UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Doctoral Thesis

NUMERICAL ANALYSIS OF CONCRETE-FILLED TUBES WITH STIFFENING PLATES UNDER LARGE DEFORMATION AXIAL LOADING

PhD Student

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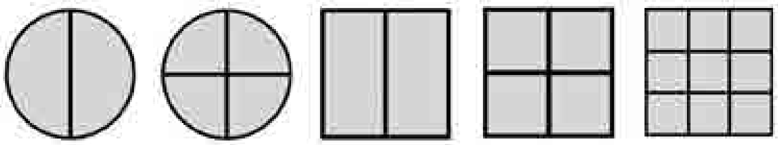
Directed by

Dr. Jordi Maristany Carreras



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Departament d'Estructures a l'Arquitectura
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A tu, Mireia

Als meus pares, Toni i Rosa Mª.

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PREFACE

In June 2009, the author of this investigation finished the Official Master of Technology in Architecture, specialized in Structural Design. This Master included a subject devoted to the initiation in structural design and research, coordinated by Professors R. Brufau Niubó, D. Garcia Carrera and J.R. Blasco Casanovas. During this course, the author carried out a final Dissertation about the effects of preloading concrete-filled tubes in high-rise construction.

This was the beginning of this line of research in composite structures, especially in concrete-filled tubes. The extraordinary structural behavior of these sections fascinated from the first moment the author of this study; few other structural fields do show such perspectives in building technology as tubular composite structures. During the preliminary investigations about the state-of-the-art, the author discovered how tubular construction, and especially composite tubular sections, was being increasingly used in emerging economies and other developed countries such as Singapore, Hong Kong or Japan. The fact that these sections were not widely used in Europe was also other incentive to start up this investigation with the final purpose of improving the typology and putting a bit in the process of structural optimization.

Thus, some of the most exciting motivations to carry out this study were: firstly, concrete-filled tubes constitute a current field of structural research in much other universities; secondly, this is a typology widely used these recent decades, especially in seismic areas; and finally, these sections are quite unknown not only in Spain, but also in Europe. Therefore, the author saw in this field the opportunity of increasing his knowledge about concrete and steel behaviors, contributing to the structural community at the same time.

The visit to the University of Hong Kong the summer of 2009 was the final confirmation that composite construction, especially concrete-filled tubes, was one of the spearheads of structural design in emerging countries. From then, this study was supported by the Department of Structures in Architecture of the Polytechnic University of Catalonia, and especially by the Department Head Professor, Dr. Jordi Maristany Carreras. The background of analyzing concrete-filled tubes has lead to generate the opportunity of getting used with the Finite Element Method, through such powerful tools as ANSYS or ABAQUS.

It is worth to admit that the author started this investigation in June 2009 with no idea of modeling, and with only basic knowledge about Theory of Classical Elasticity and constitutive behaviors of structural materials. From his point of view, the possibility of carrying out this work has been the unique and perfect excuse to acquire all this awareness. For this possibility, he wants to express all his gratitude to the Polytechnic University of Catalonia, and especially to the Department of Structures in Architecture.

AKNOWLEDGEMENTS

Firstly, I express my most honest gratitude to my Thesis Director,
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He has lived this Thesis as his own, by providing to me his valuable experience and patience.

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Secondly, I owe the origin of this work to
Dr. **ROBERT BRUFAU NIUBÓ, DAVID GARCIA CARRERA** and **JOAN RAMON BLASCO CASANOVAS**
for their encouragement to initiate this Doctoral Thesis from a Final Master Dissertation, dealing with concrete-filled tubes.
In general, they constitute one of the reasons why I am devoted to architectural structures.

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I am also very grateful to
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For his help in Theory of Classical Elasticity.

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Dr. FRANCISCO LÓPEZ ALMANSA
For his help in practical suggestions.

Dr. AGUSTÍ OBIOL SÁNCHEZ
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PUBLICATIONS

This study has motivated the presence in International Congresses:

14th INTERNATIONAL SYMPOSIUM ON TUBULAR STRUCTURES
"Concrete Filled Double Skin Asymmetric Tube Sections Subjected to Pure Bending"
11-14 September, 2012 in London [UK]
Organized by Leroy Gardner, Imperial College of London.

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SECOND INTERNATIONAL CONFERENCE STRUCTURES AND ARCHITECTURE
"Numerical Analysis of sliding rigid joints made from encased tubes for high-rise structures"
24-26 July 2013 in Guimaraes [Portugal]
Organized by Paulo J.S. Cruz, University of Minho.

And the following papers in reviews:

"Elogio de una nueva sección: a propósito de la optimización del tubo"
in the review INFORMES DE LA CONSTRUCCIÓN
accepted last December 2011.

INDEX

NOTATION

List of latin letters.

a_a, b_a, c_a	Scalar coefficients, steel
a_c, b_c, c_c	Scalar coefficients, concrete
a_1, a_2, a_3	Scalar coefficients.
A	Coefficient [Lamé]; Amplitude
A_0	Initial area
A_1, A_2, A_3, A_4, A_5	Scalar coefficients
A_a, A_c, A_s	Area of steel, concrete and reinforcements
A_{ac}	Area of the composite section
b	Width of a rectangular section
b_f	Width of the stiffening plate
b_i, c_i	Coefficients for material [*i*]
b_w	Width of the analyzed plate
B	Coefficient [Lamé]
c	Cohesion
$c_{i,0}$	Initial coefficient for material [*i*]
C_1, C_2, C_3, C_4	Scalar coefficients
d_c	Compressive damage ratio
d_t	Tensile damage ratio
D_r	Flexural rigidity of the shell
dy	Coefficient
d	Damage ratio
D	Diameter; Flexural rigidity of the shell
e	Scalar coefficient
E^{el}, E_0^{el}	Elastic Young Modulus; Intial elastic Young Modulus
E_a, E_a^t	Elastic Young Modulus, steel; Tangent Young Modulus, steel
E_c, E'_c	Elastic Young Modulus, concrete; Damaged Young Modulus, concrete
E_{cr}	Tangent modulus of elasticity of concrete in the lateral direction
E_i	Elastic Young Modulus, material [*i*]
f	Function; strength
f_{ac}	Maximum compressive strength, composite section
f_{b0}	Biaxial compressive strength of concrete
f_c, f_t	Maximum compressive strength, concrete; Maximum tensile strength, concrete
f_{cc}	Maximum confined strength of concrete
f_{ci}	Compressive strength of concrete at point [*i*]
$f_r, f_{r,eq}$	Lateral pressure; Lateral equivalent pressure

