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Earthquake resistance frames with combination of rigid and semi-rigid connections

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ABSTRACT

The concept of the hybrid steel frame system, as it pertains to mixtures of fully-rigid and semi-rigid steel connections used in 20-story SAC frames, is presented herein. Several different patterns and locations of semi-rigid connection replacements within the frame were examined in order to identify hybrid frames with the best seismic performance. The effective connection stiffness was identified by performing a parametric study on the initial stiffness of the semi-rigid connections. Then, the cyclic behavior of the connections with the most effective stiffness was obtained, using nonlinear finite element analysis. Inelastic dynamic analyses were conducted on the proposed selected frames by subjecting them to Los Angeles earthquake records characterized as those with 2% and 10% probabilities of exceedance in fifty years. The maximum story drift for the hybrid frames was determined and compared with the "life safety" and "collapse prevention" performance limits, as recommended by FEMA 356 [12]. The story drift and member forces for the proposed hybrid frames were compared with those of conventional SAC frames without semi-rigid connections. Finally, a reliability analysis, utilizing the collapse margin ratio presented in FEMA P695, was performed to quantify and compare the collapse performance of the proposed hybrid frames and conventional rigid frames.

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1. Introduction

Seismic performance of structural systems has been at the forefront of research for many years. Occurrences of more than 18 severe earthquakes, with magnitudes of more than 5.8 Richter in the state of California in the 15-year period between 1979 and 1994, have been reported. The premature brittle failures of welded connections after the Northridge earthquake of 1994 particularly motivated researchers to look beyond the conventional design philosophies

In the past few decades, several researchers have introduced new design concepts and approaches to improve the seismic performance of steel structures. These include, but are not limited to, the introduction of more ductile connections and new lateral resistant systems, including energy dissipating technologies such as base isolators, frictional or visco-elastic dampers, and active control elements.

An innovative seismic design method is the Performance Based Plastic Design (PBPD) that was introduced and developed by Professor Goel and his associates at the University of Michigan [14,17]. The development of this method was in response to shortages in the current seismic design codes on satisfying a performance objective in a direct manner. In PBPD, the base shear is calculated by equating the work done by pushing the structure to a predefined target drift monotonically to the work done by an equivalent elastic-perfectly plastic single degree of freedom system. The idealized inelastic response spectra by [19] are used in this study.

Development of the seismic eccentric braced frames (EBF), introduced by Popov and Englehardt in 1988, was another attempt to enhance the seismic behavior of steel frames. Well-designed EBFs, constructed with shear links, provide high elastic stiffness and strength under low to moderate ground motions, combined with high ductility and energy dissipation capabilities in severe ground motions.

Recently, Abolmaali et al. [4] introduced a new lateral resistant steel moment frame referred to as a "Hybrid Steel Frame." This system, which was the foundation of the research leading to the work that is being presented in this manuscript, is based on the concept of introducing energy dissipating mechanisms in the structural frame systems by targeting and replacing selected rigid connections with more ductile energy dissipating semi-rigid connections.

The proposed structural system enhances the seismic behavior of the steel frames by taking advantage of the inelastic energy dissipative semi-rigid connections, along with stiffer and higher strength rigid connections. In the case of low intensity earthquakes, while rigid

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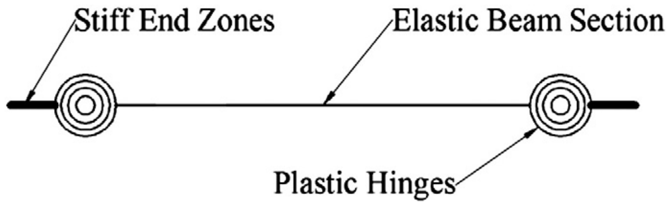


Fig. 1. Beam compound with stiff end zone and plastic hinges.

connections remain elastic, the semi-rigid connections absorb seismic energy and assist the system in damping out the base motion acceleration at a faster rate. On the other hand, in the case of higher intensity earthquakes, this study shows that hybrid frames reduce the risk of collapse when compared with its corresponding SMFs.

Current design codes have almost eliminated the partially restrained connections in high seismic zones. However, there are several studies that show high energy dissipating characteristics of the semi-rigid connections with high stiffness and strength, as reported by Ackroyd and Gerstle [5], Bjorhovde et al. [10], Astaneh et al. [6], Astaneh-Asl et al. [8], Astaneh-Asl [7], Kukreti and Abolmaali [16], Abolmaali et al. [1], Abolmaali et al. [2], and Abolmaali et al. [3].

Seismic behavior of SMFs with semi-rigid connections has been investigated in several studies, both theoretically and experimentally [18]. Excessive inter-story drift was a major concern for using semi-rigid connections in steel frames. These studies showed that when connection stiffness increases, base shear increases; however, inter-story drift does not decrease proportionally.

