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Structural evaluation of steel self-centering moment-resisting frames under far-field and near-field earthquakes

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ABSTRACT

The design formulations, structural performance, and energy-based results of steel buildings of self-centering moment-resisting frames (SC-MRFs) with post-tensioned (PT) connections of three different energy dissipation devices including bolted top and seat angles, beam bottom flange friction devices, and bolted web friction devices are investigated under far-field and near-field earthquakes. The results of nonlinear time-history analysis using DRAIN-2DX program show that the simplified analysis used to estimate the inertial forces distributed through collector beams is not sufficiently precise since it leads to the underestimation of design beam axial forces and connection moments in exterior bays. The overestimation of design displacement demands of SC-MRFs with bottom flange friction devices results in bigger sections of beams and columns than are necessary. In addition, this SC-MRF system is not as effective as other two systems to dissipate the input energy. It is recommended to symmetrically use beam flange friction devices to achieve higher level of energy dissipation and lower fabrication costs. On the other hand, SC-MRFs with web friction devices is identified as the most efficient system to minimize the recoverable energy and SC-MRFs with top and seat angles provides medium level of energy dissipation. Different from far-field earthquakes, the input energies of SC-MRF structures under near-field ground motions are distinguishable by hikes of maximum values at the early stages of earthquakes. Furthermore, absolute energy components are substantially higher than relative energy components under near-field earthquakes. These phenomena should be considered in the formulations of energy factor and energy-based design procedures of SC-MRF systems.

1. Introduction

In seismic regions, remarkable amount of energy released from strong ground motions contributes to over-deformation, damage or even collapse of the structures. Therefore, the input energy of seismic loadings to structures should be appropriately dissipated to minimize the risk of failure. Housner [1] has introduced the concept of energy-based analysis to design the earthquake-resisting structures. The energy-based approach has been implemented as an alternative methodology to the conventional design based on force approach [2,3]. Benavent-Climent et al. [4] and Surahman [5] have investigated the aspects of design parameters based on energy approach and various sets of earthquake excitation records. Mollaioli et al. [6] have assessed the seismic design based on balance of dissipated energy and absorbed energy. Leelataviwat et al. [7] have modified the energy-based formulations regarding the elastoplastic single-degree-of-freedom (SDOF) system to incorporate the inelastic properties of structures and developed the interaction between earthquake characteristics and system nonlinearity by an energy factor that can be associated with the deformation and strength indices. Jiang et al. [8] have calculated the structures energy demand using the energy factor and introduced a procedure of pushover analysis based on the energy balance concept. Ke et al. [9] have developed the energy factor for steel self-centering (SC) systems and evaluated it for SDOF systems under near-field earthquake excitations. They have shown that hysteretic nonlinear parameters have substantial effects on this energy factor [9]. Further investigations are still required to develop a comprehensive energy-based seismic design procedure and evaluate the influence of different earthquake properties on this energy factor for steel SC structures.

Steel moment-resisting frames (MRFs) are capable to withstand severe earthquakes. In recent years, widespread research have been conducted to study the behavior of steel self-centering MRFs (SC-MRFs) with post-tensioned (PT) beam-to-column connections. The main characteristic of PT connections under lateral loadings is the gap-opening at beam-column interface. In general, PT connections include high-strength steel strands or bars and energy dissipation devices. Steel strands or bars provide SC-MRF with self-centering capability returning it to the primary position without residual drift before the earthquake and the input seismic energy is dissipated by damping devices. As a

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result, SC-MRFs take advantage of minimum repair by concentrating damage to energy dissipation devices during severe earthquakes. The PT connections with top and seat angles as energy dissipation devices bolted to column and beam flanges have investigated in various research [10–14]. Garlock et al. [15] have provided a step-by-step method to design SC-MRFs with this type of PT connection under earthquake. Wolski et al. [16] have proposed SC-MRFs with PT connections made up of friction devices that are only installed at beam bottom flange. Zhang et al. [17] have evaluated a prefabricated PT connection that consists of friction device bolted to beam web, three components of the PT connection including vertical plates, steel strands, and beam are considered as a single beam.

Furthermore, other types of practical energy dissipaters have been proposed for PT connections. Christopoulos et al. [18] have investigated yielding devices including steel bars in confinement of steel cylinders welded to the interior surfaces of beam flanges to eliminate interferences with the floor slab. Rojas et al. [19] have introduced friction devices consisting of brass-steel surfaces located on beam flanges. Chou et al. [20] have assessed PT connections with buckling-restrained reduced flange plates in steel beam to concrete-filled tubular column under cyclic loadings. Kim and Christopoulos [21] have used a friction device at the beam flanges resulting in stable hysteretic behavior of PT connections. Tsai et al. [22] have studied PT connections with bolted web friction devices reliably dissipating energy under extreme loadings. Chou and Lai [23] have used a PT connection including steel plate set up at the beam bottom flange as energy dissipater yielding under earthquake. Vasdravellis et al. [24] have numerically investigated hourglass-shaped energy dissipating device placed between beam flanges to eliminate beam damage under seismic loadings, and have experimentally examined the behavior of the proposed PT connection [25]. Tzimas et al. [26] have studied SC-MRFs with this kind of energy dissipaters and viscous dampers near fault areas to reduce the risk of collapse. In addition, U-shaped steel damper has been proposed as energy dissipation devices of PT connections [27].

