Journal of Constructional Steel Research 66 (2010) 1354–1365

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

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

Tests and analyses of a full-scale post-tensioned RCS frame subassembly

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ARTICLE INFO

Article history:
Received 16 November 2009
Accepted 26 April 2010

Keywords:
Post-tensioned self-centering frame
Cyclic test
Analytical model
Time-history analysis

ABSTRACT

A series of cyclic tests of a full-scale one-story two-bay specimen frame, a substructure of a three-story post-tensioned (PT) self-centering (SC) building using reinforced concrete columns and steel beams, were conducted in the Taiwan National Center for Research on Earthquake Engineering. The objectives of the tests were: (1) to examine the connection performance, progress of damage, and strength degradation of the frame, (2) to assess the hysteretic responses of the frame subjected to various loading patterns, and (3) to study the effects of column restraints on the frame expansion. Time-history analyses of the three-story PT building subjected to the design basis earthquake (DBE) and the maximum considered earthquake (MCE) were conducted to investigate seismic demands of the proposed system. These tests confirmed the SC response of the PT frame and explored failure of the beam compression toe, which was never observed in prior tests of beam–column subassemblages. The nonlinear structural analysis computer program PISA could be used to simulate the experimental results well; time-history analyses of the three-story building showed that the proposed frame can meet seismic demands by MCE level ground motions.

1. Introduction

In the past few decades, mixed steel–concrete structural frames have gained popularity in the construction of buildings. These frames are named as RCS (reinforced concrete steel) systems with steel beams and reinforced concrete columns. In the US and Japan, RCS frames have been developed as an alternative to typical reinforced concrete construction for buildings because of (1) reductions in concrete form work, (2) increased space availability by enlarging beam spans, and (3) economics in construction by using precast subassemblies [1–3]. Special consideration is given to detail RCS connections where the steel beam runs continuous through the concrete column to form an integral component (Fig. 1(a)). The light steel column embedded inside the concrete column is used for erection loads only, and the RCS connection, which is distinct from the more typical SRC (steel reinforced concrete) connection [4,5], is designed to transfer large forces between the steel beam and the concrete column. Test data confirmed that the cyclic performance of well-designed RCS connections can achieve high levels of interstory drift (i.e. 4%). The maximum strength is controlled by either (1) local buckling of the beam flanges and web that occur after significant yielding in the hinge region outside the column face, or (2) shear yielding of the steel web panel and compression failure of concrete in the connection. Significant strength reduction and residual deformation are typical behaviors at the end of connection tests.

The connection configuration in this study is shown in Fig. 1(b), where the post-tensioning strands are utilized to compress the steel beams against the concrete column. A reduced flange plate (RFP), which was proposed by Chou and co-workers [6–9], is incorporated in the connection to increase energy dissipation. The size of the RFP is determined based on expected moment of the RFP at a target drift, where a maximum tensile strain in the narrowest section is limited to 0.1 [9]. Slotted holes near the column face are used to allow for pass of bolts for connecting the T-shaped stiffener and the beam flange and have no adverse effects on the energy dissipation based on the prior studies [7,9]. This detail eliminates the embedment of a steel beam in the connection, improving the constructability of traditional RCS connections in the field. The post-tensioned (PT) connection also decreases residual deformations by the elastic responses of PT strands and steel beams. Many researchers have experimentally validated the self-centering (SC) behaviors of PT connections with gap-opening, closing at the beam-to-column interface [7–12]. Ricles et al. [10,11] utilized PT strands as the SC element and angles as the energy-dissipating element to eliminate field welding and reduce residual deformations of steel moment connections. Cyclic

