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Axial and lateral stress–strain model for concrete-filled steel tubes

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ABSTRACT

The confining stress acting on the concrete in a concrete-filled steel tube is dependent on the lateral strain of the confined concrete whilst the lateral strain of the confined concrete is dependent on the confining stress. Hence, the lateral strain and confining stress are inter-related. Up to now, it remains a difficult task to evaluate the lateral strain of concrete confined by a steel tube and the confining stress acting on the concrete. To resolve this problem, a theoretical model for evaluating the lateral strain and confining stress in a concrete-filled steel tube system at various stages of loading is developed. The theoretical model is first applied to analyze concrete-filled steel tube specimens tested by other researchers to verify its accuracy and then used to work out the required thickness-to-diameter ratios of steel tubes for achieving different levels of ductility.

1. Introduction

Due to rapid advancement of concrete technology, high-performance concrete [1], which has high strength and high performance in other aspects, is now commonly used in the construction industry. However, a higher strength concrete is generally more brittleness and for this reason, there has been hesitation in the use of high-performance concrete with strength higher than a certain limit. To ensure minimum ductility, transverse reinforcement for confining the concrete has to be provided. But, as the concrete strength becomes higher and higher, the effectiveness of transverse reinforcement decreases and the demand of transverse reinforcement increases [2]. Moreover, closely spaced transverse reinforcement would lead to steel congestion inside the mould, thus posing difficulties in concrete casting. Therefore, it has been advocated to adopt the concrete-filled steel tube system so to provide confinement to concrete columns without causing steel congestion inside the mould.

For developing the concrete-filled steel tube system, a lot of effort has been spent on testing concrete-filled steel tube specimens to study the influence of type of steel tube [3,4], yield strength of steel tube [5,6], thickness-to-diameter ratio of steel tube [7–11], concrete strength [12–17], and bond condition [18,19] and bond strength [20, 21] at the steel–concrete interface. Several general observations can be made from the test results published in the literature: (1) Delamination at the steel-concrete interface occurs at the initial elastic stage due to the larger Poisson's ratio of steel compared to that of concrete. (2) The confining stress developed in a concrete-filled steel tube is largely dependent on the yield strength and thickness-to-diameter ratio of the steel tube. (3) The axial load–strain curve of a concrete-filled steel tube exhibits strain softening under low confinement and strain hardening under heavy confinement. (4) A higher strength concrete generally requires a larger amount of confinement to maintain the same level of strength enhancement or the same level of ductility. However, the above observations direct from the test results are mostly qualitative, lacking in-depth explanation and quantitative analysis of the confining mechanism in the concrete-filled steel tube system.

To quantify the strength enhancement arising from the provision of a steel tube, design formulas have been proposed. The design formulas given in the AS code [22] and the ACI code [23] do not consider the confinement effect and just assume that the concrete attains the peak axial stress of unconfined concrete when the steel tube yields. These formulas have been found to be grossly inaccurate and overly conservative, especially when heavy confinement is provided. To achieve better accuracy, Giakoumelis and Lam [14] refined these formulas to account for the confinement effect based on the test results of concrete-filled steel tubes with various thickness-to-diameter ratios. Later design formulas given by the AISC code [24] and the Euro code [25] include the confinement effect and are therefore more accurate. Recently, several design formulas based on a confinement factor [26,27] or a constant confining stress [28,29] have also been proposed.

The above formulas have certain limitations: (1) There is no consensus on the definition of load carrying capacity, especially when there is no obvious yield point in the axial load–strain curve. Different definitions would lead to slightly different values of load carrying capacity. (2) If it is not certain whether the steel tube is yielding, it is not possible to determine the axial load taken by the steel tube because the axial stress and lateral stress in the steel tube are not known. (3) Even assuming that the steel tube is yielding, it is not easy to determine the axial load taken by the steel tube because the steel tube is yielding under both axial stress and lateral stress.

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To overcome these limitations, study on the full range axial load–strain behaviour of concrete-filled steel tube columns has recently attracted the interest of many researchers. Ding et al. [26] proposed an elasto-plastic model to analyse the stress–strain behaviour of concrete-filled steel tube columns, in which no delamination between the steel tube and concrete is allowed and both the steel tube and concrete are assumed isotropic even after yielding and cracking. Such implicit assumptions are obviously unrealistic. Apart from this model, several other models [17,30–34] have been developed by adopting a constant confining stress, which is dependent on the yield strength and thickness-to-diameter ratio of the steel tube and some other material properties, in the post-yield analysis. But, in these models, the variation of confining stress with axial strain cannot be accurately captured.

For the sake of modelling the confinement effect in the concrete-filled steel tube system, an axial stress–strain model of confined concrete incorporating the confinement effect has been derived based on a large amount of test results by Han et al. [35]. This model was later adopted by Xue et al. [18] and Liao et al. [19] in their research. However, although the confinement effect on axial stress–strain relation of confined concrete is taken into account, the lateral strain of confined concrete cannot be determined and thus the effects of the lateral strain on the confining stress and axial stress–strain relation cannot be explicitly considered.

