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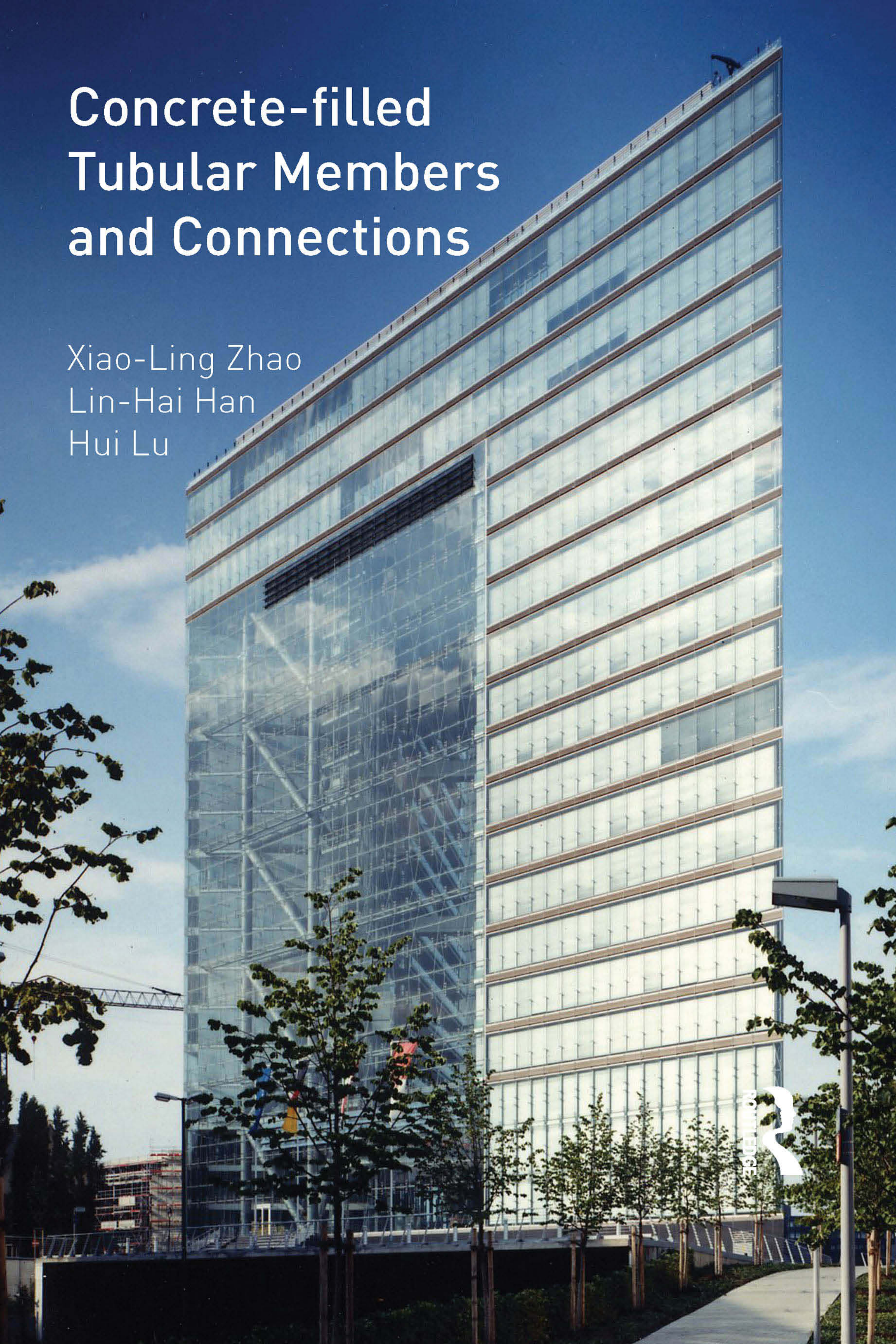

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Preface

Concrete-filled steel tubes (CFSTs) have been used in many structural engineering applications, such as columns in high-rise buildings and bridge piers. CFSTs can be used in various fields ranging from civil and industrial construction through to the mining industry.

A series of design guides on tubular structures have been produced by CIDECT (International Committee for the Development and Study of Tubular Structures) to assist practising engineers. The ones relevant to concrete-filled steel tubes are CIDECT Design Guides No. 4, No. 5, No. 7 and No. 9. There are a few books relevant to CFST members and connections. Some of the books are not focused on concrete-filled steel tubes. For those which do, explanations of failure mechanism and mechanics are not covered in detail. Most of the designs are based on Eurocode 4. There is a lack of comparison of different design standards. Seismic resistance has received only very little coverage. Worked examples are very limited. This book will fill these gaps.

