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Stress–strain model for concrete in FRP-confined steel tubular columns

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ABSTRACT

Concrete-filled steel tubes (CFTs) are widely used as columns in many structural systems. In CFTs, degradation in steel confinement, strength and ductility can result from inelastic outward local buckling. To overcome this deficiency of CFTs, external confinement of CFTs with an FRP jacket has been explored in recent studies. This paper presents a theoretical model in an incremental–iterative form for circular FRP-confined CFTs (CCFTs) under monotonic axial compression, with the focus being on the stress–strain behavior of the confined concrete. The proposed stress–strain model for concrete in CCFTs is based on the same approach as that commonly adopted by existing models for FRP-confined concrete and includes three components: (a) an active-confinement model; (b) a lateral strain equation; and (c) equations for determining the total confining pressure from the steel tube and the FRP jacket. It is shown that the lateral dilation behavior of concrete in CCFTs differs significantly from that of FRP-confined concrete in the initial stage because the former experiences more severe micro-cracking than the latter in the initial stage of loading; this difference is reflected in the proposed model. In general, the predictions of the proposed model are in close agreement with existing test results. The proposed model provides a useful tool for a parametric study on the stress–strain behavior of confined concrete in CCFTs to produce results for the formulation of simple stress–strain model in closed-form expressions for design use.

1. Introduction

Concrete-filled steel tubes (CFTs) are widely used as columns in many structural systems [1–4]. In CFTs, inward buckling deformations of the steel tube are prevented by the concrete core, but degradation in steel confinement, strength and ductility can result from inelastic outward local buckling. To overcome this deficiency of CFTs, Xiao [5] proposed a novel form of concrete-filled tubular (CFT) columns, named by him as confined CFT (or CCFT) columns in which the end portions are confined with steel tube segments or fiber-reinforced polymer (FRP) wraps. In these columns, due to the additional confinement from the FRP or steel segment, both the inward and the outward buckling deformations of the steel tube are constrained, so the ductility and strength of the column can be substantially enhanced. In addition, the concrete receives confinement from both the original steel tube and the FRP or steel segment.

Following Xiao's initial work [5], a number of studies have been conducted by Xiao and associates [6–8] as well as other researchers [9–13] on the effectiveness of FRP confinement in improving the structural behavior of both circular [7–12] and square/rectangular CFTs [8,11–13]. As part of a larger study undertaken at The Hong Kong Polytechnic University (PolyU) [14], the authors' group [15,16] has also conducted several series of axial compression tests on circular CFT columns confined with a glass FRP (GFRP) wrap. In particular, in the tests conducted by Hu et al. [16], a large number of strain gauges and transducers were employed to measure axial and hoop strains, leading to a good understanding of both the behavior of FRP-confined CFTs under axial compression and the confining mechanism for the concrete in such columns.

Despite the significant amount of existing experimental research on FRP-confined CFTs under axial compression, no theoretical model has been developed for predicting this behavior except for the model published by Choi and Xiao [17] during the finalization process of the present study. Choi and Xiao's model [17] is briefly discussed in the next section. The present study is aimed at the development of a theoretical model which can closely predict the axial compressive behavior of CCFTs, with the focus being on the modeling of the stress–strain behavior of the confined concrete. The model proposed in the present study adopts an approach which is different from and conceptually simpler than that used in Choi and Xiao's model [17].

This paper starts with a review of existing theoretical models for confined concrete in similar columns (i.e. FRP-confined concrete columns and concrete-filled steel tubes), based on which

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the rationale of the proposed model for CCFTs is explained. The proposed model is then presented in detail, and verified with test results from both the authors' group and other researchers.

2. Stress–strain models for confined concrete

Extensive research has been conducted on modeling the stress–strain behavior of FRP-confined concrete. Existing stress–strain models include design-oriented models in closed-form expressions (e.g. [18,19]) and analysis-oriented models (e.g. [20,21]) which predict stress–strain curves via an incremental procedure. Design-oriented models are based on the direct interpretation and regression analysis of experimental results, so the accuracy of these models depends on whether the test database is reliable and sufficiently large, and whether the variables selected for inclusion in the closed-form equations are reasonable and sufficient to depict the behavior of FRP-confined concrete. Obviously, existing design-oriented stress–strain models for FRP-confined concrete [18,19] are unsuitable for confined concrete in CCFTs, given the unique behavior of the latter which is subjected to confinement from both the FRP and the steel tube [16]; it is also difficult to be extend the former for accurate prediction of the behavior of the latter.

