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

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A R T I C L E I N F O

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A B S T R A C T

This paper reports the studies on the behaviors of slender square tubed-reinforced-concrete (TRC) columns under eccentric loading. Eight specimens with the key parameters of length to width ratio (6, 10), load eccentricity (25 mm, 50 mm), and width to thickness ratio of the steel tube (133, 160) were tested. The test results indicate that the slender square TRC columns exhibit good ductile behavior during the eccentric loading with a global bending failure mode. A finite element (FE) analysis model was developed and the predicted results are in fine agreement with the test results. Parametric analyses were carried out to investigate the influence of the key parameters on the moment magnification factor of square TRC columns. Based on the test and parametric analyses, a regression formula of moment magnification factor is proposed to estimate the second order effect on the slender square TRC columns subjected to eccentric compression.

1. Introduction

The tubed-reinforced-concrete (TRC) column has been gradually used in China recently due to its good structural behaviors. Fig. 1**(a)** shows a building under construction adopting the TRC columns to improve the seismic resistance of the bottom three stories and Fig. 1**(b and c)** shows the details of a TRC column and its beam-to-column connection in practical projects. The thin-walled steel tube in TRC columns does not pass through the beam-to-column connection and terminates at the column ends to avoid direct loading. This kind of constitution intends to make a better use of the steel tube for confining the concrete core [1,2]. Compared to the traditional RC columns, the TRC columns possess higher load-carrying capacity and better deformability due to the confinement [3,4]. Besides, the steel tube can effectively prevent the concrete cover from spalling off and protect the longitudinal bars from bucking in an earthquake event. The TRC columns also exhibit a good fire-resistance performance since most of the steel is embedded in concrete in the form of reinforcements [5–7].

Tomii et al. [8,9] firstly investigated the TRC columns in building structures to improve the shear strength and ductility of short RC columns, and excellent seismic behaviors of the TRC columns were observed in their tests. Sun et al. [9–12] 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 on the seismic behavior of square TRC columns were discussed. Aboutaha et al. [13,14] discovered that the rectangular TRC columns exhibited higher lateral strength and ductility than traditional RC columns while the influence on the flexural strength was slight. Liu and Zhou [15–18] conducted a series of experimental studies to investigate the static and seismic behavior of the TRC columns with circular and square sections. Wang [19,20] investigated the behavior of circular TRC columns under eccentric compression and proposed the corresponding design methods. Liu [21] investigated the behavior of short square TRC columns subjected to eccentric loading and modified the parameters in concrete stress block method for the steel-tubed concrete to calculate the sectional load-carrying capacity.

On the basis of the recently reported work by the authors on the sectional capacity analysis of short square TRC columns [21], 8 slender square TRC specimens were tested in this paper. The steel tube of the specimens is disconnected by girth gaps at the column ends and the mid-height section. The studied parameters are length to width ratio, load eccentricity, and width to thickness ratio of the steel tube. A FE model was developed to simulate the behavior of the tested columns and parametric analyses were carried out. Based the test and FE analyses, moment magnification factor is suggested to consider the second order effect on the slender square TRC columns subjected to eccentric compression.

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Nomenclature

B	width of cross-section
e	load eccentricity
E_c	elastic modulus of the concrete
E_{sec}	secant modulus of the concrete
$f_{cu,100}$	100 mm cube compressive strength of the concrete
f_{co}	cylinder compressive strength of the concrete
f_{cc}	compressive strength of the confined concrete
f_{ct}	tensile strength of the concrete
f_{ty}	yield stress of the steel tube
f_{by}	yield stress of the longitudinal reinforcing bar
f_{sy}	yield stress of the stirrup
f_{b0}/f_{c0}	ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress defined in ABAQUS
K_c	ratio of the second stress invariant on the tensile meridian defined in ABAQUS
L	length of the specimen
P	axial load
t	wall thickness of the steel tube
α_b	longitudinal reinforcements to concrete area ratio
α_t	steel tube to concrete area ratio
η	moment magnification factor
ε_{cr}	strain of concrete corresponding to f_{ct}
ε_{co}	strain of concrete corresponding to f_{co}
ε_{cc}	strain of confined concrete corresponding to f_{cc}
ε_{tu}	ultimate tensile strain of the concrete

2. Test study

2.1. Specimens

A total of 8 square TRC columns were prepared and details of the specimens are shown in Table 1, in which L is the length of the specimen, B is width of the cross section, t is the wall thickness of the steel tube, α_t is the steel tube to concrete area ratio, α_b is the longitudinal reinforcements to concrete area ratio, f_{ty}, f_{by}, and f_{sy} are respectively the yield strength of steel tube, longitudinal reinforcement, and stirrup, $f_{cu,100}$, f_{co}, and E_c are respectively 100 mm cube strength, cylinder strength, and elastic modulus of the concrete. Using the designation "S200-6–25" as an example, "S200" denotes a square TRC column with a width of 200 mm, the second number "6" denotes that the length to width ratio is 6, and the third number "25" denotes that the load eccentricity is 25 mm.

The dimensional sketch of the specimen is shown in Fig. 2. The square steel tube was cold-formed by bending the steel plate and the lines of butt weld joint were reinforced by 50 mm wide steel plate to prevent premature failure of the weld. Eight reinforcing bars with a diameter of 20 mm were symmetrically arranged in the square steel tube and the distance of between the bar's outer perimeter and tube's inner face is 15 mm. Stirrups with a diameter of 8 mm were arranged at 200 mm intervals to erect the longitudinal bars. All the specimens were cast from the same batch of concrete and layered concrete pouring process was adopted to ensure more uniform and compact concrete. Two 10 mm thick enlarged end plates were welded to the ends of each test specimen. To prevent the tube from direct axial loading, three 10 mm wide girth strips were cut off from the steel tube after the concrete was hardened. One of the strips is located at the mid-height section and the other two are located at 30 mm away from the end plates.

2.2. Test setup and instrumentation

The columns with constant eccentricity were tested under monotonically increasing axial compression using a hydraulic testing machine at the Structural and Seismic Test Research Center, Harbin Institute of Technology. An adjustable knife-edge articulation system was used to provide the required end eccentricity and the pin supports. Five linear variable displacement transducers (LVDTs) were applied to measure the lateral displacements of the specimens and four additional LVDTs to monitor the overall axial displacement. The testing device and instrumentations are shown in Fig. 3.

3. Test results

3.1. Failure mode

The failure mode of the examined slender square TRC columns was generally characterized by global bending failure with a critical section at the mid-height or 1/4-height of the columns, as shown in Fig. 4**(a-c)**. For specimens with a failure section at mid-height, no local buckling of the steel tube was observed until the load began to decline; the damage of concrete also occurred at the mid-height section, and a significant crack accompanied with several small cracks could be seen in the

(a) TRC columns in the bottom three stories (b) Details of a TRC column (c) Details of the beam-to-column connection

Fig. 1. The building using TRC columns.