This book contains descriptions and explanation of some basic concepts. It not only summarises the research performed to date on concrete-filled tubular members and connections but also compares the design rules in various standards (Eurocode 4, BS5400 Part 5, AS5100 Part 6 and Chinese Standard DBJ13-51), and provides design examples. It also presents some recent developments in concrete-filled tubular members and connections. It is suitable for structural engineers, researchers and university students who are interested in composite tubular structures.

Chapter 1 outlines the application and advantages of concrete-filled steel tubes (CFSTs). Chapter 2 presents the material properties of steel tubes and concrete given in various standards. The limit states design method is described. The differences among the Australian, British, Chinese and European standards are pointed out to help the readers to interpret the design comparison later in the book. CFST members are covered in Chapter 3 (bending), Chapter 4 (compression) and Chapter 5 (combined actions). Chapter 6 and Chapter 7 present the performance and design methods of CFST structures under seismic loading and fire conditions. Steel or RC beam to CFST column connection details and designing approaches are covered in Chapter 8. Finally, Chapter 9 introduces some recent developments on concrete-filled steel tubular structures, e.g. the effect of long-term loading on the behaviour of CFST columns, the effect of axial local compression and pre-loads on the CFST column capacity, SCC (self-consolidating concrete)-filled tubular members, concrete-filled double skin tubes (CFDST) and FRP (Fibre Reinforced Polymer)-confined CFST columns. Comprehensive up-to-date references are given in the book.

We appreciated the comments from Dr. Mohamed Elchalakani at Higher Colleges of Technology, Dubai Mens College on Chapter 3, Dr. Ben Young at The University of Hong Kong on Chapter 4, Dr. Leroy Gardner at Imperial College, London, on Chapter 5, Prof. Amir Fam and Dr. Pedram Sadeghian at Queen's University, Canada, on Chapter 6, Prof. Yong-Chang Wang at The University of Manchester on Chapter 7, Prof. Akihiko Kawano at Kyushu University on Chapter 8 and Dr. Zhong Tao at Fuzhou University on Chapter 9.

We would like to thank Prof. Dennis Lam at The University of Leeds, UK, for providing necessary documents regarding BS5400 Part 5, Prof. Hanbin Ge at Meijo University, Japan, for obtaining some relevant Japanese documents and Prof. Peter Schaumann at The University of Hannover for discussions on fire design in Eurocode 4. We are very grateful to Mr. Robert Alexander at Monash University for preparing most of the diagrams and Ms. Dominique Thomson at Monash University for checking the English. We wish to thank Thyssen Krupp Steel for providing the front cover photo. We also wish to thank Simon Bates at Taylor & Francis for his advice on the format of the book.

Finally, we wish to thank our families for their support and understanding during the many years that we have been undertaking research on composite tubular structures and during the preparation of this book.

Xiao-Ling Zhao, Lin-Hai Han and Hui Lu
January 2010

Notation

The following notation is used in this book. Where non-dimensional ratios are involved, both the numerator and denominator are expressed in identical units. The dimensional units for length and stress in all expressions or equations are to be taken as millimetres and megapascals (N/mm^2) respectively, unless specifically noted otherwise. When more than one meaning is assigned to one symbol, the correct one will be evident from the context in which it is used. Some symbols are not listed here because they are only used in one section and well defined in the local context.

A_a	Area of a steel hollow section defined in EC4
A_c	Area of concrete in CFST
$A_{concrete}$	Area of concrete in CFDST
$A_{c,nominal}$	Nominal cross-sectional area of concrete in CFDST
A_g	Gross cross-sectional area
A_{inner}	Area of inner steel hollow section in CFDST
A_L	Localised load area on core concrete in CFST
A_{nt}	Net area in tension for block failure
A_{nv}	Net area in shear for block failure
A_{outer}	Area of outer steel hollow section in CFDST
A_s	Area of steel in CFST
A_{sr}	Area of steel reinforcement
A_{sc}	Area of steel and concrete in CFST
B	Overall width of an RHS
B_i	Overall width of inner RHS in CFDST
B_o	Overall width of outer RHS in CFDST
C	Perimeter of CFST or carbonate aggregate
C_1, C_2 and C_3	Compressive forces in Figure 3.3
D	Overall depth of an RHS
D_e	Outside diameter of a CHS in BS5400
D_i	Overall depth of inner RHS in CFDST
D_o	Overall depth of outer RHS in CFDST
$\bar{E}$	Axial stiffness ratio of CFST
E_a	Modulus of elasticity for CHS defined in EC4
E_c	Modulus of elasticity of concrete
E_d	Design value of the effect of actions in EC4
E_s	Modulus of elasticity of steel
$E_{sc}^{elastic}$	Section modulus of a composite section
G	Shear modulus of elasticity
I_a	Second moment of area of CHS
I_b	Second moment of area of beam

