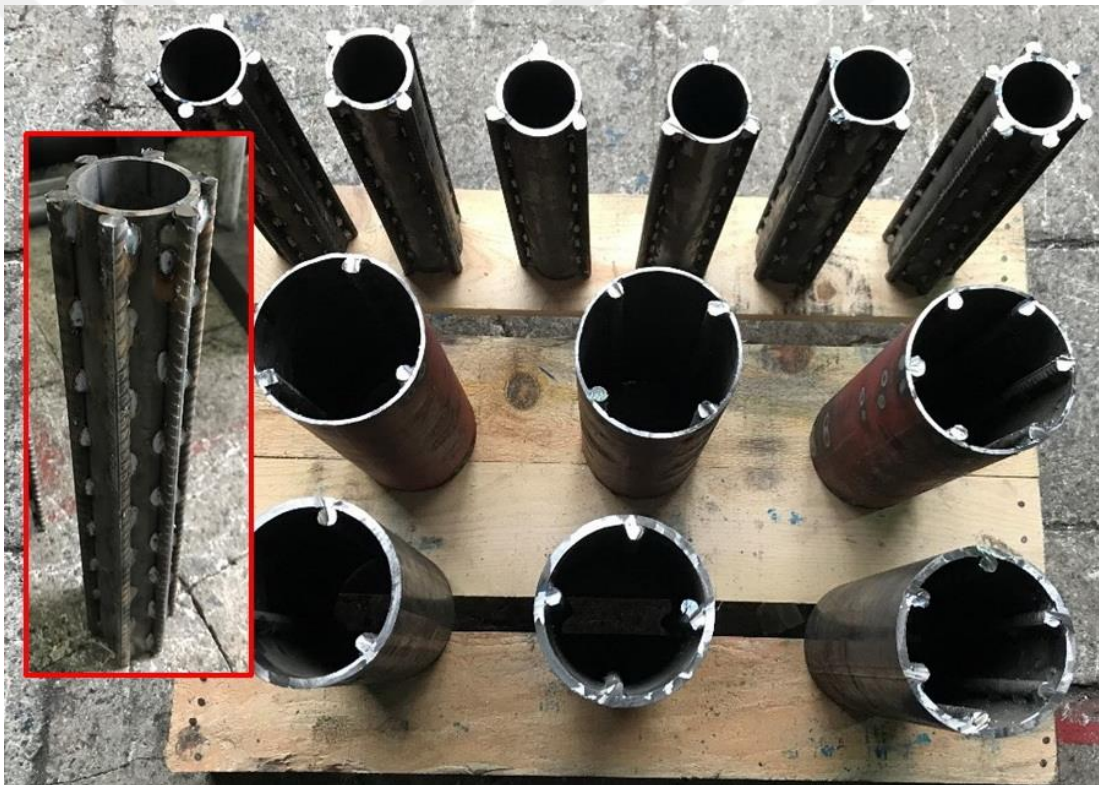


Figure 6.6 Specimens machining

Table 6.1 Details of the Specimens

Column (ID)	L/D_o	Do/t	Inner tube			Outer tube		
			D (mm)	t (mm)	f_y (Mpa)	D (mm)	t (mm)	f_y (Mpa)
Thinner-Thinner								
C-1	3.0	41.86	N/A	N/A	N/A	114.3	2.73	285
1-W0-0	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W60-3	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W114-3	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W60-4	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W114-4	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W60-6	3.0	41.86	60.3	2.56	380	114.3	2.73	285
1-W114-6	3.0	41.86	60.3	2.56	380	114.3	2.73	285
Thicker-Thicker								
C-2	3.0	19.53	N/A	N/A	N/A	114.3	5.85	455
2-W0-0	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W60-3	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W114-3	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W60-4	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W114-4	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W60-6	3.0	19.53	60.3	4.71	435	114.3	5.85	455
2-W114-6	3.0	19.53	60.3	4.71	435	114.3	5.85	455

The diameters of the outer tubes of 114.3 mm with two thicknesses, which 5.85 mm for thicker outer diameters and 2.73 mm for thinner outer diameters, whereas, the inner steel tubes have a diameter of 60.3 mm with two different thickness 4.71 mm and 2.56 mm. The diameters of reinforcing bars of 10 mm were used with a different number for each specimen (6, 4 and 3). The difference of specimens' properties was selected to discover the influence of WRBs on the performance of CFDST columns.

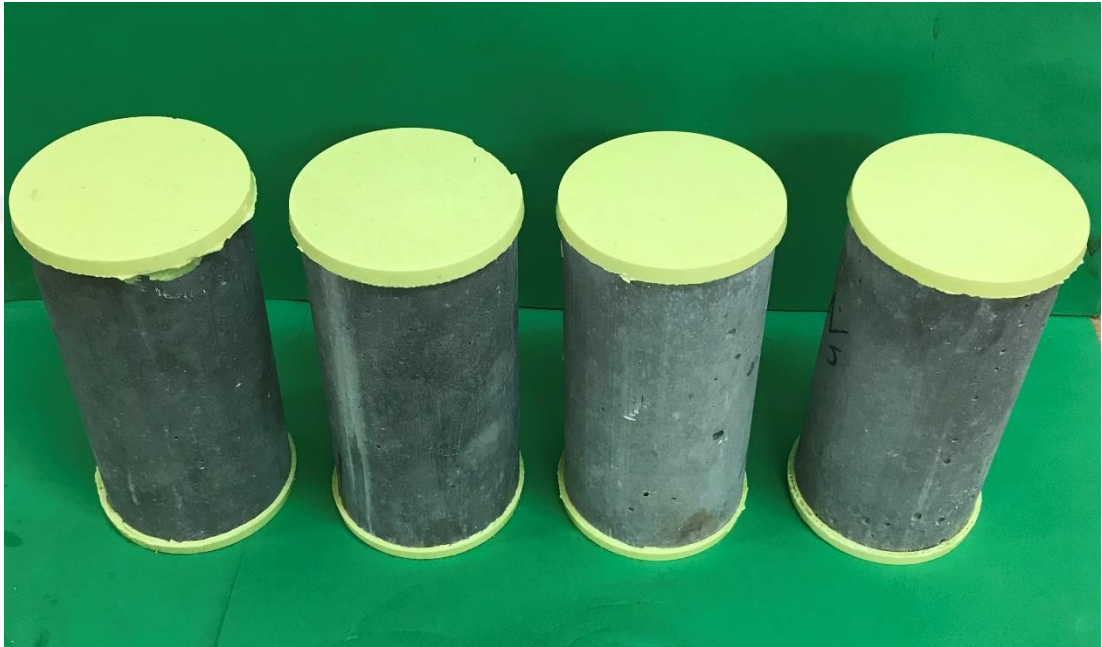


Figure 6.7 Specimens machining

All tests were completed with a universal testing machine with a capacity of 3000 kN. Moreover, two LVDTs were located at two points, to be able to measure the shortening. The average values of the two LVDTs were used to draw the compression load-end shortening curves. At the lower ends of the tubes, glass plates with a silicon were used to intercept the concrete during the casting. 3-4 mm from the top tube did not fill with concrete. The unfilled upper space is filled with high-strength levelling epoxy so that load can be applied regularly to the steel and concrete. Before the test, the silicon residues and the glass plates were removed.

Table 6.2 Experimental N_{exp} , CSCR and SI results

<i>Column (ID)</i>	<i>Experimental</i> <i>N_{exp} (kN)</i>	<i>CSCR</i>	<i>SI</i>
Thinner-thinner			
C-1	726.34	1.00	1.19
1-W0-0	758.61	1.04	1.11
1-W60-3	862.48	1.19	1.10
1-W114-3	861.77	1.18	1.10
1-W60-4	907.88	1.25	1.11
1-W114-4	880.25	1.21	1.08
1-W60-6	999.49	1.38	1.13
1-W114-6	975.55	1.34	1.10
Thicker-thicker			
C-2	1,465.76	1.00	1.22
2-W0-0	1,622.25	1.11	1.11
2-W60-3	1,812.27	1.24	1.12
2-W114-3	1,745.14	1.19	1.16
2-W60-4	1,835.22	1.25	1.12
2-W114-4	1,789.22	1.22	1.15
2-W60-6	1,916.75	1.30	1.11
2-W114-6	1,850.37	1.26	1.15

6.4 Results

The curves of compressive loading versus end shortening were offered during the tests and plotted for each specimen in Figures 6.8, 6.9, 6.10, 6.11, 6.12, 6.13, 6.14 and 6.15. Furthermore, in Table 6.2, the ultimate axial load capacities achieved in the tests for each column are listed.

6.4.1 Compression Loading Versus End Shortening Curves

6.4.1.1 Specimens with Thinner Steel Tubes

The reference specimen with thinner tubes (thin-thin) and the CFDST specimen without WRBs (C-1, 1-W0-0) are presented in Figure 6.8. In the view of the curves, it is interesting here to observe that the 1-W0-0 specimen exhibits a greater performance over the reference specimen C-1 and behaves in a different manner. Furthermore, 1-W0-0 reached a compression capacity of 758.61 kN, which exceeds the value that measured for the corresponding reference specimen C-1, which the C-1 specimen achieved 726.34 kN. At the compression capacity level, the C-1 specimen has the end shortening value of 3.41 mm. Besides, 1-W0-0 specimen behaves in a more ductile manner and has an end shortening value of 9.07 mm at the level of compression capacity. This fact explains that the increase in the nominal steel ratio helps to increase the ductility [268]. Moreover, it can be explained that they have different initial stiffness values, this difference can be attributed to substituting concrete by an inner steel tube.

Besides, as listed in Table 6.2, the compression capacity of the specimens 1-W60-3, 1-W60-4 and 1-W60-6 achieved 862.48, 907.88 and 999.49 kN, respectively, whereas, the compression capacities of the specimens 1-W114-3, 1-W114-4 and 1-W114-6 achieved 861.77, 880.25 and 975.55 kN, respectively. It means that the compression capacities of the specimens were increasing as the number of WRBs increased. In addition, the specimens that have thinner tubes with WRBs on the external surface of the inner steel tube have slightly greater compression capacities compared to the

specimens that have WRBs on the internal surface of outer steel tubes, Figures 6.9 and 6.10.

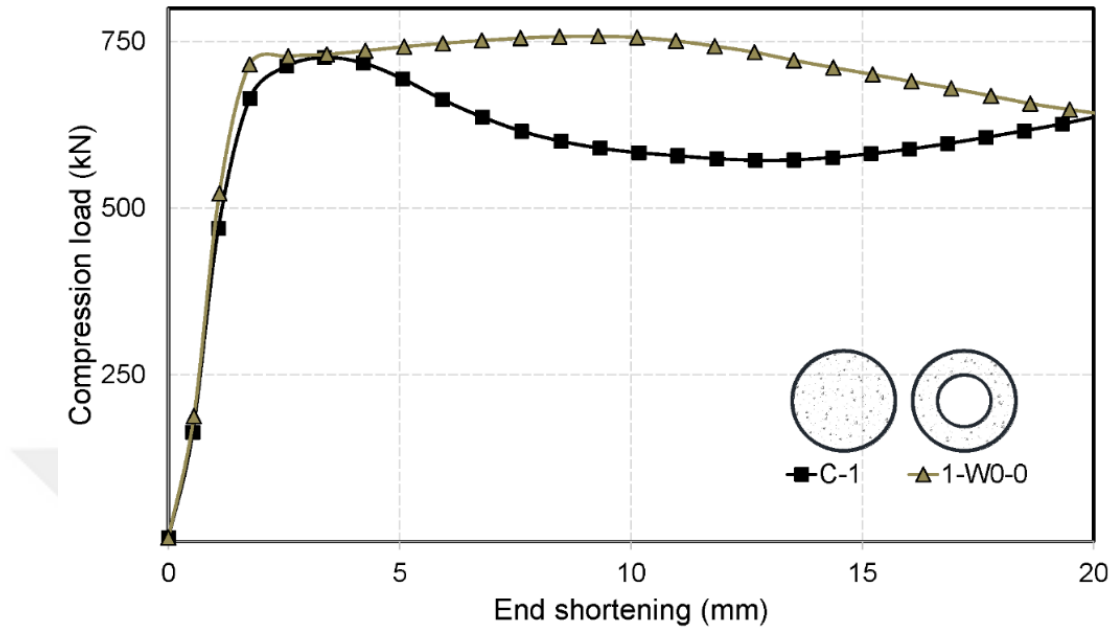


Figure 6.8 Compression load vs. end shortening curves for C-1 and 1-W0-0

At the compression capacity level, 1-W60-3 specimen has the end shortening value of 11.64 mm, whilst, 1-W114-3 specimen behaves in a less ductile manner and has an end shortening value of 10.16 mm. Besides, the specimens 1-W60-3 and 1-W114-3 behave in a similar manner, Figure 6.9. On the other hand, the curves of the remaining specimens with thinner tubes (thin-thin), 1-W60-4, 1-W114-4, 1-W60-6 and 1-W114-6 are presented in Figure 6.11 and Figure 6.12. The 1-W60-4 specimen has the end shortening value of 14.19 mm at the compression capacity level, whilst, 1-W114-4 specimen behaves in a less ductile manner and has an end shortening value of 9.07 mm. However, the compression capacity level of 1-W60-6 specimen has the end shortening value of 12.91 mm, whereas, 1-W114-6 specimen behaves in a less ductile manner and has an end shortening value of 10.92 mm at the level of compression capacity.

