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Axial and lateral stress-strain model for concrete-filled steel tubes with FRP jackets

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ABSTRACT

In a concrete-filled steel tube under axial compression, since the steel tube has a larger Poisson's ratio than the concrete, delamination at the steel-concrete interface occurs and the steel tube is ineffective in providing confinement at the elastic stage. For resolving this problem and enhancing the concrete confinement, the provision of an external FRP (fiber reinforced polymer) jacket to restrict the lateral expansion of the steel tube is an effective means. Herein, to investigate the effectiveness of FRP-jacketed steel tube confinement, a theoretical model for evaluating the lateral strain, confining stress and axial stress in a concrete-filled steel tube with FRP jacket at various stages of loading is developed. The theoretical model is first applied to analyze specimens tested by other researches to verify its accuracy and then used to work out the FRP confining stiffness required to eliminate steel-concrete delamination and the FRP confining stiffness required to achieve Level I ductility (no strain softening at the inelastic stage until failure).

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1. Introduction

To improve the ductility of concrete members under axial compression, especially those cast of high-strength concrete which tends to be more brittle than normal-strength concrete, the traditional method is to install closely spaced transverse reinforcement so as to provide better lateral confinement to the concrete. However, the effectiveness of the transverse reinforcement gradually decreases as the concrete strength becomes higher and higher [1] and thus for high-strength concrete members, the amount of transverse reinforcement needed could be very large, thereby posing difficulties to concrete placing due to steel rebar congestion.

In view of the above problems, the concrete-filled steel tube (CFST) system has been advocated [2,3] to avoid the concreting difficulties due to steel rebar congestion and provide a more uniform and continuous confinement to the concrete core. However, despite these merits, delamination at the interface between the steel tube and the concrete core could occur at the elastic stage because the Poisson's ratio of steel is larger than that of concrete (the Poisson's ratios of steel and concrete are around 0.3 and 0.2, respectively). Such delamination would delay the development of confining stress in the concrete core, decrease the effectiveness of the steel tube confinement and even cause premature buckling of the steel tube [4]. For this reason, FRP (fiber reinforced polymer) jacketing of CFST has been proposed to restrict the lateral expansion and restrain the outward buckling of the steel tube.

A lot of effort has been spent on testing FRP jacketed CFST specimens to study the influence of shape of steel tube [5–8], thickness/diameter ratio of steel tube [9–11], concrete strength [12], FRP type [13,14] and FRP confining stiffness [15–17]. From the test results, several general observations can be made: (1) the confining stress developed in a CFST with FRP jacket is often negative or zero (negative means tension) at the elastic stage, implying that delamination could still occur even with FRP jacket provided; (2) the additional confining stress provided by the FRP jacket could substantially enhance the axial load capacity; (3) the FRP jacket could delay or even suppress the outward buckling of the steel tube; and (4) FRP jacketing is an effective means of retrofitting the structurally deficient members or upgrading the key elements in CFST structures to modern seismic design standards. However, these observations direct from the test results are mostly qualitative, lacking quantitative analysis of the actual confining mechanism in the structural system.

On the other hand, design formulas for evaluating the axial load capacity of CFST with FRP jacket have been derived [11,13,14] by modifying an existing design formula originally developed for CFST without FRP jacket [18]. However, these formulas have certain limitations: (1) There is still no general consensus on the definition of axial load capacity, especially when there is no obvious yield point

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Nomenclature

E_c	Young's modulus of concrete
E_s	Young's modulus of steel tube
E_{frp}	Young's modulus of FRP
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
t_s	thickness of steel tube
t_{frp}	thickness of FRP jacket
D	outer diameter of steel tube
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_{frp}	longitudinal strain of FRP jacket
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_{frp}	longitudinal stress of FRP jacket
$d\sigma_{z,s}^i$	incremental axial stress of steel tube at step i
$d\sigma_{\theta,s}^i$	incremental circumferential stress of steel tube at step i
$d\varepsilon_{z,s}^i$	incremental axial strain of steel tube at step i
$d\varepsilon_{\theta,s}^i$	incremental circumferential strain of steel tube at step i

in the axial load-strain curve. In practice, the use of different definitions would lead to slightly different values of axial load capacity. (2) The maximum confining stress (same as the confining stress at rupture) offered by the FRP jacket is often used to evaluate the confinement index for determining the axial load capacity. In theory, the confining stiffness and rupture strain of the FRP should be separately considered because they have different effects [19]. (3) The various design formulas do not agree with each other as they were established from different sets of test results.

Regarding theoretical modelling, Choi and Xiao [20] developed in 2010 an analytical model for predicting the full range axial stress-strain behaviour of CFST with FRP jacket by employing plasticity-based constitutive models for both the concrete and the steel tube. In this model, a rather complex numerical procedure is required to solve the total of twelve compatibility and equilibrium equations involved. In 2011, Hu et al. [10] developed a simpler axial stress-strain model for FRP jacketed CFST by employing a lateral strain model for the concrete and a plastic model for the steel tube. Perfect bond between the concrete and steel tube is assumed and the lateral strain of the confined concrete is taken as an independent variable (input as prescribed values) in the analysis. In 2012, Che et al. [11] incorporated the confining effects of the steel tube and FRP jacket by modifying the axial stress-strain curve of the confined concrete. Since the properties of the steel tube and FRP jacket are embedded in the constitutive model of the confined concrete, the lateral strain of the confined concrete and the confining stresses provided by the steel tube and FRP jacket at different stages of loading cannot be evaluated directly. In 2013, Teng et al. [21] also developed an axial stress-strain model for FRP jacketed CFST, in which the lateral strain of concrete is taken as an independent variable to be input as a prescribe value rather than a dependent variable to be solved from the other stress and strain components.

Herein, a theoretical axial and lateral stress-strain model for FRP jacketed CFST, which incorporates a lateral-to-axial strain model of confined concrete recently developed by the authors [22], an axial stress-strain model of confined concrete developed by Attard and Setunge [23], a plastic model of steel based on the associated flow rule and von Mises yield criterion, and an elastic stress-strain model of FRP, is proposed. The lateral-to-axial strain model of confined concrete which is more generally applicable has been applied to finite element analysis of cylindrical FRP confined concrete under concentric loading [24] and eccentric loading [25], non-cylindrical FRP confined concrete [26], where the lateral strain and confining stress could vary across the section. In this model, the axial strain is applied incrementally, and then the lateral strain and confining stress are evaluated by solving the equations governing the compatibility and equilibrium between the confined concrete, the steel tube and the FRP jacket. 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 on the effects of the concrete, steel tube and FRP jacket properties is carried out to evaluate the FRP confining stiffness required to eliminate steel-concrete delamination and the FRP confining stiffness required to eliminate strain softening at the inelastic stage. Lastly, an appraisal of the effectiveness of FRP jacketing is presented.

2. Proposed model for CFST with FRP jacket

In general, to analyze the axial and lateral stress-strain behaviour 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 account the stress-strain behaviour of the confining materials (in this case, the steel tube and FRP jacket).

2.1. Lateral-to-axial strain model of confined concrete

In 2013, Ozbakkaloglu et al. [27] and Tao et al. [28] suggested that further research on the lateral strain of confined concrete is needed to enable more rigorous and generally applicable analysis of concrete provided with FRP and/or steel tube confinement. In a recent study [22], the authors separated the lateral strain of confined concrete into an elastic component (lateral strain due to elastic deformation) and an inelastic component (lateral strain due to formation of splitting cracks), and by analyzing published test results covering a wide range of concrete strength, have developed a new lateral-to-axial strain model, as depicted below. As the details have been published before, only the key features are presented herein.

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