

# Composite Megacolumns

Testing Multiple, Concrete-Encased,  
Hot-Rolled Steel Sections

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## About the Research Sponsor: ArcelorMittal

With annual achievable production capacity of approximately 127 million tons of crude steel, and 222,000 employees across 60 countries, ArcelorMittal is the world's leading steel and mining company. With an industrial presence in over 20 countries, they are the leader in all major global steel markets including automotive, construction, household appliances and packaging, with leading research and development and technology, sizeable captive supplies of raw materials, and extensive distribution networks.

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## 1.0 Research Executive Summary: Background and Overview

The aim of this paper is to provide an overview on the developments and achievements of the research program carried out between August 2014 and December 2015 on composite megacolumns with encased, hot-rolled steel sections.

The project was supported and funded by ArcelorMittal (AMBD). The structural engineering firm Magnusson Klemencic Associates (MKA) provided background studies on comparative composite megacolumn construction projects, both within China and other international markets. The China Academy of Building Research (CABR) was engaged to develop the testing program for the subject columns. The Council on Tall Buildings and Urban Habitat (CTBUH) assumed the role of project coordinator.

There is an ongoing need to optimize construction materials and reduce the size of elements required within the structural systems of high-rise buildings. Minimizing the size of the vertical structural elements, without compromising the economic feasibility of projects and limiting their significant share on tall buildings' floor plans, is a consistent challenge. The use of composite structural elements, such as combining concrete and steel, along with higher grade materials within each, is a viable solution.

Currently, concrete filled tubes (CFT) or concrete filled continuous caissons built-up by welding heavy plates are the common structural solutions. Their main drawbacks include high costs, the need for skilled labor, complex connections, and requiring welding conditions for heavy plates, such as preheating and repairing.

Composite megacolumns considered in this research are defined as vertical structural systems with more than one hot-rolled steel section, longitudinal rebar and ties embedded in concrete, and they are subject to significant vertical loads and secondary bending moments from wind and seismic actions. They are believed to be a convenient solution in terms of structural behavior, cost, and constructability for the design of tall buildings, including towers over 300 meters tall.

Although codes and specifications do consider composite structural elements, they do not offer specific provisions on the

design of composite sections with two or more encased steel sections (AISC 2010 Specifications for instance).

The lack of knowledge on the axial, bending, and shear behavior of composite megacolumns, along with the resulting lack of clarity in the codes, leads to the need for experimental performance tests. These tests, and the resulting findings, suggest a simplified design approach and help develop numerical methods to describe the designs and to validate the results.

The laboratory tests took place between February and September 2015 within CABR Laboratories and the Laboratories of Tsinghua University, Beijing.

The column specimens' overall layout and geometry have been based on suggested sections, from MKA and others, of representative full scale composite columns considered for high-rise buildings. Overall dimensions of the representative full scale columns considered for this testing program are 1,800 by 1,800 millimeters, with a height of 9 meters at the Lobby level (base of the tower) and 4.5 meters at the typical floor.

The laboratory tests consisted of two sets of tests that attempt to define the axial load and moment (P-M) interaction curves of the representative columns at failure. Static tests were accomplished by applying 0%, 10%, and 15% eccentricity axial loads, on six 1:4 scaled specimens, until failure. Quasi-static tests were accomplished by applying 10% and 15% eccentricity axial loads with horizontal forces on four 1:6 scaled specimens, until failure.

Results are used to investigate the specimens' maximum capacity, displacements, stress distribution, ductility, and stiffness.

Experimental results are validated by finite element method (FEM) models developed by CABR and AMBD with Abaqus and Safir software, with the numerical values in accordance with the experimental values. FEM models allow also for a deeper insight on steel-concrete interaction forces and stress distribution.

Finally, simplified design methods based on European, Chinese, and US codes are suggested and the results are compared to the numerical and experimental values. Then, through three examples of application to selected megacolumn sections, the simplified methods are proven to be an effective and useful design tool.

The present paper has undergone a peer review process before official circulation, with feedback received from professionals on tall buildings, structural designers, and professors involved in the peer review panel.