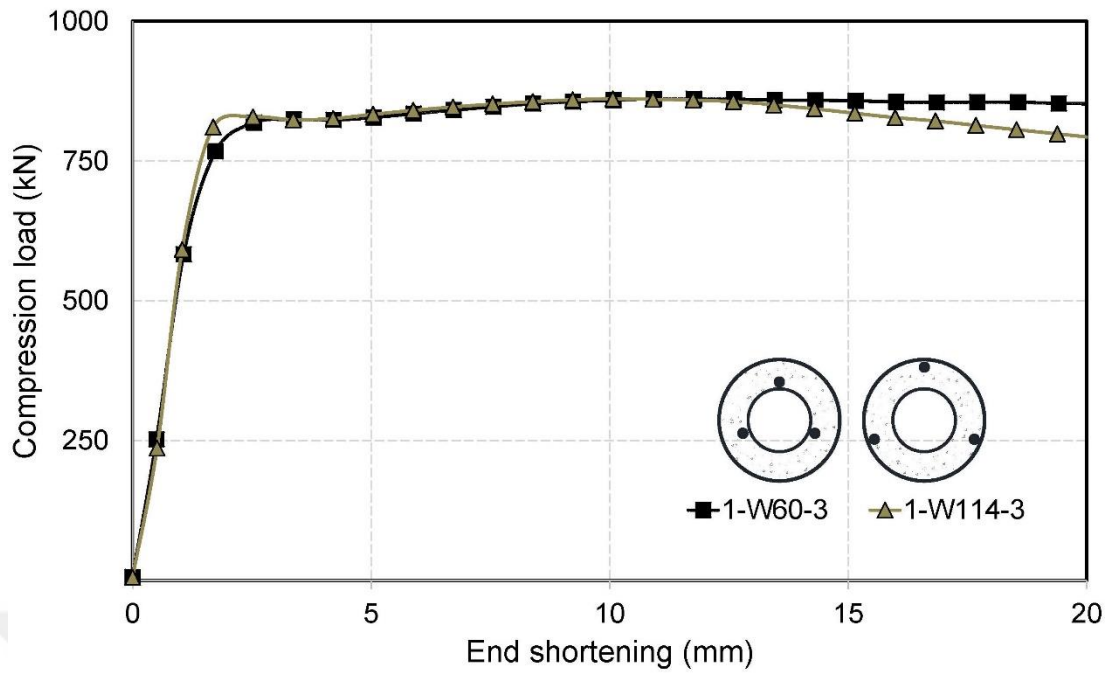


Figure 6.9 Compression load vs. end shortening curves for 1-W60-3 and 1-W114-3

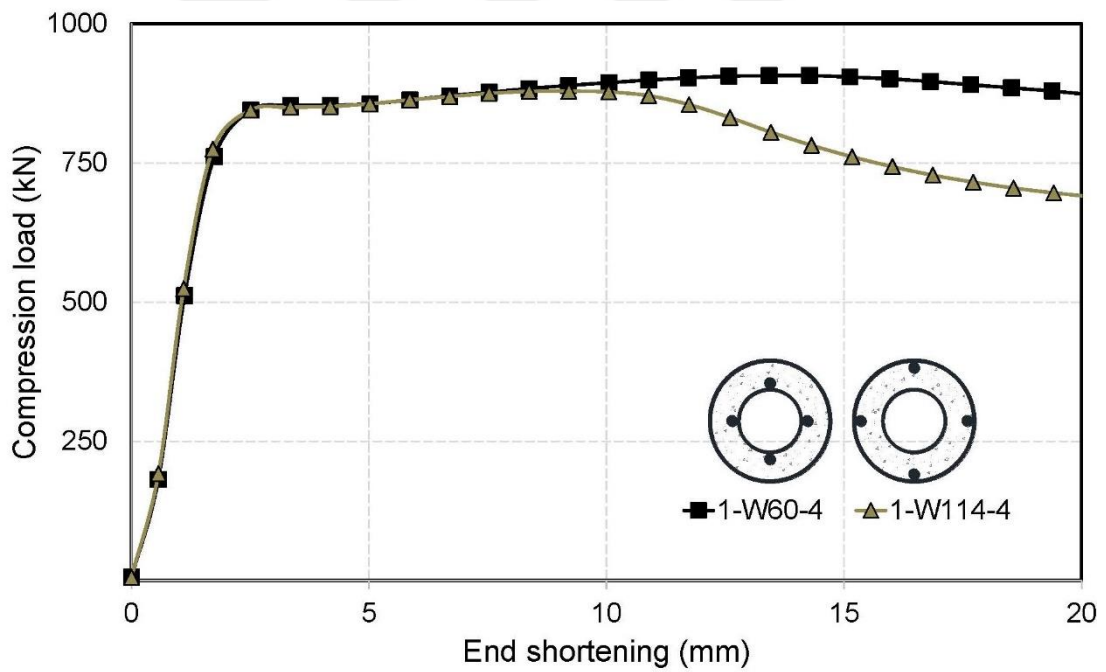


Figure 6.10 Compression load vs. end shortening curves for 1-W60-4 and 1-W114-4

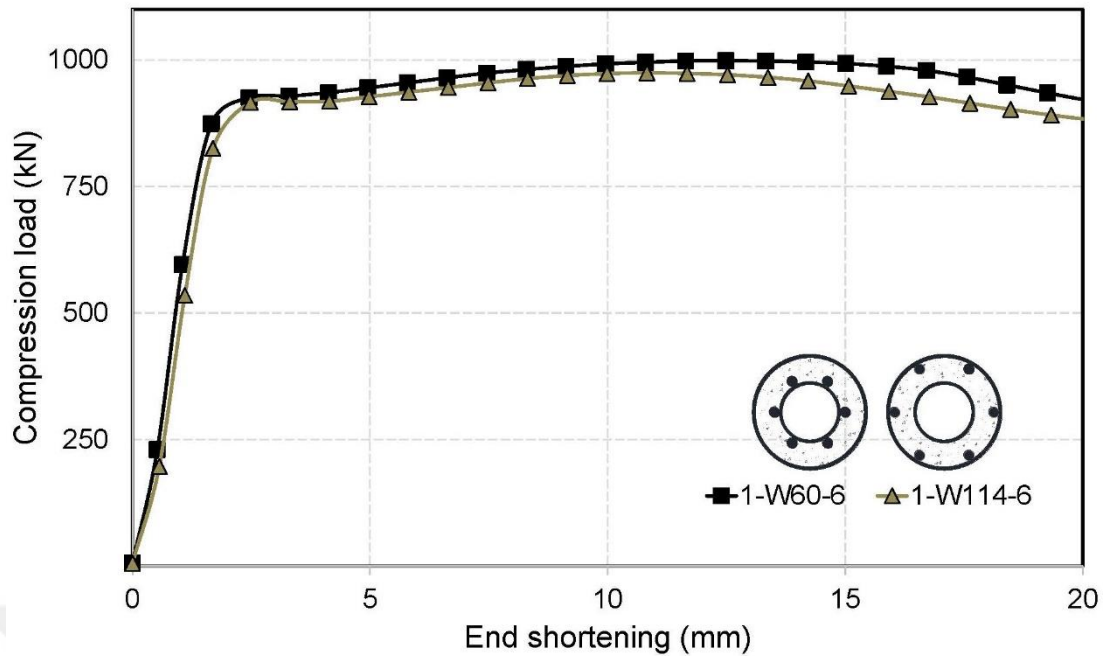


Figure 6.11 Compression load vs. end shortening curves for 1-W60-6 and 1-W114-6

In terms of the stiffness, it can be deduced that the specimens with thinner tubes have a slight difference of initial stiffness values, this difference could be attributed to the different numbers and patterns of the WRBs. Interestingly, it was observed that all columns with WRBs on the external surface of inner steel tubes (1-W60-3, 1-W60-4, 1-W60-6) had slightly more ductile behaviour compared to those of the other pattern counterparts, (1-W114-3, 1-W114-4, 1-W114-6).

6.4.1.2 Specimens with Thicker Steel Tubes

As shown in Figure 6.12, the reference specimen (C2) and the unstiffened CFDST specimen (2-W0-0) behave in a similar manner. Furthermore, the 2-W0-0 specimen exhibits a greater performance over the reference specimen C-2, which the 2-W0-0 specimen reached a compression capacity of 1,622 kN. On the other hand, the corresponding reference specimen C-2 achieved 1,465 kN, Table 6.2.

Besides, the compression capacities of the specimens 2-W60-3, 2-W60-4 and 2-W60-6 reached 1812.27, 1835.22 and 1916.75 kN, respectively. However, the compression capacities of the specimens 2-W114-3, 2-W114-4 and 2-W114-6 achieved 1745.14,

1789.22 and 1850.37 kN, respectively. It means that the compression capacities of these specimens were increasing as the number of WRBs increased. Likewise, the specimens that have thicker tubes with WRBs on the external surface of inner steel tubes have greater compression capacities compared to those of the other pattern counterparts, Figures 6.13, 6.14 and 6.15.

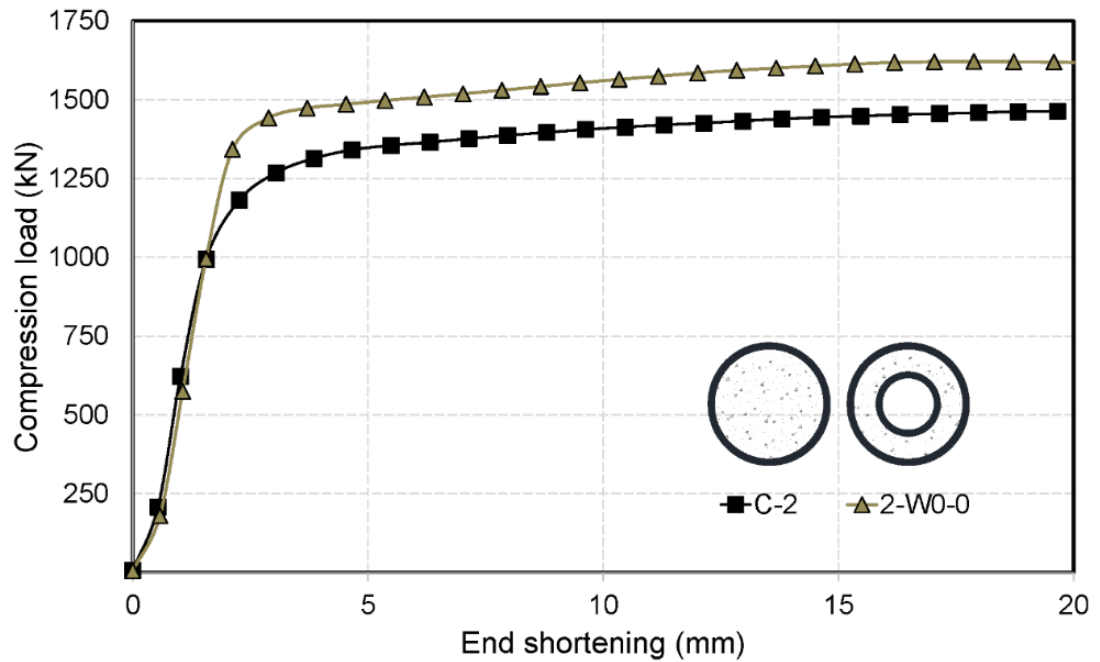


Figure 6.12 Compression load vs. end shortening curves for C-2 and 2-W0-0

In the view of curves, Figures 6.13, 6.14 and 6.15, the specimens 2-W60-3, 2-W60-4 and 2-W60-6 have a higher slope than the 2-W114-3, 2-W114-4 and 2-W114-6, respectively. On the other hand, at the compression capacities level, 2-W60-3, 2-W60-4 and 2-W60-6 specimens have the end shortening value of 19.89 mm, 18.84 mm and 20.43 mm, respectively. However, 2-W114-3, 2-W114-4 and 2-W114-6 specimens have the end shortening value of 18.09 mm, 17.8 mm and 15.64 mm, respectively. It is important to mention that the specimens that have WRBs with inner steel tubes have slightly greater initial stiffness compared to the specimens that have WRBs with outer steel tubes counterparts, Figures 6.13, 6.14 and 6.15.

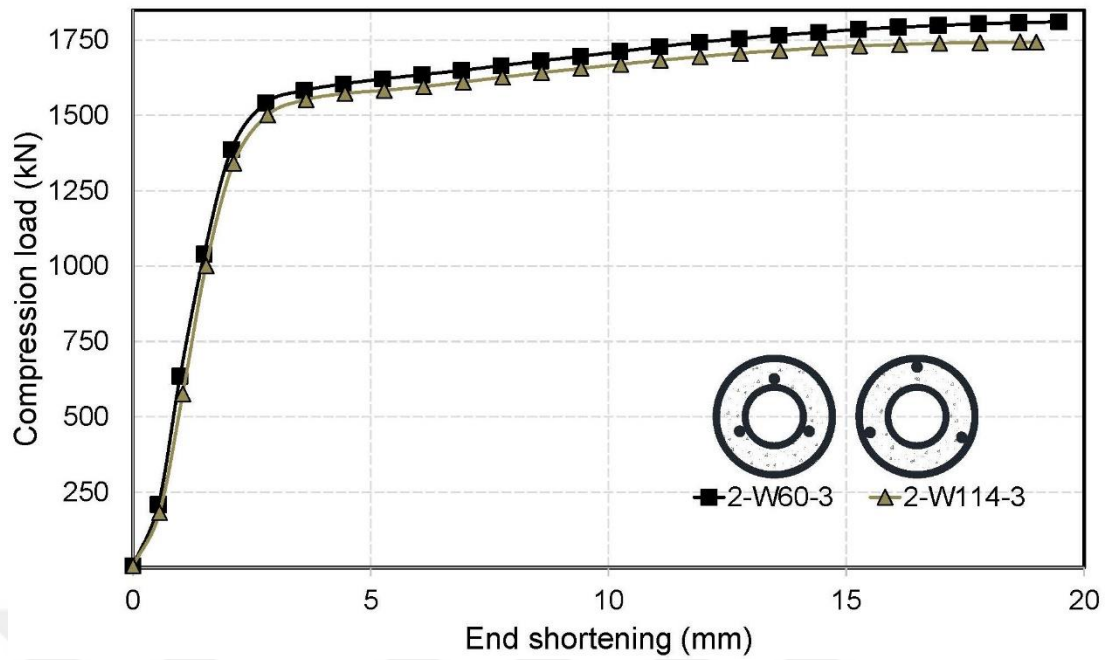


Figure 6.13 Compression load vs. end shortening curves for 2-W60-3 and 2-W114-3

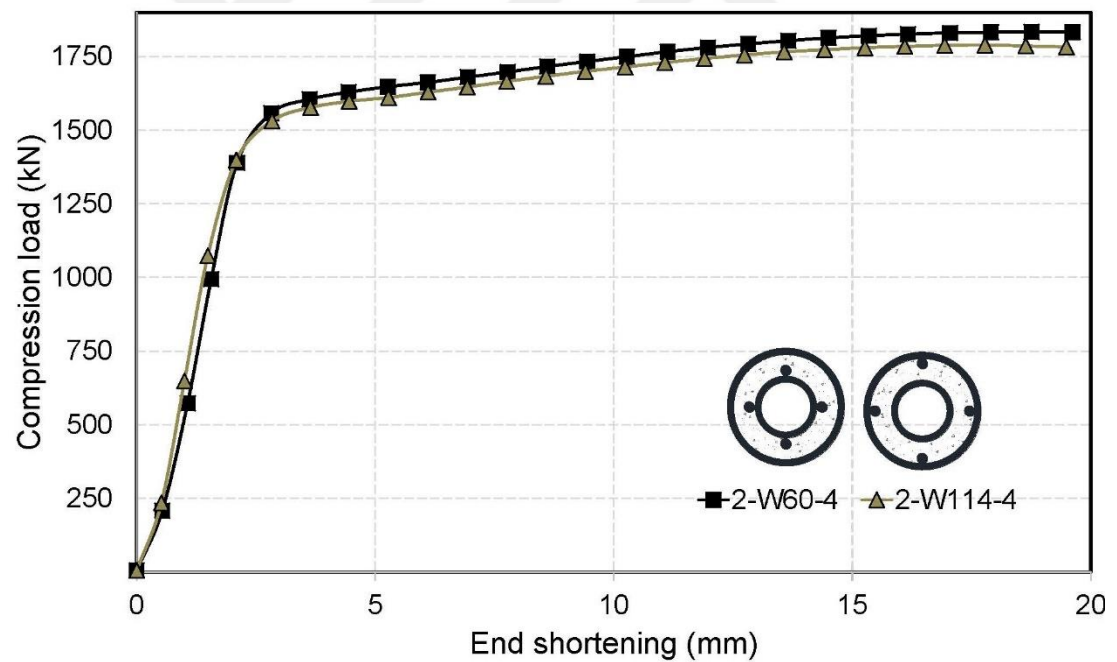


Figure 6.14 Compression load vs. end shortening curves for 2-W60-4 and 2-W114-4

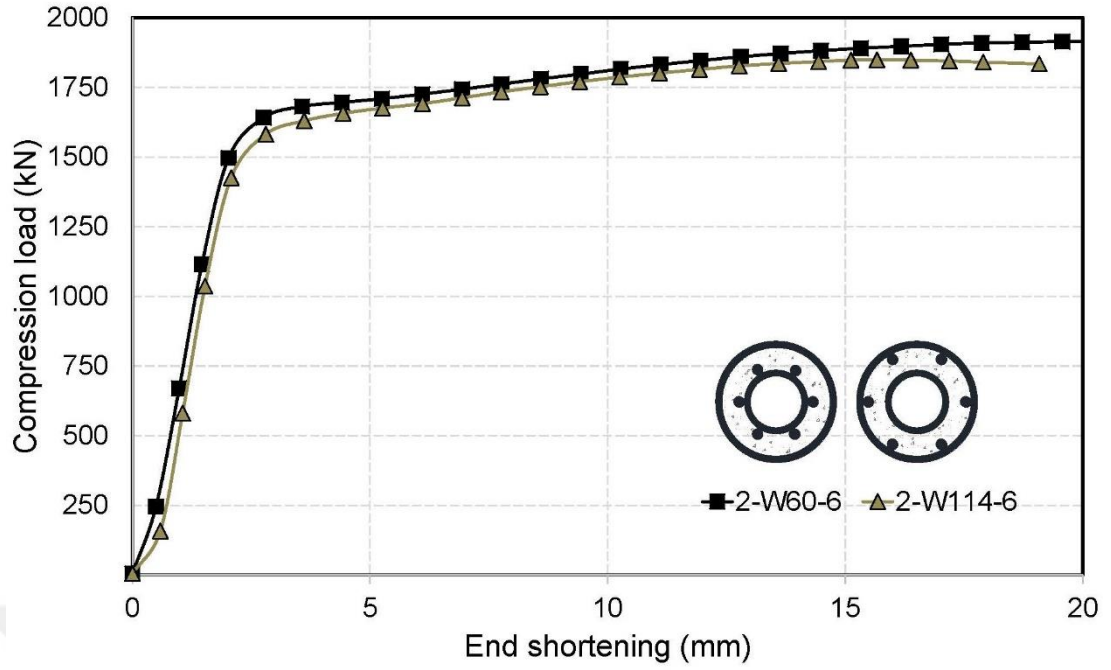


Figure 6.15 Compression load vs. end shortening curves for 2-W60-6 and 2-W114-6

6.4.2 Concrete-Steel Contribution Ratio (CSCR)

The contribution of the tubes in the double skin columns is deliberated in this study by focusing on the impact of the WRBs and the steel tubes thicknesses on the compression capacities. Besides, the abbreviation CSCR means concrete-steel contribution ratio, which utilized by Ibañez *et al.* [247]. CSCR is a ratio between $N_{u,CFDST}$ to $N_{u,CFST}$, where $N_{u,CFDST}$ is the ultimate load achieved of the CFDST specimen (stiffened or unstiffened), and $N_{u,CFST}$ is the ultimate load achieved of the ordinary CFST specimen counterpart as shown in Equation (6.1). This ratio can assess the enhanced of the mechanical response of a double skin column based on the response of a CFST column counterpart.

$$CSCR = \frac{N_{u,CFDST}}{N_{u,CFST}} \quad (6.1)$$

Figure 6.16 illustrates that the CSCRs are more than unity in the specimens with thin-thin tubes, which the specimens 1-W60-3, 1-W114-3, 1-W60-4, 1-W114-4, 1-W60-6 and 1-W114-6 have CSCRs of 1.18, 1.18, 1.24, 1.21, 1.37 and 1.34 respectively. On

the other hand, the specimens 2-W60-3, 2-W60-4, 2-W60-6, 2-W114-3, 2-W114-4 and 2-W114-6 have CSCRs of 1.24, 1.25, 1.30 1.19, 1.22 and 1.26, respectively, Figure 6.17. It indicates that the CSCRs of these specimens were increasing as the number of WRBs increased. Correspondingly, these patterns of WRBs affect positively on the mechanical response of the CFDST specimens. Moreover, it is interesting here to observe that the CSCRs of the stiffened CFDST specimens that have WRBs with inner steel tube are higher than the CSCRs of specimens that have the other pattern counterparts.

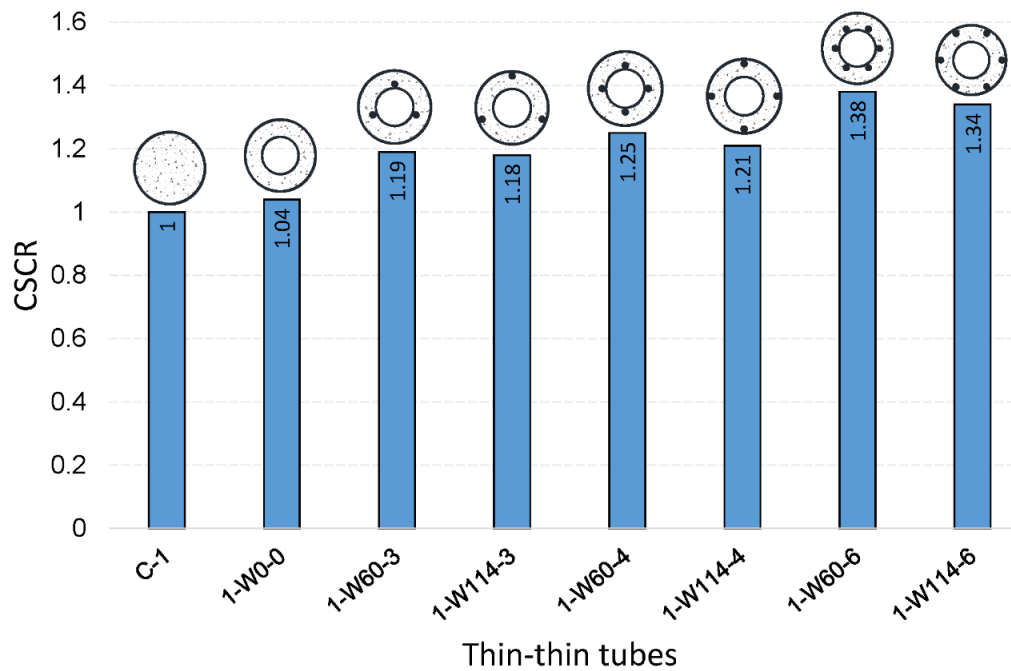


Figure 6.16 Concrete-steel contribution ratio for (thin-tin tubes) specimens

On the other hand, the CSCRs of the unstiffened CFDST specimens (without WRBs) 1-W0-0 and 2-W0-0 are more than unity, as listed in Table 6.2. It means that the inner tube affects positively on the compression capacity of the double skin columns and did enhance the behaviour of the ordinary CFST columns counterparts.