f_u	Ultimate stress, steel.
f_y	Yield limit stress, steel
f_{yd}, f_{cd}, f_{sd}	Maximum design strengths of steel, concrete and reinforcement steel.
f_{yk}, f_{ck}, f_{sk}	Maximum characteristic strengths of steel, concrete and reinforcement steel.
f'_c, f'_t	Maximum theoretical compressive strength, concrete; Maximum theoretical tensile strength, concrete
$f_{z,cc}$	Vertical confined strength, concrete
f_1, f_2	Forces
F	Applied load vector; Applied axial force.
F_{ri}	Reactions at the end of each element *i*
g	Flow potential function
$g(\sigma_{ij})$	Plastic potential function
G	Drucker Praguer hyperbolic function
H	Height
i	Increment number
I	Internal force vector
I_1,I_2,I_3	Invariants of stress tensor
J_1,J_2,J_3	Invariants of stress tensor
k	Yield stress in pure shear; constant [Drucker Praguer]; Coefficient [Attard]; Lateral stiffness
k_2	Coefficient [Zhong]
L, l	Column length
L_c	Constant value depending on material [2.2.8, del Viso]
L_E	Equivalent Length
L_i	Length of element [*i*]
L_{deformed}	Deformed length
L_{initial}	Initial length
m	Scalar coefficient [4.2, Richart], Undamaged elastic stiffness [2.2.7 CDP]
M	Diagonal lumped mass matrix
M_x, M_y	Bending moments in the [*x*],[*y*] axes
M_{xy}, M_{yx}	Twisting moments on [*x*] and to [*y*] axes
M_{xz}, M_{zx}	Twisting moments on [*x*] and to [*z*] axes
M_{yz}, M_{zy}	Twisting moments on [*y*] and to [*z*] axes
n	Scalar parameter
N_0	Axial Plastic Capacity of the section
N_{Ed}	Axial load applied
$N_{a,Ed}$, $N_{c,Ed}$	Axial load applied on steel tube, on concrete core.
$N_{pl,a}$	Maximum squash load, steel
$N_{pl,Rd}$	Plastic squash load

N_{cr}	Euler critical load
N_x, N_y, N_z	Axial force in the [*x*],[*y*],[*z*] axes
N_{xy}, N_{xy}	Tangential force parallel to [*y*] and to [*x*] axes
N_{xz}, N_{zx}	Tangential force parallel to [*z*] and to [*x*] axes
$N_{x,w}, N_{x,v}, N_{x,u}$	Component in the [w], [v] and [u] axes of force Nx
$N_{y,w}, N_{y,v}, N_{y,u}$	Component in the [w], [v] and [u] axes of force Ny
N_{yz}, N_{zy}	Tangential force parallel to [*z*] and to [*y*] axes
N'_y	Increment of N_y
p	Hydrostatic pressure
$\bar{p}, p_c$	Effective hydrostatic pressure; Contact pressure
p_{inn}, p_{out}	Inner pressure of the cylinder; Outer pressure of the cylinder
P_{Rd}	Shear force absorbed by one connector
q	Lateral pressure
$\bar{q}$	Mises equivalent effective stress
Q_x, Q_y	Transversal forces in the [*x*] and [*y*] axes
r	Radius; Inner radius; Proportional ratio [Popovics]; Radial axis; Circumferential coordinate system
r_c, r_a	Radius, inner radius, concrete, steel
r_{co}, r_{to}	Value in the π plane, corresponding to θ = 0º; Value in the π plane, corresponding to θ = 60º
R	Radius; Outer radius; Scalar parameter 1 [Saenz]; Coefficient for circular sections [Susantha]
R_c, R_a	Radius, outer radius, concrete, steel
R_t	Coefficient for square-shaped sections [Susantha]
$R_E, R_\varepsilon, R_\sigma$	Scalar parameters [4, Saenz]
s_1, s_2, s_3	Principal stress deviators
$\bar{S}$	Deviatoric part of the effective stress tensor
S_i	Area of element [*i*]
t	Wall-thickness; Time
t_f	Thickness of the analyzed plate
t_{inn}, t_{out}	Inner wall-thickness, outer wall-thickness
t_w	Thickness of the contiguous plate [stiffening plate]
u	Vertical displacements
$u, \dot{u}, \ddot{u}$	Displacement, velocity, acceleration
U	Total strain energy of the plate
U_i	Transversal displacement of element *i*
U_Γ	Energy associated to the elastic restriction against rotation
v	Circumferential displacements
V	Potential energy of the applied load

$V_{L,Ed}$	Shear force applied
V_{Rd}	Maximum shear force per column meter
$V_{sc,Rd}$	Shear force absorbed by connectors
w	Radial displacements
$w_{r,eq}$	Transversal equivalent strain
Z	Softening descending slope

List of greek letters.

α	Constant [Drucker Praguer]; Coefficient [Lubliner]; Residual stress [Susantha]
β	Strain tensor [Jankoviak]; Coefficient [Susantha]
Δ	Increment
ε	Strain
$\varepsilon_{el}, \varepsilon_{pl}$	Elastic strain; Plastic strain
$\varepsilon_i, \varepsilon_{cc}$	Strain in the coordinate [*i*]; Strain corresponding to the maximum confined stress
$\tilde{\varepsilon}^{pl}, \tilde{\varepsilon}_c^{pl}, \tilde{\varepsilon}_t^{pl}$	Hardening [softening] variable; Effective compressive plastic strain; Effective tensile plastic strain
$\varepsilon_{trans}, \varepsilon_{long}$	Transversal and longitudinal strains
$\varepsilon_r, \varepsilon_\Theta, \varepsilon_z$	Radial, circumferential, vertical strain
$\varepsilon_{r,c}, \varepsilon_{\Theta,c}, \varepsilon_{z,c}$	Radial, circumferential, vertical strain, concrete
$\varepsilon_{r,a}, \varepsilon_{\Theta,a}, \varepsilon_{z,a}$	Radial, circumferential, vertical strain, steel
ϵ_{ij}^p	Plastic strain tensor
$\tilde{\varepsilon}_t^{ck}, \tilde{\varepsilon}_c^{in}$	Stress-cracking strain in uniaxial tension; Stress-crushing strain in uniaxial compression
ϵ_v	Volumetric deformation
$\epsilon_1, \epsilon_2, \epsilon_3$	Strains in principal directions; axial and circumferential strains
ζ_r	Twisting stiffness
φ	Buckling coefficient [Zhong]
ϕ	Internal-friction angle
ϕ_1, ϕ_2, λ	Scalar coefficients
γ	Parameter [Lubliner]; Half wavelength
$\gamma_a, \gamma_c, \gamma_s$	Safety Factor for steel, concrete and reinforcements
γ_{cr}	Critical half wavelength
Θ	Angle
η_c	Coefficient of confinement, concrete, [Eurocode]
η_a	Coefficient of confinement, concrete, [Eurocode]
η_{co}, η_{ao}	Coefficients of confinement of concrete, [Eurocode]
θ	Circumferential axis, cylindrical coordinate system.
$\theta(\tilde{\varepsilon}^{pl})$	Function

