Structures 3 (2015) 211–226

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Performance of concrete-encased CFST box stub columns under axial compression

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ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 10 May 2015
Accepted 15 May 2015
Available online 3 June 2015

Keywords:
Concrete-filled steel tube (CFST)
Concrete-encased
Box section
Stub column
FEA model
Ultimate load

ABSTRACT

A finite element analysis (FEA) model is developed to predict the full range response of concrete-encased CFST box stub columns under axial compression. In the model, concrete across the composite section is divided into four regions, i.e. the outer unconfined concrete outside the stirrup, the outer concrete in the web walls, the outer confined concrete in the corners, and the core concrete in the steel tubes. Different material models are used in each region. The analytical results are compared to past experiments, and generally good agreement between the predicted and measured results is obtained. Load-axial strain, loading distribution between the inner CFST and outer RC components and interface stresses between steel and concrete are analyzed. The influence of the web wall slenderness is also investigated. Parameter studies investigate the influence of concrete and steel strength, steel ratio of CFST, longitudinal bar ratio, stirrup spacing and ratio of the diameter of CFST to the sectional width on the ultimate load. A simplified model is proposed to predict the ultimate load of the concrete-encased CFST box stub columns under axial compression.
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1. Introduction

Concrete-encased concrete-filled steel tube (CFST) box members are a newly developed steel–concrete composite system that has been used in bridge piers and arches in bridges in China [5]. Fig. 1(a) shows a typical cross-section of this composite member. The member has an encased CFST component in each of the four corners of the box as well as an outer reinforced (RC) box component. The box is constructed in four stages as illustrated in Fig. 1(b). First, the steel tubes are fixed at the proper location, and then high strength core concrete is placed into the steel tubes. The outer reinforcing cage is then placed and tied, and finally the normal strength outer concrete is poured.

Considerable research has been completed for conventional RC box member (e.g. [18,19,25]) and concrete-encased CFST member (e.g. [11,4,2]). This research provides a basic understanding of concrete-encased CFST box member behavior. An et al. [5,4] experimentally and analytically studied eccentrically loaded concrete-encased CFST box columns, since they were mainly subjected to combined axial load and bending moment as piers or arches. It was found that the crushing and spalling of the concrete in compression and concrete cracking in tension influenced the behavior of the eccentrically loaded columns. An increase in eccentricity and height-to-width ratio led to a decrease in the ultimate load capacity. The strength and stiffness of the composite columns were larger than those of the corresponding RC box columns. The moment magnification method was proposed to consider second-order effects of the eccentrically boxed columns.

The performance of concrete-encased CFST box stub columns under axial compression is different than that achieved under eccentric load, since there is no influence of bending and lateral deflection. The ultimate strength of the stub composite column under axial compression provides a critical point in the compression–bending interaction curves for these structural members. Concrete-encased CFST box members are fundamentally different than pure CFST members, because there is a much wider range of confinement of the concrete in the box section as compared to the high degree of confinement in the inner CFST component. Four concrete zones (the outer unconfined concrete outside the stirrup, the outer concrete in the web walls, the outer confined concrete within the stirrups in the corners, and the core concrete in the steel tubes) are noted in these members and the stress distribution between these zones is considered in this research. These differences introduce a range of different potential failure modes, and information on the stress distribution and confinement effects in various parts of the box section are important. Within this framework, the influence of wall slenderness ratio λ_w ($=b_c / t_c$, where b_c and t_c are the width and thickness of web walls as shown in Fig. 1(a)) is a critical parameter for RC box columns [18] and in this study, for the composite box columns.

This paper analyzes the performance of concrete-encased CFST box stub columns under axial compression. A 3-dimensional finite element analysis (FEA) model is developed. The model includes different material modeling techniques for the concrete in the four concrete regions noted earlier. The model is verified by comparison of predicted behavior and experimental results. The analysis evaluates load–strain relations,

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http://dx.doi.org/10.1016/j.istruc.2015.05.001
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Nomenclature

A_{core}	Cross-sectional area of core concrete in CFST
A_l	Cross-sectional area of longitudinal bar
A_s	Cross-sectional area of steel tube
A_{sc}	Cross-sectional area of CFST ($=A_{core}+A_s$)
A_{out}	Cross-sectional area of outer concrete
B	Sectional width of concrete-encased CFST box section
b_c	Width of web wall
D	Overall diameter of steel tube
D_i	Diameter of core concrete
E_c	Concrete modulus of elasticity
f_{ck}	Characteristic concrete strength
f_{cu}	Concrete cube strength
f_c'	Concrete cylinder compressive strength
f_{yh}	Yielding strength of stirrup
f_{yl}	Yield strength of longitudinal bar
f_{ys}	Yield strength of steel tube
N	Axial load
N_{cfst}	Strength of CFST component
N_{uc}	Predicted ultimate strength
N_{ue}	Experimental ultimate strength
$N_{uc,cfst}$	Predicted ultimate strength of CFST component
$N_{uc,rc}$	Predicted ultimate strength of RC component
P_1	Contact stress between steel tube and core concrete
P_2	Contact stress between outer concrete and steel tube
s	Stirrup spacing
DI	Strength index
t	Wall thickness of steel tube
t_c	Thickness of web wall
α_s	Steel ratio of CFST ($=A_s / A_{core}$)
α_l	Longitudinal bar ratio ($=A_l / (A_l + A_{out})$)
ε	Strain
σ	Stress
λ_w	Wall slenderness ratio ($=b_c / t_c$)
ξ	Confinement factor ($=\frac{A_s f_{ys}}{A_{core} f_{ck,core}}$) of CFST