A complete description of the present research program, including all information and data of the experimental campaign can be found in the extensive, detailed report, titled *Performance and Capacity of Isolated Steel Reinforced Concrete Columns and Design Approaches*, available at the following link and QR code:

[www.ctbuh.org/megacolumns](http://www.ctbuh.org/megacolumns)



## 2.0 Laboratory Testing

The aim of this section is to describe the laboratory testing performed between February and September 2015 within CABR Laboratories and the Laboratories of Tsinghua University, Beijing, with the purpose of quantifying the behavior of composite megacolumns under combined compression and bending conditions.

### 2.1 Static Tests

During the static tests, six 1:4 scaled specimens are tested to failure by applying a concentrated load with different eccentricities.

The total length of the specimens are 2,700 millimeters, with 450 by 450 millimeters square cross sections, simulating a megacolumn with a length of 9 meters and a 1,800 by 1,800 millimeters cross section, representative of a column located in a double-floor lobby. They all have the same configuration of four hot rolled HEM100 (120x106x12x20) steel sections encased in concrete, longitudinal rebar, and steel tie sets (see Figures 1 and 2). Studs are welded in one and two rows on the profiles inner flange, web, and outer flange (see Figure 3).

Figure 4 shows different stages of specimens' fabrication.

Selected materials are listed in Tables 1 and 2.