Herein, a theoretical axial and lateral stress–strain model for confined concrete in the concrete-filled steel tube system, incorporating a lateral-to-axial strain model of confined concrete developed recently by the authors [36], an axial stress–strain model of confined concrete developed by Attard and Setunge [37], and a plastic model for the steel tube based on the von Mises yield criterion and associated flow rule, is developed. In this model, the axial strain is applied to the concrete-filled steel tube incrementally, and then the lateral strain and confining stress are evaluated by solving the equations governing the lateral strain to confining stress relation of the confined concrete and the biaxial stress–strain relation of the steel tube. The confining stress so evaluated is substituted into the axial stress–strain model to determine the axial stress of the confined concrete. The validity and accuracy of the theoretical model are verified by comparing with published test results. Lastly, a parametric study on the effects of strength of concrete, and yield strength and thickness-to-diameter ratio of steel tube is carried out to evaluate the required thickness-to-diameter ratios for achieving different levels of ductility.

2. Proposed model for concrete-filled steel tube

In general, to analyze the axial and lateral stress–strain behaviour of confined concrete, including steel tube 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.

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

Tao et al. [38] have suggested that further research on the lateral strain of confined concrete is needed to enable more rigorous and generally applicable analysis of concrete-filled steel tube columns. In a previous study [36], the authors have separated the lateral strain of confined concrete into elastic strain (strain due to elastic deformation) and inelastic strain (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 presented below. Since the details have been published before, only the key features are presented herein.

Before the formation of splitting cracks, the concrete remains elastic and isotropic, though it may exhibit slight nonlinearity. The elastic lateral strains are given by the following equations (note that the z-direction is the longitudinal direction of the concrete column and the x- and y-directions are the lateral directions):

$$\varepsilon_x{}^e = -\nu_c \varepsilon_z{}^e + \left(1-\nu_c{}^2\right)\frac{\sigma_x}{E_c} - \left(\nu_c+\nu_c{}^2\right)\frac{\sigma_y}{E_c} \tag{1a}$$

$$\varepsilon_y{}^e = -\nu_c \varepsilon_z{}^e - \left(\nu_c+\nu_c{}^2\right)\frac{\sigma_x}{E_c} + \left(1-\nu_c{}^2\right)\frac{\sigma_y}{E_c} \tag{1b}$$

where $\varepsilon_x{}^e$, $\varepsilon_y{}^e$ and $\varepsilon_z{}^e$ are the elastic strains in x-, y- and z-directions, σ_x and σ_y are the confining stresses in x- and y-directions, E_c is the Young's modulus, and ν_c is the Poisson's ratio. For circular columns under concentric load, the lateral strain and stress are the same in all radial directions. Taking $\varepsilon_x{}^e = \varepsilon_y{}^e$ and $\sigma_x = \sigma_y = \sigma_r$, Eqs. (1a) and (1b) can be simplified as:

$$\varepsilon_x{}^e = \varepsilon_y{}^e = -\nu_c \varepsilon_z{}^e + \left(1-\nu_c-2\nu_c{}^2\right)\frac{\sigma_r}{E_c} \tag{2}$$

After the formation of splitting cracks, the concrete becomes inelastic and anisotropic. At this stage, the lateral strain $\varepsilon_x{}^T$ is taken as the summation of the elastic strain $\varepsilon_x{}^e$ induced by Poisson's ratio effect and the inelastic strain $\varepsilon_x{}^p$ induced by splitting cracks, as in the following equation:

$$\varepsilon_x{}^T = \varepsilon_x{}^e + \varepsilon_x{}^p \tag{3}$$

As reported by previous researchers [37,39], the confining stress would delay the formation of splitting cracks and restrict the widening of splitting cracks. Hence, the effects of the confining stress on formation of splitting cracks and lateral strains have to be taken into account. In their previous study, the authors have derived the following formula for the axial strain at formation of splitting cracks by analyzing the test results of both passively and actively confined concrete specimens published in the literature:

$$\frac{\varepsilon_{z0}}{\varepsilon_{co}} = \left(0.44+0.0021f'_c-0.00001f_c'^2\right)\left(1+30\exp\left(-0.013f'_c\right)\frac{\sigma_r}{f'_c}\right) \tag{4}$$

in which ε_{z0} is the axial strain at formation of splitting cracks; ε_{co} is the axial strain at peak axial stress of the unconfined concrete; f'_c is the cylinder strength of the unconfined concrete; and σ_r is the confining stress. Having determined the value of ε_{z0} from the above equation, the inelastic strain $\varepsilon_x{}^p$ may be evaluated as:

$$\varepsilon_x{}^p = -19.1(\varepsilon_z-\varepsilon_{z0})^{1.5}\left\{0.1+0.9\left[\exp\left(-5.3\left(\sigma_x/f'_c\right)^{1.1}\right)\right]\right\} \tag{5}$$

The above formula was derived by correlating the inelastic strain $\varepsilon_x{}^p$ to the post-crack axial strain $(\varepsilon_z-\varepsilon_{z0})$, concrete strength f'_c and confining stress σ_r, and conducting regression analysis of the test results of both passively and actively confined concrete specimens published in the literature.

2.2. Axial stress–strain model of confined concrete

For the axial stress–strain model, the one developed by Attard and Setunge [37], which has been shown to be applicable to a broad range of concrete strength from 20 to 130 MPa, is adopted. Its stress–strain curve is of the following form:

$$\frac{\sigma_z}{f_{cc}} = \frac{A(\varepsilon_z/\varepsilon_{cc}) + B(\varepsilon_z/\varepsilon_{cc})^2}{1+(A-2)(\varepsilon_z/\varepsilon_{cc})+(B+1)(\varepsilon_z/\varepsilon_{cc})^2} \tag{6}$$