I_c	Second moment of area of concrete
I_s	Second moment of area of steel hollow section
J	Torsion constant for a cross-section
K	Effective length factor
K_e	Flexural stiffness in the elastic stage of CFST
$K_{j,ini}$	Initial rotation stiffness of connections
K_1	Member slenderness reduction factor given in Figure 4.6
L	Member length
L_b	Span of beam
L_e	Effective length of a member
L_p	Length of shear plate
L_w	Fillet weld length
M	Bending moment
M_c	Design moment at the beam end
M_{CFDST}	Ultimate moment capacity of CFDST
M_{max}	Maximum moment for CFST under combined loads shown in Figure 5.1(d)
M_o	Elastic flexural-tensional buckling moment
M_p	Plastic moment capacity
M_s	Nominal section moment capacity
$M_{u,CFDST}$	Section bending moment capacity of CFDST
M_{ux}	Design ultimate moment of resistance of CFST about the major axis
M_{uy}	Design ultimate moment of resistance of CFST about the minor axis
M_x	Bending moment about major principal x-axis
M_y	Bending moment about minor principal y-axis or yielding moment of CFST
M_{yu}	Ultimate moment of CFST under constant axial load
N	Axial force
N_b	Tensile force in an external diaphragm induced by the axial force in beam
N_c	Design member capacity in compression
N_{CFDST}	Section capacity of CFDST in compression
N_{cr}	Critical buckling load of a compressive member
N_E	Elastic buckling load
N_o	Applied axial load on CFST
N_p	Pre-load on steel tube
N_s	Nominal section capacity of CFST
N_u	Design axial section capacity or squash load of CFST
$N_{u,CFDST}$	Section capacity of CFDST in compression
$N_{u,L}$	Ultimate load of CFST subjected to long-term sustained load
$N_{u, nominal}$	Nominal axial capacity of CFST
N_{up}	Ultimate load of CFST with pre-load on steel tube

N_{us}	Ultimate strength of unfilled steel tubular column
N_x	Design member capacity in compression under uniaxial bending about the major axis restrained from failure about the minor axis
N_{xy}	Design member capacity in compression under uniaxial bending about the major axis unrestrained from failure about the minor axis or under biaxial bending
N_y	Design member capacity in compression under uniaxial bending about the minor axis, or yield capacity of external diaphragm connections
N^*	Design axial tension load at beam end
P	Cyclic lateral load defined in Figure 6.3 or applied load in fire
P_y	Yield load of CFST or ultimate strength of CFST
Q	Shear force at beam end
R	Ultimate resistance in DBJ13-51 or fire resistance
R_d	Design resistance in EC4
R_u	Nominal capacity
R^*	Design resistance
S	Design action effects in DBJ13-51 or siliceous aggregate, or plastic section modulus of the steel section defined in BS5400
S^*	Design action effects
T	Torsion, or shear stress
T_1, T_2	Tensile forces in Figure 3.3
T_u	Torsion capacity of CFST
V	Shear force
V_{bolt}	Design shear capacity of a single bolt
V_{max}	Maximum shear force in beam web
V_u	Shear capacity of CFST
V_{weld}	Design shear capacity per unit length of fillet weld
a	Thickness of fire protection for CFST
b	Clear width of an RHS or the least lateral dimension of a column defined in BS5400 or effective width of diaphragm at critical section
b_e	Effective width of tube wall to resist tensile force in a diaphragm connection
b_f	Overall width of an RHS defined in BS5400
b_j	Total length of weld defined in Figure 8.6
b_s	Flange width of steel I beam or overall depth or width of an RHS in BS5400
d	Outside diameter of a CHS
d_b	Bolt diameter
d_i	Outside diameter of inner CHS in CFDST
d_{in}	Hole diameter of the inner diaphragm

d_1	Depth of web in steel I beam
d_n	Distance of neutral axis to interior surface of the compressive flange of an RHS
$d_{overall}$	Overall height of steel I beam
e	Load eccentricity
f_a	Design bond strength between steel and concrete in CFST
$f_{b,w,u}$	Ultimate strength of beam web
f_{bond}	Bond strength between steel and concrete in CFST
f_c	Concrete compressive strength
f_{cd}	Design cylinder strength of concrete defined in EC4
f_{ck}	Standard compressive strength of concrete (Chapter 2), or characteristic strength of concrete given in GB50010-2002 or characteristic cylinder strength of concrete at 28 days given in EC4
f_{cm}	Mean value of the compressive strength of concrete at the relevant age
f_{cu}	Characteristic compressive cube strength of concrete at 28 days
$f_{c,u}$	Ultimate strength of steel tube
$f_{c,y}$	Yield strength of steel tube
f'_c	Characteristic compressive cylinder strength of concrete at 28 days
$f_{p,u}$	Ultimate strength of shear plate
$f_{p,y}$	Yield strength of shear plate
$f_{p,u}$	Ultimate strength of shear plate
$f_{s,y}$	Yield stress of steel diaphragm
f_{tk}	Standard tensile strength of concrete
f_t	Tensile strength of concrete
f_u	Ultimate tensile strength of steel
$f_{w,y}$	Yield strength of beam web
$f_{w,u}$	Ultimate strength of beam web
f_y	Tensile yield stress of steel
f_{yd}	Design yield strength of RHS defined in EC4
h	Overall depth of an RHS without a round corner defined in EC3, or depth of concrete in BS5400 or overall depth of steel I beam
h_f	Fillet weld leg length
h_s	Distance defined in Figure 8.8
k_c	Reduction factor on concrete strength
k_e	Member effective length factor
k_f	Form factor
k_t	Strength factor under fire
l	Member length
l_e	Effective length of CFST
l_E	Length of a column for which Euler load equals the squash load
n	Load level or fire load ratio