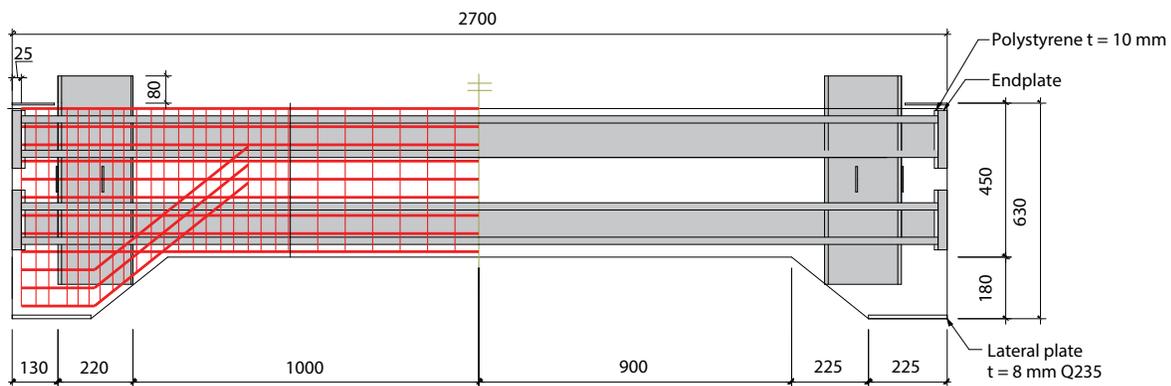


Figure 1. Static test specimens' steel layout – longitudinal. Source: CABR 2015

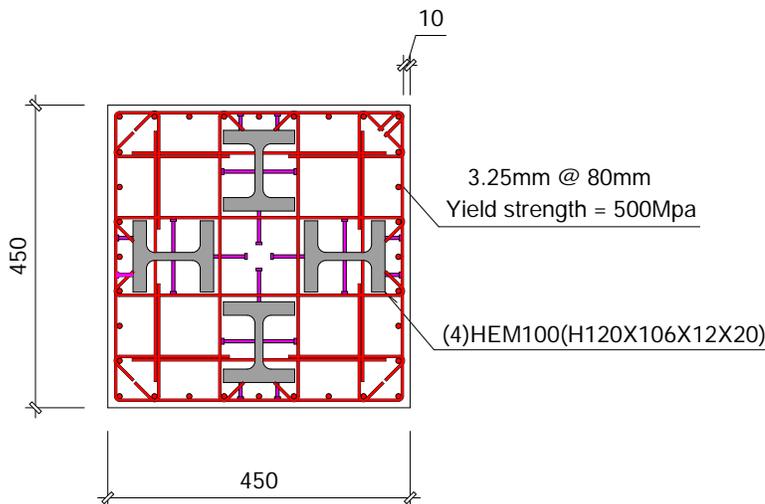


Figure 2. Static test specimens' steel layout – section. Source: CABR 2015

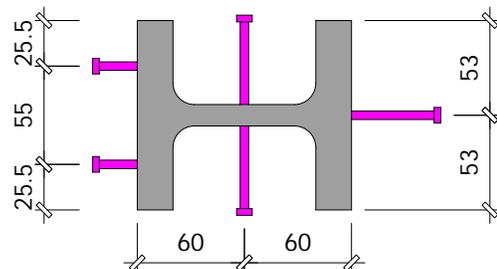


Figure 3. Static test specimens' shear studs layout. Source: CABR 2015



Figure 4. Specimen fabrication – static test, overview (a), bracket details (b), longitudinal bar details (c), and concrete mold (d). Source: CABR 2015

<b>Concrete</b>	C60 ( $f_{ck} = 60$ MPa) according to Chinese Code, with 5 mm aggregate maximum size
<b>Hot rolled jumbo sections</b>	HEM100 (120x106x12x20) ASTM A572 Gr.50 / S355 ( $f_{yk} = 355$ MPa = 50ksi)
<b>Longitudinal reinforcement</b>	$\varnothing$ 8 mm HRB400 (ASTM A615), ( $f_{yk} = 400$ MPa)
<b>Stirrups</b>	$\varnothing$ 3.25 mm @ 80 mm HRB500 ( $f_{yk} = 500$ MPa)
<b>Shear studs</b>	$\varnothing$ 6 mm x 25 mm Nelson headed studs, ASTM A108 @ 144 mm O. C. $\varnothing$ 5 mm x 20 mm Nelson headed studs, ASTM A108 @ 144 mm O. C. Grade 4.8

Table 1. Static test selected materials.  
Source: First Methodological Report 2014

Specimen ID	Concrete cubic strength (MPa)	Concrete axial strength (MPa)	Yield strength of steel section flange* (MPa)	Yield strength of steel section web* (MPa)	Yield strength of longitudinal bar (MPa)	Yield strength of transverse bar (MPa)
E00-1	61.2	61.2	408	523	438	$f_{3.25} = 59$ MPa $f_{4.80} = 438$ MPa
E00-2	56.6	55.0	398	411		
E10-1	60.9	56.4	423	435		
E10-2	72.8	59.2	383	415		
E15-1	66.1	57.2	377	404		
E15-2	67.6	56.3	389	405		
Average	64.8	57.6	396	432	-	-

\* Material strength for steel sections are provided by ArcelorMittal

Table 2. Material strengths for static tests.

# 3.0 Validation of Test Results with FEM and International Codes

This section is dedicated to the comparison between the experimental results, numerical results obtained by FEM models, and the simplified calculation methods based on codes.

## 3.1 FEM and Chinese JGJ Code Validation

CABR validated the static test results with FEM models and a simplified design method based on Chinese code *JGJ 138-2016: Code for Design of Composite Structures*.

FEM analysis has been completed for both static and quasi-static tests, using the software Abaqus.

For concrete, a damaged plasticity model with a confinement effect is adopted. A tri-linear behavior, with values from the test, is assumed for steel sections and rebar. The concrete and steel sections are simulated by three dimensional eight-node solid elements, and the bars are simulated by two dimensional three-node truss elements. To simplify the model, bars and steel beams are connected with ties to the concrete, so there is no relative displacement or strain difference. The interactions of concrete and steel sections are simulated by nonlinear springs along each dimension (see Figure 23).

Before peak point, the calculated 'axial load vs. vertical displacement' curve follows similar paths to the experimental

