Engineering Structures 126 (2016) 432–445

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic performance of fiber-reinforced concrete interior beam-column joints

Xing-wen Liang *, Ying-jun Wang, Yi Tao, Ming-ke Deng

Department of Civil Engineering, Xi'an University of Architecture and Technology, Yanta Road 13#, Xi'an 710055, China

ARTICLE INFO

Article history:
Received 25 July 2014
Revised 2 August 2016
Accepted 3 August 2016

Keywords:
Beam-column joint
Fiber-reinforced concrete
Quasi-static test
Seismic performance
Numerical simulation

ABSTRACT

Fiber-reinforced concrete (FRC), as an advanced alternative to normal concrete, has been increasingly used to construct beam-column joints which is one of the most congested parts of reinforcements in reinforced concrete (RC) structures because of its potentially beneficial properties. The present work aims to investigate the seismic performance of FRC beam-column joints experimentally and numerically. A total of eight beam-column joints, including both FRC beam-column joints and RC beam-column joint, were conducted to explore its seismically important features under quasi-static reversed cyclic load, mainly including the failure modes, hysteretic response, energy dissipation, stiffness degradation. It was found that the application of FRC can effectively improve the seismic performance of beam-column joints because it leads to higher load-carrying capacity and a greater deformation capability prior to the formation of the major diagonal cracks in the joint core zone. A numerical study, using the Open System for Earthquake Engineering Simulation (OpenSEES), was also conducted to study the seismic performance of beam-column joints deeply after its applicability and accuracy being validated with test data. The prediction from the proposed numerical model shows a good agreement with test data. Furthermore, a parametric study was generated to address and evaluate the effects on the seismic performance of FRC beam-column joints from different parameters, including the axial load ratios, transverse reinforcement ratios and FRC compressive strength. The results indicate that the increment of axial load ratios and FRC compressive strength can enhance the load-carrying capacity.

1. Introduction

Beam-column joints in RC frame structures under earthquake-induced lateral deformation are generally subjected to a large shear action that leads to serious damage and stiffness degradation of the structures. In order to provide a good seismic performance, the structural components, such as, beam-column joints, must possess enhanced deformation capability and damage tolerance. Several pioneers have devoted to investigate the seismic performance of RC joints under shear reversals [1–3], whose achievements have been contributed to unveil design guidance issued by some institutes [4,5]. The previous researches have shown that beam-column joints with good deformation capability in frame structures can deliver a positive contribution to the seismic performance of structures. The current Chinese design guidance, GB 50010-2010 [5], focuses on the following three aspects to secure the earthquake-resistance capacity of beam-column joints: (1) defining the minimum transverse reinforcement ratio and diameter, as well as the maximum transverse reinforcement spacing in the joint core zone; (2) limiting the dimensions of the joint core zone to associate the sizes of beam and column; and (3) specifying the anchorage of reinforcements passing through the joint core zone in terms of length and configuration. Meanwhile, a strong column-weak beam requirement needs to be satisfied.

Beam-column joints, which are usually expected to experience greater reversed cyclic action such as an earthquake, need to be properly designed to provide a sufficient deformation capability. Severe reinforcement congestion and construction difficulties thus may occur once the longitudinal reinforcements in both beams and columns are settled as well. Furthermore, it may either lead to a larger column and/or beam sections or a greater amount of smaller diameter bars being used in order to satisfy the minimum anchorage length requirements crossing the joint core zone, which could deteriorate the reinforcement congestion or construction difficulties.

The seismic design of structures has evolved towards a performance-based design method in recent years. Therefore, there

* Corresponding author.
E-mail addresses: liangxingwen2000@163.com (X.-w. Liang), yingzikd@126.com (Y.-j. Wang), taoyi01@gmail.com (Y. Tao), dengmingke@126.com (M.-k. Deng).

http://dx.doi.org/10.1016/j.engstruct.2016.08.001
0141-0296/

is need for new structural members and systems that possess enhanced deformation capability and damage tolerance without complex reinforcement arrangements. The development of highly damage-tolerant beam-column joints would allow moderate shear distortions in the joint core zone, reduce rotation demands in plastic hinge zone of beam ends, and avoid seismic strengthening of the joint core zone. One option for achieving this goal is to use FRC [6,7] to upgrade the deformation capability of beam-column joints. Experimental studies [8,9] have proved that an improved seismic performance can be achieved, in terms of the shear-critical members such as beam-column joints, squat walls, coupling beams, and flexural members subjected to high shear stress by using FRC.

The objective of this study is to verify the feasibility of FRC as a replacement of normal concrete used in the joint core zone, adjacent beam end and column end, to increase stirrup spacing, reduce steel reinforcement congestion as well as construction difficulty of the joint core zone without reduction of load-carrying capacity and deformation capability by the usage of FRC, to study the influence of axial load ratios of column top on the general performance of FRC specimens, and to verify the numerical simulation results by experimental data and produce a comprehensive parametric study by using OpenSEES [10]. The present work builds upon the limited earlier work in the literatures to investigate the contribution of FRC material in enhancing the seismic performance of beam-column joints during earthquake excitation and to analyze the parameters influencing the seismic performance of FRC beam-column joints.