λ	Positive scalar factor
$\bar{\lambda}$	Non-dimensional slenderness
μ	Friction coefficient; Scalar coefficient
ν_a	Elastic Poisson's coefficient, steel.
ν_a^t	Poisson's coefficient in the elastic-plastic range, steel.
ν_i	Poisson's coefficient of component *i*.
ν_c	Elastic Poisson's coefficient, concrete.
ν_e'	Apparent Poisson's ratio of concrete.
ξ	Vertical axis, cylindrical coordinate system.
ξ_0	Coefficient of contribution of steel [Zhong]
Π	Potential energy of a plate
ρ	Scalar coefficient ranging from 0.64 to 0.80; radius
$\sigma, \bar{\sigma}$	Cauchy stress tensor; Effective stress tensor
$\bar{\sigma}_c, \bar{\sigma}_t$	Effective compresive cohesion stress; Effective tensile cohesion stress
σ_{cr}	Critical stress
σ_E, σ_T	Engineering, true stress
σ_f	Fracture stress, steel.
σ_h	Ambient hydrostatic pressure
σ_i	Stress in the coordinate [*i*]
σ_{ij}	Stress tensor
$\bar{\sigma}_{max}$	Algebraically maximum eigenvalue of $\bar{\sigma}$
σ_{mises}	Von Mises stress
σ_{pl}	Plastic stress, proportionality limit.
σ_r	Stress in the radial direction
$\sigma_{r,i}, \sigma_{\theta,i}, \sigma_{z,i}$	Stress in the radial/circumferential/vertical direction, material *i*
$\sigma_{r,c}, \sigma_{\theta,c}, \sigma_{z,c}$	Stress in the radial/circumferential/vertical direction, concrete
$\sigma_{r,a}, \sigma_{\theta,a}, \sigma_{z,a}$	Stress in the radial/circumferential/vertical direction, steel
σ_u	Ultimate Stress, steel.
$\sigma_x, \sigma_y, \sigma_z$	Stresses in the [x], [y] and [z] axes.
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma_{1,cub}$	Principal vertical stress of the cubic specimen.
$\lvert\tau\rvert$	Limit shearing stress
τ_{oct}	Octahedral stress
τ_{Rd}	Maximum tangential stress absorbed
τ_{xy}	Tangential stress
χ	Coefficient of elastic restraint; Buckling coefficient, [Eurocode]
χ_x	Change of curvature

Chapter I

INTRODUCTION

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This investigation is devoted to the study of concrete-filled tubes. The origin of this investigation comes from the interest of the engineering community about the extraordinary mechanical capacities of these sections.

Thus, a short introduction of the introduction of composite columns in architecture is shown in this Chapter. This short presentation is especially focused on concrete-filled tubes and their importance in the construction of some recent tall buildings in seismic areas.

Apart from this historical approach, also the objectives and the background of this work are presented in Sections 1.4 and 1.5.

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Chapter I

INTRODUCTION

1.1 Tubular construction in Architecture.

The evolution of structural typologies has been a process based on optimization, from several points of view: optimization referred to geometry, to material behaviors and to sectional typology, with the final purpose of going further in structural efficiency. In the beginning of architecture, the form was subjected to the structural response in order to make the maximum profit of materials. Centuries later, with the initiation of the Industrial Revolution, new materials appeared, and an unprecedented extraordinary progress of structural optimization started. This progress entailed an important advance in terms of sectional performance; each advance in structural optimization has been converted into new architectural challenges.

Tubular sections has been used relatively late in architectural designs, may be owing to its predominant industrial use or due to the inherent complexity of the execution of joints. These sections have been relegated from the sectional repertoire despite their extraordinary qualities.

The use of tubular sections starts with cast iron columns in the origins of the material; buildings such as Cristal Palace incorporate repeatedly this typology of closed sections. Renowned designers such as Violet le Duc predicted their extraordinary response under compression, with the objective of solving problems of contemporary complexity [Fig. I.1]. Although the advantages provided by tubular sections had been already considered for singular buildings, the industry was reluctant to replace the common I or H-shaped profiles for building purposes.

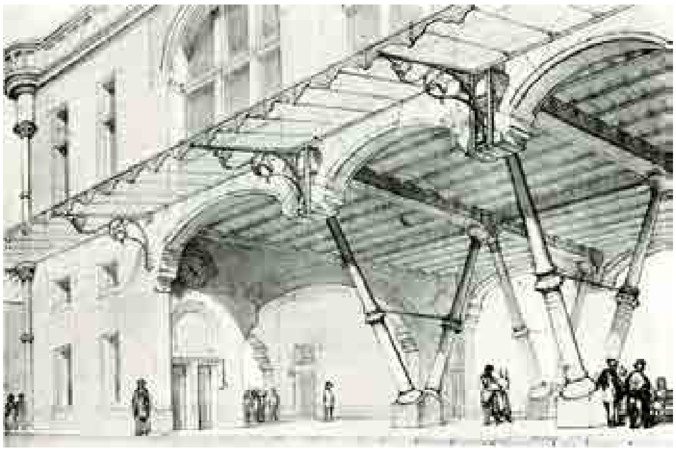

Fig. I.1 Sketch done by Violet-le-Duc.
First applications of tubular sections in columns.

All these initial applications were always made of cast iron profiles. The steel was not fabricated until much time later, and this is basically the reason why first tubular sections worked only under pure compression forces. The explicit use of tubular profiles for civil works was proposed seriously for the first time 150 years ago, in two renowned railway bridges: the *"Britannia Railway Bridge"* and the *"Saltash Railway Bridge"*. From this moment, these sections were slowly widespread for industrial uses, and between the years 1882 and 1890 a large civil work, made entirely with rivets, was built for the first time: the well-known bridge *"Firth of Forth"* in the Scottish city of Edinburgh [Fig. I.2]. The bridge became a reference in civil engineering and it established the precedents for the divulgation of a new sectional typology, with which H-shaped sections could not compete in terms of efficiency.

Fig. I.2 ***Firth of Forth*** **bridge, Edinburgh.**
It was the first civil entirely built with tubular sections.

The following step in the generalization of tubular sections–this time decisive- was carried out by Alexander Graham Bell, who built for the first time a three-dimensional mesh for aeronautic purposes. This mesh was formed by a collection of independent steel tubular bars, which few time later was progressively introduced in civil structures. This one is considered the first three-dimensional mesh, built in history, thought from the beginning with tubular elements. In the forties, tubular sections were widely used, especially in those three-dimensional structures; in 1942, Max Mangeringhausen proposed the first three-dimensional mesh formed by a collection of tubular bars, totally hinged at their nodes. From that moment, the use of tubular sections for light structures was really widespread.

The appearance of CIDECT[1] made possible a divulgation process about the extraordinary advantages of these sections. Thanks to this organization, tubes were fully implemented in the architecture of the XXth Century. A decisive factor in this expansion was the introduction of concrete within, by converting steel structures into composite, with a quite higher structural performance.

