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# Behavior and design of slender circular tubed-reinforced-concrete columns subjected to eccentric compression

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ABSTRACT

The tubed-reinforced-concrete (TRC) column is a relatively new kind of confined reinforced-concrete (RC) columns, where the outer encasing thin-walled steel tube is discontinued at the beam–column joint and thus the axial load is transferred to the RC core only. In this paper, the behavior of slender circular TRC columns under eccentric compression loads was studied. A total of sixteen specimens considering the following primary system parameters were tested: two slenderness ratios (24, 40), two load eccentricities (25 mm, 50 mm), two diameter-to-thickness ratios of the steel tube (133, 160), and two continuity conditions for the steel tube (continuous, discontinuous at mid-height). The test results indicate that the slender circular TRC specimens exhibit fairly ductile behavior and the discontinuity of the steel tube at mid-height has a small effect (≈5% on average) on the bearing capacity. A finite element (FE) model was developed to simulate the behavior of circular TRC columns under eccentric compression loads. The predicted load versus mid-span lateral displacement curves are generally in good agreements with the measured ones. To identify the influence of the key parameters on the second order effects of circular TRC columns, an extensive parametric study was carried out using the FE model. Lastly, a regression formula is suggested to estimate the moment magnification factor and simplified design equations for slender circular TRC columns under eccentric compression loads are proposed based on the section capacity analysis.

## 1. Introduction

The tubed-reinforced-concrete (TRC) column is a special reinforced-concrete (RC) column where the closely arranged stirrups are replaced by an outer encasing thin-walled steel tube with only a few stirrups, as shown in Fig. 1. Note that the steel tube is made slightly shorter than the column and thus not passing through the beam–column joints to ensure that the axial load is transferred to the RC core only. Contrasting to the traditional RC columns (Fig. 2a and b), the steel tube in TRC columns serves two purposes: (1) Protect the concrete cover from spalling off during an earthquake event; and (2) enhance the load-carrying capacity, deformability, and seismic performance of RC columns [1,2]. In addition, the TRC columns possess higher construction efficiency than RC columns as less transverse reinforcement is needed and the steel tube can serve as the permanent formwork for concrete pouring. Compared to the traditional hollow composite steel members such as concrete filled steel tube (CFT) columns (Fig. 2b and c), the steel tube in TRC columns does not carry a direct axial load. As such, the confinement effect is maximized and the potential of local buckling in the steel tube is minimized [3–7]; Moreover, the TRC columns exhibit a better fire-resistance performance than CFT columns since the majority of reinforcing steel is embedded in the concrete [8–11].

Tomii et al. [12,13] first investigated the TRC columns in buildings to improve the shear strength and ductility of short RC columns. Priestley et al. [14,15] conducted theoretical and experimental investigations to study the effectiveness of steel jackets for retrofitting and shear strength enhancement of RC bridge columns. Sun et al. [16–18] examined the earthquake-resisting performance of square TRC columns. In their studies, the effects of the wall thickness of steel tubes and the shear span ratio of column on the seismic behavior of square TRC columns were discussed. Aboutaha et al. [19,20] experimentally investigated the cyclic response of tubed high-strength RC columns and concluded that TRC columns were more ductile and had better seismic performance than ordinary RC columns. Han et al. [21] conducted a test on thin-walled steel tube confined concrete column to RC beam joints subjected to cyclic loading and showed the good seismic