In this research, middle-rise buildings of SC-MRF systems with three different types of PT connections are analyzed under far-field and near-field ground motions to evaluate design process, structural performance, and energy-based results of steel structures with SC-MRFs and represent their capabilities to dissipate the input energy from two types of earthquakes.

2. Evaluation of steel buildings with SC-MRF systems

Prototype office steel buildings of five-story and seven-bay have been considered to study the design formulations, structural performance and energy-based responses of SC-MRF systems subjected to far-field and near-field earthquakes. Steel buildings with SC-MRFs including three different types of PT connections proposed by Garlock et al. [15], Wolski et al. [16], and Zhang et al. [17] have been analyzed.

2.1. Design of SC-MRFs with PT connections

The SC-MRFs with PT connections have been designed based on the reference studies [15–17]. The details of selected PT connections are shown in Fig. 1.

The first system namely SC-MRFs (1) with PT connections includes bolted top and seat steel angles as yielding devices to dissipate the earthquake input energy as represented in Fig. 1(a), the step-by-step design process of SC-MRFs (1) is given in Garlock et al. [15]. The second prototype building of SC-MRFs (2) with PT connections consists of beam bottom flange friction devices including brass-steel plates as shown in Fig. 1(b). This PT connection has been designed according to the research conducted by Wolski et al. [16]. Fig. 1(c) represents the PT connection of the next selected system as SC-MRFs (3). This prefabricated PT connection includes different bolted web friction device. The single beam consists of three main connecting components of beam, vertical plates, and PT strands. The reference research carried out by Zhang et al. [17] provides the design procedure for such PT connection in SC-MRFs (3).

The following assumptions have been adopted in the design of prototype buildings with SC-MRFs: (i) Equivalent lateral forces (ELF) based on IBC 2000 provisions [28] for SC-MRFs considered as special MRFs are applicable. (ii) The prototype buildings consisting of five-story and seven-bay with five-bay perimeter SC-MRFs with PT connections as shown in Fig. 2 are office buildings established on hard rock conditions in Los Angeles, California. (iii) The material types of steel components include ASTM A416 G270 [29] with the yield stress assumed as 90% of the ultimate stress for steel strands with the area of 140 mm^2 each, ASTM A490 G50 [30] for high-strength steel bolts, and ASTM A572 G50 [31] with the yielding strength of 345 MPa for the other structural members. (iv) Following the gap-opening at the beam-column interface, the beams in PT connections rotate as rigid-body around the neutral axis. (v) Coefficient of friction for energy dissipaters in SC-MRFs (2) and SC-MRFs (3) has been assumed 0.40 on the basis of experiment conducted by Petty [32] on brass plates sandwiched between steel plates. (vi) The axial stiffness for the whole length of steel strands is constant. (vii) The occurrence of gap-opening in PT connections at the beam-column interface is unrestrained and has been considered the same in the bays of each floor. (viii) The inertial forces of earthquake have been transmitted to the SC-MRFs through the collector beams. (ix) The shear forces in interior columns are the same. (x) The shear forces in exterior columns are the same and half of that in the interior columns. (xi) The design dead loads for floors and roof are 5.28 kPa (110 psf) and 4.32 kPa (90 psf), respectively.

The design procedure of buildings with steel SC-MRFs has been described as follows. The comprehensive details of SC-MRFs design have been provided in Garlock et al. [15]. The structural amplified code-based demands of the prototype buildings have been quantified for the seismic input level of maximum considered earthquake (MCE). The MCE ground motion is considered to have a 2% probability of exceedance in 50 years [33]. The damages to the buildings of SC-MRFs undergone the MCE level should satisfy the performance level of collapse prevention (CP) in which the buildings are on the brink of partial or complete collapse [34].

Initially, the design demands of prototype buildings have been estimated as those with special MRFs using ELF procedure of IBC 2000 provisions [28]. The design live loads have been applied based on ASCE/SEI 7 [35]. The response modification factor of 8 has been used to determine design base shear in ELF procedure [28]. The beam and column sections should satisfy the strong column-weak beam principle as well as the slenderness limits of web and flange for compact members described in AISC Seismic Provisions [36]. The beams have been laterally braced according to AISC Seismic Provisions [36]. The floor system satisfy the requirements of lateral bracing. The linear elastic analysis of the steel MRFs with fully-rigid connections has been carried out by SAP 2000 [37] to check if the limit of maximum story drift [28] is satisfied based on ELF corresponding to design base shear, and the beam and column sizes have been iteratively modified to finally meet the limitation of story drift [28]. The selected section of collector beams are required to satisfy the strength and stiffness criteria [15]. The structural demands of prototype buildings have ultimately determined based on amplified code demands for the MCE input level. The period correction factors used for displacement demands (roof displacement, story drift, and relative rotation of PT connections) of SC-MRFs (1), SC-MRFs (2), and SC-MRFs (3) for the MCE level have been calculated 0.589, 0.607 and 0.562, respectively, and the damping ratio of 5% has resulted in the damping correction factor of 1.0. Furthermore, the base shear demands for the MCE have been determined using the overstrength factor of 2.5 [38]. After the design moments of PT connections at the beam-column interface have been determined, the design parameters of PT connections including the initial post-tensioning force and number of strands (based on the assumption of strands with the area of 140 mm^2 each)