1.2 Concrete-filled tubes in Architecture.

Similar to the case of tubular sections, the concept of "*composite section*" applied to columns -where the steel tube and concrete filling work together- did not appear until the mid XXth Century. The first time that steel profiles were embedded in concrete of columns of tall buildings in the United States, was only for fire protection purpose; buildings like the *Seagram* of Mies van der Rohe in New York does not consider the compressive strength of concrete in the axial response of their columns [Fig. I.3]. In 1969, Fazlur R. Kahn proposed for the first time a building formed by composite columns strictly, where the concrete strength was considered together with that of steel. The appearance of the concept "*composite section*" for heavily loaded columns in architecture had a similar impact to the introduction of reinforced concrete at the end of the XIXth century.

[1] Comité International pour le Développement et l'Etude de la Construction Tubulaire.

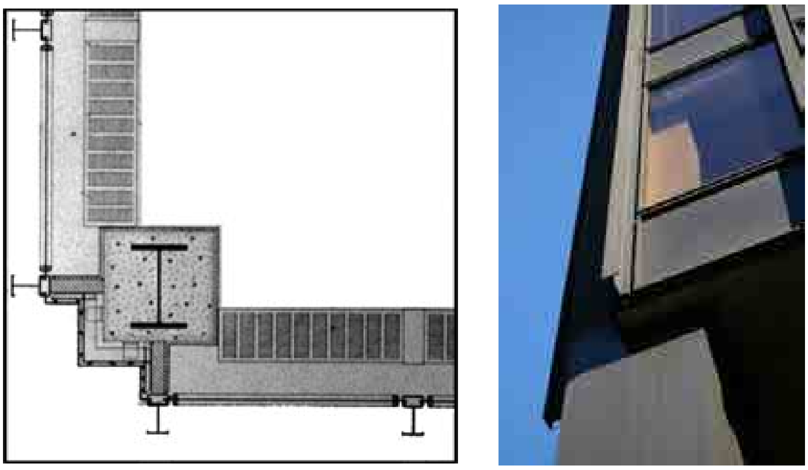

Fig. I.3 Detail of composite columns in the *Seagram* building, Mies van der Rohe.
Concrete here was only considered for fire protection, picture from (Diego Caballero, 2008)

Most part of the tallest buildings which have been built these recent decades would not have been possible without the use of composite slabs and, especially, the use of composite columns. The concrete provides to steel a set of extraordinary qualities referring to energy absorption and fire protection that otherwise, would be very difficult to achieve strictly with steel. The concept of "*composite column*" has evolved from a simple H-shape profile embedded in concrete [cases **"a"** to "**c**" in figure I.4], up to the reinforced "*supercolumns"* with embedded profiles of the Bank of China, a work of I.M. Pei in the city of Hong Kong. Their use has been clearly widespread as a consequence of the increasing need of tall buildings in seismic areas. In these cases, the capacity of absorbing energy, together with an extended ductility and an improved strength, constitute a set of necessary requirements for this kind of buildings. Different typologies of composite columns are summarized in the following figure I.4[2]:

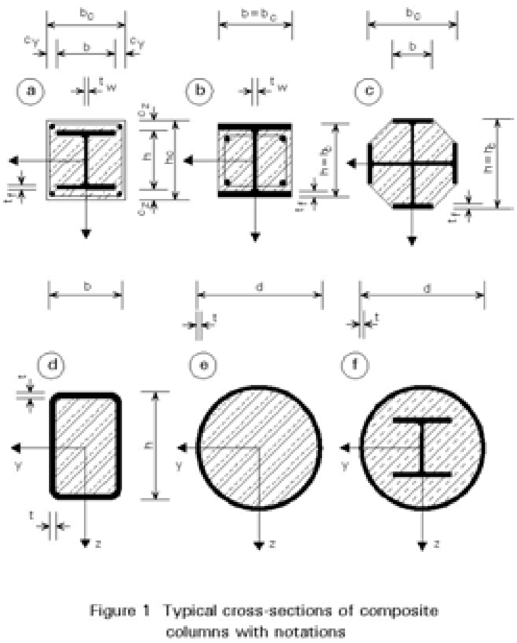

Fig. I.4 Different typologies of composite sections used for columns.
The first three are embedded H-shaped sections, and the second three are concrete-filled tubes.

[2] Sections described by the EC-4, Eurocode 4 (ENV1994-1-1, 1990).

Different from the case of H-shaped embedded profiles is the case of CFT sections[3] [those sections made of steel tubes, and filled with concrete]. The unknowns about their behavior –some of them not well described until these recent years- delayed the implementation of these sections worldwide, up to the second half of the XXth Century. AG Tarics of Reid & Tarics Associates designed for the first time in 1972 an entire building formed by concrete-filled tubes in the city center of Seattle: the *Two Union Square Building*. During the following decades, it was demonstrated that the intuition of Tarics of Reid was in the right direction: the confined concrete of the core in CFT sections do show an excellent faculty of energy absorption, for instance that energy coming from seismic loading. This is the reason why these sections have become really useful for structural designs in seismic areas.

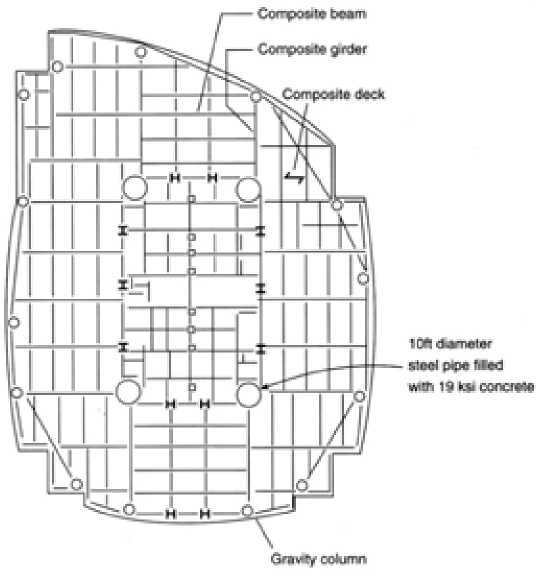

Fig. I.5 General plan and view of Two Union Square Building, Seattle.
First building thought entirely using CFT sections, AG Tarics of Reid & Reid Associates, picture from (Bertolet, 2008)

This typology predicts lots of possibilities, and it has not been still fully exploited. The fact of combining the two materials –a usual fact in composite sections- not only allows making the best of their resistant qualities, but also to enhance them notably. The fact of filling the steel tubes converts these sections into a perfect symbiosis between the two materials, by optimizing their performance. From the erection of the Two Union Square Building, most application codes worldwide have been adding CFT sections in their pages, by proposing different simplified design methods. The first code which incorporated them was the Japanese AIJ Standards, but all the rest did the same progressively later from different points of view.

