Journal of Constructional Steel Research 95 (2014) 90–105

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental research and cyclic behavior of buckling-restrained braced composite frame

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ARTICLE INFO

Article history:
Received 3 May 2013
Accepted 23 November 2013
Available online 29 December 2013

Keywords:
Buckling-restrained brace
Concrete-filled steel tube
Composite frame
Cyclic behavior
Welded splices connection

ABSTRACT

The pseudo-static tests (PSTs) of one 1/3 scale 2-story 1-bay buckling-restrained braced composite frame (BRBCF) system consisting of concrete-filled circular hollow section (CHS) steel columns, steel beams and BRBs were tested in Harbin Institute of Technology, a same bare composite frame (CF) was tested to compare with BRBCF. The test BRBCF exhibited excellent performance and sustained no strength or stiffness degradation during the significant drift demands imposed by the subsequent quasi-static cyclic test, which possessed good ductility and energy dissipation capacity. Compared with CF system, the stiffness, load-bearing capacity and energy dissipation capacity of BRBCF system increased evidently. The welded splices beam–column-BRB connections are cheap joints and are convenient to install BRBs in construction site, the experiment demonstrated their ability to withstand major ductility demands. The BRBs didn't show global buckling, local buckling and fracture of inner cores. Test also found the damage in beam–column–BRB connections region, including fractures of the gusset and beam welds, local buckling of flanges and webs of beams and enforced loops due to frame and brace action forces, which should be considered in the design of BRBCF. For frames using the proposed gusset connection, the maximum frame drift prior to failure will be governed by the rotational capacity of the beam-to-column connection, not the axial deformation of the BRB. The fracture and buckle of CHS steel tubes at the first story base indicated the thickness of CHS steel tube of composite columns in BRBCF should be enlarged to avoid the early failure of composite columns.

1. Introduction

Steel braces are used as an economic means of providing lateral stiffness to a steel structure. However, the ductility and energy dissipation capacity of a steel braced structure subjected to earthquakes are limited due to buckling of braces with unsymmetrical mechanical behavior in tension and compression. The braced frame typically exhibits substantial deterioration of strength when loaded in compression monotonically or cyclically. If the buckling of a steel brace is restrained and the same strength is ensured in both tension and compression, stable performance of braces will be assured and the ductility and hysteretic behavior will be improved [1–3]. The buckling-restrained brace consists of a steel core encased in a steel tube filled with concrete. The steel core carries the axial load while the outer tube, via the concrete (buckling–restraining mechanism), provides lateral support to the core and prevents global and local buckling. A thin layer of unbounded material along the steel core at the concrete interface eliminates shear transfer during elongation and contraction of the steel core and also accommodates its lateral expansion in compression. It is the ability of the steel core to contract and elongate freely within the confining steel concrete-tube assembly that leads to the name unbounded brace (UB). Results from past studies [2–6] showed that BRBs can undergo fully-reversed axial yield cycles without loss of stiffness or strength, which exhibits similar yielding and ultimate strength and good seismic energy dissipation, and the ultimate ductility and cumulative plastic ductility of that are quite beyond demand.

A 0.7-scale one-bay one-story Buckling-Restrained Braced Frame (BRBF) was tested under cyclic displacement histories by Aiken et al. [7] at the University of California, Berkeley. Cracks occur in the beam, column, beam–column–brace connections and gusset plates due to torsional buckling of the beam and out-of-plane displacement of the BRBs. Tsai et al. [8,9] conducted two tests on big-scale BRBFs at the National Center for Research on Earthquake Engineering (NCREE). Long brace-gusset plate connection of BRBs leaded to buckling of gussets at story drift of 0.01 rad. The cyclic behaviors of five full-scale one-bay one-story BRBFs were tested by Christopulos [10]. BRBs were connected to the frame with gusset plates and bolts; and beams were connected to the columns with single-plate shear tabs. The beams and columns close to BRB connections yielded and buckled, and then BRBs failed. Roeder et al. [11] conducted the tests of five full-scale one-bay one-story BRBFs at the University of Washington. The performances of BRBFs were influenced by gusset plate geometry, type of bolted

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http://dx.doi.org/10.1016/j.jcsr.2013.11.021

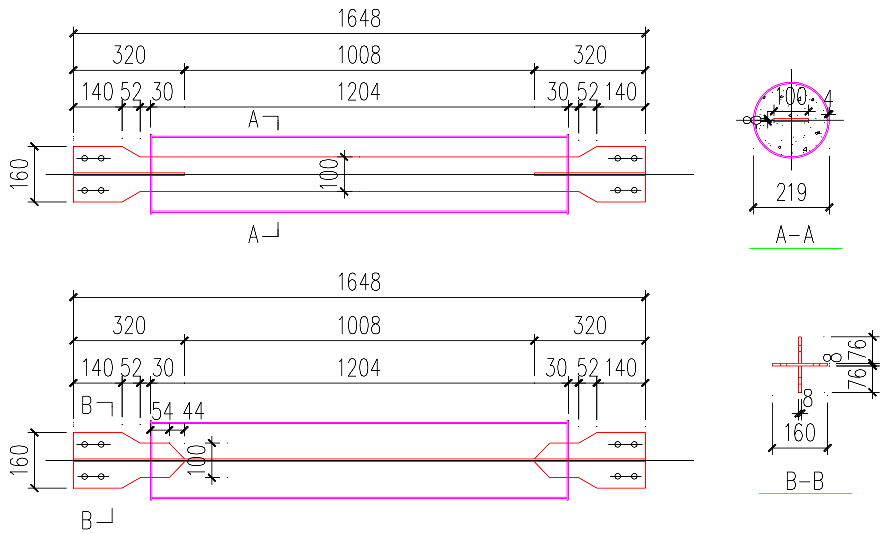

Fig. 1. Details of BRB specimens.

