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Axial and lateral stress–strain model for circular concrete-filled steel tubes with external steel confinement

A.K.H. Kwan [a], C.X. Dong [a], J.C.M. Ho [b],*

[a] Department of Civil Engineering, The University of Hong Kong, Hong Kong, China
[b] School of Civil Engineering, The University of Queensland, Brisbane, Australia

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ABSTRACT

In a concrete-filled steel tube, delamination often occurs at the steel tube–concrete core interface due to the larger Poisson's ratio of the steel tube. For resolving this problem, it has been advocated to install external restraints in the form of steel rings or spirals so as to restrain the lateral expansion of the steel tube. This also provides additional confinement to the concrete core. To study the effectiveness of such external steel confinement, a theoretical model for evaluating the confining stress and axial load in a concrete-filled steel tube with external steel confinement up to the post-peak stage is developed. The theoretical model is first verified by analyzing a total of 98 specimens tested by previous researchers and comparing the measured and predicted lateral strain–axial strain curves and axial load–strain curves of the specimens. It is then used to perform a parametric study to evaluate the required equivalent thickness/diameter ratios of the external steel confinement for eliminating the delamination effect and for achieving Level I ductility.

1. Introduction

The concrete-filled steel tube (CFST) system, first proposed in the 1960s [1], has been proven to be an effective means of improving the ductility of high-strength concrete, which tends to have a lower ductility, by restraining the lateral expansion and avoiding explosive failure of the high-strength concrete. In a CFST column, the steel tube acts as both longitudinal reinforcement to carry axial load and transverse reinforcement to provide lateral confinement to the concrete core [2,3]. Besides, the steel tube can also serve as a permanent formwork to expedite the concrete casting and also to resolve the steel rebar congestion problem in heavily loaded concrete columns. Although the CFST system is particularly useful for high-strength concrete columns, it may also be applied to normal-strength concrete columns.

However, despite these merits, delamination at the interface between the steel tube and the concrete core often occurs at the elastic stage because the Poisson's ratio of the steel tube is larger than that of the concrete core (note that the Poisson's ratio of steel is about 0.3 and the Poisson's ratio of concrete is about 0.18). Due to the larger Poisson's ratio of the steel tube, the lateral expansion of the steel tube is larger than that of the concrete core at the elastic stage, causing the concrete core to be unconfined initially until splitting cracks are formed and the lateral expansion of the concrete core becomes larger than that of the steel tube. This phenomenon delays the development of confining stress, reduces the effectiveness of the steel tube and at times may even cause premature buckling of the steel tube [4].

To overcome this problem, internal stiffeners in the forms of steel strips [5–9], inclined tie bars [10] and tab stiffeners [11] have been proposed. However, while the internal stiffeners could effectively enhance the steel–concrete bond and buckling capacity of the steel tube, they would not provide any additional confinement to the concrete core. As a result, their installation gives only marginal increases in the strength and ductility of the CFST columns. Moreover, the installation of such internal stiffeners is feasible only in large size steel tubes. An alternative solution of installing external confinements in the forms of FRP jackets [12–14], steel rings [15,16] or steel spirals [17,18] have also been proposed. In addition to enhancing the steel–concrete bond and buckling capacity, such external confinements would also provide additional confinement to the concrete core to increase both the strength and ductility of the CFST columns. Among the different materials used for the external confinement, steel should be better than FRP because of its lower cost, better fire resistance, higher durability and larger rupture strain.

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* Corresponding author.
E-mail address: johnny.ho@uq.edu.au (J.C.M. Ho).

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Nomenclature

E_c	Young's modulus of concrete
E_s	Young's modulus of steel tube
E_{sr}	Young's modulus of external steel rings/spirals
f'_c	unconfined concrete strength (concrete cylinder strength)
f_{cc}	peak axial stress on stress–strain curve of confined concrete
f_{sy}	yield strength of steel tube
f_{sr}	yield strength of external steel rings/spirals
t_s	thickness of steel tube
t_{sr}	equivalent thickness of external steel rings/spirals
D_o	outer diameter of steel tube
D_i	inner diameter of steel tube
d_{sr}	diameter of external steel rings/spirals
s	spacing of external steel rings/spirals
α	inclined angle of external steel spirals with respect to transverse plane
ε_{co}	axial strain at peak axial stress of unconfined concrete
ε_{cc}	axial strain at peak axial stress of confined concrete
ε_x^e	elastic strain in x-direction
ε_x^p	inelastic strain in x-direction
ε_x^T	total strain in x-direction (lateral strain in x-direction)
ε_y^e	elastic strain in y-direction
ε_z	axial strain in z-direction
ε_z^e	elastic strain in z-direction
ε_{z0}	axial strain at formation of splitting cracks
$\varepsilon_{z,s}$	axial strain of steel tube
$\varepsilon_{\theta,s}$	circumferential strain of steel tube
ε_{sr}	tensile strain of external steel rings/spirals
ν_c	Poisson's ratio of concrete
ν_s	Poisson's ratio of steel tube
σ_x	normal stress (confining stress) in x-direction
σ_y	normal stress (confining stress) in y-direction
σ_z	normal stress (axial stress) in z-direction
σ_r	confining stress in radial direction
$\sigma_{z,s}$	axial stress of steel tube
$\sigma_{\theta,s}$	circumferential stress of steel tube
σ_{sr}	tensile stress of external steel rings/spirals
$d\sigma_{z,s}^i$	incremental axial stress of steel tube at step i
$d\sigma_{\theta,s}^i$	incremental circumferential stress of steel tube at step i