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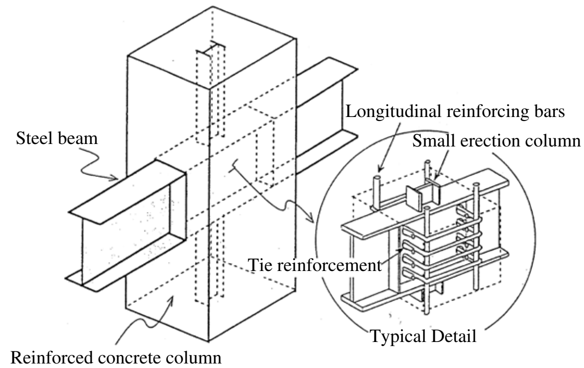
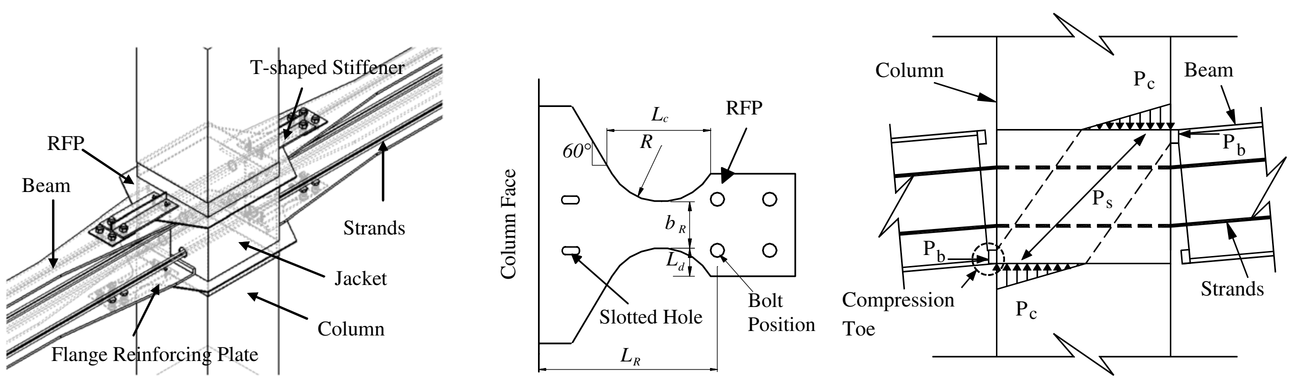
0143-974X/$ – see front matter
doi:10.1016/j.jcsr.2010.04.013



(a) Traditional RCS connection [3].



(b) PT beam–column connection and RFP details.

(c) Concrete strut in connection.

Fig. 1. Beam–column connection details.

tests demonstrated SC hysteretic responses of the PT connection, and frame dynamic analyses showed superior seismic performance in PT frames than in moment-resisting frames (MRFs) with typical welded connections. Christopoulos et al. [12] tested a PT connection with energy-dissipating bars, successfully eliminating permanent damage of energy-dissipating devices after cyclic loads. A flag-shaped hysteretic response of the PT connection could be simulated analytically by using rotational springs in the beam–column joint.

When the gap opens at the beam-to-column interface, the concrete slab if it does not open along the column lines produces restraints to PT connections, altering the SC capability [13]. Garlock et al. [14–16] suggested the collector beams or bays to transfer floor inertia forces to the PT frame and accommodate frame expansion. Kim and Christopoulos [17] proposed details along the boundaries of the slabs that allow for the gap-openings to be accommodated and elimination of the restraints to PT connections. Recently, Chou et al. [9] demonstrated that the PT connection with a continuous composite slab self-centers with low residual deformations as long as negative connection moments provided by slab reinforcements are considered in design. Chou et al. [18] also showed similar cyclic responses between a bare PT connection and a composite PT connection with a discontinuous composite slab, which opens freely along with the gap-opening at the beam-to-column interface.

The approach in seismic design, developed under the US PRESSS program coordinated by the University of California, San Diego [19,20] for precast concrete buildings with SC connections, was verified from a 3/5 scale five-story self-centering concrete test building. The SC behavior of the test building was extremely satisfactory without significant strength loss up to drift levels of 4.5%. This post-tensioning technology was successfully extended to steel MRFs by shake table tests of a 1/3 scale one-story two-bay frame [21]. A recent project focusing on the design and experimental performance of a steel SC-MRF was conducted at the Lehigh University [22]. The test structure for the experimental program was a 3/5 scale four-story two-bay SC-MRF. The static and pseudo-dynamic tests of this SC-MRF showed the self-centering capability of the frame and good energy dissipation of the web-friction device as observed in the connection test [23]. Sake table tests with a 1/3 scale steel MRF and SC-MRF also demonstrated that the maximum interstory drifts of the SC-MRF specimen are similar or slightly higher compared to those in the MRF specimen [24]. Tests conducted on large- or full-scale post-tensioned self-centering frames were rather limited. Thus, to understand system performance, a full-scale one-story two-bay PT frame (Fig. 2) was designed, built, and tested at the National Center for Research on Earthquake Engineering (NCREE), Taiwan. The three-story prototype building was designed for a high seismic location in either Taiwan or the US. The bay width was 5 m and the first-story height was 3.92 m. Several quasi-static load tests were conducted to cyclically load the frame to large drifts to examine the performance of the frame. This paper describes the detailed experimental observation, including damage of the beam and the RFP that occurred during the tests, and discusses an analytical computer model made after the tests for the correlation study. Inelastic time-history analyses of the prototype building subjected to 15 ground motions are conducted to examine seismic demands of the proposed frame at the design basis earthquake (DBE) and the maximum considered earthquake (MCE) levels.

2. Test program

2.1. Design of a prototype building

A procedure proposed by Garlock [14] was adopted to design a three-story PT prototype frame, which is required to self-center at the DBE and MCE earthquake levels. Fig. 2 shows the plan and