Engineering Structures 56 (2013) 682–690

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Cyclic loading tests and finite element analyses on performance of ring beam connections

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ARTICLE INFO

Article history:
Received 29 August 2012
Revised 16 May 2013
Accepted 17 May 2013
Available online 4 July 2013

Keywords:
Ring-beam connection
SRC column
Cyclic loading test
Finite element analysis

ABSTRACT

A novel ring-beam connection is proposed for steel reinforced concrete (SRC) columns and reinforced concrete (RC) beams, avoiding difficult design and complex construction. The seismic performance of this ring-beam connection is investigated through experimental tests and finite element analysis (FEA). Four reduced-scale specimens were tested under cyclic loading to examine the effects of longitudinal reinforcements, stirrups and different anti-shear parts in the ring-beam connection. The results from tests show that the ring-beam connections with an appropriate design have a good seismic performance and satisfy strong connection weak beam requirement effectively. As further investigation, finite element analyses are carried out, and the analyses results agree well with the experiments.

1. Introduction

Composite structures are widely used in high-rise buildings, and an appropriate design of the beam-to-column connection is one of the key issues in the applications. In many countries, beam-to-column connections of the composite structures link steel beams and steel reinforced concrete (SRC) columns [1–3]. However, reinforced concrete (RC) beams are more commonly used in China. This is mainly because RC beams have better performances in terms of fire resistance, durability and are less expensive. On the other hand, seismic behavior of connections is always of great concern in engineering society, particularly for high-rise buildings [1,4]. Previous researches show that the seismic performance of connections is critical to maintain the stiffness and strength of the entire structure [5,6], i.e. the failure of the connection may result in structural collapse [7]. Therefore, investigations on the seismic behavior of the connections between RC beams and SRC columns are very important.

The construction details of the connection between the SRC columns and the RC beams are quite different from those for the connection between the SRC columns and steel beams [8]. Up to present, few studies have been conducted on the connections between SRC columns and RC beams. The major construction details of the connections include outside-located ring-beam connection [9,10], rebar encircled connection [11,12], rebar through connection [13,14], welded rebar connection with bracket or reinforced plate [14,15], hybrid connection [14,16] and so on. Among above construction details, outside-located ring-beam connection is very appealing because it can avoid difficult design and complex construction. However, its seismic performance has not been well studied.

A high-rise structure constructed recently in Beijing of China adopts SRC columns and concrete beams for the underground and the first floor. A new ring-beam connection was proposed and finally adopted for the project. In this paper, the configuration of the new ring-beam connection located at the bottom floor of the Beijing high-rise project is first introduced. Second, four reduced-scale specimens were designed and tested under cyclic loading, and the effects of longitudinal reinforcements, stirrups and different anti-shear parts in the ring-beam connection were examined. Finally, finite element analyses are carried out, and the analyses results are compared with the test results to investigate the accuracy of the numerical analysis to the ring-beam connection.

2. Configuration of ring-beam connection

As shown as Fig. 1a, the new SRC column-RC beam ring-beam connection located at the bottom floor is consisted of a frame beam, a ring beam and a frame column. The part of column above the ring beam is a square steel tube column filled with concrete within a certain height, while the part of column below the ring beam is a SRC column using the previous square steel tube as reinforcement. Longitudinal reinforcements and stirrups of the ring

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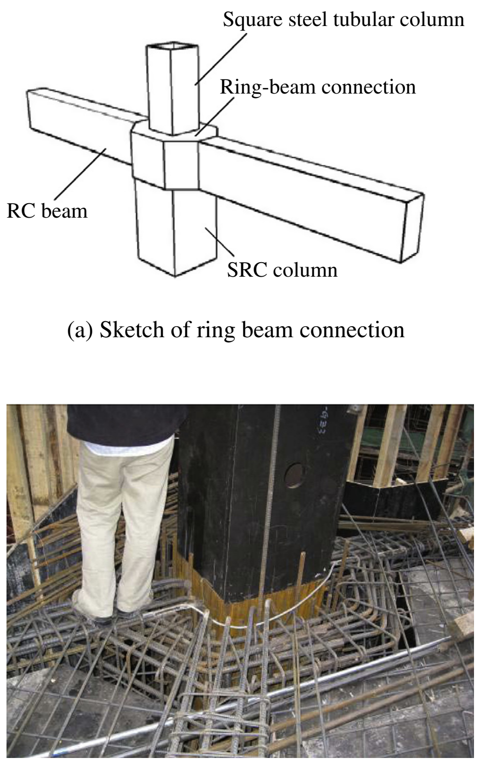
http://dx.doi.org/10.1016/j.engstruct.2013.05.033



