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Effects of external confinement on structural performance of concrete-filled steel tubes

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ABSTRACT

The provision of external confinement in the forms of either FRP wraps or steel rings to concrete-filled steel tubes (CFST) would alleviate delamination at steel-concrete interface and increase both strength and ductility. To investigate the effectiveness of such external confinement, a parametric study on the effects of external confinement on the structural performance of CFST has been conducted. The axial and lateral stress-strain models of confined concrete previously developed by the authors were used in the study. The parameters studied include the concrete strength, steel tube yield strength and thickness, FRP confining stiffness and rupture strain, and steel ring yield strength and equivalent thickness, while the performance attributes evaluated include the yield strength, ultimate strength and ductility of the externally confined CFST. From the study, an equation for the minimum confining stiffness to avoid delamination is derived, formulas for predicting the yield and ultimate strengths are developed and charts for achieving Level I ductility are presented.

1. Introduction

Due to rapid advancement of concrete technology, high-strength concrete (HSC) is nowadays readily produced and commonly used. However, the relatively low ductility of HSC has aroused major concern, especially when the HSC is to be used in columns with high ductility demand. To enhance the ductility of HSC columns, the traditional method is to put in closely-spaced transverse reinforcement, which may cause steel congestion and difficulties in concrete casting [1]. To push up the limit of concrete strength that may be used without suffering from reduced ductility, the structural system of concrete-filled steel tube (CFST) has been proposed [2]. In this system, the steel tube would act as transverse reinforcement to provide confinement to the concrete core, and at the same time as permanent formwork to shorten the construction cycle and reduce the construction cost.

Somehow, owing to the higher Poisson's ratio of the steel tube compared with that of the concrete (the Poisson's ratios of the steel tube and concrete are about 0.30 and 0.18, respectively), there is an intrinsic problem of delamination at the steel-concrete interface, which would reduce the effectiveness of the confinement provided by the steel tube [3]. To resolve this problem, external confinement in the form of FRP wraps or steel rings has been advocated to restrict the lateral expansion of the steel tube when subjected to axial compression so as to restore perfect bonding between the steel tube and the concrete. Needless to say, the installation of such FRP or steel ring confinement would also enhance the confinement provided to the concrete core to improve the overall structural performance.

Throughout the years, a lot of effort has been spent on testing numerous CFST columns without external confinement to study the influence of concrete strength [4–9], type of steel tube [10,11], yield strength of steel tube [12,13], thickness-to-diameter ratio of steel tube [14–18], and bond condition and bond strength at steel-concrete interface [19,20]. Recently, extensive test programmes have been carried out on CFST columns with external confinement to study the influence of FRP confining stiffness [21–24], FRP rupture strain [25,26], steel ring yield strength [27], and steel ring equivalent thickness-to-diameter ratio [28–30]. However, the combined effects of these structural parameters on the yield strength, ultimate strength and ductility of CFST columns are rather complicated and up to now not completely quantified due to the high cost of laboratory testing.

For quantifying the strength enhancement due to the provision of steel tube and/or external confinement, various design formulas have been proposed. To predict the ultimate strength of CFST columns without external confinement, Giakoumelis and Lam [6] have refined the design formulas given in the AS code [31] and ACI code [32] by taking into account the confinement effect based on the test results of 15 CFST specimens with concrete cube strength ranging from 31 to 105 MPa, and steel tube thickness-to-diameter ratio ranging from 0.035 to 0.048. Likewise, Ding et al. [33] have also proposed a design formula to predict the ultimate strength of CFST without external confinement. It is based on an elasto-plastic analysis method, which assumes perfect bond between

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the steel tube and the concrete core (any possible delamination at the steel-concrete interface is ignored). Moreover, in the analysis, it employs the tangent stiffness which may become negative at the post-peak stage.

To predict the ultimate strength of CFST columns with external FRP confinement, Tao et al. [21] have derived a design formula by combining the formula for CFST columns without external confinement and the formula for FRP-confined concrete columns. Park et al. [34] have also proposed a design formula derived by calibrating against the test results of 11 specimens published in the literature. On the other hand, Lai and Ho [35] have proposed a design formula for predicting the ultimate strength of CFST columns with external steel ring confinement based on their own test results. In their design formula, the hoop stress in the steel tube is assumed constant and correlated to a confinement factor.

Most of these design formulas were each developed based on a limited number of test specimens with rather small ranges of structural parameters. Therefore, their applicability to CFST columns with structural parameters outside the ranges of the test specimens employed for the calibration or verification is questionable. Moreover, all these design formulas are only for the prediction of the ultimate strength, defined as the maximum axial load at failure. However, the ultimate strength might not be fully developed until the axial strain is very large (often greater than 3% in a strain hardening CFST). In practice, it should be more reasonable to define the ultimate strength as the strength that could be developed up to a certain finite axial strain in the structural design, as will be explained in more details later in this paper.