n_b	Number of bolts
p_r	Percentage of reinforcement in CFST
r	Radius of gyration
r_c	Diameter of core concrete in CFST
r_{ext}	External corner radius of an RHS
r_i	Inner radius of a CHS
r_{int}	Internal corner radius of an RHS
r_m	Middle radius between inner and outer surfaces of a CHS
t	Tube wall thickness or time
$t_{b,f}$	Thickness of flange of steel I beam
$t_{b,w}$	Thickness of web of steel I beam
t_c	Tube wall thickness
t_f	Wall thickness of an RHS defined in BS5400
t_i	Wall thickness of inner steel tube in CFDST
t_l	Thickness of diaphragm
t_p	Thickness of shear plate
t_o	Wall thickness of outer steel tube in CFDST
t_s	Thickness of steel beam flange
α	Steel ratio or angle between tensile force and critical section in external diaphragm connection
α_b	Section constant of compression members
α_c	Concrete contribution factor defined in BS5400, or member slenderness reduction factor defined in AS5100
α_s	Steel ratio
β	Depth-to-width ratio for RHS or local compression area ratio
β_m	Equivalent moment factor defined in GB50017
β_x	Ratio of smaller to larger bending moment at the ends of a member about major axis
β_y	Ratio of smaller to larger bending moment at the ends of a member about minor axis
χ	Member slenderness reduction factor giver in Figure 4.9
Δ	Lateral deflection
Δ_p	Lateral displacement corresponding to P_y as defined in Figure 6.1
Δ_u	Lateral displacement defined in Figure 6.1
Δ_y	Yield displacement defined in Figure 6.1
δ	Deflection of structures or steel contribution ratio defined in EC4
δ_{max}	Deflection limit of structures
δ_o	Hogging of beams in the unloaded state
δ_1	Variation of the deflection of beams due to the permanent loads immediately after loading

δ_2	Variation of the deflection of beams due to the variable loading plus the long-term deformation due to the permanent load
ε_{sh}	Shrinkage strain of core concrete in CFSTs
Φ_1	Resistance factor for yield of steel
Φ_3	Resistance factor for failure associated with a connector
ϕ	Capacity factor or capacity factor for steel hollow section or curvature
ϕ_c	Capacity factor for concrete
ϕ_y	Curvature corresponding to the yield moment
φ	Slenderness reduction factor or stability factor
γ_c	Material property factor of concrete
γ_o	Coefficient of the building importance in DBJ13-51
γ_{Rd}	Partial factor covering uncertainty in the resistance model plus geometric deviation in EC4
γ_s	Material property factor of steel
κ	Curvature
λ	Non-dimensional slenderness
$\bar{\lambda}$	Relative slenderness
λ_e	Slenderness ratio of a steel hollow section
λ_{ep}	Plate element plasticity slenderness limit
λ_{ey}	Plate element yield slenderness limit
λ_n	Modified compression member slenderness
λ_r	Relative slenderness of CFST defined in AS5100
λ_s	Section slenderness
λ_{sp}	Section plasticity slenderness limit
λ_{sy}	Section yield slenderness limit
λ_w	λ_e for the web in compression only
λ_{wy}	λ_{ey} for the web in compression only
λ_x	λ about major axis
λ_y	λ about minor axis
μ	Ductility ratio or degree of utilisation in determining fire resistance
ρ	Saturated surface-dry density of concrete in Chapter 2, or ratio of the average compressive stress in the concrete at failure to the design yield stress of the steel as defined in BS5400
σ_0	Pre-stress in the steel tube
ξ	Nominal constraining factor
ξ_o	Design constraining factor

AIJ	Architectural Institute of Japan
AISC	American Institute of Steel Construction or Australian Institute of Steel Construction