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## Nomenclature

| | |
|---|---|
| $A_b$ | cross-sectional area of longitudinal reinforcing bars |
| $A_{bi}$ | cross-sectional area of the *i*th longitudinal reinforcing bar |
| $A_c$ | cross-sectional area of concrete |
| $A_t$ | cross-sectional area of steel tube |
| $D$ | diameter of the cross-section |
| $e$ | load eccentricity |
| $E_c$ | elastic modulus of concrete |
| $f_{cu,100}$ | 100 mm cube compressive strength of concrete |
| $f_{co}$ | cylinder compressive strength of concrete |
| $f_{cc}$ | compressive strength of the confined concrete |
| $f_{ct}$ | tensile strength of concrete |
| $f_{ty}$ | yield strength of steel tube |
| $f_{by}$ | yield strength of longitudinal reinforcing bar |
| $f_{sy}$ | yield strength of stirrup |
| $f_l$ | effective lateral confining stress |
| $f_{b0}/f_{c0}$ | the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress defined in ABAQUS |
| $K$ | initial stiffness |
| $K_c$ | the ratio of the second stress invariant on the tensile meridian defined in ABAQUS |
| $L$ | length of the specimen |
| $n_b$ | number of longitudinal reinforcements |
| $N_u$ | nominal axial load-carry capacity |
| $M_u$ | nominal bending moment |
| $P_u$ | axial peak load |
| $r$ | radius of the specimen cross section |
| $r_b$ | radius of reinforcing bar circle |
| $t$ | wall thickness of steel tube |
| $u$ | lateral displacement along the column height |
| $\alpha$ | strength reduction factor in stress block method |
| $\alpha_b$ | longitudinal reinforcement to concrete area ratio |
| $\alpha_t$ | steel tube to concrete area ratio |
| $\delta$ | mid-span lateral displacement of the specimen |
| $\delta_m$ | mid-span lateral displacement corresponding to the peak axial load |
| $\varepsilon_{cr}$ | tensile strain of concrete corresponding to $f_{ct}$ |
| $\varepsilon_{co}$ | strain of concrete corresponding to $f_{co}$ |
| $\varepsilon_{cc}$ | strain of confined concrete corresponding to $f_{cc}$ |
| $\varepsilon_{tu}$ | ultimate tensile strain of concrete |
| $\varphi_i$ | angle between the horizontal line and the line connecting the centroid of the section and the centroid of the *i*th longitudinal reinforcement bar |
| $\lambda$ | slenderness ratio of the specimen |
| $\theta$ | one-half of the angle subtended at the center of the cross section by concrete compression stress block |
| $\sigma_{bi}$ | stress of the *i*th longitudinal reinforcement bar in the critical state |
| $\sigma_h$ | circumferential stress of steel tube |
| $\sigma_v$ | longitudinal stress of steel tube |
| $\sigma_z$ | equivalent stress of steel tube |
| $\xi$ | the confinement factor = $\frac{A_t f_{ty}}{A_c f_{co}}$ |

performance. Zhang and Liu et al. [22–24] carried out a series of experimental and theoretical studies to investigate the axial strength and seismic behavior of circular/square TRC columns and proposed the corresponding design methods. Zhou et al. [25] tested six short TRC columns and two ordinary short RC columns subjected to a constant axial compression load combined with lateral cyclic loading. They concluded that the confinement from the steel tube could effectively improve the brittle shear failure mode of short RC columns. Liu et al. [26,27] developed a nonlinear three-dimensional finite element model to simulate the behavior of TRC column under monotonic and cyclic loading and proposed a method to estimate the shear strength of TRC columns. Wang et al. [28,29] investigated the behavior of short TRC columns under eccentric compression loads and developed the axial force versus moment capacity interaction diagrams by modifying the parameters as used in the stress block method.

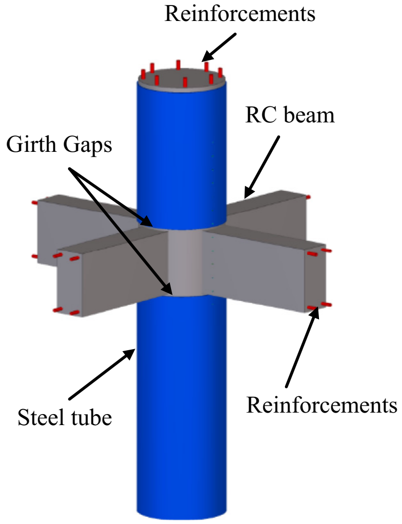

**Fig. 1.** The TRC column and beam–column connection.

To this date, there has been virtually no published literature discussing the behavior of slender TRC columns subjected to eccentric compression loads. For confined RC members, the confinement increases the bearing capacity of a section within the confinement-enhanced resistance range, but the corresponding flexural rigidity is much lower than its initial flexural rigidity [30–32]. On the basis of the recently reported work by the authors on sectional capacity of short TRC columns [28], the present paper investigates the behavior of slender circular TRC columns under eccentric compression loads.

Sixteen circular TRC specimens considering the primary parameters of slenderness ratio, load eccentricity, and diameter-to-thickness ratio of the steel tube were tested. In reality, the bending moments at the column ends are quite large under seismic effects. However, the steel tube in a TRC column resists virtually no end moment because of the shortening mentioned above. To examine the influence of the continuity of the steel tube at critical sections, specimens with an additional girth gap at the mid-height section were also included in the tests. A finite element (FE) model was developed, which predicts the results in good agreement with the experimental data. Based on the FE model, parametric analyses were carried out and the design equations accounting for the second-order effects of slender circular TRC columns were derived and are suggested in this paper.

## 2. The experimental study

### 2.1. Specimens

A total of 16 slender circular TRC columns were prepared and tested in this study. The investigated parameters of the specimens