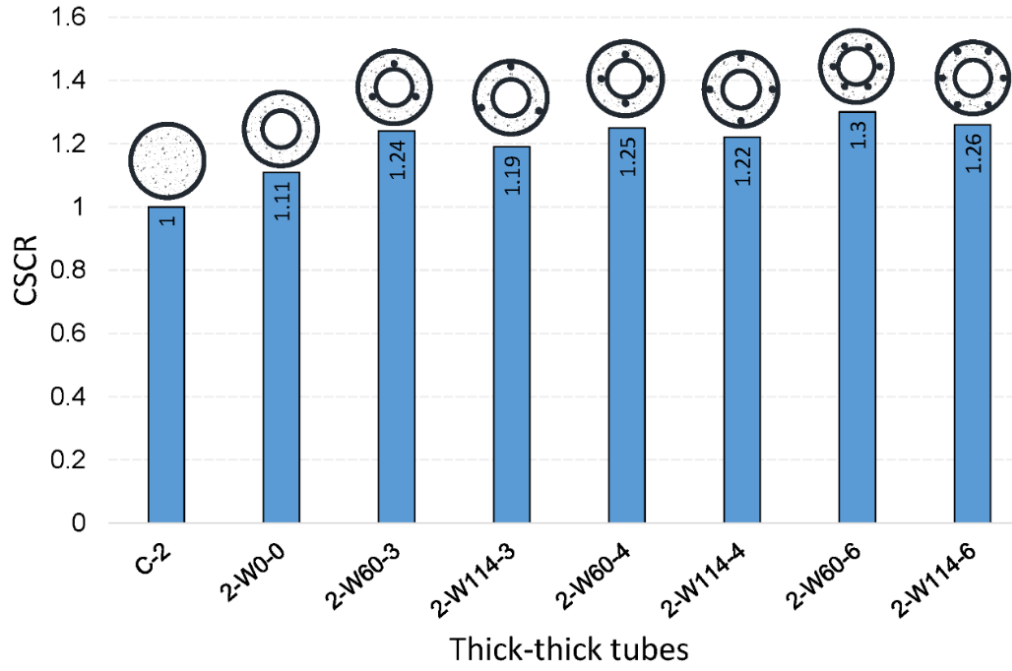


Figure 6.17 Concrete-steel contribution ratio for (thick-thick tubes) specimens

6.4.3 Compressive Strength Index (SI)

The SI is a ratio between the ultimate load of the specimen divided by the resistance of cross-section as defined in Equation (6.2). In a CFDST specimen, the strength is including four elements: the shell concrete, the inner tube, the outer tube, and WRBs.

$$SI = \frac{N_{exp}}{A_{so}f_{yo} + 0.85 A_c f_c + A_{si}f_{yi} + A_{sb}f_{ysb}} \quad (6.2)$$

where N_{exp} is the calculated ultimate strength of a specimen and A_{so} , A_c , A_{si} and A_{sb} are the areas of the outer tube, sandwiched concrete, inner tube, and WRB, respectively. The Equation (6.2) is used for specimens C-1 and C-2 after ignoring both terms of $A_{si}f_{yi}$ and $A_{sb}f_{ysb}$ for these specimens. Likewise, it is used for 1-W0-0 and 2-W0-0 also after ignoring the terms of $A_{sb}f_{ysb}$ for these specimens. As listed in Table 6.2, the SIs for all columns are more than unity. It means that the confinement of the concrete in the specimens is clear, leading to apparent concrete strength improvement [237]. It can indicate that the confinement performance of the specimen is increasing as the number

of WRBs increase. Furthermore, it seems that the specimens with WRBs on the external surface of inner steel tubes have slightly greater SIs compared to SIs of the specimens that have WRBs with outer steel tubes counterparts.

6.5 Failure Modes

In order to differentiate the performance of CFDST and the extent of the WRBs contribution of these columns, it is essential to observe the shape of the tube's failure. The failure modes of the specimens could disclose the individual physical behaviour of constituent parts of the columns and the composite action among them.

The specimens C-1 and 1-W0-0 used for comparison purposes. The failure mode of the specimen 1-W0-0 is different when compared to the failure modes of the remain specimens as shown in Figure 6.18 and Figure 6.19. It has a harsh and intense local failure mode, especially at the inner steel tube. This level of inward and outward buckling occurred due to the weakness of the inner support with a thinner inner and outer tubes against expansion in the shell concrete, as shown in Figure 6.18-b. It is crucial here to note that the specimens with thinner tubes showed evidence of shear cracks in concrete.

On the other hand, Figures 6.18 and 6.19 show, the increasing number of the WRBs eliminate the harmful effect of the local bulking. Furthermore, the specimens 1-W60-4 and 1-W60-6 have significant resistance against inward and outward distortions, whereas, the specimens 1-W114-4 and 1-W114-6 exhibited significantly inward and outward distortions, Figure 6.19. This means the WRBs on the external surface of the thinner inner tubes in CFDST specimens have a promising performance and achieved smaller inward and outward distortions than the specimens with WRBs on the internal surface of the outer tubes.

Generally, it could be observed that the specimens with thinner tubes exhibit significantly more lateral deformations compared to the specimens with thicker tubes. It indicates that the thinner tubes cannot provide an appropriate composite action,

which the composite action allows the concrete and steel tube to serve together properly. It is important in composite structural members to satisfy this harmony.



Figure 6.18 Failure modes of C-1, 1-W0-0, 1-W60-3 and 1-W114-3 specimens

Besides, as can be observed in Figure 6.20 and Figure 6.21, the thicker steel tubes have a very promising performance, which these configurations (thick-thick) attained very small inward and outward distortions. It indicates that a thicker inner tube with a thicker outer tube serve the cross-sectional capacity efficiently. Hence, this configuration can develop good “composite action” with the shell concrete. Besides, the thicker tubes governed the compression behaviour of the columns and did not allow the specimens to exhibit shear failure modes.



Figure 6.19 Failure modes of 1-W60-4, 1-W114-4, 1-W60-6 and 1-W114-6 specimens

6.6 Comparisons with Design Methods of CFDST Columns

The purpose of this section is to estimate the compressive strengths of the stiffened double skin columns by using the design methods that proposed by several researchers. Generally, the design procedures of unstiffened CFDST column were extended for stiffened CFDST column by changing certain parameters, such as Han *et al.* [268], and Yu *et al.* [269] methods which were used in this study. In addition, the design process of columns that detailed in the Eurocode 4 [137] and AISC-360 [310] standard were

also modified to predict the cross-section capacities of circular stiffened CFDST columns.

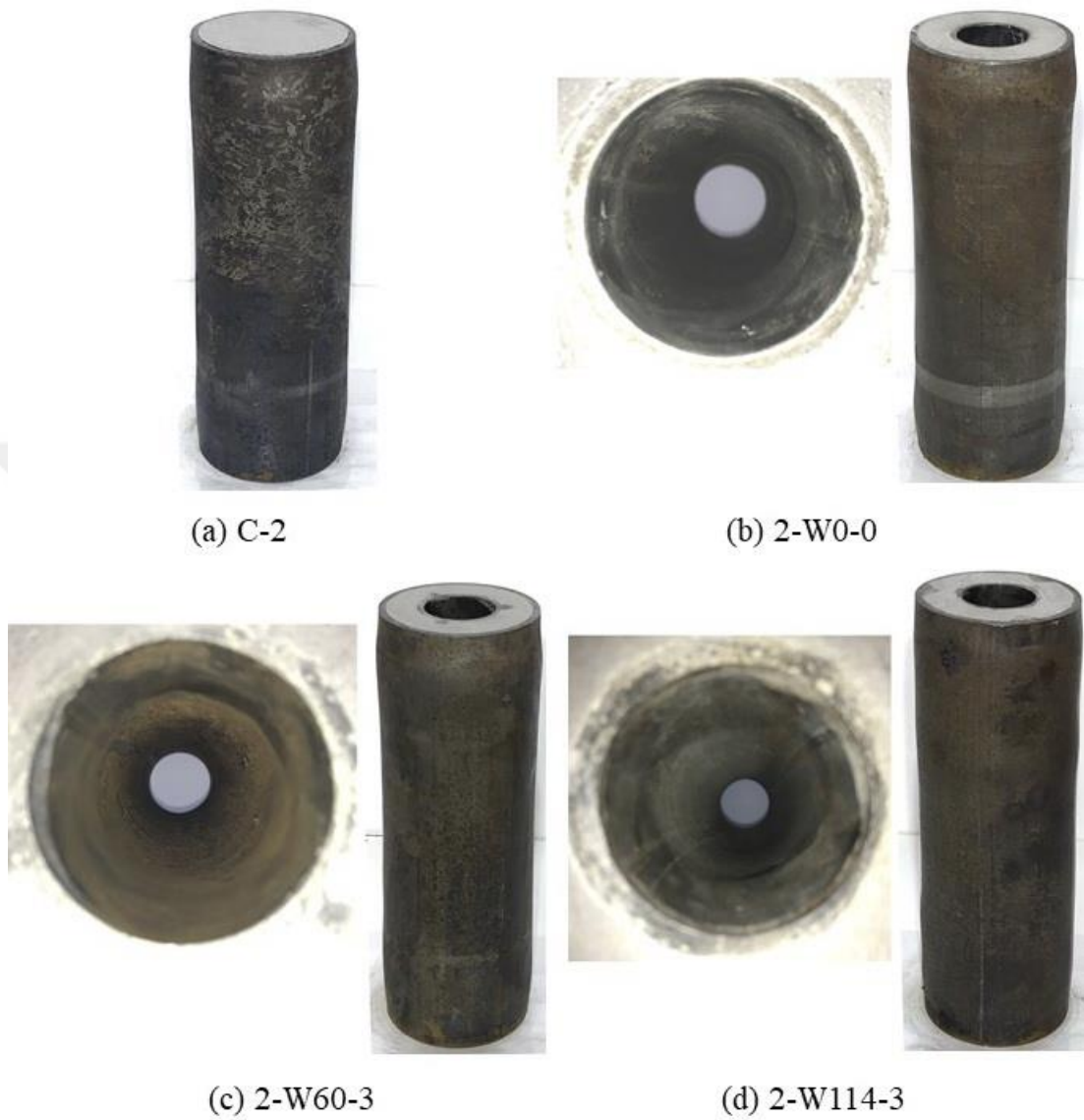


Figure 6.20 Failure modes of C-2, 2-W0-0, 2-W60-3 and 2-W114-3 specimens



Figure 6.21 Failure modes of 2-W60-4, 2-W114-4, 2-W60-6 and 2-W114-6 specimens

6.6.1 AISC-360

The strength capacity (N_n) of the ordinary CFST column in Equation (6.3) [310] was changed to use for CFDST column by Sulthana and Jayachandran [126], as a given in Equation (6.4). Furthermore, the author proposed the Equation (6.5), which the strength generated by the WRBs added to Equation (6.4).

$$P_n = f_{yo}A_{so} + C_2f_c'A_c \quad (6.3)$$

$$P_n = f_{yo}A_{so} + A_i f_{yi} + C_2 f_c' A_c \quad (6.4)$$

$$P_{n,mod} = f_{yo}A_{so} + A_i f_{yi} + C_2 f_c' A_c + A_{sb} f_{ysb} \quad (6.5)$$

The C_2 factor takes 0.95 when the inner and outer steel tubes are circular, otherwise, it assumes 0.85. The elastic buckling load (P_{cr}) and the strength capacity (P_{AISC}) of a column are displayed in Equations. (6.7) and (6.6) respectively.

$$P_{AISC,mod} = \begin{cases} P_n [0.658^{P_n/P_{cr}}] & : \frac{P_n}{P_{cr}} \leq 2.25 \\ 0.877 P_{cr} & : \frac{P_n}{P_{cr}} > 2.25 \end{cases} \quad (6.6)$$

$$P_{cr} = \frac{\pi^2 EI_{eff}}{L^2} \quad (6.7)$$

where EI_{eff} is the effective flexural rigidity of the cross-section. However, the $E_c I_c$ is reduced by the C_3 factor, according to the fact that large cracks in the concrete lose its stiffness before the column buckling occurred, [126], as given in Equations (6.8) and (6.9).

$$EI_{eff} = E_{so} I_{so} + E_{si} I_{si} + C_3 E_c I_c \quad (6.8)$$

$$C_3 = 0.6 + 2 \left(\frac{A_{so} + A_{si}}{A_{so} + A_{si} + A_c} \right) \leq 0.9 \quad (6.9)$$

6.6.2 EC4

The strength of cross-section (N_n) of ordinary CFST column according to EC4 [137] is given in Equation (6.10). Based on EC4, Pagoulatou *et al.* [235] suggested the compressive strength equation for CFDST columns with inner and outer tubes, as given in Equation (6.11). Moreover, the strength capacity of WRBs added to Equation

(6.11) by authors as shown in Equation (6.12). Worth mentioning, the concrete enhancement isn't considered in EC4 when the slenderness ratio (λ) is more than 0.5 [235].

$$N_u = \eta_s A_s f_y + A_c f_c \left(1 + \eta_c \frac{t}{D} \frac{f_y}{f_c} \right); \text{ for CFST} \quad (6.10)$$

$$N_u = \eta_{so} (A_{so} f_{yo} + A_{si} f_{yi}) + A_c f_c \left(1 + \eta_c \frac{t_o}{D_o} \frac{f_{yo}}{f_c} \right); \text{ for CFDST} \quad (6.11)$$

$$N_{u,mod} = \eta_{so} (A_{so} f_{yo} + A_{si} f_{yi} + A_{sb} f_{ysb}) + A_c f_c \left(1 + \eta_c \frac{t_o}{D_o} \frac{f_{yo}}{f_c} \right); \text{ for} \quad (6.12)$$

CFDST with welded reinforcing bars

The squash load of the column reduces by the stability reduction factor χ , which depends on the slenderness ratio (λ), as given in Equation (6.15). The calculation of λ is assumed in Equation (6.13), where N_{cr} is the elastic buckling load of the column and N_u is the cross-section capacity. Furthermore, the effective flexural rigidity (EI_{eff}) is specified in Equation (6.14).

$$\lambda = \sqrt{\frac{N_u}{N_{cr}}} \quad (6.13)$$

$$EI_{eff} = E_{so} I_{so} + E_{si} I_{si} + 0.6 E_c I_c \quad (6.14)$$

$$N_{u,EC4,mod} = \chi (A_{so} f_{yo} + A_{si} f_{yi} + A_c f_c + A_{sb} f_{ysb}) \quad (6.15)$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \quad (6.16)$$

$$\phi = 0.5(1 + \alpha(\lambda - 0.2) + \lambda^2) \quad (6.17)$$

6.6.3 Design Strength by Han *et al.* [268]

Han *et al.* [268] proposed a new formulation to predict the cross-section capacity of unstiffened CFDST specimen, where the effect of the confinement is considered in the shell concrete strength. The maximum squash load of the unstiffened CFDST column measured as follows:

$$N_{u,Han} = N_{i,u} + N_{osc,u} \quad (6.18)$$

In the present study, the cross-section capacity of the WRBs is linearly added to the squash load equation of CFDST column as follows:

$$N_{u,Han,mod} = N_{i,u} + N_{sb} + N_{osc,u} \quad (6.19)$$

where $N_{i,u} = A_{si} f_{syi}$; $N_{sb} = A_{sb} f_{ysb}$; $N_{osc,u} = f_{scy} A_{sco}$; $k_1 = 1$ when the tube thickness is less than 16 mm;

$$f_{scy} = k_1 C_1 \chi^2 f_{syo} + C_2 (1.14 + 1.02 \xi_o) f_{ck} \quad (6.20)$$

where: $\chi = \frac{d}{D-2t_o}$; $\alpha = \frac{A_{so}}{A_c}$; $\alpha_n = \frac{A_{so}}{A_{ce}}$; $A_{ce} = \frac{\pi}{4} (D - 2t_{so})^2$; $C_1 = \frac{\alpha}{(1+\alpha)}$;

$\xi = \alpha_n \frac{f_{syo}}{f_{ck}}$; $C_2 = \frac{(1+\alpha_n)}{(1+\alpha)}$; $A_{sco} = A_{so} + A_c$; $f_{ck} = \frac{f_{ct}}{1.5}$

The χ is hollowness ratio and ξ is a confinement ratio factor. Besides, C_1 and C_2 are factors based on component area (area of concrete and steel).

6.6.4 Design Strength by Yu *et al.* [269]

A strength capacity of the CFST column was suggested by Yu *et al.* [269], as follows:

$$N_{u,Yu} = \left(1 + 0.5 \left(\frac{\xi}{1 + \xi}\right) \Omega\right) (f_{sy} A_s + f_{ck} A_c) \quad (6.21)$$

where, $\zeta = (\alpha \cdot f_{sy} / f_{ck})$, $\alpha = (A_s / A_c)$, Ω is a solid proportion, which $\Omega = A_c / (A_c + A_k)$, A_s is an outer steel tube area, A_c is a shell concrete area, and A_k is a hollow part area. Besides, the strength capacity ($N_{u,Yu,CFDST}$) of the unstiffened CFDST column was modified by Hassanein and Kharoob [134], where the squash load of inner steel tube added to Equation (6.21), hence, the equation of the unstiffened CFDST columns is considered as:

$$N_{u,Yu,CFDST} = \left(1 + 0.5 \left(\frac{\xi}{1 + \xi}\right) \Omega\right) (f_{sy0} A_{so} + f_{ck} A_c) + N_{i,u} ; (N_{i,u} = f_{syi} A_{si}) \quad (6.22)$$

Herein, the strength generated by the welded reinforcing bars (N_{sb}) added to Equation (6.22) to obtain the squash load of the stiffened CFDST column as follows:

$$N_{u,Yu,mod} = \left(1 + 0.5 \left(\frac{\xi}{1 + \xi}\right) \Omega\right) (f_{sy0} A_{so} + f_{ck} A_c) + N_{i,u} + N_{sb} \quad (6.23)$$

where $N_{sb} = f_{sby} A_{sb}$, A_{si} is an area of the inner tube, A_{so} is an area of the outer tube, f_{syi} is yield stress of the inner tube, f_{sy0} is yield stress of the outer tube and f_{sby} is yield stress of the reinforcing bars.