brace–gusset plate connection, and orientation of the BRB core plate. Failures of BRBFs were attributed to out-of-plane distortion of the BRB at story drift ratio between 0.022 and 0.024. Fahnestock and Victoria [12] did the experimental research of a 0.6-scale four-story BRBF by using hybrid pseudo-dynamic earthquake simulations and quasi-static cyclic loading. The beams were connected to beam stubs using bolted web splices and BRB were pinned to gusset at beam–column joints. During the earthquake simulations, the frame did not exhibit substantial deterioration of strength and stiffness at a story drift ratio of 0.48. The test was finished when yielding segments of inner core of BRBs fractured. It is concluded that the frame with proper design had the ability to withstand severe earthquake and maintain its load-bearing and deformation capacity. It is found that one main failure mode of BRBF is the fracture of beam–column–brace gusset welds due to frame action. A four-story BRBF tested by Victoria and Fahnestock [13] was analyzed based on a three-dimensional FE mode in ABAQUS, which was calibrated with test results. The influences on global structural response and local connection demand for different types of connection configurations are studied. BRBFs may not allow the braces to realize their full ductility capacity due to connection failure modes. Connection configuration is shown to have a significant impact on global system response and localized connection demand.

Chou and Chen [14] proposed an inelastic plate buckling equation together with coefficient charts to predict ultimate load of gusset plate connections of BRBF. Free-edge stiffeners welded to central gusset plates were demonstrated to be an effective way to increase yielding load or post-yield strength of gusset plate connections. The dual gusset plates sandwiching a BRB core reduce gusset plate size, eliminate the need for splice plates, and enhance connection stability under compression. Chou and Liou [15] conducted the experimental and nonlinear finite element analysis program to investigate ultimate compression load and bending rigidity by testing ten large dual-gusset-plate connections used for BRBFs. The ultimate compression load of the dual-gusset-plate connection was reasonably predicted by suggested computation model. A design procedure which considers both frame and brace action forces on the corner gusset connections was proposed by Chou and Liu [16]. The research of Chou and Liu [17] found that without free edge stiffeners, the single corner gusset plate buckled at a significantly lower strength and the buckling could be eliminated by using dual corner gusset plates similar in size to the single gusset plate. At low drifts, the frame action force on the corner gusset was of the same magnitude as the brace force. At high drifts, however, the frame action force significantly increased and caused weld fractures at column-to-gusset edges.

Jeffrey [18] proposed a novel connection where the gusset is only connected to the beam and is offset from the column face. A three-story frame with the novel connection was tested under quasi-static cyclic loading. The connection can withstand 3% frame drift and the

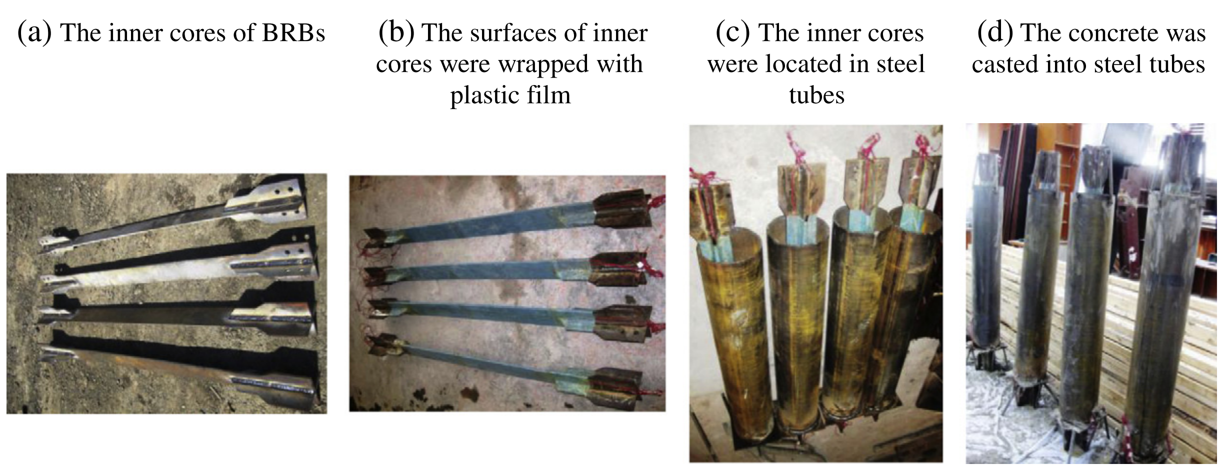

Fig. 2. Fabrication of BRB specimens. (a) The inner cores of BRBs, (b) The surfaces of inner cores were wrapped with plastic film, (c) The inner cores were located in steel tubes, (d) The concrete was casted into steel tubes.