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Modeling and seismic collapse resistance study of a steel SC-MRF

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ABSTRACT

A self-centering (SC) moment resisting frame (MRF) is an alternative to a conventional steel special moment resisting frame (SMRF) with welded beam-to-column connections for seismic-resistant steel frame buildings. The beams in an SC-MRF are post-tensioned to the columns by high strength post-tensioning (PT) strands that are oriented parallel to the beams, providing restoring forces to control gap opening at the beam-column interface. Little is known about the collapse resistance of SC-MRFs under extreme seismic ground motions. Incremental Dynamic Analyses (IDA) are performed to determine the collapse margin ratio of a 4-story low-rise steel building with perimeter SC-MRFs. The structural model for the SC-MRF for the IDA includes shell finite elements to enable important limit states, including local buckling in the beams, to be included in the analyses. The results from the IDA show that the collapse resistance of an SC-MRF system is comparable to that of a conventional steel SMRF.

1. Introduction

Conventional steel special moment resisting frames (SMRFs) use fully restrained welded connections between the beams and columns. SMRFs are designed to dissipate energy under the design earthquake by yielding in the main structural members. This yielding can lead to significant inelastic deformations and plastic hinges in the beams, leading to permanent structural damage as well as large residual story drifts following the earthquake. To avoid such structural damage and residual drift, post-tensioned beam-to-column connections for self-centering (SC) moment resisting frames (SC-MRFs) were proposed by Ricles et al. [1]. In these SC-MRFs, energy is dissipated by special energy dissipation devices, rather than by inelastic deformations in the structural members. This innovative lateral resisting system provides both a softening mechanism to the frame without structural damage, a SC capability that leads to minimal residual drift under the design earthquake.

In an SC-MRF, the beams are post-tensioned to the columns by high strength post-tensioning (PT) strands oriented parallel to the beams, as shown in Fig. 1. A web friction device (WFD), shown in Fig. 1, is the energy dissipation device utilized in the connection. The WFD is made of a pair of channels, a set of friction bolts and friction brass plates sandwiched between the channels and beam web. Reinforcing plates welded on the outside faces of the beam flanges are used to avoid excessive yielding in the beam flanges from bearing stresses at the beam-to-column interface during gap opening and along the beam due to the combined flexural and axial forces imposed on the beam. The column flange shim plates shown in Fig. 1 are attached to the column flange to provide good contact between the beam and column flanges.

Several variations of beam-to-column connections for SC-MRFs with post-tensioning (PT) and various types of energy dissipating devices have been proposed by Christopoulos et al. [2], Garlock et al. [3], Rojas et al. [4], Tsai et al. [5], Kim and Christopoulos [6], and Wolski et al. [7]. Previous studies focused mainly on SC beam-to-column connection behavior in subassembly experiments under cyclic pseudo-static loading. In the experimental work performed by Chou et al. [8], Kim and Christopoulos [6], and Garlock [9] the test specimens were loaded to their ultimate capacity. During these tests, local buckling was observed in the beam flanges and web, causing beam shortening, loss of PT force and subsequent loss of moment capacity of the connection. The local buckling was identified as an important limit state that leads to a deterioration in strength and stiffness. Kim and Christopoulos [10] suggested the need for analysis models that include continuum (brick) finite element (FE) to fully capture the cyclic response of SC connections at their ultimate drift levels, where local buckling of the beams may be expected to occur. They developed a solid FE model which captured the beam local buckling response of SC connection subassembly specimens tested under cyclic loading by Kim and Christopoulos [6]. Comparisons with test results demonstrated that the FE models accurately predicted the hysteretic behavior of the connection, including beam local buckling.

To experimentally investigate the performance of an SC-MRF designed in accordance with a performance based design (PBD) procedure, a 0.6-scale 4-story 2-bay SC-MRF with post-tensioned connections

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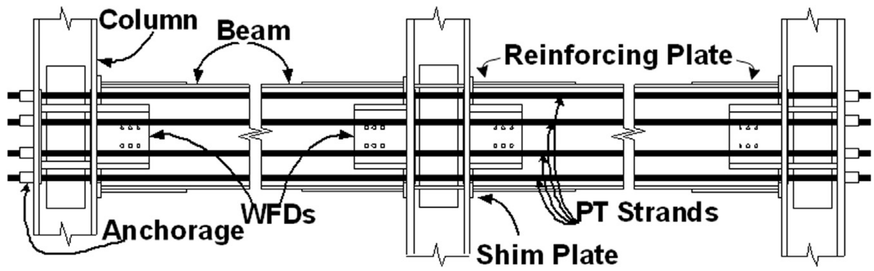

Fig. 1. Schematic of Elevation of a 2-bay SC-MRF with SC-WFDs (adapted from Lin [18]).