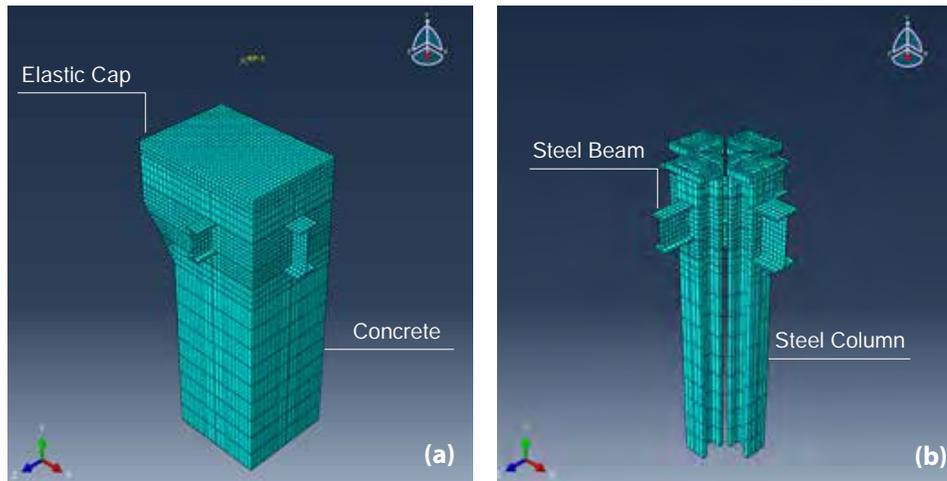


Figure 23. CABR FEM validation of static test in Abaqus concrete mesh (a) and steel section mesh (b). Source: CABR 2015

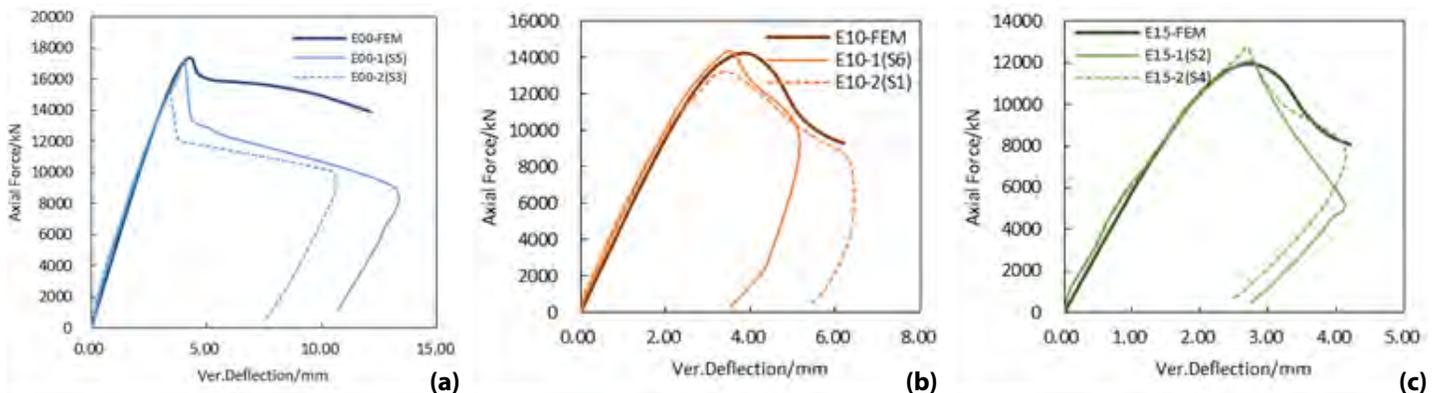


Figure 24. Calculated axial load/vertical deflection curves – E00-1 (a), E10-1 (b), and E15-1 (c). Source: CABR 2015