6.6.5 Results of Strength Predictions

The strength predictions calculated using the above-mentioned modified methods ($N_{EC4,mod}$, $N_{AISC,mod}$, $N_{Han,mod}$, and $N_{Yu,mod}$). It can be shown in Table 6.3, the $N_{EC4,mod}/N_{exp}$ ratios are less than unity with some exceptions. However, the mean value and the standard deviation of $N_{EC4,mod}/N_{exp}$ ratios are 0.97 and 0.03, respectively. Besides, the $N_{AISC,mod}/N_{exp}$ ratios are also lower than unity, which the mean value and the standard deviation of $N_{AISC,mod}/N_{exp}$ ratios are 0.90 and 0.03, respectively. This means that the EC4_{mod} method offers the best and more accurate predictions of the strength capacity for stiffened CFDST columns compared to AISC_{mod} method, Figure 6.22.

On the other hand, the $N_{\text{Han.mod}}/N_{\text{exp}}$ ratios are lower than unity with some exceptions, which the mean value and the standard deviation of $N_{\text{Han.mod}}/N_{\text{exp}}$ ratios are 0.95 and 0.04, respectively. Besides, the mean value and the standard deviation of $N_{\text{Yu.mod}}/N_{\text{exp}}$ ratios are 0.99 and 0.05, respectively. It means that the Han_{mod} method offers the safe prediction of the strength capacity of the stiffened CFDST columns compared to Yu_{mod} method. It means that the estimates of Yu_{mod} method are slightly unconservative related to thicker tubes (thick-thick) combinations in these stiffened CFDST columns.



Table 6.3 Comparison of Strength Predictions with Test Results

Specimen	N_{exp}	$NEC4.mod/N_{exp}$	$NAISC.mod/N_{exp}$	$N_{Han.mod}/N_{exp}$	$N_{Yu.mod}/N_{exp}$
Thinner-thinner					
C-1	726.34	0.89	0.89	0.88	0.93
1-W0-0	758.61	1.02	0.93	0.93	0.96
1-W60-3	862.48	0.99	0.93	0.93	0.96
1-W114-3	861.77	0.99	0.93	0.93	0.96
1-W60-4	907.88	0.97	0.92	0.92	0.95
1-W114-4	880.25	1.00	0.95	0.95	0.98
1-W60-6	999.49	0.93	0.91	0.91	0.93
1-W114-6	975.55	0.95	0.93	0.93	0.95
Thicker-thicker					
C-2	1,465.76	0.94	0.84	1.01	1.09
2-W0-0	1,622.25	1.01	0.91	1.01	1.06
2-W60-3	1,812.27	0.95	0.87	0.96	1.00
2-W114-3	1,745.14	0.99	0.90	1.00	1.04
2-W60-4	1,835.22	0.95	0.87	0.97	1.01
2-W114-4	1,789.22	0.98	0.90	0.99	1.03
2-W60-6	1,916.75	0.94	0.87	0.96	1.00
2-W114-6	1,850.37	0.97	0.90	1.00	1.04
Mean		0.97	0.90	0.95	0.99
Standard Deviations		0.03	0.03	0.04	0.05

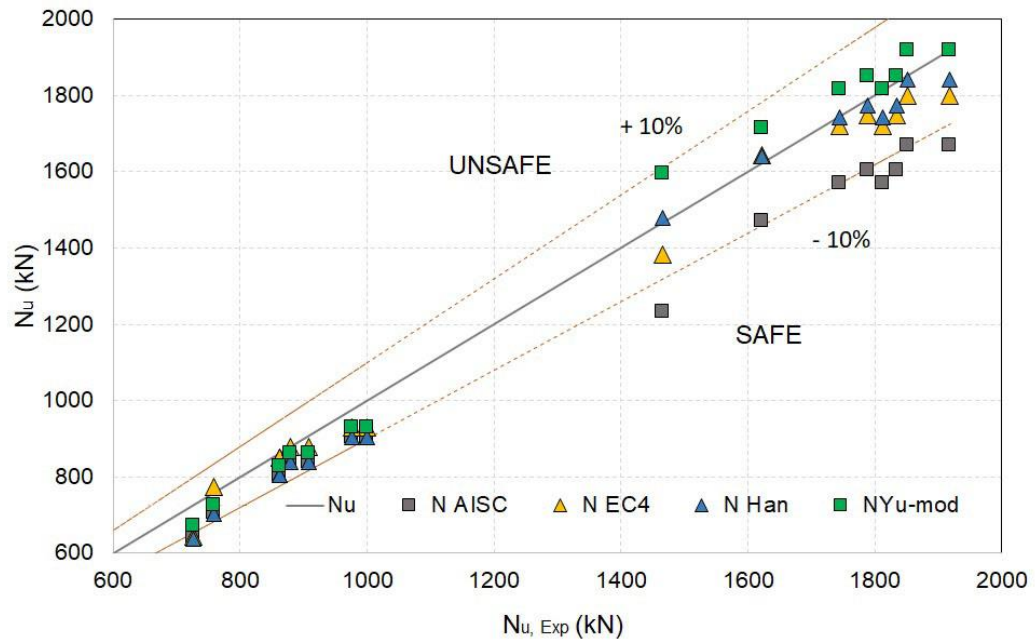


Figure 6.22 Comparison of experimental ultimate loads and design methods prediction

6.7 Conclusions

The current study presented an experimental work on the CFDST column stiffened by Welded Reinforcing Bars (WRBs) under compressive loading. A series of tests were conducted on sixteen CFDST specimens. Two different D/t ratios and different patterns of WRBs were used as parameters to enable a better understanding of the performance of the stiffened CFDST column. For that purpose, compressive loading vs. end shortening curves, failure modes, strength index and concrete-steel contribution ratio were analysed. Finally, the design methods that used in several studies have been modified for comparison with experimental results. Based on the results, the subsequent conclusions can be drawn within the scope of this study:

- The compression loading vs. end shortening curves of CFDSTs revealed that the strength capacity, ductility, stiffness, and toughness were increasing as the number of WRBs and/or thickness of the steel tubes increased. Likewise, the buckling of columns can be effectively postponed by increasing the number of WRBs on the steel tubes.

- The specimens with WRBs on the external surface of inner tubes have a greater promising performance than the specimens that have WRBs on the internal surface of outer tubes, and achieved smaller inward and outward distortions. Furthermore, the installation of the first pattern (WRBs with inner tubes) is easier than the other pattern counterpart even with the steel tubes that have a small diameter. Accordingly, to provide the desired level of performance of CFDST columns, it would be preferable to weld reinforcing bars on the external surface of the inner tubes.
- Obviously, the contribution of WRBs is less significant with the thicker tubes (thick-thick) in CFDST column, whereas, the WRBs are more significant with thinner tubes.
- In terms of CSCRs, all specimens can gain the compression capacity more than the thin-walled CFST columns counterpart with less weight. In addition, the WRBs with inner steel tubes affect positively on the mechanical response of CFDST columns, which confirm their effectiveness slightly higher than that have WRBs with outer steel tubes. Besides, SIs of the columns increased as increasing the number of WRBs, consequently, it can indicate that the confinement performance of the specimen is increasing as the number of WRBs increase.
- In terms of failure modes, the thick-thick configurations have a very promising performance and attained very small inward and outward distortions. Hence, the thicker tubes can develop good “composite action” with the shell concrete. Moreover, the thicker tubes governed the compression behaviour of the columns and did not allow the specimens to exhibit shear failure modes.
- The modified methods of EC4 and Han offer better and more accurate predictions of the strength capacity for the stiffened CFDST columns. As shown, the predictions provided by using these design methods are always in the safe side. These modified formulas will be very useful to the structural designers for a prescribed strength capacity of CFDST columns.

- The modified AISC method gives very conservative predictions of the stiffened CFDST columns, which were about 10% lower than those of the experiments.
- Finally, the modified Yu method offered an unconservative predictions of the strength capacity for stiffened CFDST columns with some exceptions related to the thin-thin steel tubes combinations, and thereby it does not satisfy the safety requirements



CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The main goal of this thesis is to investigate possible new configurations to improve the mechanical properties of CFDST columns. The proposed campaigns lead to a better understanding of the CFDST column, which discuss the topics of ductility, shortening, strength capacity, toughness, buckling, confinement effects, the bond strength, and failure modes. Overall, several specimens were tested by the impartiality of assessing the impact of the parameters, which were used different type of concrete strength, different D/t ratios, different patterns of configurations and other parameters as the main parameters in this thesis. Furthermore, to generate detailed knowledge of the strengthened CFST and CFDST performance that stiffened by reinforcing bars, the role of steel reinforcing bars within concrete-filled steel tubular columns and concrete-filled double-skin steel tubes was investigated. On the other hand, the design methods that proposed by several studies were modified to estimate the cross-section capacities of ordinary and stiffened CFDST columns, which were assessed against the experimental results to trace the suitable formulation for design purposes.

Overall, those tests were distributed between studies, with the tests described in three chapters—Chapter Four through Chapter Six.

The topics of interest were conducted to explore several areas:

Chapter Four was to examine the performances of concrete filled classical, double skin and double section stub columns which have practical range of material and geometrical properties.

Furthermore, no single study exists on the systematic comparison of the classical, double skin and double section columns which have practical range of material and geometrical properties. Experimental procedures were undertaken for composite columns with normal and high strength self-compacted concrete. Two types of outer and two types of inner steel tubes with different mechanical and geometrical properties were utilized in the second topic. In this chapter, the experimental program allows in-depth comparisons between the composite column types.

Chapter Five was conducted to explore the effect of the inner steel tube on the mechanical response of CFDST columns under axial compression. Two different D/t ratios and concrete classes (normal strength and high strength) were utilized and in total sixteen specimens were tested to failure. To be able to analysis the impact of the parameters, failure modes, compression loading versus end shortening curves and the concrete-steel contribution ratios were detailed.

Chapter Six was to explore experimentally and analytically the mechanical performance of CFDST columns stiffened by an innovative type of stiffening members. 16 specimens have been tested to assess the impact of the parameters. Two different patterns of WRBs, the first pattern includes reinforcing bars welded on the external surface of the inner steel tube, whereas the second pattern includes reinforcing bars welded on the internal surface of the outer tubes. The analytical methods that were proposed by several investigators for unstiffened CFDST columns were developed to estimate the cross-section capacities of stiffened CFDST columns. It is shown in this study that the modified design methods have the potential to be utilized for stiffened CFDST columns.

7.2 Conclusions

Based on the results, the subsequent conclusions can be drawn within the scope of this thesis:

- In all cases, double section columns always exhibited significantly greater compression performances compared to classical CFST and double skin specimens. Also, double section columns always experienced superior ductility behaviour. Double section column configuration allows a complete utilization of the yield capacity of the inner steel tube and crushing capacity of the core concrete. In addition, a further level of confinement could be obtained in this type of column. Although high strength concrete improves the capacity of the columns, it adversely affects the confinement effect and ductility due to lower dilatation. Moreover, it was shown that lower dilatation of the high strength concrete causes the column to attain early local buckling.
- In double skin columns which have thinner inner steel tubes, the effect of the high D/t ratio led to harsh inward local buckling behaviours. On the other hand, the thicker inner steel tubes did not show any evidence of harsh inward local buckling which significantly improved the column capacity and confinement. The presence of the inner steel tube has a vital role on the performance of CFDST columns. Inner tubes provided compression capacity increments in the range of 18.95–65.44 %. However, it is important noting that the thinner inner tubes ($D/t = 23.93$) suffer from early local buckling which prevents cross sectional-area of such a tube to be exploited efficiently and causes less confinement for the shell concrete.
- For “composite action” between the shell concrete and steel tubes, the inner steel tube helps the concrete to be entirely confined by limiting its expansion in inward direction during the loading process. It can be concluded that when the hollow concrete is used without inner steel tube, the outer tube cannot develop the proper confinement for the concrete. The results confirmed that the thin inner tube ($D/t = 23.93$) cannot improve the compression capacity of CFDST with high strength concrete (HSC). However, such a tube could provide remarkable performance with normal strength concrete (NSC) compared to the performance of classical CFST counterpart. In contrast, the

thick inner tube ($D/t = 10.45$) can develop good “composite action” even with HSC. The CSCR values and the compression loading versus end shortening curves support these findings.

- The compression loading vs. end shortening curves of CFDSTs indicate that the compression performance, toughness and ductility increase with increasing the thickness of the inner tube. Furthermore, the absence of the inner tube (columns with hollow concrete) leads the columns to reach the compression capacity at very early level of end shortening which implies a poor ductility behaviour. The results corroborate that the contribution of the shell concrete strength is less important with the thick outer tube ($D/t = 19.45$) in CFDST column. However, the effect of the shell concrete strength is more significant with thin-outer tubes ($D/t = 41.87$). Likewise, the SI ratios of the specimens indicate that the effect of confinement increases when the thickness of the inner tube increases. Therefore, in CFDST columns, the confinement effect of the inner tube must be considered in design calculations. The failure shape mostly is dependent on the D/t ratio of the outer tube. On the other hand, the thinner inner tubes experience intensive level of inward early local buckling which compromise the performance of the column. The thicker inner steel tubes could contribute cross sectional capacities efficiently and do not exhibit harsh local buckling.
- Examining the performance of standard prediction methods (with modified versions), it could be concluded that EC4 has better predictions for CFDST columns compared to the predictions of this method for the classical CFST columns. The conservative predictions of the AISC 360-16 showed itself for classical and double skin columns. However, for the CFDST columns it has also better predictions compared to the predictions for classical CFST columns. The capacity methods provided by Hassanein and Kharoob [134] and Yu *et al.* [269] perform very well in predicting the capacity of the double skin columns.

Nevertheless, it is worth noting that these methods were formulated for stub columns and do not consider L/D effect.

- The compression loading vs. end shortening curves of CFDSTs revealed that the strength capacity, ductility, stiffness, and toughness were increasing as the number of Welded Reinforcing Bars (WRBs) and/or thickness of the steel tubes increased. Likewise, the buckling of columns can be effectively postponed by increasing the number of WRBs on the steel tubes. The specimens with WRBs on the external surface of inner tubes have a greater promising performance than the specimens that have WRBs on the internal surface of outer tubes, and achieved smaller inward and outward distortions. Furthermore, the installation of the first pattern (WRBs with inner tubes) is easier than the other pattern counterpart even with the steel tubes that have a small diameter. Accordingly, to provide the desired level of performance of CFDST columns, it would be preferable to weld reinforcing bars on the external surface of the inner tubes. Obviously, the contribution of WRBs is less significant with the thicker tubes (thick-thick) in CFDST column, whereas, the WRBs are more significant with thinner tubes.
- In terms of CSCRs, all specimens can gain the compression capacity more than the thin-walled CFST columns counterpart with less weight. In addition, the WRBs with inner steel tubes affect positively on the mechanical response of CFDST columns, which confirm their effectiveness slightly higher than that have WRBs with outer steel tubes. Besides, SIs of the columns increased as increasing the number of WRBs, consequently, it can indicate that the confinement performance of the specimen is increasing as the number of WRBs increase. On the other hand, in terms of failure modes, the thick-thick configurations have a very promising performance and attained very small inward and outward distortions. Hence, the thicker tubes can develop good “composite action” with the shell concrete. Moreover, the thicker tubes

governed the compression behaviour of the columns and did not allow the specimens to exhibit shear failure modes.

- The modified methods of EC4 and Han offer better and more accurate predictions of the strength capacity for the stiffened CFDST columns. As shown, the predictions provided by using these design methods are always in the safe side. These modified formulas will be very useful to the structural designers for a prescribed strength capacity of CFDST columns. The modified AISC method gives very conservative predictions of the stiffened CFDST columns, which were about 10% lower than those of the experiments. Finally, the modified Yu method offered an unconservative predictions of the strength capacity for stiffened CFDST columns with some exceptions related to the thin-thin steel tubes combinations, and thereby it does not satisfy the safety requirements.

REFERENCES

- [1] Kitada, T. (1998). Ultimate Strength and Ductility of State of the Art Concrete-Filled Steel Bridge Piers in Japan. *Engineering Structures*, **20(4-6)**, 347-354.
- [2] Li, Y., Zhao, X., Singh, R. R. Al-Saadi, S. (2016). Experimental Study on Seawater and Sea Sand Concrete Filled GFRP and Stainless Steel Tubular Stub Columns. *Thin-Walled Structures*, **106**, 390-406.
- [3] Ekmekyapar, T., Alwan, O. H., Hasan, H. G., Shehab, B. A. AL-Eliwi, B. J. (2019). Comparison of Classical, Double Skin and Double Section CFST Stub Columns: Experiments and Design Formulations. *Journal of Constructional Steel Research*, **155**, 192-204.
- [4] Shanmugam, N. E. Lakshmi, B. (2001). State of the Art Report on Steel–Concrete Composite Columns. *Journal of Constructional Steel Research*, **57(10)**, 1041-1080.
- [5] Kwan, A., Dong, C. Ho, J. (2016). Axial and Lateral Stress–Strain Model for Circular Concrete-Filled Steel Tubes with External Steel Confinement. *Engineering Structures*, **117**, 528-541.
- [6] Chang, X., Luo, X., Zhu, C. Tang, C. (2014). Analysis of Circular Concrete-Filled Steel Tube (Cft) Support in High Ground Stress Conditions. *Tunnelling and Underground Space Technology*, **43**, 41-48.
- [7] Ekmekyapar, T. (2016). Experimental Performance of Concrete Filled Welded Steel Tube Columns. *Journal of Constructional Steel Research*, **117**, 175-184.
- [8] Chen, J., Wang, J., Xie, F. Duan, A. (2016). Behavior of Thin-Walled Dodecagonal Section Double Skin Concrete-Filled Steel Tubular Beam-Columns. *Thin-Walled Structures*, **104**, 135-143.
- [9] Eggemann, H. (2003). Development of Composite Columns. Emperger's Effort. 1st Int Congress on Construction History, Madrid.
- [10] Brown, N., Kowalsky, M. Nau, J. (2015). Impact of D/T on Seismic Behavior of Reinforced Concrete Filled Steel Tubes. *Journal of Constructional Steel Research*, **107**, 111-123.
- [11] Han, L.-H., Zhao, X.-L. Tao, Z. (2001). Tests and Mechanics Model for Concrete-Filled Shs Stub Columns, Columns and Beam-Columns. *Steel and Composite Structures*, **1(1)**, 51-74.
- [12] Zhang, Y., Huang, Y., Lei, K., Pei, J. Zhang, Q. (2017). Seismic Behaviors of Steel Bar Reinforced Joints of Concrete Filled Steel Tubular Laminated Columns. *KSCE Journal of Civil Engineering*, **22(9)**, 3491–3503.