A lot of tests on CFST columns with external steel confinement have been carried out to study the effects of the concrete strength [15], spacing and diameter of the external steel rings/spirals [15–18] and yield strength and thickness/diameter ratio of the steel tube [16,18]. From the test results, several observations have been made: (1) the confining stress in a CFST with external steel confinement is often negative or zero (negative means tension) at the elastic stage, indicating that delamination can occur even with external confinement provided; (2) the external steel confinement is effective in restraining the lateral expansion of the steel tube and concrete core, and thus can provide additional confinement; (3) a CFST column with external steel confinement may exhibit strain hardening or softening at the post-peak stage, depending on the amount of additional confinement provided; and (4) the external steel confinement can delay or even suppress the outward buckling of the steel tube. However, these observations are mostly qualitative, lacking quantitative analysis of the actual confining mechanism in the structural system.

Regarding design methods and formulas, Lai and Ho in 2012 [16] derived an analytical model to predict the axial load capacity of external steel rings confined CFST columns. In the model, the compressive strength of concrete, yield strength of steel tube, diameter of concrete core and equivalent area of external steel rings are combined to evaluate a confinement index, based on which the hoop stress in the steel tube and the confining stress in the concrete core at maximum load are worked out. Later, Lai and Ho in 2014 [19] refined their model by including additional test results in the derivation to improve the accuracy of the model in the prediction of axial load capacity. Subsequently, Lai and Ho in 2015 [18] extended their model originally derived for external steel rings confined CFST columns to cover also external steel spirals confined CFST columns by further considering the combined confining effects of the steel tube, external steel rings and external steel spirals.

However, these design methods and formulas have certain limitations: (1) there is still no general consensus on the definition of axial load capacity, especially when there is no peak on the axial load–strain curve (the use of different definitions may lead to different values of axial load capacity); (2) the stress states of the steel tube and external steel rings/spirals are quite different (the steel tube is under biaxial stress state while the external steel rings/spirals are under uniaxial stress state) and therefore the effects of the area of steel tube and the equivalent area of steel rings/spirals should be separately considered; and (3) the confining stress used to evaluate the axial load capacity of external steel ring/spirals confined CFST column is only a representative value because it actually varies during loading. To evaluate the variations of confining stress and axial load during the entire loading process for ductility and deformability analysis, a more rigorous theoretical model considering both force equilibrium and strain compatibility conditions is needed.

Herein, a rigorous theoretical axial and lateral stress–strain model, which incorporates a lateral-to-axial strain model of confined concrete recently developed by the authors [20], an axial stress–strain model of confined concrete developed by Attard and Setunge [21], a plastic model for the steel tube based on the associated flow rule and von Mises yield criterion, and a uniaxial stress–strain model for the steel rings/spirals, is developed. In this model, the axial strain is applied incrementally and the lateral strain and confining stress are evaluated by solving the constitutive equations. The confining stress so evaluated is then substituted into the axial stress–strain model of confined concrete to determine the axial stress in the concrete. The validity and accuracy of the theoretical model are verified by comparing with published test results. Moreover, a parametric study is carried out to evaluate the equivalent thickness/diameter ratios of the external steel confinement required to eliminate steel–concrete delamination and to achieve Level I ductility (the level of ductility with no strain softening after yielding). Lastly, an appraisal of the effectiveness of external steel rings/spirals is presented.

2. Proposed model for CFST with external steel rings/spirals

In general, to analyze the axial and lateral stress–strain behavior of confined concrete, a total of three constitutive models are needed: (1) a lateral-to-axial strain model of concrete with various concrete strengths and under different confining stresses; (2) an axial stress–strain model of concrete with various concrete strengths and under different confining stresses; and (3) a confining stress–lateral strain model of the confinement taking into