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Behavior of a steel coupled beam moment frame based on nonlinear analyses

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ABSTRACT

A steel coupled beam moment frame (CBMF) is an innovative seismic resisting moment resisting frame that is composed of coupled beams and steel columns. A coupled beam features a pair of steel beams, post-tensioning elements, and energy dissipation devices. Coupled beams can be fabricated in shop and pin-connected to columns on site, facilitating the field construction. Energy dissipation is provided by a special energy dissipation device, not by damage to the main structural members or to the energy dissipation device itself. Rotations at beam–column joints are the result of a relative slide mechanism of the coupled beams, not the result of beam plastic hinges. During unloading, the force in the PT elements eliminates coupled beam relative slide as well as rotations at beam–column joints, offering the potential of minimal residual rotations to coupled beam–column connections. This paper presents conceptual details, conceptual behavior, and design considerations for CBMFs. For behavior study, a prototype building using CBMFs as the lateral resisting frames was designed. A nonlinear analysis model for the prototype building was created. Static pushover and cyclic push analyses were conducted to assess the concepts. Dynamic time history analyses using a 44-ground motion record set were performed to study the post-earthquake residual story drift and residual connection rotation response of the prototype CBMF building. Analysis results showed that the global behavior and connection response of the prototype CBMF supported the conceptual behavior and design considerations, and that post-earthquake story drifts and connection rotations of the prototype CBMF building are ignorably small.

1. Introduction

Increasing ductility has been an important design philosophy for conventional steel moment resisting frames (MRFs) for decades after the 1994 Northridge earthquake. However, conventional MRFs per current design practice are designed as intended to develop ductile plastic hinges for energy dissipation during earthquakes. After dissipating energy, these plastic hinges leave permanent deformations in structural members and permanent rotations at beam–column connections (i.e., damage). Research on steel moment connections [1–6] had shown that higher ductility resulted in larger permanent deformations and rotations (i.e., more severe damage). A building or MRF with damaged members and connections is usually out-of-plumb [7–9] and is unsafe for use. Damaged members might be repairable; however, rebuild rather than repair an out-of-plumb building might be more economic [10,11].

To eliminate permanent connection rotations and lateral drifts of steel MRFs, innovative post-tensioned moment connections [12–20] were developed. They were characterized by gap opening at beam–column connections of MRFs. Field construction of the MRFs with post-tensioned moment connections is challenging [21]. Accommodating the gap opening requires either yielding in members of gravity bearing frames [22] or a complete change in the gravity bearing frame design and construction method [15,23]. A building with undamaged lateral resisting frames and yielded gravity bearing frames might still require repair. In addition, challenging field construction efforts and complete changing in design for both lateral resisting and gravity bearing frames hamper the potential for these innovative post-tensioned moment connections of being widely used in practice.

This paper presents a new steel MRF system: coupled beam moment frame (CBMF) system. A CBMF system offers advantages in both constructability and damage-free behavior over current MRF systems. The scope of this paper is to: (1) present conceptual details, behavior, and design considerations for CBMFs; (2) assess the concepts using results of static analyses from a nonlinear model for a prototype CBMF building; and (3) study post-earthquake story drift and connection rotation response using results from dynamic time history analyses.

2. Coupled beam moment frame description

A CBMF, as schematically shown in Fig. 1, is composed of steel columns and coupled beams. The columns and coupled beams are pin-

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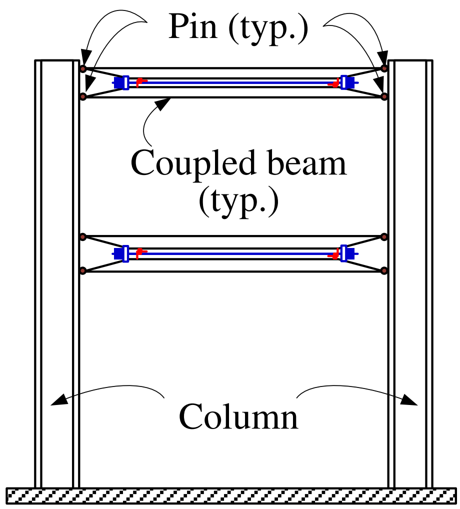

Fig. 1. Schematics of elevation of one-bay CBMF.

connected at the joints. The pins that connect the coupled beams to the columns are denoted beam–column pins. A coupled beam, as shown in Fig. 2(a), is composed of two wide flange beams (denoted WF beams), PT elements, and energy dissipation (ED) devices. Each couple of WF beams is configured with one placed on the top of the other. Each of the WF beams is cropped at beam ends, as shown in Fig. 2(a), to form an appropriate angle. When a beam–column relative rotation occurs (see Fig. 2(b)), the angled beam ends provide a space for the columns to rotate without contacting the WF beams at the locations other than the beam–column pins. During a beam–column relative rotation, a horizontal relative slide (see Fig. 2(b)) that occurs between the top and bottom WF beams enables the relative rotation. Thus, beam–column relative rotations of a CBMF are not a result of plastic hinges as formed in the beams of a conventional MRF. Fig. 2(c) illustrates a conceptual detail of a beam–column pin connection, which includes two steel plates welded to the column face, a cropped beam web plate, and a pin passing through these three plates. This detail is similar to clevis pin connections commonly used in practice that permit rotational mechanism at joints.