the strength distribution between the inner CFST component and outer RC component, the interaction between steel and concrete, and the stress distribution in various elements of the box member. The influence of wall slenderness ratio is examined, and a parametric study is performed to examine key parameters that affect the box member performance. A superposition method to predict the ultimate strength of the composite stub box columns is proposed.

2. Finite element analysis (FEA) model

The proposed finite element analysis (FEA) model of concrete-encased CFST box stub column under axial compression is shown in Fig. 2. The model utilizes the ABAQUS/Standard module software [14], and this model is based on the previous analytical work of concrete-encased CFST stub columns provided by Han and An [11] and An et al. [3]. However, the box section has different concrete regions and confinement conditions, which increase the complexity of the analysis of the concrete-encased CFST box column.

2.1. Element type, mesh, boundary conditions and interface model

Four-node conventional shell elements, 2-node truss elements and 8-node 3-D solid elements are used for the steel tube, reinforcing bar and concrete, respectively. The structured meshing technique is assigned to have a proper element shape. In order to achieve reliable results with reasonable computation times, a mesh convergence study is performed to identify an appropriate mesh size. One quarter of the column is modeled due to symmetry of loading and geometry as shown in Fig. 2. The load is simulated by applying uniform displacement to one end plate, while the displacement and rotation of the other end plate are fixed. The contact between the steel tube and concrete surfaces is modeled by the contact surface model with “Hard contact” in the normal direction and the Mohr–Coulomb friction model in tangential directions. When the shear stress is smaller than the shear limitation (the bond stress), there is no relative slip between the two surfaces, but the shear force is calculated by a friction coefficient and contact pressure after initial slip. The frictional coefficient was taken as 0.6 and the bond stress between the steel tube and the concrete was determined according to Han and An [11]. The bond stress is defined as follows which is based on the study of Roeder et al. [20].

$$\tau_{bond} = 2.314-0.0195\left(\frac{D_i}{t}\right) \quad \left(\mathrm{N/mm^2}\right) \tag{1}$$

where D_i and t are diameter of core concrete and thickness of the steel tube.

Similar to Han and An [11], the embedded element technique is used between the rebar and the outer concrete, and the translational degrees of freedom at the rebar node are restricted.

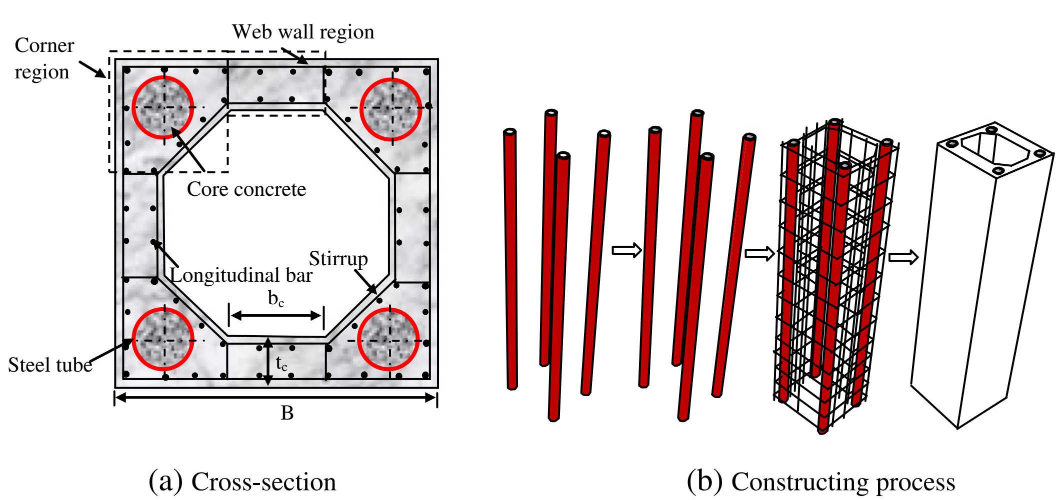

Fig. 1. A schematic view of the concrete-encased CFST box column.

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