Astaneh et al. [6] and Abolmaali et al. [3] studied the energy dissipation characteristics of different types of semi-rigid connections and showed that they are capable of undergoing large inelastic rotation (in excess of 0.05 rad), given that the connection is designed so that the angle or plate yielding governs the behavior. In other words, if the plate or angle thickness is relatively small compared to the bolt diameter, bolt yielding and fractures are prevented, and plate yielding results in a ductile connection behavior by undergoing large inelastic rotation.

In this research, The Los Angeles 20-story SAC frame is used as a case study. SAC frame dimensions are presented in [15]. Selected rigid connections were replaced by ductile semi-rigid connections. A suit of 20 accelerograms [22], which was developed as a part of the SAC project for the Los Angeles site, with different frequencies was applied during inelastic dynamic analyses, and the results were compared with the corresponding responses of the fully rigid SAC frames.

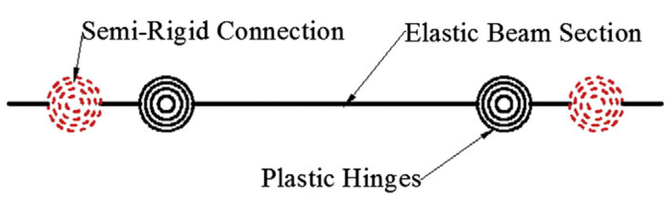


Fig. 2. Beam compound with semi-rigid connections and plastic hinges.

A reliability-based analysis utilizing the Collapse Margin Ratio (CMR), proposed in FEMA p695, was performed to quantify the collapse performance of the Los Angeles SAC 20-story rigid frames and their corresponding hybrid frames.

1.1. Nonlinear modeling

The concentrated plastic hinge model was adopted to introduce nonlinear behavior in beams with rigid connections, beams with semi rigid connections, and columns of structures. Beams with rigid connections and columns, as shown in Fig. 1, were modeled as compound elements consisting of an elastic Bernoulli beam element at the middle and confined by two plastic hinges and two end-zones that connect the member to the rigid connections. The assumption of the formation of plastic hinges at the two ends of beams and columns was adopted based on the hypothesis that the failure mechanism is governed by the seismic loading.

The semi-rigid beam compounds, as shown in Fig. 2, were defined by replacing the two stiff end zones with two non-linear moment-rotation semi-rigid hinges in the rigid beam compounds. In this configuration, plastic hinges and semi-rigid connections are both sources of nonlinearity. However, since the plastic moment of semi-rigid connections is usually much smaller than the plastic moment of beam sections, the behavior of the beam compound is governed by the behavior of the semi rigid connections. In fact, the moment demand in beams cannot exceed the plastic moment of the semi-rigid connections; therefore, it will not reach the plastic moment of the beam section.

The nonlinear behavior of plastic hinges is commonly expressed by presenting their moment-rotation backbone-curves. In this study, the backbone curve for different beam and column members were constructed based on the beam deterioration modeling guideline provided in ATC-72 [9] as shown in Fig. 3.

The plastic hinge parameters for the beams used in this study are summarized in Table 1.

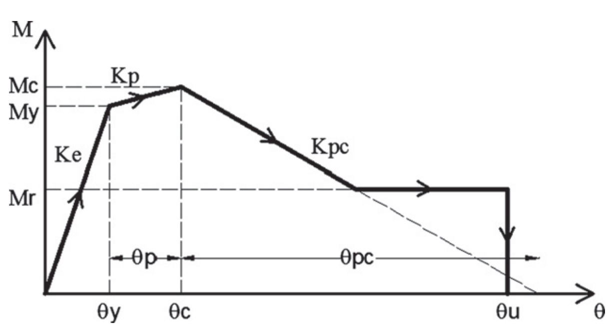
Parameters used for modeling of semi-rigid connections will be presented after the effective connection parameters are identified.

2. Selection of hybrid frame patterns

For a reasonable placement of semi-rigid connections in a hybrid frame, it is necessary to investigate the local and global effects of adding semi-rigid connections to the moment resistance frames' performance. These effects were investigated as follows.

2.1. Moment redistribution/act as a fuse

Semi-rigid connections act as rotational springs; consequently, they change the distribution of moments between beams and columns. Moreover, the plastic moment of semi-rigid connections is generally



Pre-capping plastic rotation (θ_p)
Post-capping rotation range (θ_{pc})
Ultimate rotation (θ_u)
Effective yield strength and rotation (M_y and θ_y)
Capping strength and rotation, (M_c and θ_c)
Residual strength, M_r
Effective elastic stiffness, K_e
Post yield tangent stiffness, K_p
Effective post capping tangent stiffness, K_{pc}
Deterioration parameter (Λ)

Fig. 3. Parameters of the monotonic backbone curve of the modified Ibarra–Krawinkler model. After ATC72-10.