ASCCS	Association for Steel-Concrete Composite Structures
ASI	Australian Steel Institute
AS5100	Australian bridge design standard AS5100
BSI	British Standards Institution
BS5400	British bridge code BS5400
CFST	Concrete-filled steel tubes
CFRP	Carbon fibre reinforced polymer
CFDST	Concrete-filled double skin tubes
CHS	Circular hollow section
CIDECT	International Committee for the Development and Study of Tubular Structures
DBJ13-51	Chinese code DBJ13-51
EC3	Eurocode 3
EC4	Eurocode 4
FR	Fire resistance in minutes
FRP	Fibre reinforced polymer
IIW	International Institute of Welding
kN	Kilonewton
LSD	Limit states design
MPa	Megapascal (N/mm^2)
m	Metre
mm	Millimetre
PLR	Pre-load ratio
RHS	Rectangular hollow section
RSI	Residual strength index
SCC	Self-consolidating concrete
SHS	Square hollow section

CHAPTER ONE

Introduction

1.1 APPLICATIONS OF CONCRETE-FILLED STEEL TUBES

Using steel and concrete together utilises the beneficial material properties of both elements. Reinforced concrete (RC) sections are one example of this composite construction. This type of section primarily involves the use of a concrete section which is reinforced with steel rods in the tension regions.

This book deals with another type of concrete–steel composite construction, namely concrete-filled steel tubes (CFSTs). The hollow steel tubes can be fabricated by welding steel plates together or by hot-rolled process, or by cold-formed process. Figure 1.1 shows some typical CFST section shapes commonly found in practice, namely circular, square and rectangular. They are often called concrete-filled CHS (circular hollow section), SHS (square hollow section) and RHS (rectangular hollow section), respectively.

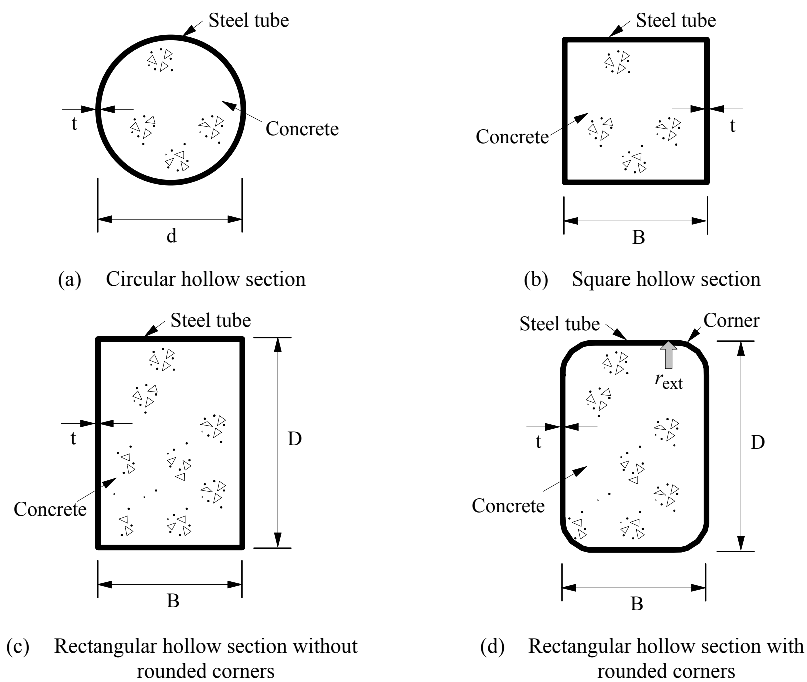


Figure 1.1 Typical CFST sections

In Figure 1.1, d is the outer diameter of the circular section, B is the width of the square or the rectangular sections, D is the overall depth of the rectangular section and t is the steel wall thickness. SHS can be treated as a special case of RHS when D equals B. For cold-formed RHS, rounded corners exist (Zhao *et al.* 2005), as shown in Figure 1.1(d), where r_{ext} is the external corner radius.

There is an increasing trend in using concrete-filled steel tubes in recent decades, such as in industrial buildings, structural frames and supports, electricity transmitting poles and spatial construction. In recent years, such composite columns are more and more popular in high-rise or super-high-rise buildings and bridge structures.

A few examples are presented here to give an appreciation of the scale of such composite structures. Figure 1.2 shows the using of CFST columns in one workshop. It is well known that the columns in a subway may be subjected to very high axial compression. CFST is very suitable for supporting columns in subways. One subway under construction can be seen in Figure 1.3. Figure 1.4 shows an electricity transmitting pole with CFST legs. CFST columns have very high load-bearing capacity, which thus can be used in spacious construction. An example is given in Figure 1.5.