PT elements are placed between and parallel to the WF beams and anchored at the beam ends on the shorter flange using floating anchor plates as shown in Fig. 2(a). Fin plates as shown in Fig. 2(a) and (d) are welded on the shorter flange of the WF beams. During a horizontal relative slide, the floating anchor plates are supported by the fin plates and moved along with the contacted flange, stretching the PT elements as shown in Fig. 2(b).

Energy dissipation devices are placed between the WF beams on the shorter flanges as shown in Fig. 2(a). Frictional ED devices (FEDs), rather than yield-type ED devices, are used in the present study for the purpose of avoiding permanent inelastic deformations (i.e., damage) and preventing replacement usually required for yield-type ED devices. A FED [15–21] is consisted of sandwiched steel plates and bolts as illustrated in Fig. 2(e). Energy dissipation by a FED is activated when a relative slide occurs.

3. Conceptual behavior

3.1. CBMF base shear-roof drift

The conceptual behavior of a CBMF is presented using the base shear (V_{base}) roof drift (θ_{rf}) response in Fig. 3. The limit states of a CBMF include imminent relative slide, member yield, and PT element yield. The first softening point is expected to occur when imminent relative slide (IRS) limit state is attained. The second and third softening points occur at column base yield (CBY) and PT ultimate strength (PTU) limit states, respectively. The base shear at IRS limit state is denoted V_{IRS}, which is used later for prototype CBMF design.

3.2. Connection moment-relative rotation

The conceptual moment-relative rotation ($M-\theta_r$) behavior of a coupled beam–column moment connection is shown in Fig. 4. Two softening points due to IRS and PTU limit states are expected. PTU limit state is attained at large θ_r. When M reaches the imminent relative slide moment (M_{IRS}), the top and bottom WF beams slide relatively to each other, and θ_r initiates. After θ_r initiates, using the free body diagram for the column as shown in Fig. 5 and summing moment about the coupled beam centerline point projected on the column (denoted C_b in Fig. 5), M can be calculated as follows:

$$M=\left(F_{bot}-F_{top}\right)d_1 \tag{1}$$

where F_{bot} and F_{top} are the forces in the bottom and top beam–column pins, respectively; d_1 is the moment arm from C_b to F_{top} or F_{bot}. Using

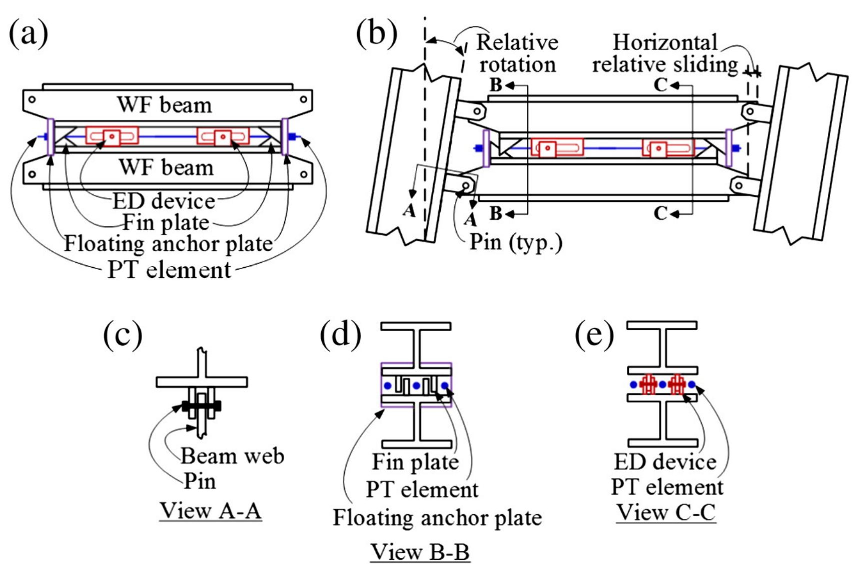

Fig. 2. Schematics: (a) coupled beam before relative slide; (b) coupled beam during relative slide; (c) beam–column pin connection; (d) floating anchor with fin plates; (e) sandwiched FED device.