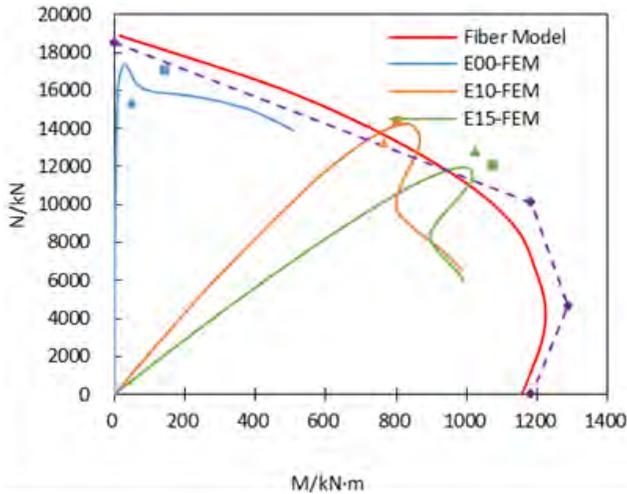


Figure 25. Calculated, FEM and static test interaction curve. Source: CABR 2015

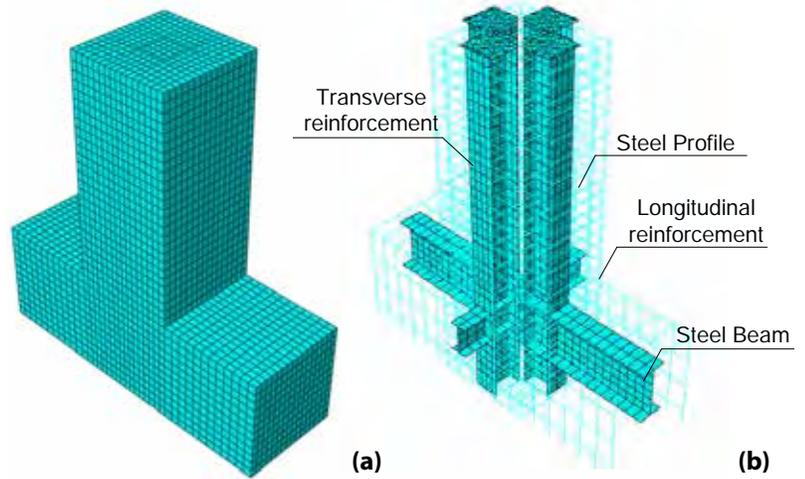


Figure 26. CABR FEM validation of static test in Abaqus – concrete mesh (a) and steel sections mesh (b). Source: CABR 2015

curve. The difference between the curves widen after peak point (see Figure 24).

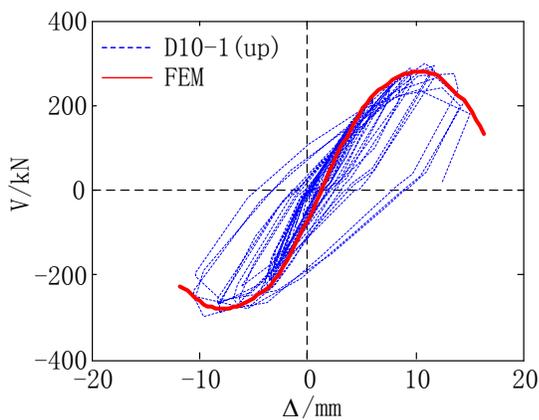
Once calculated, the FEM models and test interaction curves, presented in Figure 25, show results similar to the capacity of a megacolumn.

Additional deformation and stress distribution findings based on FEM results are detected. Deformations correspond to the experimental data for both purely axial and eccentric specimens.

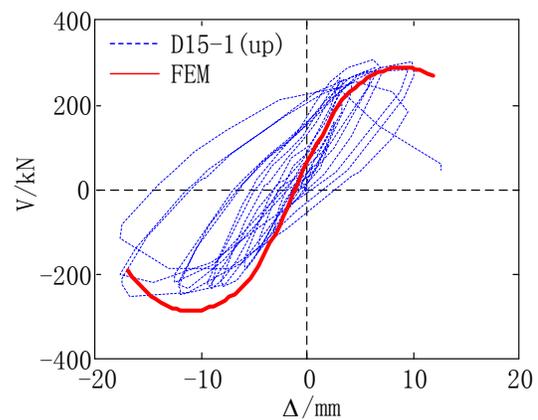
Through the behavior of the springs, additional analyses on shear studs are conducted. The FEM results show that the steel beams play an important role in providing shear resistance along a concrete-steel interface. However, the mechanism may change when the boundary condition changes.

Quasi-static tests have been validated through similar FEM tests, using Abaqus (see Figure 26).

Calculated envelope curves validate the resultant curves from the tests (see Figure 27).



(a)



(b)

Figure 27. CABR FEM validation of quasi static test envelop curves in Abaqus of the D10-1 upper section (a) and the D15-1 upper section (b). Source: CABR 2015

## 4.0 Simplified Design Methods and Examples

As previously stated, no available design standards provide information on how to properly design reinforced column sections with more than one embedded steel profile.