Figure 1.6 shows the SEG Plaza in Shenzhen during construction. It is the tallest building in China using CFST columns. SEG Plaza is a 76-storey Grade A office block with a four-level basement, each basement floor having an area of 9653m^2. The main structure is 291.6m high with an additional roof feature giving a total height of 361m (Wu and Hua 2000, Zhong 1999). The steel parts of the columns were shipped to the site in lengths of three storeys. After being mounted, they were connected to the I-beams by bolts and were brought into the exact position. Then, the steel tubes were filled with concrete, and the deck floors were constructed at the same time. In this way, up to two-and-a-half storeys could be built each week, demonstrating the efficiency of this technology. The diameter of the columns used in the building ranges from 900mm to 1600mm. Concrete was poured in from the top of the column. The concrete was vibrated to ensure the compaction. The SEG Plaza was the first application of circular concrete-filled steel tubes in super-high-rise buildings on such a large scale in China (Zhong 1999). This technology offers numerous new possibilities, such as new types of CFST column to steel beam connections, increased fire performance of CFST columns, etc.

In recent years, CFST columns with square and rectangular sections are also becoming popular in high-rise buildings. Figure 1.7 presents a high-rise building during construction using square and rectangular CFST columns, i.e. Wuhan International Securities Building (WISB) in Wuhan, China. The main structure is 249.2m high, and was completed in 2004.

The use of CFST in arch bridges reasonably exploits the advantages of such kind of structures (Han and Yang 2007, Zhou and Zhu 1997, Ding 2001). An important advantage of using CFST in arch bridges is that, during the stage of erection, the hollow steel tubes can serve as the formwork for casting the concrete, which can reduce construction cost. Furthermore, the composite arch can be erected without the aid of a temporary bridge due to the good stability of the steel tubular structure. The steel tubes can be filled with concrete to convert the system into a composite structure and capable of bearing the service load. Since the weight of the hollow steel tubes is comparatively small, relatively simple construction technology can be used for the erection. The popular methods being used include cantilever launching methods, and either horizontal or vertical "swing" methods, whereby each half-arch can be rotated horizontally into position (Zhou and Zhu 1997).

Figure 1.8 illustrates the process of an arch rib during construction. An elevation of the bridge after construction is shown in Figure 1.9. More than 100 bridges of this type have been constructed so far in China. There is much attention being paid both by researchers and the practising engineers to this kind of composite bridge.

Figure 1.2 CFST used in a workshop (Han 2007)

Figure 1.3 A subway station using CFST columns (under construction)

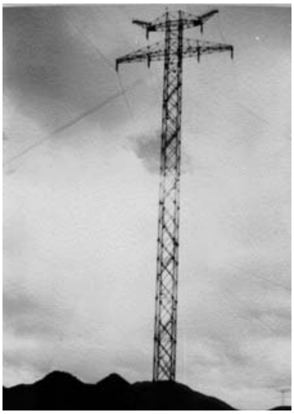
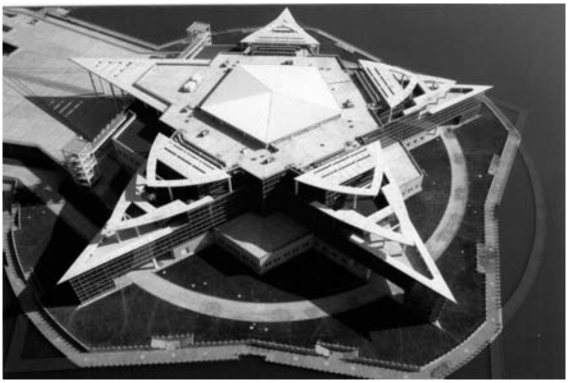


Figure 1.4 A transmitting pole with CFST legs (Han 2007)

(a) During construction

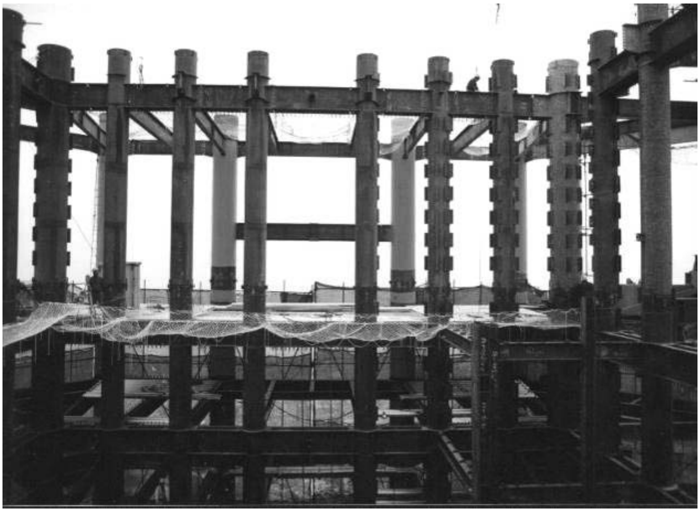


(b) After construction

Figure 1.5 CFST in spacious construction (Han and Yang 2007)

(a)

(b)