Such is the complexity of the behavior of these sections and many their qualities, that lots of different current lines of research exist worldwide, devoted to their analysis. The American and Chinese structural designers, after the Japanese, are the more interested in their application for evident reasons of seismicity of the respective regions. Clear examples are those constituted by tall buildings entirely supported by CFT sections, existing in San Francisco, Hong Kong, Canton and Beijing. Especially notorious is the case of the Cheung Kong Center, a 283-meter-tall building in

[3] CFT: Concrete-filled Tubes.

Hong Kong, made of a combination of concrete-filled tubes along the perimeter and a massive central concrete core. This was one of the first examples -raised in 1999, by hands of Cesar Pelli- of the new high-rise buildings arising in Asia, exhibiting all the capabilities of concrete-filled tubes.

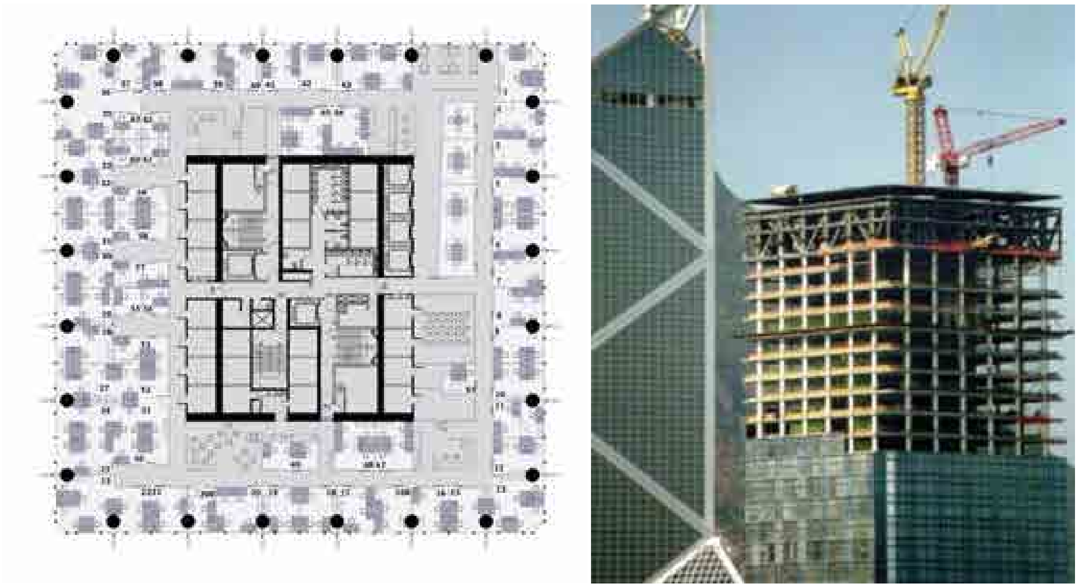

Fig. I.6 General plan and construction phase view, Cheung Kong Center in Hong Kong.
A full CFT-raised building in the city center of Hong Kong, pictures from (Wong, 2003) and (Hutchison Whampoa, 1998)

The Cheung Kong Center demonstrated to the world the functionality and effectiveness of concrete-filled tubes, since this typology allowed implementing a new high-rise construction method. In the following figures shown below, it can be seen how the workers fell into place the tubes which were injected of concrete subsequently. The construction method is really fast, as no formwork for columns is needed; besides, the tubes arrive in the worksite almost ready for being assembled.

Fig. I.7 Detailed view of a CFT column and the assembling process.
The Cheung Kong Center is the maximum exponent of the high-rise construction method.
Original photographs of Raymond Wong, (Wong, 2003).

Thanks to the knowledge acquired through several decades by Japanese engineers referring to concrete-filled tubes, they have always been the leaders in implementing new challenges by using this typology. One spectacular case is the well-known Pacific Century Place Morunouchi in the city center of Tokyo. It consists of four giant CFT columns of 55 meters tall and 3.4 meters diameter that supports an administrative building over the public space; never before CFT sections of this caliber were used in any other civil or architectonical structure. The main reason why concrete-filled tubes were proposed in this case was their improved resistance in front of dynamic loading -really frequent in this area. A building like this tends to amplify the effects of the earthquakes, since the entire load is located at a height of 55 meters.

Fig. I.8 General view of Pacific Century Place Morunouchi, in Tokyo.
First structure erected using four giant CFT columns of 3.4 m. diameter.

Much later than the Americans or Japanese, the Europeans discovered also the capabilities of composite sections although Europe is not especially a seismic area. Some of the tall buildings existing in the financial centers of big cities have been built also using CFT sections. One of the most known and celebrated case was the Commerzbank Building in Frankfurt, a work of Sir Norman Foster & Partners; its structure does not only make profit of concrete-filled tubes for structural purposes, but also for innovating in sectional shapes and typologies. This structure is formed by a set of innovative triangular-shaped tubes, filled with concrete and with a massive steel core inside [see figure I.9].

Fig. I.9 Images corresponding to the Commerzbank Building, Frankfurt [Germany]
This is an example of the European contribution to CFT application and development.

As it has been said before, needless to say that China is the current worldwide leader referring to high-rise structures, and the use of concrete-filled tubes. The fast metamorphosis of the Chinese economy implies the implementation of a high-rise building typology which allows the erection of any kind of structures in the speediest way as possible. The leadership in the application of CFT sections is not only based on architectonical buildings, but also in other civil structures. Two of the most representative examples of civil constructions are the Xisha Bridge in Chongquing, and the Canton Tower in Guangzhou [Figs. I.10, I.11]. Both structures use large diameter tubes -all them filled with concrete- in order to resist heavy compressive and dynamic loads. Thus, the spreading of tubular composite sections in all kinds of structures is more a present than a future trend.

Fig. I.10 Xisha Bridge, made with CFT sections, Chongquing [China].
Concrete-filled tubes are not only used as columns.

Fig. I.11 Canton Tower, entirely made of concrete-filled tubes.
Architects, Hemel+Kuit; consultant engineers, Arup, (Arup, 2011)

1.3 Object.

Concrete-filled tubes are increasingly used, owing to their improved response under combined states. As it has been mentioned in the previous Section, concrete and steel of these sections not only work as two independent components as in other composite sections, but also they enhance their mechanical qualities. Concrete filling inside the tube becomes severely confined, and this fact involves a considerably gain in compressive strength. This phenomenon leads to an excellent axial response, especially for columns of tall buildings subjected to high compressive loads (Uy, et al., 1996); besides, this confinement effect on the core clearly delays the degradation through crushing of concrete, and this is basically the reason why these sections show usually significant ratios of ductility.

