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Concrete-encased CFST columns under combined compression and torsion: Analytical behaviour

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ABSTRACT

This paper presents the analytical behaviour of concrete-encased concrete filled steel tubular members (concrete-encased CFST members for short) under the combined effects of compression and torsion, which is a typical loading condition for structural members such as bridge piers under earthquake. A finite element model (FEM) is established to account for the complex material nonlinearity and interaction, accuracy of which is verified by a set of test data. Full range analysis of the composite members under combined compression and torsion is then presented. Typical failure modes are investigated, whilst the behaviour of RC and CFST components in the composite members are compared with those of individual RC members and CFST members under the same loading condition. Parametric analysis is carried out as well to evaluate the influence of significant factors, including the material strengths, arrangement of rebars, steel ratio of inner CFST component and CFST ratio. Torsion-compression relations of concrete-encased CFST are investigated. A simplified calculation method is validated using the simulation results in order to predict the torsional capacity of axially loaded concrete-encased CFST.

1. Introduction

Concrete-encased concrete-filled steel tube (concrete-encased CFST for short) is an innovative type of composite members with favorable strength and stiffness, which has been used in high-rise buildings, industrial workshops and long-span bridges in recent years [1]. Fig. 1 shows the schematic views of concrete-encased CFST used as main columns in practice. Compared to the conventional reinforced concrete (RC) members, the capacity and ductility of the composite members are enhanced due to the existence of the inner CFST component. Meanwhile, compared to conventional CFST members, the fire resistance is improved due to the protection provided by the outer RC component. Fig. 2 gives the schematic views of typical concrete-encased CFST cross-sections, which consist of CFST component in the center and the outer reinforced concrete (RC) component. Concrete-encased CFST profiles with circular CFST components encased by circular or square RC components are focused on in the current study since they are most commonly used in practice, as shown in Fig. 2 (a) and Fig. 2 (b). In the figure, d_i represents the diameter of the inner circular CFST, B represents the width of the square section, and D represents the diameter of the circular section.

Under complex loading circumstances, structural members are often subjected to combined compression and torsion, such as building columns subjected to horizontal earthquake loading (Fig. 1a) or curved bridge piers subjected to vehicle loading (Fig. 1b). A series of tests were carried out on 20 concrete-encased CFST specimens under combined compression and torsion, in which inner CFST component and outer RC component could work together during testing. No obvious friction marks were found between those two components after being tested. A superposition method was suggested to calculate the torsional strength [2]. However, no effective 3-D finite element model has been reported for detailed analytical behaviour of concrete-encased CFST members under combined compression and torsion with extended parameters. Previously, there was some research reported on concrete-encased CFST under other types of loading, including monotonous and cyclic loading. For concrete-encased CFST under axial compression, experiments were conducted [3–5] and finite element analysis was carried out, where superposition method was introduced to calculate the axial loading capacity [6]. Flexural behaviour of concrete-encased CFST was investigated [7] whilst the behaviour under combined compression and bending was studied [8] as well. Han et al. [9] conducted experiments on concrete-encased CFST under axial tension with a FEM study proposed as well. As for cyclic loading cases, the behaviour of concrete-encased CFST is studied under cyclic lateral loading [10,11] and cyclic bending [12].

Some previous research has been carried out on the performance of individual CFST and RC members under torsion. The performance of CFST under torsion was theoretically investigated [13,14] whilst several experiments were conducted as well [15,16]. Han et al. [17] developed a

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Nomenclature

A_c	sectional area of core concrete in CFST
A_{oc}	sectional area of outer concrete
A_s	sectional area of steel tube
A_{stl}	sectional area of longitudinal rebar
B	sectional width of square concrete-encased CFST
D	diameter of circular concrete-encased CFST
d_i	diameter of the steel tube of CFST
$f_{ck,core}$	characteristic compressive strength of core concrete
$f_{ck,out}$	characteristic compressive strength of outer concrete
$f_{cu,core}$	cubic compressive strength of core concrete
$f_{cu,out}$	cubic compressive strength of outer concrete
f_{yl}	yield strength of longitudinal rebar
f_{ys}	yield strength of stirrup
f_{yv}	yield strength of steel tube
H	height of specimen
n	axial load ratio
N_o	axial compressive load
N_u	ultimate axial compressive strength of the concrete-encased CFST
$N_{u,cfst}$	ultimate axial compressive strength of the CFST
$N_{u,rc}$	ultimate axial compressive strength of the RC
s	stirrup space
T	torsion moment
t	thickness of the steel tube
T_{cecfst}	sectional torsion moment of concrete-encased CFST
T_{cfst}	sectional torsion moment of CFST component
T_{rc}	sectional torsion moment of RC component
$T_{u,cecfst}$	torsional capacity of concrete-encased CFST under pure torsion
$T_{u,cfst}$	torsional capacity of CFST component under pure torsion
$T_{u,rc}$	torsional capacity of RC component under pure torsion
γ	maximum shearing strain of steel tube
θ	rotational angle
ξ	confinement factor of the inner CFST ($=f_{yv}A_s/f_{ck,core}A_c$)
α_{cfst}	CFST ratio ($=(A_c+A_s)/(A_c+A_s+A_{oc})$)
α_s	steel ratio of the inner CFST ($=A_s/A_c$)
α_l	longitudinal rebar ratio ($=A_{stl}/A_{oc}$)