- [13] Yang, Z., Li, G., Lang, Y. Fang, C. (2017). Flexural Behavior of High Strength Concrete Filled Square Steel Tube with Inner CFRP Circular Tube. *KSCE Journal of Civil Engineering*, **21(7)**, 2728-2737.
- [14] Kim, D.-W. Shim, C.-S. (2016). Experiments on Flexural Strength on Composite Modular Bridge Pier Cap for Cft Columns. *KSCE Journal of Civil Engineering*, **20(6)**, 2483-2491.
- [15] Li, Y.-J., Han, L.-H., Xu, W. Tao, Z. (2016). Circular Concrete-Encased Concrete-Filled Steel Tube (CFST) Stub Columns Subjected to Axial Compression. *Magazine of Concrete Research*, **68(19)**, 995-1010.
- [16] Lai, M. Ho, J. (2015). Optimal Design of External Rings for Confined CFST Columns. *Magazine of Concrete Research*, **67(19)**, 1017-1032.
- [17] Gupta, P. K., Ahuja, A. K. Khaudhair, Z. A. (2014). Modelling, Verification and Investigation of Behaviour of Circular CFST Columns. *Structural Concrete*, **15(3)**, 340-349.
- [18] Lee, S.-H., Choi, Y.-H., Kim, Y.-H. Choi, S.-M. (2012). Structural Performance of Welded Built-up Square CFST Stub Columns. *Thin-Walled Structures*, **52**, 12-20.
- [19] Han, L.-H., He, S.-H. Liao, F.-Y. (2011). Performance and Calculations of Concrete Filled Steel Tubes (CFST) under Axial Tension. *Journal of Constructional Steel Research*, **67(11)**, 1699-1709.
- [20] Han, L.-H., Ren, Q.-X. Li, W. (2010). Tests on Inclined, Tapered and Sts Concrete-Filled Steel Tubular (CFST) Stub Columns. *Journal of Constructional Steel Research*, **66(10)**, 1186-1195.
- [21] Ding, F.-x., Li, Z., Cheng, S. Yu, Z.-w. (2016). Composite Action of Hexagonal Concrete-Filled Steel Tubular Stub Columns under Axial Loading. *Thin-Walled Structures*, **107**, 502-513.
- [22] Park, T., Hwang, W.-S., Leon, R. T. Hu, J. W. (2011). Damage Evaluation of Composite-Special Moment Frames with Concrete-Filled Tube Columns under Strong Seismic Loads. *KSCE Journal of Civil Engineering*, **15(8)**, 1381-1394.
- [23] Abbas, H., Al-Salloum, Y., Alsayed, S., Alhaddad, M. Iqbal, R. (2017). Post-Heating Response of Concrete-Filled Circular Steel Columns. *KSCE Journal of Civil Engineering*, **21(4)**, 1367-1378.
- [24] Fu, Z., Wang, Q., Wang, Y. Ji, B. (2018). Bending Performance of Lightweight Aggregate Concrete-Filled Steel Tube Composite Beam. *KSCE Journal of Civil Engineering*, **22(10)**, 3894–3902.
- [25] Han, L.-h. Tao, Z. (2000). Ductility Coefficient of Concrete Filled Steel Tubular Columns with Square Sections [J]. *Earthquake Engineering and Engineering Vibration*, **4**, 56-65.

- [26] Shakir-Khalil, H. (1988). Steel-Concrete Composite Columns I. *Steel-concrete composite structures: stability and strength*, 163-193.
- [27] Ellobody, E., Young, B. Lam, D. (2006). Behaviour of Normal and High Strength Concrete-Filled Compact Steel Tube Circular Stub Columns. *Journal of Constructional Steel Research*, **62(7)**, 706-715.
- [28] Han, L.-H., Li, W. Bjorhovde, R. (2014). Developments and Advanced Applications of Concrete-Filled Steel Tubular (CFST) Structures: Members. *Journal of Constructional Steel Research*, **100**, 211-228.
- [29] Essopjee, Y. Dundu, M. (2015). Performance of Concrete-Filled Double-Skin Circular Tubes in Compression. *Composite Structures*, **133**, 1276-1283.
- [30] Hassan, M. M., Mahmoud, A. A. Serror, M. H. (2016). Behavior of Concrete-Filled Double Skin Steel Tube Beam-Columns. *Steel and Composite Structures*, **22(5)**, 1141-1162.
- [31] Zhao, X.-L. Grzebieta, R. (2002). Strength and Ductility of Concrete Filled Double Skin (Shs Inner and Shs Outer) Tubes. *Thin-Walled Structures*, **40(2)**, 199-213.
- [32] Imani, R., Mosqueda, G. Bruneau, M. (2015). Finite Element Simulation of Concrete-Filled Double-Skin Tube Columns Subjected to Postearthquake Fires. *Journal of Structural Engineering*, **141(12)**, 04015055.
- [33] Zhao, X. L. Han, L. H. (2006). Double Skin Composite Construction. *Progress in structural engineering and materials*, **8(3)**, 93-102.
- [34] Han, L.-H., Huo, J.-S. Wang, Y.-C. (2005). Compressive and Flexural Behaviour of Concrete Filled Steel Tubes after Exposure to Standard Fire. *Journal of Constructional Steel Research*, **61(7)**, 882-901.
- [35] Ekmekyapar, T. Ghanim Hasan, H. (2019). The Influence of the Inner Steel Tube on the Compression Behaviour of the Concrete Filled Double Skin Steel Tube (CFDST) Columns. *Marine Structures*, **66**, 197-212.
- [36] Uenaka, K. (2016). CFDST Stub Columns Having Outer Circular and Inner Square Sections under Compression. *Journal of Constructional Steel Research*, **120**, 1-7.
- [37] Lin, M. Tsai, K.-C. (2001). Behavior of Double-Skinned Composite Steel Tubular Columns Subjected to Combined Axial and Flexural Loads. *Proceedings of the first international conference on steel and composite structures*, Pusan, Korea.
- [38] Wei, S., Mau, S., Vipulanandan, C. Mantrala, S. (1995). Performance of New Sandwich Tube under Axial Loading: Experiment. *Journal of Structural Engineering*, **121(12)**, 1806-1814.
- [39] Elchalakani, M., Zhao, X.-L. Grzebieta, R. (2002). Tests on Concrete Filled Double-Skin (Chs Outer and Shs Inner) Composite Short Columns under Axial Compression. *Thin-Walled Structures*, **40(5)**, 415-441.

- [40] Lu, H., Zhao, X.-L. Han, L.-H. (2010). Testing of Self-Consolidating Concrete-Filled Double Skin Tubular Stub Columns Exposed to Fire. *Journal of Constructional Steel Research*, **66(8)**, 1069-1080.
- [41] Chen, J., Ni, Y.-Y. Jin, W.-l. (2015). Column Tests of Dodecagonal Section Double Skin Concrete-Filled Steel Tubes. *Thin-Walled Structures*, **88**, 28-40.
- [42] Hong, T. Z. H. L. H. (2004). Mechanical Behaviour of Concrete-Filled Double Skin Steel Tubular Columns with Circular Cular Sections [J]. *China Civil Engineering Journal*, **10**, 005.
- [43] Liu, F., Wang, Y. Chan, T.-m. (2017). Behaviour of Concrete-Filled Cold-Formed Elliptical Hollow Sections with Varying Aspect Ratios. *Thin-Walled Structures*, **110**, 47-61.
- [44] Jameel, M. T., Sheikh, M. N. Hadi, M. N. (2017). Behaviour of Circularized and FRP Wrapped Hollow Concrete Specimens under Axial Compressive Load. *Composite Structures*, **171**, 538-548.
- [45] Ghanim Hasan, H. Ekmekyapar, T. (2019). Mechanical Performance of Stiffened Concrete Filled Double Skin Steel Tubular Stub Columns under Axial Compression. *KSCE Journal of Civil Engineering*, **23(5)**, 2281-2292.
- [46] Zhang, J., Denavit, M. D., Hajjar, J. F. Lu, X. (2012). Bond Behavior of Concrete-Filled Steel Tube (Cft) Structures. *Engineering journal-american institute of steel construction*, **49(4)**, 169-185.
- [47] Yu, T. Teng, J. (2012). Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns with a Square Outer Tube and a Circular Inner Tube Subjected to Axial Compression. *Journal of Composites for Construction*, **17(2)**, 271-279.
- [48] Wang, Y., Li, M., Hua Xu, J. Zhang, Z. (2012). Comparison between New Concrete Filled Steel Tube Frame Structure and Steel Frame Structure. *Applied Mechanics and Materials*, **204-208**, 1024-1027.
- [49] Nie, J.-g., Wang, Y.-h. Fan, J.-s. (2012). Experimental Study on Seismic Behavior of Concrete Filled Steel Tube Columns under Pure Torsion and Compression–Torsion Cyclic Load. *Journal of Constructional Steel Research*, **79**, 115-126.
- [50] Moon, J., Roeder, C. W., Lehman, D. E. Lee, H.-E. (2012). Analytical Modeling of Bending of Circular Concrete-Filled Steel Tubes. *Engineering Structures*, **42**, 349-361.
- [51] Ho, J. Luo, L. (2012). Uni-Axial Behaviour of Normal-Strength Concrete-Filled-Steel-Tube Columns with External Confinement. *Earthquakes and Structures*, **3(6)**, 889-910.
- [52] Chang, X., Wei, Y.-Y. Yun, Y.-C. (2012). Analysis of Steel-Reinforced Concrete-Filled-Steel Tubular (SRCFST) Columns under Cyclic Loading. *Construction and Building Materials*, **28(1)**, 88-95.

- [53] Yang, Y.-F. (2011). Behaviour of Recycled Aggregate Concrete-Filled Steel Tubular Columns under Long-Term Sustained Loads. *Advances in Structural Engineering*, **14**(2), 189-206.
- [54] Portolés, J., Romero, M., Filippou, F. Bonet, J. (2011). Simulation and Design Recommendations of Eccentrically Loaded Slender Concrete-Filled Tubular Columns. *Engineering Structures*, **33**(5), 1576-1593.
- [55] Ma, Y., Wang, Y. Mao, Z. (2011). Creep Effects on Dynamic Behavior of Concrete Filled Steel Tube Arch Bridge. *Structural engineering & mechanics*, **37**(3), 321.
- [56] Karimi, K., Tait, M. J. El-Dakhakhni, W. W. (2011). Testing and Modeling of a Novel FRP-Encased Steel–Concrete Composite Column. *Composite Structures*, **93**(5), 1463-1473.
- [57] Ding, F.-x., Yu, Z.-w., Bai, Y. Gong, Y.-z. (2011). Elasto-Plastic Analysis of Circular Concrete-Filled Steel Tube Stub Columns. *Journal of Constructional Steel Research*, **67**(10), 1567-1577.
- [58] Denavit, M. D. Hajjar, J. F. (2011). Nonlinear Seismic Analysis of Circular Concrete-Filled Steel Tube Members and Frames. *Journal of Structural Engineering*, **138**(9), 1089-1098.
- [59] Chen, B. L., Wang, L. G. Qin, G. P. (2011). Bearing Capacity Calculating of GFRP Tube Filled with Steel-Reinforced Concrete Composite Column Subjected to Eccentric Loading. *Advanced Materials Research*.
- [60] Belenkiy, L. M., Raskin, Y. N. Vuillemin, J. (2007). Effective Plating in Elastic–Plastic Range of Primary Support Members in Double-Skin Ship Structures. *Marine Structures*, **20**(3), 115-123.
- [61] Johansson, M. 2002. *Composite Action and Confinement Effects in Tubular Steel-Concrete Columns*. ed.: Chalmers University of Technology.
- [62] Uenaka, K., Kitoh, H. Sonoda, K. (2010). Concrete Filled Double Skin Circular Stub Columns under Compression. *Thin-Walled Structures*, **48**(1), 19-24.
- [63] Zhu, M., Liu, J., Wang, Q. Feng, X. (2010). Experimental Research on Square Steel Tubular Columns Filled with Steel-Reinforced Self-Consolidating High-Strength Concrete under Axial Load. *Engineering Structures*, **32**(8), 2278-2286.
- [64] Yu, M., Zha, X., Ye, J. She, C. (2010). A Unified Formulation for Hollow and Solid Concrete-Filled Steel Tube Columns under Axial Compression. *Engineering Structures*, **32**(4), 1046-1053.
- [65] Yin, X. Lu, X. (2010). Study on Push-out Test and Bond Stress-Slip Relationship of Circular Concrete Filled Steel Tube. *Steel and Composite Structures*, **10**(4), 317-329.

- [66] Xu, T., Xiang, T., Zhao, R. Zhan, Y. (2010). Nonlinear Finite Element Analysis of Circular Concrete-Filled Steel Tube Structures. *Structural engineering & mechanics*, **35(3)**, 315.
- [67] Starossek, U., Falah, N. Lohning, T. (2010). Numerical Analyses of the Force Transfer in Concrete-Filled Steel Tube Columns. *Structural Engineering and Mechanics*, **35(2)**, 241-256.
- [68] Roeder, C. W., Lehman, D. E. Bishop, E. (2010). Strength and Stiffness of Circular Concrete-Filled Tubes. *Journal of Structural Engineering*, **136(12)**, 1545-1553.
- [69] Liew, J. R. Sohel, K. (2010). Structural Performance of Steel-Concrete-Steel Sandwich Composite Structures. *Advances in Structural Engineering*, **13(3)**, 453-470.
- [70] Han, T. H., Stallings, J. M. Kang, Y. J. (2010). Nonlinear Concrete Model for Double-Skinned Composite Tubular Columns. *Construction and Building Materials*, **24(12)**, 2542-2553.
- [71] Gardner, L., Saari, N. Wang, F. (2010). Comparative Experimental Study of Hot-Rolled and Cold-Formed Rectangular Hollow Sections. *Thin-Walled Structures*, **48(7)**, 495-507.
- [72] Dai, X. Lam, D. (2010). Numerical Modelling of the Axial Compressive Behaviour of Short Concrete-Filled Elliptical Steel Columns. *Journal of Constructional Steel Research*, **66(7)**, 931-942.
- [73] Chitawadagi, M. V., Narasimhan, M. C. Kulkarni, S. (2010). Axial Capacity of Rectangular Concrete-Filled Steel Tube Columns–Doe Approach. *Construction and Building Materials*, **24(4)**, 585-595.
- [74] Hu, H.-T. Su, F.-C. (2011). Nonlinear Analysis of Short Concrete-Filled Double Skin Tube Columns Subjected to Axial Compressive Forces. *Marine Structures*, **24(4)**, 319-337.
- [75] Wang, F.-C. Han, L.-H. (2019). Analytical Behavior of Carbon Steel-Concrete-Stainless Steel Double-Skin Tube (Dst) Used in Submarine Pipeline Structure. *Marine Structures*, **63**, 99-116.
- [76] Dundu, M. (2012). Compressive Strength of Circular Concrete Filled Steel Tube Columns. *Thin-Walled Structures*, **56**, 62-70.
- [77] Liu, X., Xu, C., Liu, J. Yang, Y. (2018). Research on Special-Shaped Concrete-Filled Steel Tubular Columns under Axial Compression. *Journal of Constructional Steel Research*, **147**, 203-223.
- [78] Lacki, P., Derlatka, A. Kasza, P. (2018). Comparison of Steel-Concrete Composite Column and Steel Column. *Composite Structures*, **202**, 82-88.

- [79] Chen, S., Zhang, R., Jia, L.-J., Wang, J.-Y. Gu, P. (2018). Structural Behavior of Uhpcc Filled Steel Tube Columns under Axial Loading. *Thin-Walled Structures*, **130**, 550-563.
- [80] Li, W., Luo, Z., Tao, Z., Duan, W. H. Shah, S. P. (2017). Mechanical Behavior of Recycled Aggregate Concrete-Filled Steel Tube Stub Columns after Exposure to Elevated Temperatures. *Construction and Building Materials*, **146**, 571-581.
- [81] Hou, C., Han, L.-H. Zhao, X.-L. (2013). Concrete-Filled Circular Steel Tubes Subjected to Local Bearing Force: Experiments. *Journal of Constructional Steel Research*, **83**, 90-104.
- [82] Lai, M. Ho, J. (2015). Axial Strengthening of Thin-Walled Concrete-Filled-Steel-Tube Columns by Circular Steel Jackets. *Thin-Walled Structures*, **97**, 11-21.
- [83] Han, L.-h., Tao, Z. Liu, W. (2001). Concrete Filled Steel Tubular Structures from Theory to Practice [J]. *Journal of Fuzhou University (Natural Sciences Edition)*, **6**, 003.
- [84] Johansson, M. (2002). The Efficiency of Passive Confinement in CFT Columns. *Steel and Composite Structures*, **2(5)**, 379-396.
- [85] Gopal, S. R. (2017). An Experimental Study on FRC Infilled Steel Tubular Columns under Eccentric Loading. *KSCE Journal of Civil Engineering*, **21(3)**, 923-927.
- [86] Yu, Z.-w., Ding, F.-x. Cai, C. (2007). Experimental Behavior of Circular Concrete-Filled Steel Tube Stub Columns. *Journal of Constructional Steel Research*, **63(2)**, 165-174.
- [87] Zeghiche, J. Chaoui, K. (2005). An Experimental Behaviour of Concrete-Filled Steel Tubular Columns. *Journal of Constructional Steel Research*, **61(1)**, 53-66.
- [88] Lai, M. Ho, J. (2014). Confinement Effect of Ring-Confined Concrete-Filled-Steel-Tube Columns under Uni-Axial Load. *Engineering Structures*, **67**, 123-141.
- [89] Sakino, K., Nakahara, H., Morino, S. Nishiyama, I. (2004). Behavior of Centrally Loaded Concrete-Filled Steel-Tube Short Columns. *Journal of Structural Engineering*, **130(2)**, 180-188.
- [90] Güneyisi, E., Gesoglu, M., Ghanim Hasan, H., İpek, S. Taha, I. (2016). Influence of the Artificial Lightweight Aggregate on Fresh Properties and Compressive Strength of the Self-Compacting Mortars. *Construction and Building Materials*, **116**, 151-158.
- [91] Ghanim Hasan, H., Ekmekyapar, T. Shehab, B. A. (2019). Mechanical Performances of Stiffened and Reinforced Concrete-Filled Steel Tubes under Axial Compression. *Marine Structures*, **65**, 417-432.