(a) Sketch of ring beam connection

(b) Ring beam connection on site

Fig. 1. Configuration of the ring-beam connection.

beam are first assembled around the column and form a steel meshwork in which the longitudinal reinforcements of the RC frame beam and the lower part of the SRC column are anchored to. At last the structure is filled with concrete. The force transferring mechanism is as follows: shear forces and bending moments of the RC beams are first transferred to ring-beam connections and then to SRC columns. This novel ring-beam connection has the advantage to give an easy construction for which complex fabrication and hole drilling can be avoided. A photo showing the on-site construction details of the ring beam adopted in the Beijing project is given in Fig. 1b.

One of the key issues for the design of the ring-beam connection is how to realize strong connection weak beam mechanism. The design criterion used in this study is as follows (refer to Fig. 2):

$$T_{r1}\cos\theta_1 + T_{r2}\cos\theta_2 = \beta T_b \quad (1)$$

In Eq. (1), T_{r1} and T_{r2} stand for the combined force of the ring beam pulling reinforcement on each side of the column; θ_1 and θ_2 are the angles between the directions of T_{r1} and T_{r2}, and the axis of the frame beam; T_b is the combined force of the frame beam pulling reinforcement; β is the strong connection weak component coefficient, which is adopted as 1.1 for the standard connection in this study.

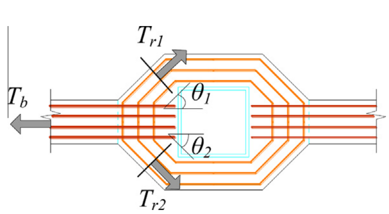


Fig. 2. Equilibrium of reinforcement forces.

3. Experimental design

3.1. Specimen

Four specimens with a reduced-scale of 1:2.57 are made to conduct the reciprocating test. They are labeled according to different arrangements of reinforcement: W-QQ, W-RZ, W-RG and W-RS. In particular, W-QQ is designed as the standard specimen in this test to verify the seismic performance of the connection in practice. The reinforcement arrangement of the frame beam and ring beam is shown in Fig. 3. According to the equal strength replacement rule, the effective area ratio of the longitudinal rebars in the ring beam to those in the frame beam is 0.75:1. The reinforcement of the column and the structure of the encased steel are shown in Fig. 4. In order to study the failure mode of the connection and the function of the reinforcement and stirrups in the ring beam as well as studs on the surface of the encased steel, each of the other three specimens differs from W-QQ. W-RZ just reduces half of the longitudinal rebars in the ring beam on the basis of W-QQ to investigate the influence the longitudinal rebars have on the seismic performance. W-RG reduces half of the stirrups in the ring beam on the basis of W-QQ to investigate the effect of stirrups on seismic performance. Since it is not convenient to install studs on the encased steel, W-RS has the same arrangement than W-QQ but changes the studs with a spacing of 150 mm into shear rings set in interval of 100 mm to investigate their influence. The specific characteristics are shown in Table 1.

3.2. Material test

Coupon tests are conducted on the rebars before the connection test and their average strengths are given in Table 2. The encased steel is made of Q345B steel and the average strength of 8 mm thick steel plate is 335 MPa. On the same day when the tests are conducted, concrete cubes of 150 mm × 150 mm × 150 mm are tested and their average strengths have been converted to the axial compressive strength as seen in Table 3. It should be noted that concrete strength in the SRC column is higher than in the ring beam and the frame beam.

3.3. Loading device and loading system

The loading device is shown in Fig. 5. The column is hinged at both ends and a jack of 500t is set on the top of the column to simulate the axial force applied on the column. Four jacks of 60t are set in both sides of the frame beam ends which are 1600 mm away from the column axis to simulate the reciprocating seismic load.

The loading scheme is as follows: (1) an axial force of 1900 kN is first exerted on the top of the column, which corresponds to a 0.3 axial force ratio of the steel column, to simulate the effects of gravity; (2) the two ends of the beam are loaded asymmetrically, the loadings are controlled by force before yielding, the force amplitude is increased by 10 kN per cycle, and the yielding displacement is obtained; (3) the loads are controlled by displacement after yielding and the amplitude is set to *Dy*, 2*Dy*, 3*Dy*, 4*Dy*... note that *Dy* indicates the yielding displacement and two reciprocating loadings are conducted for each amplitude; (4) loading is ended when the displacement of beam end reached 1/40 of the beam length, which is slightly larger than the maximum allowable displacement prescribed in Chinese seismic design code.