3-D finite element model to study the behaviour of CFST under torsion and the model was verified by test results. Chen et al. [18] studied the behaviour and design of thin-walled centrifugal CFST under torsion. Regarding RC members, experiments were presented to study the behaviour of RC components under complex loading conditions including torsion [19–22]. As can be deduced, the mechanism of CFST and RC members subjected to torsion is significantly different. For CFST members, the torsional capacity is mainly contributed by the outer steel tube whilst the infilled concrete prevents the steel tube from inward local buckling, inducing significant improvement in the torsional capacity and ductility [23]. The mechanism for RC members under torsion is complex. A rotating-angle softened truss model theory is commonly used to describe the mechanism of RC members under torsion, in which the contribution of concrete inside the stirrups is neglected and the members can be regarded as a truss mechanism, i.e., the longitudinal rebars act as the chord in tension and the stirrups act as the vertical web in tension, whilst the concrete between the cracks acts as the inclined web in compression [24].

The performance of concrete-encased CFST members under torsion is expected to be complex considering the nonlinearity of materials and the combined torsional mechanism of the CFST and RC components. The composite interaction between RC and CFST component distinguishes it from the conventional independent RC and CFST member. Therefore, this paper aims to investigate the analytical behaviour of concrete-encased CFST members under combined compression and torsion. A verified finite element model (FEM) is proposed and used to study the full-range behaviour of concrete-encased CFST. Based on extended parametric analysis through FEM, detailed torsion-compression relation and mechanism are developed. Finally, simplified formulae for the calculation of torsional capacity of axially loaded concrete-encased CFST are proposed and validated.

2. Finite element model (FEM)

Based on the finite element analysis of axially loaded concrete-encased CFST developed by Han and An [6], a 3-D FEM is established in ABAQUS platform in order to simulate the behaviour of concrete-encased CFST members under combined compression and torsion. Fig. 3(a) and (b) illustrate the schematic view and cross section of the finite element model. One of the key features of this model is the simulations of the three types of concrete under different confinement conditions, i.e., the outer unconfined concrete, the outer concrete confined by stirrups and the core concrete in CFST confined by the steel tube.

In this model, one endplate is fixed with all degrees of freedom restrained whilst concentrated force and rotational angle is applied on the other endplate to simulate the axial compressive load N and torsional moment T, as shown in Fig. 3(a). In the model, the concentrated force is defined in the first step and the rotational angle is defined in the following one, which is in accordance to the designed loading path illustrated in Fig. 3(c).

2.1. Description of the FEM

2.1.1. Material properties

Elastic-plastic models are involved to describe the constitutive relation of steel under the assumption of isotropic hardening. A five-stage stress-strain model proposed by Han [25] is employed to describe the uniaxial behaviour of the steel tube, as demonstrated in Fig. 4(a). A simplified two-stage stress-strain model shown in Fig. 4(b) is adopted for the constitutive model of the rebars, where E_s represents the elastic modulus of steel [25]. More details can be found in the corresponding reference.

Damage plasticity model provided by ABAQUS is adopted for the concrete material in the FEM. When no material test data is provided, the elastic modulus of concrete is taken as $4730\sqrt{f_c'}$ according to ACI 318-11 [26], where f_c' is the cylinder compressive strength of the concrete. The fracture energy model suggested by Hillerborg et al. [27] is used to account for the tensile softening of the concrete. For compressive behaviour, the material uniaxial stress-strain relations proposed by Han and An [6] for simulating the behaviour of concrete-encased CFST under axial compression are utilized, i.e., customized constitutive models are chosen for concrete under different types of confinement, as shown in Fig. 5. For outer unconfined concrete, the stress-strain model proposed by Attard and Setunge [28] is applied, shown in Fig. 5(a). For outer concrete confined by the stirrups, the stress–strain relation suitable for damage plasticity model developed by Han and An [6] is chosen, shown in Fig. 5(b). For concrete confined by the inner steel tube, the model proposed by Han [25] is adopted, in which the increasing of the plasticity depends on the confinement factor ξ, as shown in Fig. 5(c). This model has been widely used in previous research [29–31]. More details can be found in the corresponding references.

2.1.2. Element type, meshing and boundary condition

The concrete and endplates are simulated by C3D8R elements in ABAQUS, which are 3-D solid elements with reduced integration. The elements of steel tube are selected as S4R, a four-node shell element with reduced integration. The longitudinal rebars and stirrups are simulated