- [92] Zongping Chen Liu, X. (2018). Seismic Behavior of Steel Reinforced Concrete Cross-Shaped Column under Combined Torsion. *Steel and Composite Structures*, **26(4)**, 407-420.
- [93] Zhou, S., Sun, Q. Wu, X. (2018). Impact of D/T Ratio on Circular Concrete-Filled High-Strength Steel Tubular Stub Columns under Axial Compression. *Thin-Walled Structures*, **132**, 461-474.
- [94] Liu, J.-P., Xu, T.-X., Wang, Y.-H. Guo, Y. (2018). Axial Behaviour of Circular Steel Tubed Concrete Stub Columns Confined by CFRP Materials. *Construction and Building Materials*, **168**, 221-231.
- [95] Hwang, J.-y., Kwak, H.-G. Kwon, Y. (2018). A Numerical Model for Considering the Bond-Slip Effect in Axially Loaded Circular Concrete-Filled Tube Columns. *Advances in Structural Engineering*, 1-13.
- [96] Wang, H., Wu, C., Zhang, F., Fang, Q., Xiang, H., Li, P. *et al.* (2017). Experimental Study of Large-Sized Concrete Filled Steel Tube Columns under Blast Load. *Construction and Building Materials*, **134**, 131-141.
- [97] Jegadesh, J. S. Jayalekshmi, S. (2016). Using Fibres and Fly Ash in Concrete-Filled Steel Tube Columns. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **169(10)**, 741-755.
- [98] Ho, J., Lai, M. Luo, L. (2014). Uniaxial Behaviour of Confined High-Strength Concrete-Filled-Steel-Tube Columns. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 1-14.
- [99] Kloppel, K. Goder, W. (1957). Collapse Load Tests on Concrete Filled Steel Tubes and Derivation of a Design Formula. *Der Stahlbau, Berlin*, **26(1)**, 1.
- [100] Kloppel, V. Goder, W. (1957). An Investigation of the Load Carrying Capacity of Concrete-Filled Steel Tubes and Development of Design Formula. *Der Stahlbau*, **26(1)**, 1-10.
- [101] Gardner, N. J. Jacobson, E. R. (1967). Structural Behavior of Concrete Filled Steel Tubes. *Journal Proceedings*, **64(7)**, 404-413.
- [102] O'Shea, M. D. Bridge, R. Q. (2000). Design of Circular Thin-Walled Concrete Filled Steel Tubes. *Journal of Structural Engineering*, **126(11)**, 1295-1303.
- [103] Giakoumelis, G. Lam, D. (2004). Axial Capacity of Circular Concrete-Filled Tube Columns. *Journal of Constructional Steel Research*, **60(7)**, 1049-1068.
- [104] Chen, Y., Feng, R., Shao, Y. Zhang, X. (2017). Bond-Slip Behaviour of Concrete-Filled Stainless Steel Circular Hollow Section Tubes. *Journal of Constructional Steel Research*, **130**, 248-263.
- [105] Lutz, L. A. Gergely, P. (1967). Mechanics of Bond and Slip of Deformed Bars in Concrete. *Journal Proceedings*, **64(11)**, 711-721.

- [106] Tao, Z., Song, T.-Y., Uy, B. Han, L.-H. (2016). Bond Behavior in Concrete-Filled Steel Tubes. *Journal of Constructional Steel Research*, **120**, 81-93.
- [107] Johansson, M. (2003). Composite Action in Connection Regions of Concrete-Filled Steel Tube Columns. *Steel and Composite Structures*, **3(1)**, 47-64.
- [108] Xu, C., Chengkui, H., Decheng, J. Yuancheng, S. (2009). Push-out Test of Pre-Stressing Concrete Filled Circular Steel Tube Columns by Means of Expansive Cement. *Construction and Building Materials*, **23(1)**, 491-497.
- [109] Lu, Y., Liu, Z., Li, S. Li, N. (2018). Bond Behavior of Steel Fibers Reinforced Self-Stressing and Self-Compacting Concrete Filled Steel Tube Columns. *Construction and Building Materials*, **158**, 894-909.
- [110] Roeder, C. W., Cameron, B. Brown, C. B. (1999). Composite Action in Concrete Filled Tubes. *Journal of Structural Engineering*, **125(5)**, 477-484.
- [111] Ke, X., Sun, Y. Yang, Z. (2016). Calculation on Bond Strength of High-Strength Concrete Filled Steel Tube. *Proceedings of the 4th International Conference on Sensors, Measurement and Intelligent Materials*.
- [112] Tao, Z., Han, L.-H., Uy, B. Chen, X. (2011). Post-Fire Bond between the Steel Tube and Concrete in Concrete-Filled Steel Tubular Columns. *Journal of Constructional Steel Research*, **67(3)**, 484-496.
- [113] Lu, Y., Liu, Z., Li, S. Tang, W. (2018). Bond Behavior of Steel-Fiber-Reinforced Self-Stressing and Self-Compacting Concrete-Filled Steel Tube Columns for a Period of 2.5 Years. *Construction and Building Materials*, **167**, 33-43.
- [114] Aly, T., Elchalakani, M., Thayalan, P. Patnaikuni, I. (2010). Incremental Collapse Threshold for Pushout Resistance of Circular Concrete Filled Steel Tubular Columns. *Journal of Constructional Steel Research*, **66(1)**, 11-18.
- [115] Mohd Zuki, S., Jayaprakash, J., Shahidan, S. Chong Yong, O. (2015). Behavior of Fire Exposed Concrete-Filled Double Skin Steel Tubular (CFDST) Columns under Concentric Axial Loads. *Applied Mechanics and Materials*, **773**, 938-942.
- [116] Shakir-Khalil, H. (1991). Composite Columns of Double-Skinned Shells. *Journal of Constructional Steel Research*, **19(2)**, 133-152.
- [117] Wright, H., Oduyemi, T. Evans, H. (1991). The Experimental Behaviour of Double Skin Composite Elements. *Journal of Constructional Steel Research*, **19(2)**, 97-110.
- [118] Nakanishi, K., Kitada, T. Nakai, H. (1999). Experimental Study on Ultimate Strength and Ductility of Concrete Filled Steel Columns under Strong Earthquake. *Journal of Constructional Steel Research*, **51(3)**, 297-319.
- [119] Montague, P. (1975). A Simple Composite Construction for Cylindrical Shells Subjected to External Pressure. *Journal of Mechanical Engineering Science*, **17(2)**, 105-113.

- [120] Goode, C., Montague, P. Nash, T. (1996). Large Reinforced Concrete Cylinders under External Pressure. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **116(2)**, 163-173.
- [121] Johansson, M. Gylltoft, K. (2002). Mechanical Behavior of Circular Steel–Concrete Composite Stub Columns. *Journal of Structural Engineering*, **128(8)**, 1073-1081.
- [122] Dong, C. Ho, J. (2012). Uni-Axial Behaviour of Normal-Strength CFDST Columns with External Steel Rings. *Steel and Composite Structures*, **13(6)**, 587-606.
- [123] Tao, Z. Han, L.-H. (2006). Behaviour of Concrete-Filled Double Skin Rectangular Steel Tubular Beam–Columns. *Journal of Constructional Steel Research*, **62(7)**, 631-646.
- [124] Tao, Z., Han, L.-H. Zhao, X.-L. (2004). Behaviour of Concrete-Filled Double Skin (Chs Inner and Chs Outer) Steel Tubular Stub Columns and Beam-Columns. *Journal of Constructional Steel Research*, **60(8)**, 1129-1158.
- [125] Yagishita, F., Kitoh, H., Sugimoto, M., Tanihira, T. Sonoda, K. (2000). Double Skin Composite Tubular Columns Subjected to Cyclic Horizontal Force and Constant Axial Force. *Proc, 6th ASCCS Int Conf on Steel-Concrete Composite Structures*.
- [126] Sulthana, U. Jayachandran, S. (2017). Axial Compression Behaviour of Long Concrete Filled Double Skinned Steel Tubular Columns. *Structures*, **9**, 157-164.
- [127] Li, W., Han, L.-H. Zhao, X.-L. (2012). Axial Strength of Concrete-Filled Double Skin Steel Tubular (CFDST) Columns with Preload on Steel Tubes. *Thin-Walled Structures*, **56**, 9-20.
- [128] Yang, J., Xu, H. Peng, G. (2008). Behavior of Concrete-Filled Double Skin Steel Tubular Columns with Octagon Section under Axial Compression. *Frontiers of Architecture and Civil Engineering in China*, **2(3)**, 205-210.
- [129] Yuan, W.-b. Yang, J.-j. (2013). Experimental and Numerical Studies of Short Concrete-Filled Double Skin Composite Tube Columns under Axially Compressive Loads. *Journal of Constructional Steel Research*, **80**, 23-31.
- [130] Yang, Y.-F., Han, L.-H. Sun, B.-H. (2012). Experimental Behaviour of Partially Loaded Concrete Filled Double-Skin Steel Tube (CFDST) Sections. *Journal of Constructional Steel Research*, **71**, 63-73.
- [131] Hassanein, M. Kharoob, O. (2014). Analysis of Circular Concrete-Filled Double Skin Tubular Slender Columns with External Stainless Steel Tubes. *Thin-Walled Structures*, **79**, 23-37.
- [132] Han, L.-H., Huang, H., Tao, Z. Zhao, X.-L. (2006). Concrete-Filled Double Skin Steel Tubular (CFDST) Beam–Columns Subjected to Cyclic Bending. *Engineering Structures*, **28(12)**, 1698-1714.

- [133] Li, W., Ren, Q.-X., Han, L.-H. Zhao, X.-L. (2012). Behaviour of Tapered Concrete-Filled Double Skin Steel Tubular (CFDST) Stub Columns. *Thin-Walled Structures*, **57**, 37-48.
- [134] Hassanein, M. Kharoob, O. (2014). Compressive Strength of Circular Concrete-Filled Double Skin Tubular Short Columns. *Thin-Walled Structures*, **77**, 165-173.
- [135] Hassanein, M., Kharoob, O. Gardner, L. (2015). Behaviour and Design of Square Concrete-Filled Double Skin Tubular Columns with Inner Circular Tubes. *Engineering Structures*, **100**, 410-424.
- [136] AISC-360. 2010. Load and Resistance Factor Design Specification, for Structural Steel Buildings. Chicago, Illinois, U.S.A.
- [137] EC4. 2004. Eurocode 4: Design of Composite Steel and Concrete Structures, Part 1-1: General Rules for Buildings. British Standards Institution, London, UK.
- [138] Han, L.-H., Li, Y.-J. Liao, F.-Y. (2011). Concrete-Filled Double Skin Steel Tubular (CFDST) Columns Subjected to Long-Term Sustained Loading. *Thin-Walled Structures*, **49(12)**, 1534-1543.
- [139] Romero, M., Espinós, A., Portolés, J., Hospitaler, A. Ibañez, C. (2015). Slender Double-Tube Ultra-High Strength Concrete-Filled Tubular Columns under Ambient Temperature and Fire. *Engineering Structures*, **99**, 536-545.
- [140] Moliner, V., Espinos, A., Romero, M. Hospitaler, A. (2013). Fire Behavior of Eccentrically Loaded Slender High Strength Concrete-Filled Tubular Columns. *Journal of Constructional Steel Research*, **83**, 137-146.
- [141] Romero, M. L., Moliner, V., Espinos, A., Ibañez, C. Hospitaler, A. (2011). Fire Behavior of Axially Loaded Slender High Strength Concrete-Filled Tubular Columns. *Journal of Constructional Steel Research*, **67(12)**, 1953-1965.
- [142] Uy, B. (2001). Strength of Short Concrete Filled High Strength Steel Box Columns. *Journal of Constructional Steel Research*, **57(2)**, 113-134.
- [143] Fanggi, B. L. Ozbakkloglu, T. (2014). Influence of Concrete-Filling Inner Steel Tube on Compressive Behavior of Double-Skin Tubular Columns. *Adv Mater Res*, 838-841.
- [144] Portolés, J., Romero, M. L., Bonet, J. Filippou, F. (2011). Experimental Study of High Strength Concrete-Filled Circular Tubular Columns under Eccentric Loading. *Journal of Constructional Steel Research*, **67(4)**, 623-633.
- [145] Gourley, B. C., Tort, C., Denavit, M. D., Schiller, P. H. Hajjar, J. F. (2008). A Synopsis of Studies of the Monotonic and Cyclic Behavior of Concrete-Filled Steel Tube Members, Connections, and Frames.

- [146] Hassanein, M., Elchalakani, M. Patel, V. (2017). Overall Buckling Behaviour of Circular Concrete-Filled Dual Steel Tubular Columns with Stainless Steel External Tubes. *Thin-Walled Structures*, **115**, 336-348.
- [147] Romero, M. L., Ibañez, C., Espinós, A., Portolés, J. Hospitaler, A. (2017). Influence of Ultra-High Strength Concrete on Circular Concrete-Filled Dual Steel Columns. *Structures*, **9**, 13-20.
- [148] De oliveira, W. L. A., De nardin, S., De cresce El, A. L. H. El debs, M. K. (2009). Influence of Concrete Strength and Length/Diameter on the Axial Capacity of Cft Columns. *Journal of Constructional Steel Research*, **65(12)**, 2103-2110.
- [149] CAN/CSA. 2001. S16-01:2001 Limit States Design of Steel Structures. Canadian Standards Association, Ontario, Canada.
- [150] Eurocode-4.1. 2004. Design of Composite Steel and Concrete Structures. European Committee for Standardization, Brussels.
- [151] Varma, A. H., Ricles, J. M., Sause, R. Lu, L.-W. (2002). Experimental Behavior of High Strength Square Concrete-Filled Steel Tube Beam-Columns. *Journal of Structural Engineering*, **128(3)**, 309-318.
- [152] Farahi, M., Heidarpour, A., Zhao, X.-L. Al-Mahaidi, R. (2017). Effect of Ultra-High Strength Steel on Mitigation of Non-Ductile Yielding of Concrete-Filled Double-Skin Columns. *Construction and Building Materials*, **147**, 736-749.
- [153] Muhammad, N. B., Fan, J. S. Nie, J. G. (2011). Effects of Hollowness on Strength of Double Skinned Concrete Filled Steel Tubular Columns of Different Geometries under Axial Loading. *Applied Mechanics and Materials*, **94**, 1746-1751.
- [154] Han, L.-H., Ren, Q.-X. Li, W. (2011). Tests on Stub Stainless Steel–Concrete–Carbon Steel Double-Skin Tubular (Dst) Columns. *Journal of Constructional Steel Research*, **67(3)**, 437-452.
- [155] Baddoo, N. (2008). Stainless Steel in Construction: A Review of Research, Applications, Challenges and Opportunities. *Journal of Constructional Steel Research*, **64(11)**, 1199-1206.
- [156] Zheng, Y., He, C. Zheng, L. (2018). Experimental and Numerical Investigation of Circular Double-Tube Concrete-Filled Stainless Steel Tubular Columns under Cyclic Loading. *Thin-Walled Structures*, **132**, 151-166.
- [157] Wang, F.-c., Han, L.-h. Li, W. (2018). Analytical Behavior of CFDST Stub Columns with External Stainless Steel Tubes under Axial Compression. *Thin-Walled Structures*, **127**, 756-768.
- [158] Li, Y., Zhao, X., Raman, R. S. Yu, X. (2018). Axial Compression Tests on Seawater and Sea Sand Concrete-Filled Double-Skin Stainless Steel Circular Tubes. *Engineering Structures*, **176**, 426-438.

- [159] Zhou, F. Xu, W. (2016). Cyclic Loading Tests on Concrete-Filled Double-Skin (Shs Outer and Chs Inner) Stainless Steel Tubular Beam-Columns. *Engineering Structures*, **127**, 304-318.
- [160] Wang, F., Young, B. Gardner, L. (2016). Experimental Investigation of Concrete-Filled Double Skin Tubular Stub Columns with Stainless Steel Outer Tubes. *Proceedings of the 8th International Conference on Steel and Aluminium Structures*, Hong Kong, China, paper.
- [161] Hassanein, M., Kharoob, O. Liang, Q. (2013). Behaviour of Circular Concrete-Filled Lean Duplex Stainless Steel Tubular Short Columns. *Thin-Walled Structures*, **68**, 113-123.
- [162] Hassanein, M., Kharoob, O. Liang, Q. (2013). Circular Concrete-Filled Double Skin Tubular Short Columns with External Stainless Steel Tubes under Axial Compression. *Thin-Walled Structures*, **73**, 252-263.
- [163] Lam, D. Gardner, L. (2008). Structural Design of Stainless Steel Concrete Filled Columns. *Journal of Constructional Steel Research*, **64(11)**, 1275-1282.
- [164] Gardner, L. (2005). The Use of Stainless Steel in Structures. *Progress in structural engineering and materials*, **7(2)**, 45-55.
- [165] Teng, J., Yu, T., Wong, Y. Dong, S. (2007). Hybrid FRP–Concrete–Steel Tubular Columns: Concept and Behavior. *Construction and Building Materials*, **21(4)**, 846-854.
- [166] Wong, Y., Yu, T., Teng, J. Dong, S. (2008). Behavior of FRP-Confined Concrete in Annular Section Columns. *Composites Part B: Engineering*, **39(3)**, 451-466.
- [167] Yu, T., Wong, Y. Teng, J. (2010). Behavior of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns Subjected to Eccentric Compression. *Advances in Structural Engineering*, **13(5)**, 961-974.
- [168] Nabati, A., Ghanbari-Ghazijahani, T. Ng, C.-T. (2019). CFRP-Reinforced Concrete-Filled Steel Tubes with Timber Core under Axial Loading. *Composite Structures*, **217**, 37-49.
- [169] Lu, Y., Liu, Z., Li, S. Hu, J. (2018). Axial Compression Behavior of Hybrid Fiber Reinforced Concrete Filled Steel Tube Stub Column. *Construction and Building Materials*, **174**, 96-107.
- [170] Vijay Shankar, G., Sundarraja, M., Kim, Y. Y. Ganesh Prabhu, G. (2017). Using Carbon-Fibre-Reinforced Polymer to Strengthen Concrete-Filled Steel Tubular Columns. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **170(12)**, 917-927.
- [171] Daugevičius, M. Valivonis, J. (2017). Concrete and Reinforced Concrete Elements Strengthened with Hpfrc. *KSCE Journal of Civil Engineering*, 1-9.