Furthermore, their load-bearing capacity -even in states where the concrete filling is completely crushed- makes these sections really useful for structures in seismic regions (Hajjar, 2000). Under severe dynamic loading, the concrete of the core starts degrading with almost no loss of axial strength (Xiao, et al., 2003). This quality -together with its extraordinary compressive strength- has given a decisive role to those structures made with CFT sections in the recent decades, and several researchers have been interested in their complex behavior.

The qualities of CFT sections are not only mechanical; the current need of new high-rise buildings in the emerging economies -often close to seismic areas- implies considering some alternatives to the traditional formwork for concrete elements (Uy, 1998). This way, CFT sections avoid any type of provisional structures for concreting, since the steel tube already plays this role.

1.3.1 The description

Concrete strength and ductility is notably enhanced in CFT sections, owing to the confinement effect provided by the tube. In circular sections, this confinement is uniform on the entire core; contrary, in rectangular and square concrete-filled tubes, the slenderness of the plates clearly limits its effectiveness. This is the reason why most application codes do not consider the effect of confinement in rectangular sections, while in circular sections some of they do it [see Section 1.5.1].

Then, the confinement effect on concrete core is directly related to the tensile capacity of the outer tube, thanks to the strength of steel and its wall-thickness. The size of the section, especially in rectangular and square-shaped sections, plays a decisive role in the final compressive strength. Furthermore, a low hydrostatic state promotes a faster degradation of the cohesive material actively, owing to crushing [see Chapter V].

1.3.2 The hypothesis.

The hypothesis presented in this investigation is based on arguing that the introduction of stiffening plates in the core may have a determining influence on the confinement effect and the ductility of CFT sections, especially in those square-shaped ones. This influence would come from the increment of rigidity of the tube provided by these extra plates; besides, the reduction of the cell size which contains the concrete filling, could also improve the general ductility ratio of the section.

Thus, this work is entirely devoted to describe the axial compressive response and possible advantages of introducing these mentioned stiffening plates in concrete filling. This hypothesis is not exactly a new proposal, since several Japanese authors have been carrying out some studies related with stiffened concrete-filled tubes previously [as it will be widely explained in Chapter II]. This investigation pretends to be a continuation of their contributions, providing a full description of the behavior and some simplified design criteria.

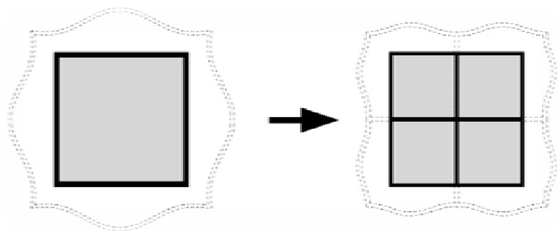

Fig. I.12 The hypothesis proposed is based on the influence of stiffening plates on CFT sections.
Stiffening plates reduce the deformability of the tube, improving the confinement effect.

As it will be demonstrated in Chapters VI and VII, this hypothesis works perfectly well for the case of square-shaped CFT sections, but it is not exactly accurate for circular sections. It will be shown how the circular shape is really more effective than the cruciform, in terms of confinement effect of the core and ductility.

1.3.3 The purpose.

The final purpose of this investigation is to give a new point of view about concrete-filled tubes. The study is focused on large deformation axial loading, since this way it is possible to have a clear image of the ductility and the capacity of absorbing energy of these sections.

Thus, the spirit of this work is to introduce in architectural design a new sectional typology, which is derived from CFT sections, few studied until our days. The advance of this typology is online with the progress of structural optimization, mentioned in Sections 1.1 and 1.2: the idea is always to make more profit of materials with the minimal area as possible. With this premise, there is no doubt that concrete-filled tubes, especially those stiffened with plates, have something to say.

Thus, this work is oriented to describe the behavior of reticulated concrete-filled tubes. The willingness of this study is not specifically the obtaining of universal expressions in order to calculate their axial squash load, but to illustrate the compressive response and behavior of these sections until the final collapse.

1.4 Objectives of the study.

Although this study starts up with a clear hypothesis to describe and validate, it is obvious that this is only the final purpose, but not the unique.

1.4.1 General objectives.

General objectives of this investigation are:

- To understand the large deformation axial loading of CFT sections.
- To describe the influence of introducing stiffening plates on the CFT compressive response.
- To be capable of using powerful tools of numerical analysis, such as ANSYS or ABAQUS.
- To acquire specific knowledge referring to constitutive models of concrete and steel, and the interaction between them.

1.4.2 Objectives referring to the analytical approach.

Although in most cases a manual approach is not sufficient to describe the behavior of CFT sections, some especial cases can be simplified and considered analytically. In Chapter III, the analysis of a circular CFT section under compression is presented, by using the Theory of Classical Elasticity. In addition, a complementary elastic buckling analysis of circular and square tubes of concrete-filled tube sections is also presented. Main objectives of all these analytical approaches are the following:

- To understand the analytical basis of the proposed expression for the *squash load,* provided by the Eurocode 4. It is crucial to relate the experimental results with those coming from the Theory of Classical Elasticity, in order to be capable of comprehending the compressive behavior of these sections [see Chapter III].
- To incorporate the simplified constitutive laws of concrete and steel in the analysis, in order to validate the analytical model. Although material behaviors will be reproduced later with their entire complexity in the FE models, several uniaxial approaches can be easily used for simplified analyses –also presented in Chapter III.
- To validate numerical results, presented later. To carry out an analytical approach, previous to the entire FE analysis, is really useful for this investigation; this way, the evolution of components can be controlled accurately, and results obtained become more contrasted.
- To know and detect the modes of buckling and critical loads of both circular and square CFT typologies. Although most part of the specimens have been considered expressly thick-walled in order to avoid second-order effects, it is strictly necessary to know the mode of buckling of these plates and shells in the course of an investigation of these characteristics.

1.4.3 Objectives referring to the FE model

Main objective referring to the finite element model is to develop a robust, three-dimensional and continuum model, capable of reproducing the behavior of composite sections formed by concrete and steel. Other derived objectives of the FE model are the following:

- To calibrate a constitutive material model for concrete, capable of simulating the complexity of its plastic behavior and the volumetric expansion under high hydrostatic pressures. Main objective is to achieve the enhancement of the compressive strength of the material under confinement [see Chapters II-IV].
- To compare the values obtained by using an elastic perfectly-plastic model for concrete, with those coming from a damaged plasticity model. Differences can be explicit, but it is really interesting to see the relation between the two constitutive models [see Chapters II-IV].
- To determine the properties of the contact governing the interaction between steel and concrete in composite sections. Depending on the way of loading, contact of the interface is crucial in order to transfer loads from steel to the core [see Chapter IV].
- To calibrate a sufficiently fine mesh to be capable of reproducing the behavior of thin-walled plates in concrete-filled tubes, by considering second-order effects. Element size must be enough fine to consider also buckling effects [see Chapters III and IV].
- To determine the way of loading of CFT sections, in order to achieve the convergence of the analysis. By reaching the collapse of the sections, most part of the loading process belongs to plasticity, where for small loads large strain increments take place.