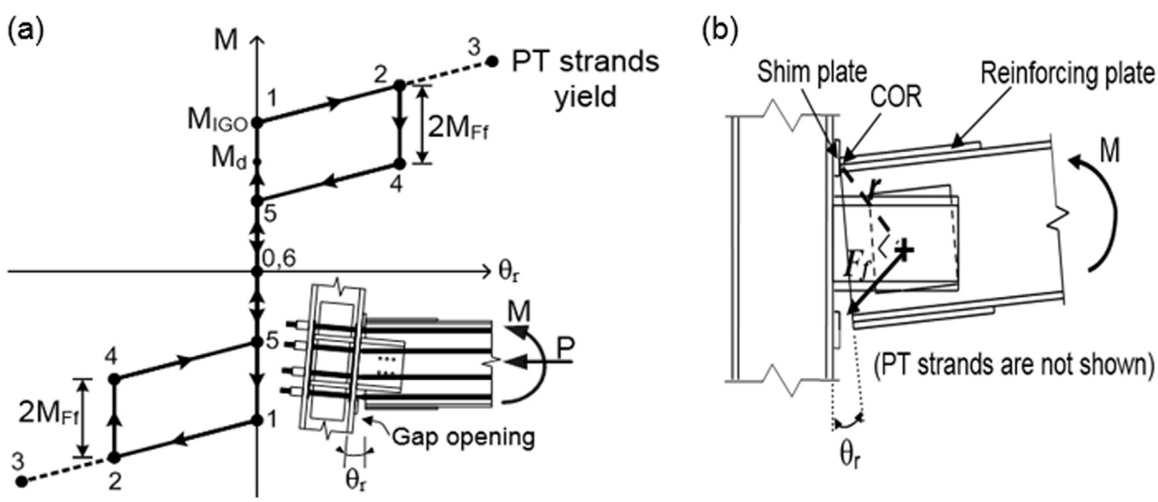

Fig. 2. SC-WFD connection: (a) conceptual moment-relative rotation (M-θ_r) behavior; and, (b) illustration of beam-to-column connection rotation (adapted from Lin [18]).

with web friction devices (WFDs) was designed and tested by Lin et al. [11,12]. Using the hybrid simulation method, the SC-MRF was subjected to a series of ground motions corresponding to the design basis earthquake (DBE) and the maximum considered earthquake (MCE). The DBE intensity is equal to two-thirds the MCE intensity, where the former has an approximate 10% probability of being exceeded in 50 years, and the latter has a 2% probability of exceedance in 50 years [13]. For the DBE and MCE simulations, beam flange and web local buckling did not occur. However, tests that imposed drift associated with seismic demands beyond the MCE resulted in beam local buckling and subsequent loss of PT force. The experiments by Lin et al. [11,12] showed that SC-MRFs can be designed to provide SC response and sustain only minor damage under the DBE and MCE, and that the ultimate response of the SC-MRF is governed by beam local buckling and subsequent loss of PT strand force.

Although past research has demonstrated that, under the design earthquake, a properly designed steel SC-MRF provides softening behavior without significant inelastic deformation and structural damage and provides reliable SC response with negligible residual drift, a comprehensive understanding of the collapse resistance of the SC-MRFs under extreme earthquake ground motions is lacking. Pirmoz and Lui [14] performed numerical studies to investigate the progressive collapse resistance of steel SC-MRFs. Their study was limited to the effects of redistributing gravity loads due to column removal. Guo et al. [15] performed numerical simulations and seismic fragility analysis of the 4-story self-centering steel MRF tested by Lin et al. [11,12]. Guo et al. [15] modeled the effects of local buckling using a zero length element located at the end of the beam compression flanges. The effects of variable axial force and moment occurring in the beam, and the penetration of local buckling into the beam web are not properly captured by this model, where the latter leads to an accelerated shortening of the beam and subsequent strength and stiffness deterioration. Consequently, the accuracy of the seismic collapse resistance predicted by Guo et al. [15] are questionable, and, as suggested by Kim and Christopoulos [6], a more realistic and refined modeling approach is needed.

The need for refined modeling and better understanding of the seismic collapse resistance of SC-MRFs is the motivation for this paper. The collapse resistance of 4-story perimeter steel SC-MRF system with WFDs is assessed using the methodology in FEMA P695 [16] based on incremental dynamic analyses. To capture the beam local buckling limit state, nonlinear finite element models of the SC-MRF are developed that use shell elements in the regions of the members where local buckling is expected. The models are calibrated against test data, and show exceptional accuracy in predicting the deterioration in SC-MRF test specimen strength and PT strand force under cyclic loading. These models are subsequently used to investigate the effect of the post-gap opening stiffness of SC beam-to-column connections on the collapse resistance of an SC-MRF, and the probability of PT strand fracture under severe ground motions. The results for the SC-MRF are compared to results for a 4-story conventional steel SMRF to assess the relative collapse resistance of these two types of seismic-resistant MRFs.

2. SC-WFD connection conceptual behavior

Fig. 2(a) shows the conceptual moment-relative rotation behavior for an SC connection with WFD (denoted as the SC-WFD connection) based on Lin et al. [11], where θ_r is the relative rotation between the beam and column, and M is the connection moment (Fig. 2(b)). The resisting moment of the connection is provided by the beam axial force P and WFD friction force resultant F_f. P is assumed equal to the total PT strand force T, plus the inertial force in the floor diaphragm that is transferred to the beam.

Prior to gap opening, from event 0–1 in Fig. 2(a), $\theta_r = 0$ and the