2. Research objectives and significance

Under seismic actions, the joint core zone is in tension on one diagonal direction of the joint and compression on other diagonal direction, so the joint core zone easily happens to shear failure, which causes collapse of whole structure. By the usage of FRC, the seismic performance of whole structure can be improved.

The main objective of this research is to investigate the structural behavior of beam-column joints by substituting normal concrete with FRC in the joint core zone, adjacent beam end and column end, and reducing the amount of transverse reinforcements in the joint core zone, to investigate the influence of axial load ratio of column top on the structural behavior, as well as to analyze the influence of main parameters on the structural behavior of FRC beam-column joints by numerical simulation. The study aims to improve seismic performance of FRC beam-column joints, including load-carrying capacity, energy absorption capacity and stiffness degradation.

The outcome of this study would be helpful to support the ongoing theory calculation model study of FRC beam-column joints [11,12] and their effective use in structural applications. It will be particularly helpful to make use of local materials to prepare FRC, improve seismic performance of structures, reduce property loss and secure the safety of life.

3. Review of related literatures

During the past 40 years, a limited number of researches [13–25] have been conducted to verify whether normal concrete can be substituted with FRC in the joint core zone, plastic hinge zone of beam end and column end, and the transverse reinforcements of the joint core zone can be reduced without reduction of load-carrying capacity and deformation capability. A brief overview of the study done and the main results reported in four of the most relevant studies are as follows.

In 1977, Henager [13] conducted FRC beam-column joints to reduce reinforcement congestion of the joint core zone. Experimental results indicate that the damage tolerance and crack resistant of FRC beam-column joints is better than that of RC beam-column joints.

In 1994, Filiatrault et al. [14] conducted four full-scale exterior beam-column joints with steel fiber reinforced concrete in the joint core zone. Experimental results indicate that steel fiber reinforced concrete is a promising material to substitute conventional confining reinforcements, the joint shear strength by the usage of steel fiber can be improved and the transverse reinforcements of the joint core zone can be reduced.

In 2005, Parra-Montesinos et al. [15] conducted two approximately 3/4 scale high-performance fiber-reinforced cement composites (HPFRCCs) beam-column joints with a small axial load corresponding to approximate 4.0% of the column axial load capacity and without transverse reinforcement in the joint core zone to evaluate the adequacy of the proposed joint design for use in zones of high seismicity. HPFRCC material was used in the joint core zone and adjacent beam regions over a length equal to twice the beam depth. Experimental results indicate that HPFRCC beam-column joints have excellent damage tolerance under large shear reversals, deformation capability, and bond capacity between beam longitudinal reinforcement and surrounding HPFRCC material even though the joint design did not satisfy minimum anchorage length requirements specified in the ACI Building Code. In addition, the ACI joint shear stress limit of $5/4\sqrt{f'_c}$ (MPa) can be also safely used in HPFRCC joint without transverse reinforcements.

In 2014, Qudah and Maalej [16] conducted nine one-third scale Engineered Cementitious Composites (ECC) beam-column joints, with different transverse reinforcement spacing and arrangement in the plastic hinge zone of beam end, column end, and/or joint core zone and without axial load on the top of column to evaluate the feasibility of enhancing performance by substituting normal concrete and partial transverse reinforcements with ECC. Experimental results indicates that the usage of ECC material as a replacement of normal concrete and partial replacement of transverse reinforcements can significantly enhance shear resistance, energy absorption capacity and cracking response, and reduce reinforcement congestion and construction complexity of the joint core zone.

In summary, the results of these studies are encouraging. However, a large amount of experimental evidences are required before the reasonable calculation model of FRC beam-column joint is determined and these proposed special designs can be applied in practical projects widely.

4. Experimental program

4.1. Description of specimens

In the present study, a total of eight 1/2 scale beam-column joints, namely, FRCJ1–FRCJ7 representing FRC specimens and RCJ1 representing RC specimen, were constructed and tested. In terms of FRC specimens, FRCJ1 was the control specimen and the others were constructed with representative characteristics. Specimen RCJ1 was casted using normal concrete for comparison.

Fig. 1 illustrates detailing of geometry and reinforcement configuration in the beam-column joints. Ends of columns and beams were points of contra-flexure. All columns have a cross section of 250 × 250 mm with a total height of 2000 mm and the transverse beam has a cross section of 150 × 300 mm with a total length of 2650 mm. Longitudinal reinforcements in the columns consisted of 4⌀16 bars (a diameter of 16 mm and the grade HRB400 steel), and those for beams consisted of 3⌀16 bars top bars and 3⌀16 bottom bars. Transverse reinforcements in columns, beams and joint core zone consisted of 6 mm-diameter reinforcement.