1.4.4 Objectives referring to the compressive behavior of concrete-filled tubes.

Thanks to the need of modeling the compressive behavior of reticulated CFT sections, in order to analyze the central hypothesis of this investigation, some objectives focused on the description of the compressive behavior of CFT sections, have been imposed too. Some of these derived objectives are the following:

- To describe the relation between the softening behavior of concrete and the rigidity of the steel tube. The thickness, the diameter and the strength of the steel tube are some of the variables which determine the percentage of stiffness degradation of the concrete core [see Chapters IV and V].
- To describe the evolution of the confinement effect on concrete core and its influence on its axial strength. Concrete subjected to high hydrostatic stress states improves its maximum compressive strength; this confinement depends on the shape and rigidity of the steel tube [see Chapter V].
- To describe the evolution of vertical and hoop stresses of the steel tube in CFT sections. There is a clear relation between the confinement effect on the core and the distribution of the stress components in the tube [see Chapter V].
- To determine and describe the evolution of the stiffness degradation of concrete core, and to compare the evolution of damage ratio with the evolution of vertical stress. The concrete contained in a recipient can resist compressive forces even being completely damaged [see Chapter V].
- To describe the ductility of CFT sections, by means of reaching their collapse. Circular sections are much more ductile than those square-shaped, thanks to the rigidity of the annular shape [see Chapter V].

- To compare effectiveness of confinement and ductility between circular and rectangular CFT sections. Not only the confinement effect is much softer in rectangular sections; ductility is also clearly lower, since the collapse of these sections occurs always earlier.

1.4.5 Objectives referring to the influence of stiffening plates.

Obviously, the main objective of this investigation is to determine the influence of introducing stiffening plates in CFT sections, on the large deformation axial loading response of these sections. Thus, the objectives referring to validate this initial hypothesis are the following:

- To determine and describe the effect on confinement effect of introducing these extra plates in CFT sections. The purpose of this investigation is more oriented to describe the pattern of confinement of each typology, than providing specific values or design laws [see Chapters VI and VII].
- To determine the effect on ductility of those mentioned stiffening plates. Since the analysis is focused on large deformation axial loading, the specimens are compressed until the collapse. An enhancement of ductility is clearly traduced into energy absorption or energy of fracture; this property becomes extraordinarily useful for seismic designs [see Chapters VI and VII].
- To describe the existing differences between the influences provided by stiffening plates in circular and square-shaped sections. The effects of these plates in the second group are not the same than in the first group [see Chapter VII].
- To describe the restriction to buckling of the embedded plates in the core. Plates located inside the core are supposed to be restricted to buckling, but this restriction may depend on some variables [see Chapter VII].
- And finally, to provide some simplified design criteria for each specific typology, in order to facilitate their use as columns of tall buildings.

1.5 Background.

As it has been explained in Section 1.2, from the mid XXth century, concrete-filled tubes have been spreading worldwide due to their inherent mechanical and practical advantages. This generalization has involved an increasing interest in their behavior and their improvement for specific civil and architectural applications; this is the reason why most important application codes and several engineering universities have been implemented these sections in the list of their priorities these past decades. This investigation includes the contributions of most part of these researchers, starting by taking into account the accepted criteria by different civil and structural applicative codes.

1.5.1 Application codes of reference.

The majority of the important application codes worldwide include one specific chapter devoted to concrete-filled tubes in their pages. This fact is derived from the importance that these sections have in the conception of tall buildings in seismic areas, such as Hong Kong or Singapore.

The first code which incorporated CFT sections was the Japanese AIJ Standards, published in the year 1967; it was based on the research carried out during the sixties by different engineers. This first edition considered already three different sectional typologies: concrete-filled tubes, composite sections with embedded tubes and composite sections with embedded profiles. This instruction was revised in 1980 and was absorbed by the SRC [AIJ Standard for composite and steel sections].

Several years later, in 2001, a new version of *AIJ Standards* was published, much more complete than the previous one: 60MPa concrete was also considered for the filling and the essential parts of the design process were completely revised. All these revisions were made according to the content of the *CFT Recommendations*, published by the same Japanese Institute in the year 1997, according to Morino and Tsuda (Morino, et al., 2003). The expression proposed by the *SRC AIJ Standards* to calculate the maximum compressive strength of a composite section is the following:

$$N_{pl,Rd} = N_{pl,c,Rd} + (1 + \eta) \cdot N_{pl,a,Rd} \quad [SRC\ AIJ] \qquad \textbf{(1.1)}$$

being $N_{pl,c,Rd}$ and $N_{pl,a,Rd}$ the axial load capacity of concrete and steel respectively, and η a coefficient ranging from 0, for rectangular sections, to 0.27 for circular tubes.

The following code to introduce concrete-filled tubes was the American ACI; before the year 1986, the unique requirements existing for the design of CFT tubes in America could be found in the ACI code, devoted to concrete behavior. In 1986 it was published the AISC-LRFD[4] referring to steel structures, and then two different codes were coexisting for a period, with slight different criteria for calculating these sections. While the ACI code established the analysis of concrete-filled tubes using the same method as for reinforced concrete sections, the LRFD proposed their calculation by comparing the procedure to the one used for steel. The second instruction proposed a minimum of 4% of reinforcing steel in the concrete core, while the first allowed considering CFT sections made of plain concrete.

In 2005, the AISC published a new code, the AISC360-05, which pretended to replace and combine the ancient LRFD *Load and Resistant Factor Design Specification for Structural Steel Buildings* [of December, 1999] and the *Specification for Structural Steel Buildings-Allowable Stress Design and Plastic Design* [june of 1989] including also the *Load and Resistance Factor Design Specification for the Design of the Steel Hollow Structural Sections* [published on November of the year 2000], and specific for CFT sections, (Berge, 1998).

According to the AISC360-05, the maximum compressive load of a CFT section is:

$$N_{pl,Rd} = A_a \cdot f_{yd} + A_s \cdot f_{sd} + C_2 \cdot A_c \cdot f_c \quad [\text{AISC360\_05}] \qquad \textbf{(1.2)}$$

being C_2 = 0,85 for rectangular sections, and C_2 = 0,95 for circular sections.

After the Japanese and the American instructions, come the Eurocodes. Before the year 1994, no instructions referring to CFT sections existed in Europe. With the appearance of the Eurocodes, the European Commission for Standardization decided to incorporate a special Eurocode [Eurocode 4] devoted to composite sections, including also concrete-filled tubes. Previously to the Eurocodes, sixty-two pre-standards [ENVs] were published between 1992 and 1998, and it was in this last year when all these application codes were finally converted to the final renown Standards.