The research team applied existing methods for design of composite compression members with one encased section based on three main codes to typical sections of megacolumns with four encased steel sections:

1. European code Eurocode 4 (2004): *Design of Composite Steel and Concrete Structures*
2. US AISC 2016 draft version / *ACI 318-14*
3. Chinese code JGJ 138 - 2016: *Code for Design of Composite Structures*

The three listed codes' design methods for composite members are applied to examples of megacolumn sections to demonstrate that code provisions are valid for megacolumns with more than one encased steel section as well.

Megacolumn section layout has been provided by MKA based on actual project requirements for high-rise buildings within China today.

In this section, a simplified method is presented. This allows the calculation of the mechanical properties of the section (moment of inertia and plastic moment) and allows the evaluation of flexural stiffness.

These are necessary for applying the codes.

Please refer to the *Performance and Capacity of Isolated Steel Reinforced Concrete Columns and Design Approaches* report ([www.ctbuh.org/megacolumns](http://www.ctbuh.org/megacolumns)) for the code application examples.

### 4.1 Notation

$A_a$	= area of one steel profile
$A_c$	= area of concrete shape
$A_g$	= gross cross-sectional area of composite section
$A_s$	= total area of the steel profiles
$A_{s1}$	= equivalent steel plate placed along the $x$ -axis
$A_{s2}$	= equivalent steel plate placed along the $y$ -axis
$A_{sr}$	= area of the continuous reinforcing bars
$A_{sri}$	= cross-sectional area of one reinforcing bar
$A_{sr}$	= area of continuous reinforcing bars
$b$	= width of the steel profile
$d$	= height of the steel profile
$b_{s1}$	= width of $A_{s1}$ plate, mm
$b_{s2}$	= width of $A_{s2}$ plate, mm
$c_x$	= concrete cover, on $x$ - direction
$c_y$	= concrete cover, on $y$ - direction
$d_b$	= diameter of the longitudinal reinforcement
$d_x$	= the distance between the two steel profiles, on $y$ - direction
$d_y$	= the distance between the two steel profiles on $x$ - direction
$d_{sx}$	= the distance from the local centroid of the steel profile to the section neutral axis, on $x$ - direction
$d_{sy}$	= the distance from the local centroid of the steel profile to the section neutral axis, on $y$ - direction
$d_{s2x}$	= the distance from the local centroid of $A_{s1}$ plate to the section neutral axis, on $x$ - direction
$d_{s1y}$	= the distance from the local centroid of $A_{s2}$ plate to the section neutral axis, on $y$ - direction
$f_{ck}$	= characteristic value of compressive cylinder strength of concrete
$f_{cd}$	= design value of compressive cylinder strength of concrete
$f_y$	= specified minimum yield stress of steel shape
$f_{yd}$	= design value of specified minimum yield stress of steel shape
$f_{sy}$	= yield stress of reinforcing steel
$f_{sd}$	= design value of yield stress of reinforcing steel