- [172] Zhou, Y., Liu, X., Xing, F., Cui, H. Sui, L. (2016). Axial Compressive Behavior of FRP-Confined Lightweight Aggregate Concrete: An Experimental Study and Stress-Strain Relation Model. *Construction and Building Materials*, **119**, 1-15.
- [173] Kumar, A. P. Senthil, R. (2016). Axial Behaviour of CFRP-Strengthened Circular Steel Hollow Sections. *Arabian Journal for Science and Engineering*, **41(10)**, 3841-3850.
- [174] Wang, J., Liu, W., Zhou, D., Zhu, L. Fang, H. (2014). Mechanical Behaviour of Concrete Filled Double Skin Steel Tubular Stub Columns Confined by FRP under Axial Compression. *Steel Compos Struct*, **17(4)**, 431-452.
- [175] Prabhu, G. G. Sundarraja, M. (2013). Behaviour of Concrete Filled Steel Tubular (CFST) Short Columns Externally Reinforced Using CFRP Strips Composite. *Construction and Building Materials*, **47**, 1362-1371.
- [176] Tao, Z., Han, L.-H. Zhuang, J.-P. (2007). Axial Loading Behavior of CFRP Strengthened Concrete-Filled Steel Tubular Stub Columns. *Advances in Structural Engineering*, **10(1)**, 37-46.
- [177] Ozbakkloglu, T. Fanggi, B. A. L. (2013). An Experimental Study on Behavior of FRP-HSC-Steel Double-Skin Tubular Columns under Concentric Compression. *Applied Mechanics and Materials*, **357**, 565-569.
- [178] Zhou, Y., Liu, X., Xing, F., Li, D., Wang, Y. Sui, L. (2017). Behavior and Modeling of FRP-Concrete-Steel Double-Skin Tubular Columns Made of Full Lightweight Aggregate Concrete. *Construction and Building Materials*, **139**, 52-63.
- [179] Yu, T., Zhang, S., Huang, L. Chan, C. (2017). Compressive Behavior of Hybrid Double-Skin Tubular Columns with a Large Rupture Strain FRP Tube. *Composite Structures*, **171**, 10-18.
- [180] Han, L.-H., Tao, Z., Huang, H. Zhao, X.-L. (2004). Concrete-Filled Double Skin (Shs Outer and Chs Inner) Steel Tubular Beam-Columns. *Thin-Walled Structures*, **42(9)**, 1329-1355.
- [181] Lu, H., Han, L.-H. Zhao, X.-L. (2010). Fire Performance of Self-Consolidating Concrete Filled Double Skin Steel Tubular Columns: Experiments. *Fire safety journal*, **45(2)**, 106-115.
- [182] Shekastehband, B., Taromi, A. Abedi, K. (2017). Fire Performance of Stiffened Concrete Filled Double Skin Steel Tubular Columns. *Fire safety journal*, **88**, 13-25.
- [183] Wan, C.-Y., Zha, X.-X. Dassekpo, J.-B. M. (2017). Analysis of Axially Loaded Concrete Filled Circular Hollow Double Steel Tubular Columns Exposed to Fire. *Fire safety journal*, **88**, 1-12.

- [184] Yao, Y., Li, H. Tan, K. (2016). Theoretical and Numerical Analysis to Concrete Filled Double Skin Steel Tubular Columns under Fire Conditions. *Thin-Walled Structures*, **98**, 547-557.
- [185] Won, D. H., Han, T. H., Kim, S. Kang, Y. J. (2016). Fire Resistance of Double-Skinned Composite Tubular Columns Including Concrete Confinement. *Materials and Structures*, **49(4)**, 1269-1284.
- [186] Imani, R., Bruneau, M. Mosqueda, G. (2015). Simplified Analytical Solution for Axial Load Capacity of Concrete-Filled Double-Skin Tube (CFDST) Columns Subjected to Fire. *Engineering Structures*, **102**, 156-175.
- [187] Imani, R., Mosqueda, G. Bruneau, M. (2014). Experimental Study on Post-Earthquake Fire Resistance of Ductile Concrete-Filled Double-Skin Tube Columns. *Journal of Structural Engineering*, **141(8)**, 04014192.
- [188] Yang, Y. Han, L.-H. (2008). Concrete-Filled Double-Skin Tubular Columns under Fire. *Magazine of Concrete Research*, **60(3)**, 211-222.
- [189] Han, L.-H., Zhao, X.-L., Yang, Y.-F. Feng, J.-B. (2003). Experimental Study and Calculation of Fire Resistance of Concrete-Filled Hollow Steel Columns. *Journal of Structural Engineering*, **129(3)**, 346-356.
- [190] Li, W., Wang, D. Han, L.-H. (2017). Behaviour of Grout-Filled Double Skin Steel Tubes under Compression and Bending: Experiments. *Thin-Walled Structures*, **116**, 307-319.
- [191] Li, X. H., Lei, J. P. Wang, R. (2013). Finite Element Analysis of Concrete-Filled Double Skin Steel Tubes with Simply Supported under Lateral Impact. *Applied Mechanics and Materials*, **405**, 1106-1109.
- [192] Kuranovas, A. Kvedaras, A. K. (2007). Behaviour of Hollow Concrete-Filled Steel Tubular Composite Elements. *Journal of Civil Engineering and Management*, **13(2)**, 131-141.
- [193] Kvedaras, A. Sapalas, A. (1999). Research and Practice of Concrete-Filled Steel Tubes in Lithuania. *Journal of Constructional Steel Research*, **49(2)**, 197-212.
- [194] Liang, Q. Q. (2017). Nonlinear Analysis of Circular Double-Skin Concrete-Filled Steel Tubular Columns under Axial Compression. *Engineering Structures*, **131**, 639-650.
- [195] Wardenier, J., Packer, J., Zhao, X. Van der Vegte, G. 2002. *Hollow Sections in Structural Applications*. ed.: Bouwen met Staal Rotterdam,, The Netherlands.
- [196] BS-EN. 2006. Cold Formed Welded Structural Hollow Sections of Non-Alloy and Fine Grain Steels-Part 1, 10219-1. The European Standard-British-Standard, UK.
- [197] ASTM E8/E8M-16. (2015). Standard Test Methods for Tension Testing of Metallic Materials-Standard, E8/E8m-15a. ASTM International.

- [198] EFNARC. 2005. The European Guidelines for Self-Compacting Concrete: Specification, Production and Use. SCC European Project Group, Association House, UK.
- [199] ASTM C39/C39M-03. 2003. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA 19428-2959, United States.
- [200] ASTM A615/A615M. 2015. Standard Test Method for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. West Conshohocken, PA 19428-2959. United States.
- [201] Zhu, A., Zhang, X., Zhu, H., Zhu, J. Lu, Y. (2017). Experimental Study of Concrete Filled Cold-Formed Steel Tubular Stub Columns. *Journal of Constructional Steel Research*, **134**, 17-27.
- [202] Aghdamy, S., Thambiratnam, D., Dhanasekar, M. Saiedi, S. (2017). Effects of Load-Related Parameters on the Response of Concrete-Filled Double-Skin Steel Tube Columns Subjected to Lateral Impact. *Journal of Constructional Steel Research*, **138**, 642-662.
- [203] Abdelkarim, O. I., ElGawady, M. A., Anumolu, S., Ghenni, A. Sanders, G. E. (2017). Behavior of Hollow-Core FRP-Concrete-Steel Columns under Static Cyclic Flexural Loading. *Journal of Structural Engineering*, **144**(2), 04017188.
- [204] Lai, M. H. Ho, J. (2016). Confining and Hoop Stresses in Ring-Confined Thin-Walled Concrete-Filled Steel Tube Columns. *Magazine of Concrete Research*, **68**(18), 916-935.
- [205] Duarte, A., Silva, B., Silvestre, N., De Brito, J., Júlio, E. Castro, J. (2016). Experimental Study on Short Rubberized Concrete-Filled Steel Tubes under Cyclic Loading. *Composite Structures*, **136**, 394-404.
- [206] Duarte, A., Silva, B., Silvestre, N., De Brito, J., Júlio, E. Castro, J. (2016). Finite Element Modelling of Short Steel Tubes Filled with Rubberized Concrete. *Composite Structures*, **150**, 28-40.
- [207] Du, Y., Chen, Z. Yu, Y. (2016). Behavior of Rectangular Concrete-Filled High-Strength Steel Tubular Columns with Different Aspect Ratio. *Thin-Walled Structures*, **109**, 304-318.
- [208] Ding, F.-X., Fu, L., Liu, X.-M. Liu, J. (2016). Mechanical Performances of Track-Shaped Rebar Stiffened Concrete-Filled Steel Tubular (SCFRT) Stub Columns under Axial Compression. *Thin-Walled Structures*, **99**, 168-181.
- [209] Aghdamy, S., Thambiratnam, D., Dhanasekar, M. Saiedi, S. (2016). Effects of Structure-Related Parameters on the Response of Concrete-Filled Double-Skin Steel Tube Columns to Lateral Impact. *Thin-Walled Structures*, **108**, 351-368.

- [210] Abdelkarim, O. I. ElGawady, M. A. (2016). Behavior of Hollow FRP–Concrete–Steel Columns under Static Cyclic Axial Compressive Loading. *Engineering Structures*, **123**, 77-88.
- [211] Yang, Y.-F., Hou, C., Meng, C.-Y. Han, L.-H. (2015). Investigation on Square Concrete Filled Double-Skin Steel Tube (CFDST) Subjected to Local Bearing Force: Experiments. *Thin-Walled Structures*, **94**, 394-409.
- [212] Wang, Y., Chen, J. Geng, Y. (2015). Testing and Analysis of Axially Loaded Normal-Strength Recycled Aggregate Concrete Filled Steel Tubular Stub Columns. *Engineering Structures*, **86**, 192-212.
- [213] Song, T.-Y., Tao, Z., Uy, B. Han, L.-H. (2015). Bond Strength in Full-Scale Concrete-Filled Steel Tubular Columns. Proceedings of the 2015 World Congress on Advances in Structural Engineering and Mechanics (ASEM15), Incheon, Korea.
- [214] Oktavianus, Y., Yao, H., Goldsworthy, H. M. Gad, E. F. (2015). Pull-out Behaviour of Blind Bolts from Concrete-Filled Tubes. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **168(10)**, 747-759.
- [215] Luo, Y., Guo, X., Li, J., Xiong, Z., Meng, L., Dong, N. *et al.* (2015). Experimental Research on Seismic Behaviour of the Concrete-Filled Double-Steel-Plate Composite Wall. *Advances in Structural Engineering*, **18(11)**, 1845-1858.
- [216] Lu, Y., Li, N., Li, S. Liang, H. (2015). Behavior of Steel Fiber Reinforced Concrete-Filled Steel Tube Columns under Axial Compression. *Construction and Building Materials*, **95**, 74-85.
- [217] Kang, W.-H., Uy, B., Tao, Z. Hicks, S. (2015). Design Strength of Concrete-Filled Steel Columns. *Advanced Steel Construction*, **11(2)**, 165-184.
- [218] Jegadesh, S. Jayalekshmi, S. (2015). Load-Bearing Capacity of Axially Loaded Circular Concrete-Filled Steel Tubular Columns. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **169(7)**, 508-523.
- [219] Idris, Y. Ozbakkloglu, T. (2015). FRP-Concrete-Steel Double Skin Tubular Cantilever Beams: Behavior under Cyclic Loading. *Applied Mechanics and Materials*, **752**, 572-577.
- [220] Huang, Y., Xiao, J., Yang, Z. Wang, Q. (2015). Behaviour of Concrete Filled-Steel Tubes under Axial Load. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **169(3)**, 210-222.
- [221] Chan, T.-M., Huai, Y.-M. Wang, W. (2015). Experimental Investigation on Lightweight Concrete-Filled Cold-Formed Elliptical Hollow Section Stub Columns. *Journal of Constructional Steel Research*, **115**, 434-444.

- [222] Aslani, F., Uy, B., Tao, Z. Mashiri, F. (2015). Predicting the Axial Load Capacity of High-Strength Concrete Filled Steel Tubular Columns. *Steel and Composite Structures*, **19(4)**, 967-993.
- [223] Aslani, F., Uy, B., Tao, Z. Mashiri, F. (2015). Behaviour and Design of Composite Columns Incorporating Compact High-Strength Steel Plates. *Journal of Constructional Steel Research*, **107**, 94-110.
- [224] Yuan, H., Wang, Y., Gardner, L. Shi, Y. (2014). Local–Overall Interactive Buckling of Welded Stainless Steel Box Section Compression Members. *Engineering Structures*, **67**, 62-76.
- [225] Won, D. H., Park, W. S., Yi, J. H., Han, S. H. Han, T. H. (2014). Effect of Welding Heat on Precast Steel Composite Hollow Columns. *Structural Concrete*, **15(3)**, 350-360.
- [226] Ren, Q.-X., Hou, C., Lam, D. Han, L.-H. (2014). Experiments on the Bearing Capacity of Tapered Concrete Filled Double Skin Steel Tubular (CFDST) Stub Columns. *Steel and Composite Structures*, **17(5)**, 667-686.
- [227] Ren, Q.-X., Han, L.-H., Lam, D. Li, W. (2014). Tests on Elliptical Concrete Filled Steel Tubular (CFST) Beams and Columns. *Journal of Constructional Steel Research*, **99**, 149-160.
- [228] Prince, M. J. R. Singh, B. (2014). Investigation of Bond Behaviour between Recycled Aggregate Concrete and Deformed Steel Bars. *Structural Concrete*, **15(2)**, 154-168.
- [229] Patel, V. I., Liang, Q. Q. Hadi, M. N. (2014). Nonlinear Analysis of Axially Loaded Circular Concrete-Filled Stainless Steel Tubular Short Columns. *Journal of Constructional Steel Research*, **101**, 9-18.
- [230] Ho, J. Dong, C. (2014). Improving Strength, Stiffness and Ductility of CFDST Columns by External Confinement. *Thin-Walled Structures*, **75**, 18-29.
- [231] Ho, J. Dong, C. (2014). Simplified Design Model for Uni-Axially Loaded Double-Skinned Concrete-Filled-Steel-Tubular Columns with External Confinement. *Advanced Steel Construction*, **10(2)**, 179-199.
- [232] Espinós, A., Romero, M. L., Portolés, J. Hospitaler, A. (2014). Ambient and Fire Behavior of Eccentrically Loaded Elliptical Slender Concrete-Filled Tubular Columns. *Journal of Constructional Steel Research*, **100**, 97-107.
- [233] Dai, X., Lam, D., Jamaluddin, N. Ye, J. (2014). Numerical Analysis of Slender Elliptical Concrete Filled Columns under Axial Compression. *Thin-Walled Structures*, **77**, 26-35.
- [234] Chithira, K. Baskar, K. (2014). Experimental Study on Circular Concrete Filled Steel Tubes with and without Shear Connectors. *Steel and Composite Structures*, **16(1)**, 97-114.

- [235] Pagoulatou, M., Sheehan, T., Dai, X. Lam, D. (2014). Finite Element Analysis on the Capacity of Circular Concrete-Filled Double-Skin Steel Tubular (CFDST) Stub Columns. *Engineering Structures*, **72**, 102-112.
- [236] Cai, J., Pan, J. Wu, Y. (2015). Mechanical Behavior of Steel-Reinforced Concrete-Filled Steel Tubular (SRCFST) Columns under Uniaxial Compressive Loading. *Thin-Walled Structures*, **97**, 1-10.
- [237] Wang, Z.-B., Tao, Z. Yu, Q. (2017). Axial Compressive Behaviour of Concrete-Filled Double-Tube Stub Columns with Stiffeners. *Thin-Walled Structures*, **120**, 91-104.
- [238] Yu-hang, W., Jian-guo, N. Jian-sheng, F. (2013). Theoretical Model and Investigation of Concrete Filled Steel Tube Columns under Axial Force–Torsion Combined Action. *Thin-Walled Structures*, **69**, 1-9.
- [239] Xu, L. Liu, Y.-B. (2013). Concrete Filled Steel Tube Reinforced Concrete (CFSTRC) Columns Subjected to ISO-834 Standard Fire: Experiment. *Advances in Structural Engineering*, **16(7)**, 1263-1282.
- [240] Shen, Z.-Y., Lei, M., Li, Y.-Q., Lin, Z.-Y. Luo, J.-H. (2013). Experimental Study on Seismic Behavior of Concrete-Filled L-Shaped Steel Tube Columns. *Advances in Structural Engineering*, **16(7)**, 1235-1247.
- [241] Jamaluddin, N., Lam, D., Dai, X. Ye, J. (2013). An Experimental Study on Elliptical Concrete Filled Columns under Axial Compression. *Journal of Constructional Steel Research*, **87**, 6-16.
- [242] Guler, S., Lale, E. Aydogan, M. (2013). Non-Linear Analysis of Steel Fibre Reinforced Concrete-Filled Steel Tube Columns. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **166(6)**, 298-306.
- [243] Dong, C. Ho, J. C. M. (2013). Improving Interface Bonding of Double-Skinned CFST Columns. *Magazine of Concrete Research*, **65(20)**, 1199-1211.
- [244] Chang, X., Fu, L., Zhao, H.-B. Zhang, Y.-B. (2013). Behaviors of Axially Loaded Circular Concrete-Filled Steel Tube (CFT) Stub Columns with Notch in Steel Tubes. *Thin-Walled Structures*, **73**, 273-280.
- [245] An, Y.-F., Han, L.-H. Zhao, X.-L. (2013). Experimental Behaviour of Box Concrete-Encased CFST Eccentrically Loaded Column. *Magazine of Concrete Research*, **65(20)**, 1219-1235.
- [246] Abed, F., AlHamaydeh, M. Abdalla, S. (2013). Experimental and Numerical Investigations of the Compressive Behavior of Concrete Filled Steel Tubes (CFSTs). *Journal of Constructional Steel Research*, **80**, 429-439.
- [247] Ibañez, C., Romero, M. L., Espinos, A., Portolés, J. Alberó, V. (2017). Ultra-High Strength Concrete on Eccentrically Loaded Slender Circular Concrete-Filled Dual Steel Columns. *Structures*, **12**, 64-74.

