Engineering Structures 159 (2018) 320–331

Contents lists available at ScienceDirect

Engineering Structures

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

Numerical study on a fully-prefabricated damage-tolerant beam to column connection for an earthquake-resilient frame

Kailai Deng[b,*], Tao Wang[a], Masahiro Kurata[c], Canhui Zhao[b], Kangkang Wang[b]

[a] Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, CEA, Harbin 150080, China
[b] Department of Bridge Engineering, Southwest Jiaotong University, Chengdu 610031, China
[c] Disaster Prevention Research Institution, Kyoto University, Kyoto 6110011, Japan

ARTICLE INFO

Keywords:
Earthquake resilience
Fully-prefabricated construction
Beam to column connection
Ultra-high-performance concrete
Parametric analysis

ABSTRACT

Seismically resilient structures are appealing because any damage can be quickly repaired and the structures can soon be reoccupied. In the present paper, a novel fully-prefabricated beam to column connection was proposed. A composite ultra-high-performance concrete (UHPC) joint and a friction damper were employed to connect a beam to a column using the proposed joint. All components were connected using bolts, which are convenient for quick replacement. Under earthquake excitation, deformation was mainly concentrated in the friction damper. The composite UHPC joint sustained little or no damage, owing to its small section height and excellent crack resistance. Numerical analyses were conducted using commercial finite element software, ABAQUS, to obtain the seismic performance of the beam to column connection. The effects of various parameters of the composite UHPC joint and the friction damper were investigated. According to the analysis, the beam to column connection delivered satisfactory mechanical characteristics and damage tolerance. Detailed design suggestions for the beam to column connection are provided.

1. Introduction

In recent years, several extreme earthquake events have occurred, including Wenchuan (2008) and in China, Kobe (1995) and Tohoku (2011) in Japan. The continuity of society and business activities has been found to be the key to quick recovery of earthquake-affected areas [4,11]. Buildings are important carriers of urban functions. However, steel-framed structures designed according to the displacement-based design method often sustain significant damage in earthquakes. Reconstruction requires enormous time and money. Earthquake-resilient structures, designed to minimize earthquake damage and allow rapid repair after earthquakes, have emerged as one of the frontiers in earthquake engineering [8,6].

Moment-resisting frames are widely used in middle- and high-rise buildings. Following the capacity design or structural fuse concept, earthquake damage is only acceptable on special components that are designed to provide adequate energy dissipation capacity or to be easily replaced. Au [1] introduced a vertical gap between pre-cast reinforced concrete (RC) beams and columns where a gap makes the sectional height of the interface quite small, resulting in the slight crack under earthquake excitation. Rojas et al. [13] tested a connection with friction device, Koetaka et al. [9] tested the Pi damper in the beam-column connection for column weak axis, and Lin et al. [10] simulated the seismic behavior of the friction connection based on a large scale hybrid test. With appropriate materials and detailing, friction devices and dampers could exhibit stable hysteretic performance under large drift ratio and fulfill the requirement to structural fuses. Cassianola et al. [2] suggested the European seismic design criteria allowing the enhancement on structural ductility and the control of damage distribution. According to the above studies, earthquake damage on beams are moved away from the column face toward the beams through special configurations. As the previous studies suggest, the structural fuse concept and the plastic hinge relocation is effective in structural seismic control but the probable damage of the slab located in the plastic hinge region have not been fully addressed. To earthquake resilient structures to be fully realized, due consideration on secondary members such as floor slab should be paid.

Meanwhile, with the development of high-performance materials, such as reactive powder concrete (RPC), ultra-high performance concrete (UHPC) and engineered cementitious composite (ECC), etc., the crack resistance of structural components have been significantly improved. Shao et al. [14] proposed the composite deck system with RPC layer, which have the initial crack stress larger than 10 MPa. Cui et al. [5] developed steel fiber reinforced cementitious composites slab for

* Corresponding author.
E-mail address: Kailai_deng@163.com (K. Deng).

https://doi.org/10.1016/j.engstruct.2018.01.011
Received 24 August 2017; Received in revised form 4 January 2018; Accepted 5 January 2018
0141-0296/

the beam to column connection in steel frame. According to Yoo's study, the UHPC slab had evidently larger initial crack strength as well as the nominal tensile stress compared with the RC components [16]. Qudah and Maalej [12] applied the ECC in the bream-column connection to improve the shear strength and energy absorbing capacity. With the application of UHPC material, the composite UHPC deck provided the excellent crack resistance and significant enhancement on the nominal tensile stress compared with traditional RC deck [17]. These high performance materials present great potential in reducing seismic damage, especially in the plastic hinge region.