(c)

(d) (e)

Figure 1.6 SEG Plaza under construction (Han and Yang 2007)

(a)

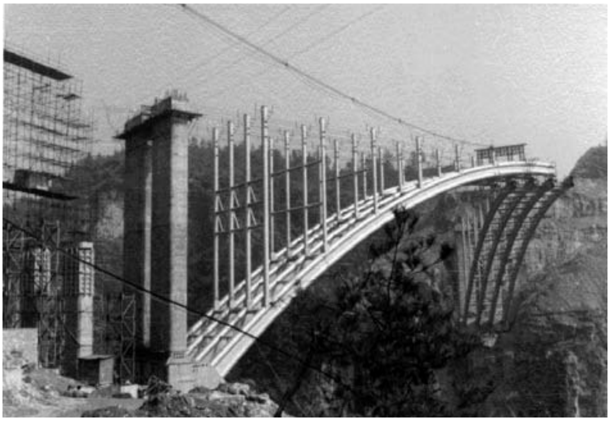
(b)

(c)

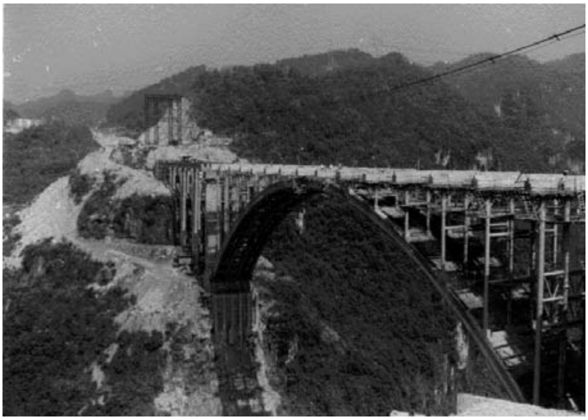
Figure 1.7 Wuhan International Securities Building under construction (Han and Yang 2004)

(a)

(b)



(c)



(d)

Figure 1.8 Elevations of the arch rib during construction (Han 2007)

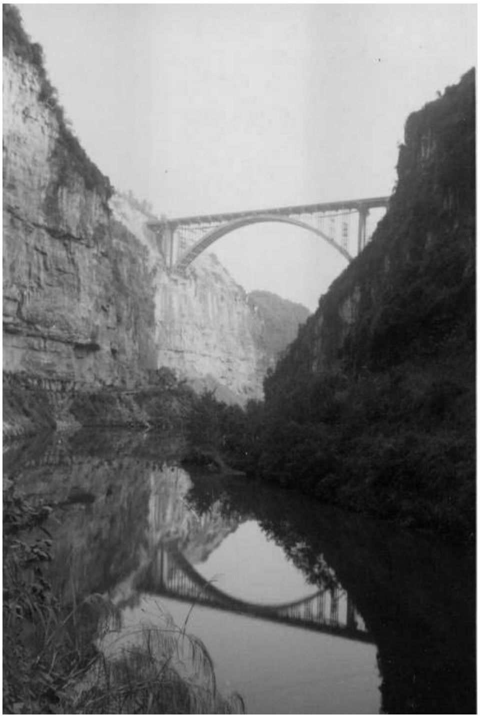


Figure 1.9 Elevation of the arch after being constructed (Han and Yang 2004)

1.2 ADVANTAGES OF CONCRETE-FILLED STEEL TUBES

It is well known that tubular sections have many advantages over conventional open sections, such as excellent strength properties (compression, bending and torsion), lower drag coefficients, less painting area, aesthetic merits and potential of void filling (Wardenier 2002).

Concrete-filled tubes involve the use of a steel tube that is then filled with concrete. This type of column has the advantage over other steel concrete composite columns, that during construction the steel tube provides permanent formwork to the concrete. The steel tube can also support a considerable amount of construction loads prior to the pumping of wet concrete, which results in quick and efficient construction. The steel tube provides confinement to the concrete core while the infill of concrete delays or eliminates local buckling of steel tubes. Compared with unfilled tubes, concrete-filled tubes demonstrate increased load-carrying capacity, ductility, energy absorption during earthquakes as well as increased fire resistance.

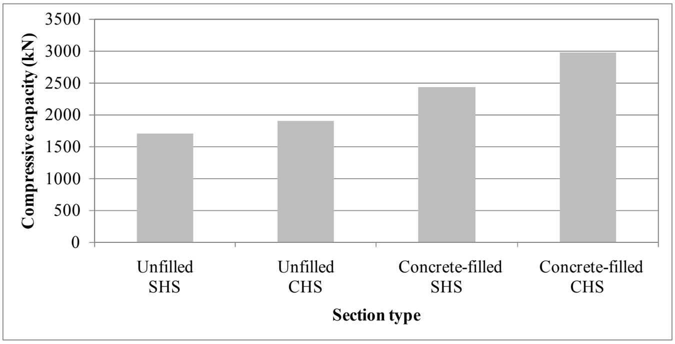
A simple comparison is given in Figure 1.10(a) for a column with an effective buckling length L_e of 5m, mass of steel section of 60kg/m and concrete core strength of 40MPa. It can be seen from Figure 1.10(a) that the compression capacity increases significantly due to concrete-filling.