After the Japanese Standards, the Eurocodes provide the most complete and accurate calculation method in order to design CFT sections for architectonical and civil structures. The expression

[4] Load and Resistant Factor Design

proposed by EC-4 (ENV1994-1-1, 1990) to obtain the maximum compressive load of a composite section is:

$$N_{pl,Rd} = \eta_a A_a f_{yd} + A_s f_{sd} + A_c f_{cd} \left[1 + \eta_c \frac{t}{d} \frac{f_y}{f_{ck}}\right] \quad [EC4] \tag{1.3}$$

being η_c = 4.9 and η_a = 0.75 for non-slender columns. This simplified method of the Eurocode 4 will be detailed in Section 2.3.2.1.

Due to the importance of composite sections in the erection of the new skylines of China, the Chinese Standards have also implemented CFT sections in their pages (Weng, et al., 2002). In China, there are three different codes which refer to composite sections: the CHN-JCJ 01-89, the CHN-CECS [28:90 and 159:2004] and the CHN-DL/T 5085. The first one was published by the *National Chinese Office of Industry and Structural Materials*; the second one, by the *Chinese Association for Standardization of Construction Engineering* and the last one, by the *National Chinese Commission of Economics.* It is worth to mention also the GJB4142-2000 code [*Technical specifications for early-strength model composite structure used for navy port emergency repair in wartime*] referring to CFT sections specifically.

The most relevant Chinese Standard for calculating CFT sections is the CHN-CECS, which can be divided into two parts, the 28:90 [*Specification for design and construction of concrete-filled steel tubular structures*] and the 159:2004 *[Technical Specification for Structures with Concrete-filled Rectangular Steel tube Members*]. These two Standards provide practical simplified methods to obtain the maximum compressive load of CFT sections, in a similar way to the Japanese or American methods:

$$N_{pl,Rd} = f_{cd} \cdot A_c \cdot \left(1 + \sqrt{\theta} + \theta\right) \quad [CECS\ 28{:}90] \tag{1.4}$$

where $\theta = f_{yd} \cdot A_a / f_{cd} \cdot A_c$

$$N_{pl,Rd} = f_{yd} \cdot A_a + f_{cd} \cdot A_c \qquad [CECS\ 159{:}2004] \tag{2.5}$$

It is evident that the 28:90 takes the confinement effect into account and that the 159:2004 does not consider these effects on strength. This is because the first one refers to circular CFT sections, while the latter refers to rectangular ones. It is worth quoting that the mentioned Standard CHN-DL/T 5085 is much more accurate than the other two, but at the same time it is much less practical; its simplified method is based on the Unified Theory proposed by Zhong (Zhong, et al., 1998) for predicting the complex behavior of CFT sections [see Section 2.3.2.2].

There are also other remarkable instructions, derived from the four mentioned and referring to composite sections, such as the Canadian Standards CAN/CSA-S16-09. This code establishes a similar expression to get the maximum compressive load, with some particularities:

$$N_{pl,Rd} = \beta_a \cdot \phi_a \cdot A_a \cdot f_{yd} + \beta_c \cdot 0{,}85 \cdot \phi_c \cdot A_c \cdot f_{cd} \tag{1.6}$$

where β_a and β_c are confinement coefficients, with a value of 1 for rectangular sections. Coefficients ϕ_a and ϕ_c are parameters of reduction of strength for steel and concrete.

1.5.2 Existing groups of research about concrete-filled tubes.

Derived from the increasing interest on the behavior of CFT sections, several researchers have been carrying out different lines of investigation during these recent decades. This research has been focused especially on those places where seismicity is more decisive.

On the one hand, there is the Japanese School through the Architectural Institute of Japan [AIJ]: they have been focused on studying the confinement effect of concrete-filled tubes and on improving the capacities of this typology; Japanese researchers have been interested from the first moment in the improved strength shown by concrete of CFT sections, by thinking also in their applications for bridge piers. Researchers such as Uenaka (Uenaka, et al., 2012), together with Yamao (Yamao, et al., 2002) have specially innovated, by proposing CFDST sections[5], those sections formed by two tubes [outer and inner], and filled with concrete between them.

On the other hand, there is the American front formed by the ASCE[6] and some leading universities. The first group composes the main part of the investigation carried out in the USA in these recent decades, with engineers such as Schneider (Schneider, 1998); and the latter group is formed by individual researchers who have been investigating about confinement of concrete during entire decades, such as Elremaily (Elremaily, et al., 2002), from the University of Nebraska-Lincoln.

Also Australia has become a worldwide reference center referring to composite columns, especially thanks to O'Shea and Bridge (O'Shea, et al., 2000) from the University of Sydney. These two researchers have devoted their efforts to test and analyze circular CFT sections, especially thin-walled. Also the Monash University [Victoria] has played an important role in the projection of CFT sections from Australia; engineers like Elchalakani (Elchalakani, et al., 2002) have carried out lots of experimental tests under compression and bending. The advances coming from Australia to the knowledge of CFT sections have contributed to the erection of the new skylines of Sydney and Melbourne.

As in many other scientific fields, China has also played an important role in the description of concrete-filled tubes behavior. In the list of Universities which have more contributed to this development, there are the Harbin Institute of Science and Technology and the Fuzhou University. The most representative contribution of Chinese researchers was the Unified Theory[7], proposed by Zhong (Zhong, et al., 1998), an engineer from the University of Fuzhou, together with Kuranovas and Kvedaras, from Lithuania.

Therefore, it is worth to recognize the contributions coming from Vilnius [Lithuania] by hands of the engineers Kuranovas and Kvedaras (Kuranovas, et al., 2007). These two researchers contributed to the Unified Theory with Zhong, and analyzed the response of hollow concrete-filled tubes later, as a clear optimization of the solid CFT sections in case of slender columns. They proposed the industrialization of these sections through concreting of the filling by using a centrifuging machine (Kuranovas, et al., 2007).

Other important focus of CFT knowledge is located in Singapore, the city of skyscrapers in the South-East of Asia. The most representative author from Singapore is Richart Liew (Liew, et al., 2009), always worried about the effects of the constructive methods on CFT sections. The school of Singapore, together with the Monash University, established an explicit line of research devoted to

[5] Concrete-filled Double Skin Tubes
[6] American Society of Civil Engineers
[7] See Section 2.3.2.2

the practical consequences of high-rise building with these typologies. This fact is directly derived from the real experience of planning and executing tall buildings in these latitudes.

And finally, less important than in the other cases, Europe has also its particular contribution to the research of CFT sections, headed by the Imperial College of London in the United Kingdom, and the University of Wuppertal, in Germany. The research in this last country has been carried out by G. Hanswille (Hanswille, 2008), from the *Institute for Steel and Composite Structures*. This engineer has been studying different sectional typologies oriented to practical cases, such as the Commerzbank building in Frankfurt [see Fig. I.9]. However, we can say clearly that Europe has not emerged as a leader in CFT construction, due to logical reasons of low seismicity.