- [248] Aslani, F., Uy, B., Wang, Z. Patel, V. (2016). Confinement Models for High Strength Short Square and Rectangular Concrete-Filled Steel Tubular Columns. *Steel and Composite Structures*, **22(5)**, 937-974.
- [249] Ding, F.-x., Zhu, J., Cheng, S. Liu, X. (2018). Comparative Study of Stirrup-Confinement Circular Concrete-Filled Steel Tubular Stub Columns under Axial Loading. *Thin-Walled Structures*, **123**, 294-304.
- [250] AL-Eliwi, B., Ekmekyapar, T., Faraj, R., Göğüs, M. AL-Shaar, A. (2017). Performance of Lightweight Aggregate and Self-Compacted Concrete-Filled Steel Tube Columns. *Steel and Composite Structures*, **25(3)**, 299-314.
- [251] EN, C. (2006). 10219-2. Cold Formed Welded Structural Hollow Sections of Non-Alloy and Fine Grains Steels—Part 2: Tolerances, Dimensions and Sectional Properties. *Brussels, Belgium: European Committee for Standardization*.
- [252] Li, S., Liu, Z., Lu, Y. Zhu, T. (2017). Shear Performance of Steel Fibers Reinforced Self-Confinement and Self-Compacting Concrete-Filled Steel Tube Stub Columns. *Construction and Building Materials*, **147**, 758-775.
- [253] ASTM-C39/C39M. 2001. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, C39/C39m ASTM International,
- [254] Ding, F.-x., Fang, C., Bai, Y. Gong, Y.-z. (2014). Mechanical Performance of Stirrup-Confinement Concrete-Filled Steel Tubular Stub Columns under Axial Loading. *Journal of Constructional Steel Research*, **98**, 146-157.
- [255] Ye, Y., Zhang, S.-J., Han, L.-H. Liu, Y. (2018). Square Concrete-Filled Stainless Steel/Carbon Steel Bimetallic Tubular Stub Columns under Axial Compression. *Journal of Constructional Steel Research*, **146**, 49-62.
- [256] Ronald, Z. D. 2010. *Guide to Stability Design Criteria for Metal Structures*. Sixth Edition ed. Canada: John Wiley and Sons, Inc.
- [257] Chitawadagi, M. V., Narasimhan, M. C. Kulkarni, S. (2010). Axial Strength of Circular Concrete-Filled Steel Tube Columns—Doe Approach. *Journal of Constructional Steel Research*, **66(10)**, 1248-1260.
- [258] Hassanein, M., Elchalakani, M., Karrech, A., Patel, V. Daher, E. (2018). Finite Element Modelling of Concrete-Filled Double-Skin Short Compression Members with Chs Outer and Shs Inner Tubes. *Marine Structures*, **61**, 85-99.
- [259] Tao, Z., Uy, B., Han, L.-H. Wang, Z.-B. (2009). Analysis and Design of Concrete-Filled Stiffened Thin-Walled Steel Tubular Columns under Axial Compression. *Thin-Walled Structures*, **47(12)**, 1544-1556.
- [260] Ekmekyapar, T. Al-Eliwi, B. J. (2016). Experimental Behaviour of Circular Concrete Filled Steel Tube Columns and Design Specifications. *Thin-Walled Structures*, **105**, 220-230.

- [261] Han, L.-H., Yang, Y.-F. Xu, L. (2003). An Experimental Study and Calculation on the Fire Resistance of Concrete-Filled SHS and RHS Columns. *Journal of Constructional Steel Research*, **59**(4), 427-452.
- [262] Zhao, X.-L., Grzebieta, R. Elchalakani, M. (2002). Tests of Concrete-Filled Double Skin Chs Composite Stub Columns. *Steel and Composite Structures*, **2**(2), 129-146.
- [263] Kim, J.-K., Kwak, H.-G. Kwak, J.-H. (2013). Behavior of Hybrid Double Skin Concrete Filled Circular Steel Tube Columns. *Steel and Composite Structures*, **14**(2), 191-204.
- [264] Han, L.-H., Yao, G.-H. Zhao, X.-L. (2005). Tests and Calculations for Hollow Structural Steel (HSS) Stub Columns Filled with Self-Consolidating Concrete (SCC). *Journal of Constructional Steel Research*, **61**(9), 1241-1269.
- [265] Ekmekyapar, T. Al-Eliwi, B. J. (2017). Concrete Filled Double Circular Steel Tube (CFDCST) Stub Columns. *Engineering Structures*, **135**, 68-80.
- [266] Mahgub, M., Ashour, A., Lam, D. Dai, X. (2017). Tests of Self-Compacting Concrete Filled Elliptical Steel Tube Columns. *Thin-Walled Structures*, **110**, 27-34.
- [267] Ding, F.-x., Liu, J., Liu, X.-m., Yu, Z.-w. Li, D.-w. (2015). Mechanical Behavior of Circular and Square Concrete Filled Steel Tube Stub Columns under Local Compression. *Thin-Walled Structures*, **94**, 155-166.
- [268] Han, L.-H., Huang, H. Zhao, X.-L. (2009). Analytical Behaviour of Concrete-Filled Double Skin Steel Tubular (CFDST) Beam-Columns under Cyclic Loading. *Thin-Walled Structures*, **47**(6), 668-680.
- [269] Yu, M., Zha, X., Ye, J. Li, Y. (2013). A Unified Formulation for Circle and Polygon Concrete-Filled Steel Tube Columns under Axial Compression. *Engineering Structures*, **49**, 1-10.
- [270] Tang, J., Hino, S.-I., Kuroda, I. Ohta, T. (1996). Modeling of Stress-Strain Relationships for Steel and Concrete in Concrete Filled Circular Steel Tubular Columns. *Kou kousou rombunshuu*, **3**(11), 35-46.
- [271] Li, G., Chen, B., Yang, Z. Feng, Y. (2018). Experimental and Numerical Behaviour of Eccentrically Loaded High Strength Concrete Filled High Strength Square Steel Tube Stub Columns. *Thin-Walled Structures*, **127**, 483-499.
- [272] Hassanein, M., Patel, V., El Hadidy, A., Al Abadi, H. Elchalakani, M. (2018). Structural Behaviour and Design of Elliptical High-Strength Concrete-Filled Steel Tubular Short Compression Members. *Engineering Structures*, **173**, 495-511.
- [273] Hassanein, M., Elchalakani, M., Karrech, A., Patel, V. Yang, B. (2018). Behaviour of Concrete-Filled Double-Skin Short Columns under Compression

- through Finite Element Modelling: SHS Outer and SHS Inner Tubes. *Structures*, **14**, 358-375.
- [274] Grammatikou, S., Biskinis, D. Fardis, M. N. (2018). Flexural Rotation Capacity Models Fitted to Test Results Using Different Statistical Approaches. *Structural Concrete*, **19(2)**, 608-624.
- [275] Feng, R., Chen, Y., Wei, J., Huang, J., Huang, J. He, K. (2018). Experimental and Numerical Investigations on Flexural Behaviour of CFRP Reinforced Concrete-Filled Stainless Steel CHS Tubes. *Engineering Structures*, **156**, 305-321.
- [276] Elchalakani, M., Hassanein, M., Karrech, A. Yang, B. (2018). Experimental Investigation of Rubberised Concrete-Filled Double Skin Square Tubular Columns under Axial Compression. *Engineering Structures*, **171**, 730-746.
- [277] Zhu, J.-Y. Chan, T.-M. (2017). Behaviour of Polygonal-Shaped Steel-Tube Columns Filled with High-Strength Concrete. *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, **171(2)**, 96-112.
- [278] Yang, L., Shi, G., Zhao, M. Zhou, W. (2017). Research on Interactive Buckling Behavior of Welded Steel Box-Section Columns. *Thin-Walled Structures*, **115**, 34-47.
- [279] Yang, J., Sheehan, T., Dai, X. Lam, D. (2017). Structural Behaviour of Beam to Concrete-Filled Elliptical Steel Tubular Column Connections. *Structures*, **9**, 41-52.
- [280] Wardeh, G., Ghorbel, E., Gomart, H. Fiorio, B. (2017). Experimental and Analytical Study of Bond Behavior between Recycled Aggregate Concrete and Steel Bars Using a Pullout Test. *Structural Concrete*, **18(5)**, 811-825.
- [281] Ge, H. Usami, T. (1992). Strength of Concrete-Filled Thin-Walled Steel Box Columns: Experiment. *Journal of Structural Engineering*, **118(11)**, 3036-3054.
- [282] Tao, Z., Han, L.-H. Wang, Z.-B. (2005). Experimental Behaviour of Stiffened Concrete-Filled Thin-Walled Hollow Steel Structural (HSS) Stub Columns. *Journal of Constructional Steel Research*, **61(7)**, 962-983.
- [283] Lin, T., Huang, C. Chen, S. (1993). Concrete-Filled Tubular Steel Columns Subjected to Eccentric Axial Load. *J Chin Inst Civil Hydraulic Eng*, **54**, 377-386.
- [284] Tao, Z., Han, L.-H. Wang, D.-Y. (2008). Strength and Ductility of Stiffened Thin-Walled Hollow Steel Structural Stub Columns Filled with Concrete. *Thin-Walled Structures*, **46(10)**, 1113-1128.
- [285] Tao, Z., Han, L. H. Wang, D. Y. (2007). Experimental Behaviour of Concrete-Filled Stiffened Thin-Walled Steel Tubular Columns. *Thin-Walled Structures*, **45(5)**, 517-527.

- [286] Zhang, S., Guo, L., Ye, Z. Wang, Y. (2005). Behavior of Steel Tube and Confined High Strength Concrete for Concrete-Filled RHS Tubes. *Advances in Structural Engineering*, **8(2)**, 101-116.
- [287] Liu, D. Gho, W.-M. (2005). Axial Load Behaviour of High-Strength Rectangular Concrete-Filled Steel Tubular Stub Columns. *Thin-Walled Structures*, **43(8)**, 1131-1142.
- [288] Liu, D. (2005). Tests on High-Strength Rectangular Concrete-Filled Steel Hollow Section Stub Columns. *Journal of Constructional Steel Research*, **61(7)**, 902-911.
- [289] Han, L.-H. Yang, Y.-F. (2005). Cyclic Performance of Concrete-Filled Steel CHS Columns under Flexural Loading. *Journal of Constructional Steel Research*, **61(4)**, 423-452.
- [290] Wang, Q., Zhao, D. Guan, P. (2004). Experimental Study on the Strength and Ductility of Steel Tubular Columns Filled with Steel-Reinforced Concrete. *Engineering Structures*, **26(7)**, 907-915.
- [291] Teng, J., Yu, T. Wong, Y. (2004). Behaviour of Hybrid FRP-Concrete-Steel Double-Skin Tubular Columns.
- [292] Tan, K. Tang, C. (2004). Interaction Model for Unprotected Concrete Filled Steel Columns under Standard Fire Conditions. *Journal of Structural Engineering*, **130(9)**, 1405-1413.
- [293] Nishiyama, I., Fujimoto, T., Fukumoto, T. Yoshioka, K. (2004). Inelastic Force-Deformation Response of Joint Shear Panels in Beam-Column Moment Connections to Concrete-Filled Tubes. *Journal of Structural Engineering*, **130(2)**, 244-252.
- [294] Marson, J. Bruneau, M. (2004). Cyclic Testing of Concrete-Filled Circular Steel Bridge Piers Having Encased Fixed-Based Detail. *Journal of Bridge Engineering*, **9(1)**, 14-23.
- [295] Herrera, R., Lewis, B., Ricles, J. Sause, R. (2004 of Conference). Experimental Studies on Steel Moment Resisting Frames with Concrete Filled Tube Columns under Earthquake Loading Conditions. *The 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada.
- [296] Han, L.-H. Yao, G.-H. (2004). Experimental Behaviour of Thin-Walled Hollow Structural Steel (HSS) Columns Filled with Self-Consolidating Concrete (SCC). *Thin-Walled Structures*, **42(9)**, 1357-1377.
- [297] Fujimoto, T., Mukai, A., Nishiyama, I. Sakino, K. (2004). Behavior of Eccentrically Loaded Concrete-Filled Steel Tubular Columns. *Journal of Structural Engineering*, **130(2)**, 203-212.
- [298] Anwar, H. Wright, H. (2004). Flexural and Shear Behaviour of Profiled Double Skin Composite Elements. *Steel and Composite Structures*, **4(2)**, 113-132.

- [299] Al-Rodan, A.-K. (2004). Comparison between BS5400 and EC4 for Concrete-Filled Steel Tubular Columns. *Advances in Structural Engineering*, **7(2)**, 159-168.
- [300] Mursi, M. Uy, B. (2003). Strength of Concrete Filled Steel Box Columns Incorporating Interaction Buckling. *Journal of Structural Engineering*, **129(5)**, 626-639.
- [301] Hu, H.-T., Huang, C.-S., Wu, M.-H. Wu, Y.-M. (2003). Nonlinear Analysis of Axially Loaded Concrete-Filled Tube Columns with Confinement Effect. *Journal of Structural Engineering*, **129(10)**, 1322-1329.
- [302] Han, L.-H. Huo, J.-s. (2003). Concrete-Filled Hollow Structural Steel Columns after Exposure to ISO-834 Fire Standard. *Journal of Structural Engineering*, **129(1)**, 68-78.
- [303] Wu, K., Chen, F., Zhang, H., Xu, C. Lin, S.-Q. (2018). Experimental Study on the Behavior of Recycled Concrete-Filled Thin-Wall Steel Tube Columns under Axial Compression. *Arabian Journal for Science and Engineering*, 1-18.
- [304] Wang, Y.-H., Lu, G.-B. Zhou, X.-H. (2018). Experimental Study of the Cyclic Behavior of Concrete-Filled Double Skin Steel Tube Columns Subjected to Pure Torsion. *Thin-Walled Structures*, **122**, 425-438.
- [305] Uenaka, K. (2018). Concrete Filled Double Skin Tubular Deep Beam Having Outer Circular and Inner Square Sections under Bending-Shear. *Structures*, **14**, 313-321.
- [306] Teng, J.-G., Wang, Z., Yu, T., Zhao, Y. Li, L.-J. (2018). Double-Tube Concrete Columns with a High-Strength Internal Steel Tube: Concept and Behaviour under Axial Compression. *Advances in Structural Engineering*, 1-10.
- [307] Shekastehband, B., Mohammadbagheri, S. Taromi, A. (2018). Seismic Behavior of Stiffened Concrete-Filled Double-Skin Tubular Columns. *Steel and Composite Structures*, **27(5)**, 577-598.
- [308] Nassirnia, M., Heidarpour, A., Zhao, X.-L., Wang, R., Li, W. Han, L.-H. (2018). Lateral Impact Response of Innovative Hollow Corrugated Members. *International Journal of Impact Engineering*, **114**, 43-52.
- [309] Liang, Q. Q. (2018). Numerical Simulation of High Strength Circular Double-Skin Concrete-Filled Steel Tubular Slender Columns. *Engineering Structures*, **168**, 205-217.
- [310] AISC360-16. 2016. Specification for Structural Steel Buildings American Institute of Steel Construction, Chicago, USA.

CURRICULUM VITAE

PERSONAL INFORMATION

Name and Surname: Hussein Ghanim HASAN

Nationality: IRAQI

Birth place and date: IRAQ – December 01,1981

Marital status: Married

Email: hussein8ghanim@gmail.com

EDUCATION

	Graduate School	Year
Master	Civil Engineering Department, College of Engineering, University of Gaziantep – Turkey	2015
Bachelor	Civil Engineering Department, College of Engineering, University of Anbar – IRAQ	2003-2004

PUBLICATIONS

- [1] **Hasan, Hussein Ghanim.**, Ekmekyapar, Talha. and Shehab, B. A. (2019). Mechanical performances of stiffened and reinforced concrete-filled steel tubes under axial compression. *Marine Structures*, **65**, 417–32.
- [2] **Hasan, Hussein Ghanim.** and Ekmekyapar, T. (2019). Mechanical Performance of Stiffened Concrete Filled Double Skin Steel Tubular Stub Columns under Axial Compression. *KSCE Journal of Civil Engineering*, **23(5)**, 2281-92.
- [3] Ekmekyapar, Talha. and **Hasan, Hussein Ghanim.** (2019). The influence of the inner steel tube on the compression behaviour of the concrete filled double skin steel tube (CFDST) columns. *Marine Structures*, **66**, 197-212.
- [4] Ekmekyapar, Talha., Alwan, O. H., **Hasan, Hussein Ghanim**, Shehab, B. A. and AL-Eliwi, B. J. (2019). Comparison of classical, double skin and double section CFST stub columns: Experiments and design formulations. *Journal of Constructional Steel Research*, **155**, 192-204.
- [5] **Hasan, Hussein Ghanim.** (2016). Influence of the artificial lightweight aggregate on fresh properties and compressive strength of the self-compacting mortars. *Construction and Building Materials*, **116**, 151-8.

FOREIGN LANGUAGE

English and Turkish

HOBBIES

1. Reading.
2. Technology News and Computer Software.
3. Photography.