- $h_1$  = height of the concrete section  
 $h_2$  = width of the concrete section  
 $h_{s1}$  = height of  $A_{s1}$  plate, mm  
 $h_{s2}$  = height of  $A_{s2}$  plate, mm  
 $h_{nx}$  = distance from centroidal axis (Y-Y) to neutral axis  
 $I_{cx}$  = moment of inertia of concrete, about  $x$ -axis  
 $I_x$  = moment of inertia of one steel shape, about  $x$ -axis  
 $I_y$  = moment of inertia of one steel shape, about  $y$ -axis  
 $I_{sx}$  = moment of inertia of steel shapes, about  $x$ -axis  
 $I_{sr1x}$  = moment of inertia about  $x$  axis of  $A_{s1}$  plate, mm  
 $I_{sr2x}$  = moment of inertia about  $x$  axis of  $A_{s2}$  plate, mm  
 $n_x$  = number of continuous reinforcing bars on  $x$  direction  
 – corresponding to one horizontal layer  
 $n_y$  = number of continuous reinforcing bars on  $y$  direction  
 – corresponding to one vertical layer  
 $i$  = number of rebar layers on  $A_{s1}$  equivalent plate  
 $j$  = number of rebar layers on  $A_{s2}$  equivalent plate  
 $s_x$  = spacing between two bars on  $x$  direction  
 $s_y$  = spacing between two bars on  $y$  direction  
 $n_x$  = number of bars on  $x$  direction on one layer  
 $n_y$  = number of bars on  $y$  direction on one layer  
 $n$  = number of steel profiles oriented on the strong axis  
 $m$  = number of steel profiles oriented on the weak axis  
 $t_f$  = steel profile flange thickness  
 $t_w$  = steel profile web thickness  
 $Z_{sr1x}$  = full  $x$ -axis plastic modulus of  $A_{s1}$  plate, mm  
 $Z_{sr2x}$  = full  $x$ -axis plastic modulus of  $A_{s2}$  plate, mm  
 $Z_x$  = full  $x$ -axis plastic modulus of one steel shape, mm  
 $Z_y$  = full  $y$ -axis plastic modulus of one steel shape, mm  
 $Z_{sx}$  = full  $x$ -axis plastic modulus of entire steel shapes, mm  
 $Z_{cx}$  = full  $x$ -axis plastic modulus of concrete shape, mm  
 $Z_{cyn}$  =  $x$ -axis plastic modulus of concrete section within the zone  $2h_n$   
 $Z_{r2xn}$  =  $x$ -axis plastic modulus of  $A_{s2}$  plates within the zone  $2h_n$   
 $Z_{cyn}$  =  $y$ -axis plastic modulus of concrete section within the zone  $2h_n$   
 $Z_{r1yn}$  =  $y$ -axis plastic modulus of  $A_{s1}$  plates within the zone  $2h_n$   
 $\delta$  = steel contribution ratio  
 $\bar{\lambda}$  = the relative slenderness

## 4.2 Design Case Sections and Properties

The development of a method of calculation for concrete sections, with several encased steel sections, requires the calculation of section characteristics, including the moment of inertia, the plastic moment, the elastic neutral axis, and the plastic neutral axis of huge megacolumn sections. Such calculations can be made through dedicated software, where all the data is given and each reinforcing bar's position and section is defined, or the calculation can be done manually, where it becomes tedious due to the high number of longitudinal bars in megacolumns. In order to facilitate such a calculation, some simplifications are proposed, where the lines of rebar are replaced by equivalent plates. These simplifications have no direct link with the main subject of the paper, which examines design under compression and bending, but they help make user friendly calculations in the design examples presented in this paper and on the shear design of megacolumns.

### 4.2.1 Flange layers of rebar – moment of inertia

In order to easily make calculations, the layers of rebar, parallel to the neutral axis, can be substituted by an equivalent plate (see Figure 32). The plate area ( $A_p$ ) can be found with the following equation:

$$A_p = 2n A_b$$

where:

$$A_b = \text{Cross sectional area of one bar}$$

$$n = \text{Number of bars in one layer}$$

The distance of the plate's geometrical center to the neutral axis ( $d_p$ ) can be found as:

$$d_p = (d_1 + d_2)/2$$

where:

- $d_1$  = The distance from the center of the first layer of rebar to the neutral axis  
 $d_2$  = The distance from the center of the second layer of rebar to the neutral axis

There is an ongoing need to optimize construction materials and reduce the size of elements required within the structural systems of high-rise buildings. Minimizing the size of the vertical structural elements, without compromising the economic feasibility of projects, is a persistent challenge of tall building design. The use of composite structural elements, such as combining concrete and steel, along with higher grade materials within each, is a viable solution.

This document is the summary of the research project on composite megacolumns, conducted by CTBUH and the China Academy of Building Research, with assistance from Magnusson Klemencic Associates and sponsorship from ArcelorMittal. Composite megacolumns considered in this research are defined as vertical structural systems that are subject to significant vertical loads and secondary bending moments from wind and seismic actions, with more than one hot-rolled steel section and longitudinal rebar and ties embedded in the concrete. They are believed to be an appropriate solution in terms of structural behavior, cost, and constructability for the design of tall buildings, including towers over 300 meters tall.

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