Based on the previous studies, this research proposes a novel fully-prefabricated beam-to-column connection in a steel frame structure. A composite UHPC joint and friction damper connects a beam and column using high-strength bolts. Employing the UHPC material in the expected plastic hinge region, the crack in the designated plastic region is limited within the acceptable level under maximum considered earthquake (MCE). Owing to the fully-prefabricated structure, the repair or replacement of the composite UHPC joint is quite convenient. The friction damper is installed below the composite UHPC joint, where it seldom disturbs building function. To allow convenient and rapid repair, and correction of any residual deformation, the bolts supporting the friction damper can be easily released, quickly decreasing the stiffness and bearing capacity of beam to column connection. After the restoring of the main structure, the friction damper can be activated by tightening the bolt.

To investigate the seismic performance of the novel beam to column connection, numerical analyses including 21 finite-element models were carried out. The deformation and damage modes, load-carrying and energy dissipation capacities were obtained, demonstrating the satisfactory seismic performance of the beam to column connection. Some important design parameters of the composite UHPC joint are discussed based on the parametric analysis. Finally, design suggestions for the beam to column connection are presented to meet the requirement of earthquake resilient frame structure.

2. Configuration of beam to column connection

Fig. 1a presents the structure of the proposed beam to column connection. The prefabricated steel column and composite beam are connected by a short composite UHPC joint and a friction damper. No on-site wet construction is needed during the assembly process. The detail structure of friction damper is also shown in Fig. 1c. Two cast iron plates clamp one steel plate through the high strength bolts. The four movable bolts could slip in the long hole in the steel plate. By adjusting the tension force of the four movable bolts, the friction force can be easily controlled. The friction damper is designed to sustain only axial force so that it is pin-connected to the column and beam by ear plates. Thus, the shear force from the composite beam is mainly carried by the composite UHPC joint. The composite UHPC joint and friction damper bear the beam bending moment by axial forces. Thus, the beam to column connection can provide adequate stiffness and load-carrying capacity in ordinary service. Under earthquake excitation, relative

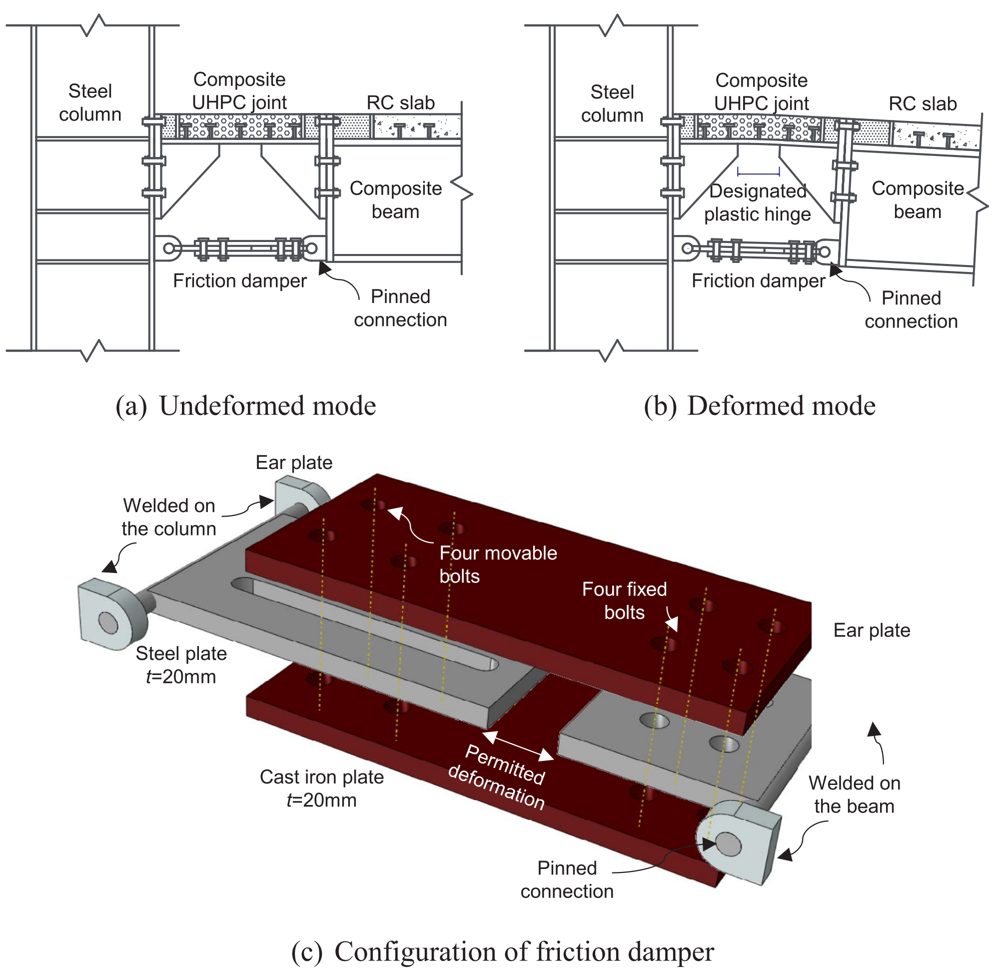

Fig. 1. Configuration of prefabricated beam to column connection.