Apart from the above, several design formulas have been given in the AS code [31], ACI code [32] and EC code [36]. In the AS code, the load capacity of a CFST column is taken as the sum of the uniaxial loads of concrete and steel tube. For the uniaxial load of concrete, a coefficient of 0.85 is applied to rectangular sections and a coefficient of 0.95 is applied to circular sections. In the ACI code, a coefficient of 0.85 is applied regardless of the shape of section. In the EC code, the uniaxial load of concrete is increased by an amplification factor dependent on the steel tube thickness-to-diameter ratio and steel tube yield strength to concrete strength ratio, whereas the uniaxial load of steel tube is decreased by a reduction factor dependent on the plastic resistance to compression and elastic critical normal force.

Regarding the ductility of externally confined CFST columns, especially those cast of HSC, there is still little research. In theory, with the provision of external FRP or steel ring confinement, the ductility of CFST columns can be further increased so as to allow the use of HSC without suffering from reduced ductility. More research on the effects of FRP confining stiffness and rupture strain, steel ring yield strength and equivalent thickness-to-diameter ratio on the ductility enhancement of CFST columns is needed. Particularly, there is a necessity to develop design guidelines for achieving different levels of ductility while using HSC in CFST columns.

In this paper, a parametric study on externally confined CFST has been carried out. It was based on theoretical analysis using a lateral-to-axial strain model of confined concrete, an axial stress-strain model of confined concrete, and the actual stress-strain relations of the steel tube, external FRP wraps and external steel rings. From the parametric study, which covered wide ranges of structural parameters, the effects of external confinement on the structural performance of CFST columns were evaluated, and design formulas for CFST columns with or without external confinement were developed. Clear definitions of the yield strength, ultimate strength and ductility of CFST were adopted for rationalization.

2. Theoretical modelling of CFST columns with external confinement

For the theoretical modelling of CFST columns with external confinement, a total of four constitutive models are needed: (1) a lateral-to-axial strain model of confined concrete; (2) an axial stress-strain model of confined concrete; (3) the stress-strain relation of steel tube; and (4) the stress-strain relation of external confinement in the forms of FRP or steel rings, if provided.

The lateral-to-axial strain model of confined concrete adopted was the one developed by the authors [37] based on a large amount of test results by other researchers from actively-confined specimens (tested under triaxial compression) and passively-confined specimens (with FRP confinement) covering a wide range of concrete strength from 25 to 120 MPa and a broad range of confining stress ratio from 0 to 0.99. It takes into account the effects of axial strain, confining stress and concrete strength, and treats the elastic component of lateral strain (due to elastic deformation) and the inelastic component of lateral strain (due to formation of splitting cracks) separately. The axial stress-strain model of confined concrete adopted was the one proposed by Attard and Setunge [38], which is applicable to a wide range of concrete strength from 20 to 130 MPa and a broad range of confining stress ratio from 0 to 1.00. On the other hand, the stress-strain relation of steel was assumed to be linearly elastic and perfectly plastic without strain hardening while the stress-strain relation of FRP was assumed to be linearly elastic until rupture. Since these constitutive models have been published before, their details are not repeated here.

The above constitutive models had been applied to the analysis of FRP confined concrete [39,40] and externally confined CFST [41], and their applicability and accuracy had been verified by comparing with the test results published in the literature by other researchers.

3. Parametric study

For the parametric study, a total of 384 CFST specimens, without external confinement, with external FRP confinement or with external steel ring confinement, have been analysed to generate their axial load-strain curves. For illustration, some measured (by others) and predicted (by present analysis) axial load-strain curves for CFST specimens with external confinement are presented in Fig. 1.

In the study, several structural parameters were varied to study their combined effects: (1) concrete strength f_c' varying from 40 to 100 MPa (actual values taken as 40, 60, 80 and 100 MPa) to cover both normal- and high-strength concrete; (2) steel tube yield strength f_y varying from 300 to 600 MPa (actual values taken as 300 and 600 MPa) to cover both normal- and high-strength steel; (3) steel tube thickness-to-diameter ratio t_s/D_i varying from 0.020 to 0.060 (actual values taken as 0.020, 0.040 and 0.060); (4) FRP confining stiffness k ranging from 500 to 2000 MPa (actual values taken as 500, 1000 and 2000 MPa); (5) FRP rupture strain ε_{rup} ranging from 0.01 to 0.02 (actual values taken as 0.01 and 0.02); (6) steel ring yield strength f_{ysr} ranging from 300 to 800 MPa (actual values taken as 300, 600 and 800 MPa); and (7) steel ring equivalent thickness-to-diameter ratio t_{sr}/D_i ranging from 0.02 to 0.06 (actual values taken as 0.02, 0.04 and 0.06). The internal diameter D_i of the CFST is kept constant at 1000 mm while the height of specimen is set as 3000 mm to maintain a relatively small aspect ratio of 3.0 for avoiding buckling. The Poisson's ratio of concrete is taken as 0.18 whereas the Poisson's ratio of steel is taken as 0.30.

3.1. Minimum confining stiffness of external confinement to avoid delamination

During the parametric study, it was found that the confining stiffness of the external confinement (defined as magnitude of confining stress per circumferential strain) has great effect on the occurrence of delamination at the steel-concrete interface. Generally, at zero or small confining stiffness (with insufficient external confinement provided), delamination would occur. Such delamination would delay the development of confining stress and reduce the effectiveness of the steel tube confinement. However, at confining stiffness larger than a certain minimum value (with sufficient external confinement provided), delamination would not occur. In addition to the parametric study, the minimum