Zhao and Grzebieta (1999) performed a series of tests on void-filled RHS subjected to pure bending. The increase in rotation angles at the ultimate moment due to the void filling was found to be 300%, as shown in Figure 1.10(b).

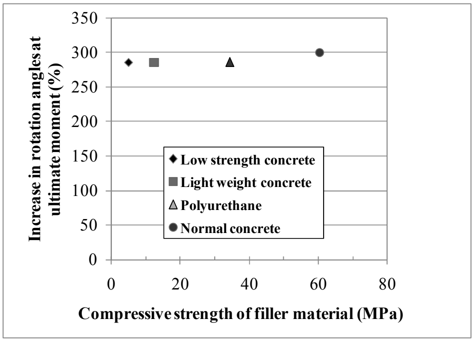
A schematic view of interaction diagrams for beam-columns is shown in Figure 1.10(c). It is clear that less reduction in moment capacity is found for CFST members. This is due to the favourable stress distribution in CFST in bending. More discussion on CFST beam-columns will be given in Chapter 5.

Zhao and Grzebieta (1999) also performed a series of tests on concrete-filled RHS subjected to large deformation cyclic bending. Typical failure modes are shown in Figure 1.10(d). For unfilled RHS beams, crack initiated at the corner and propagated across the section after several cycles. For concrete-filled RHS beams, either localised outward folding or uniform outward folding mechanism is formed without cracking.

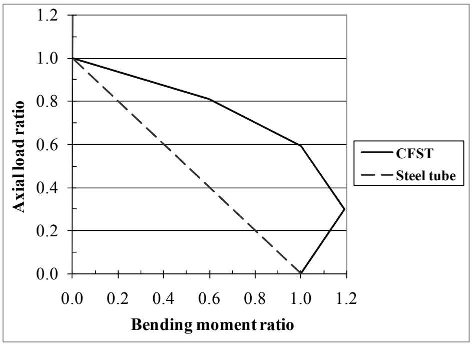
The fire resistance of unprotected RHS or CHS columns is normally found to be less than 30 minutes (Twilt *et al.* 1996). Figure 1.10(e) clearly shows that concrete-filling can significantly increase the fire resistance of tubular columns.



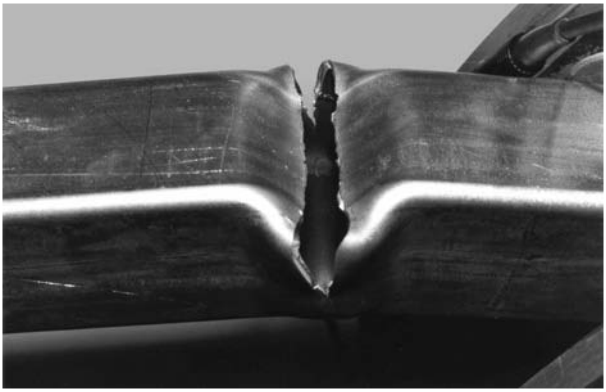
(a) For columns with L_e of 5m, mass of steel section of 60kg/m and concrete cubic strength of 40MPa



(b) Effect of concrete strength on ductility of CFST beams (adapted from Zhao and Grzebieta 1999)

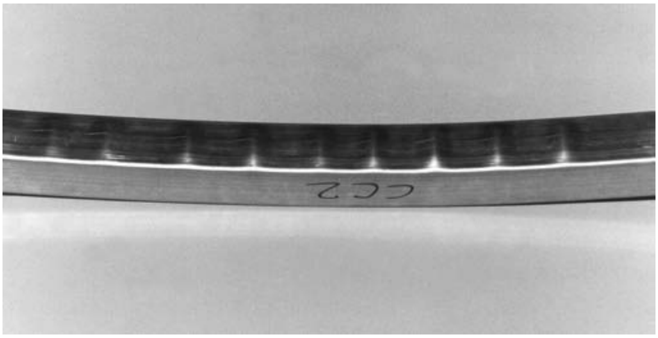


(c) Comparison of interaction diagrams (schematic view)



(i) Unfilled RHS – local (single inward folding) failure mechanism with cracking

(ii) RHS filled with low strength concrete – localised (single outward folding) mechanism without cracking



(iii) RHS filled with normal concrete – uniform (multiple outward folding) mechanism without cracking

(d) Comparison of cyclic behaviour (Zhao and Grzebieta 1999)