Analysis-oriented models for FRP-confined consider the responses of the concrete and the FRP wrap as well as their interaction in an explicit manner [20,21]. Most of the existing analysis-oriented models for FRP-confined concrete adopt the path-independence assumption, which means that the axial stress and axial strain of concrete confined with FRP at a given lateral strain are taken to be the same as those of the same concrete confined with a constant confining pressure (i.e. the pressure is present from the beginning of compressive loading and remains constant during the entire loading process) (referred to as actively-confined concrete hereafter) equal to that supplied by the FRP wrap. These models are thus based on a model for actively-confined concrete (referred to as an active-confinement model hereafter), force equilibrium and displacement compatibility in the radial direction between the concrete core and the FRP jacket [20]. The accuracy of this category of models consequently relies on the accurate prediction of the lateral expansion of the confined concrete (often represented by a relationship between the axial strain and the lateral strain of the concrete) and the use of an accurate active-confinement model. As analysis-oriented models capture the interaction between the concrete and the confining material in an explicit manner, they are expected to be easily extendable to concrete confined by other materials, such as concrete in CCFTs. Among the existing analysis-oriented models for FRP-confined concrete, Jiang and Teng's model [20], which is a refined version of the model proposed by Teng et al. [21], appears to be the most accurate. The empirical equation used in Jiang and Teng's model [21] for the axial strain-lateral strain relationship was shown by them to provide accurate predictions of unconfined, actively-confined and FRP-confined concretes. It should be noted that some earlier stress–strain models for concrete confined by steel stirrups (e.g. [22–23]) were also based on the approach of analysis-oriented models for FRP-confined concrete, but these models generally suffer from inaccuracy in predicting the lateral expansion of FRP-confined concrete. For example, the models given in Refs. [22,23] both employ an empirical equation based on Kupfer et al.'s test results [24] for predicting the lateral expansion of concrete, with an upper limit of 0.5 for the lateral-to-axial strain ratio. However, extensive test results have shown that the lateral-to-axial strain ratio of FRP-confined concrete can be much larger than 0.5 [20,21].

A number of stress–strain models have also been developed for concrete confined by a circular steel tube [25–29]. Most of these models [25,26,28,29] are based on the assumption that the confining pressure provided by the steel tube is constant during the loading process. With this assumption, the concrete is taken to be the same as actively-confined concrete. Although this assumption may lead to reasonable predictions for concrete confined by a carbon steel tube with a relatively low yield stress, it is obviously not suitable for concrete in FRP-confined CFTs where the concrete is subjected to continuously increasing confinement during the loading process due to the linear elastic nature of the FRP jacket [16]. For concrete confined by a circular steel tube, Johansson [27] proposed a model which accounts for the varying confining pressure provided by the steel tube. In Johansson's model [27], equations for the lateral dilation behavior of concrete are proposed for use with an active-confinement model; this model is thus based on the same approach as that of analysis-oriented models for FRP-confined concrete (e.g. [21]). As discussed above, this approach can be used to predict the behavior of concrete confined with various materials, as long as the equation for the lateral dilation behavior of concrete is accurate.

Choi and Xiao [17] proposed an analytical model for CCFTs. Choi and Xiao's model [17] also takes explicit account of the interaction between the three components (i.e. the concrete, the steel tube and the FRP jacket) of a CCFT through force equilibrium and deformation compatibility, but they adopted a plasticity-based constitutive model for the concrete. Their model therefore requires the evaluation of both elastic strains and plastic strains of the concrete for each incremental step after the yielding of concrete, leading to a relatively complex analysis process.

Based on the existing studies reviewed above, a new analysis-oriented stress–strain model is presented in the present study for concrete in CCFTs based on the same approach as used by Jiang and Teng [20] and Teng et al. [21]. The proposed analysis-oriented model adopts the path-independence assumption and is composed of the following three elements: (1) an active-confinement base model, (2) a lateral strain equation which depicts the relationship between the axial strain and the lateral/hoop strain of the concrete, and (3) a relationship between the lateral strain and the confining pressure. The first element is for predicting the stress–strain curve of actively-confined concrete, so the active-confinement model adopted in Ref. [20] can be directly employed here. Teng et al. [21] showed that their lateral strain equation provides accurate predictions for unconfined concrete, actively-confined concrete and FRP-confined concrete, so it can be expected that this equation can also work for concrete in CCFTs. For FRP-confined concrete, the relationship between the lateral strain and the confining pressure (i.e. the third element) can be easily defined because of the linear elastic nature of the FRP jacket, but this relationship is much more complicated for concrete in CCFTs as the confining pressure comes from both the steel tube and the FRP jacket and the steel tube experiences plastic deformation in a bi-axial stress state (if the effect of the radial pressure is ignored).

3. Modeling the stress–strain behavior: Model I

3.1. Perfect bond assumption

In the proposed model, it is assumed that the three components of a CCFT column (i.e. the concrete, the steel tube and the FRP jacket) are perfectly bonded at the two interfaces (i.e. the concrete/steel interface and the steel/FRP interface). As a result, strain compatibility in both the axial and the hoop directions needs to be satisfied, as depicted by the following equations:

$$\varepsilon_{x,c} = \varepsilon_{x,s} = \varepsilon_x \tag{1}$$

$$\varepsilon_{\theta,c} = \varepsilon_{\theta,s} = \varepsilon_{\theta,frp} = \varepsilon_\theta \tag{2}$$