Journal of Constructional Steel Research 150 (2018) 129–140

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Seismic performance of a self-centering steel moment frame building: From component-level modeling to economic loss assessment

Xingquan Guan [a,*], Henry Burton [a], Saber Moradi [b]

[a] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA
[b] Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, M5B 2K3, Canada

ARTICLE INFO

Article history:
Received 26 February 2018
Received in revised form 11 June 2018
Accepted 22 July 2018
Available online xxxx

Keywords:
Self-centering steel moment frame
Post-tensioned connection
Nonlinear static analysis
Incremental dynamic analysis
Economic seismic loss
Fragility assessment

ABSTRACT

The seismic performance and economic seismic losses of a 6-story self-centering moment resisting frame (SC-MRF) building using post-tensioned (PT) connections with top-and-seat angles is evaluated. A phenomenological model that captures the lateral load response of PT connections is developed and verified using previous experiments. A 2D model of the 6-story SC-MRF is constructed in OpenSees using the newly developed phenomenological model. Using the same member sizes as the SC-MRF, a model is also created for a welded moment resisting frame (WMRF) with reduced beam section (RBS) connections. Nonlinear static and incremental dynamic analyses are performed on the SC-MRF and WMRF models. The lateral load carrying capacity of the SC-MRF is found to be 40% lower than that of the WMRF. The dynamic analysis results show that the WMRF has higher collapse resistance, whereas the SC-MRF undergoes smaller residual drifts. Finally, the earthquake-induced economic impact to the two buildings is assessed using the FEMA P58 methodology, where the expected annual loss for the SC-MRF is computed to be 21% higher than that for the WMRF building. More specifically, the SC-MRF building (with PT connections and top-and-seat angles) has a lower expected loss associated with excessive residual drifts but higher collapse losses.

1. Introduction

In current seismic design codes, structures are designed to achieve a minimum level of collapse safety by assuring ductile response when subjected to earthquake shaking. As a result, conventional steel structures may undergo permanent (or residual) deformations after a seismic event. Mitigation of residual displacements in steel buildings is a critical issue as it directly relates to the repair cost. In fact, large permanent deformations can render a building irreparable. For example, because of excessive residual drifts, many buildings surviving the 2011 Christchurch earthquake were declared unusable. The reconstruction cost for these buildings was estimated to be 40 billion New Zealand dollars [1].

With the goal of minimizing residual deformations, researchers have been investigating the application of alternative materials such as shape memory alloys [2–4]. However, the widespread application of these new systems has been impeded by their high cost and the need for new construction techniques and structural systems. To meet this challenge, post-tensioned (PT) moment frame connections with top-and-seat angles have been proposed as an efficient approach to reduce residual deformations in steel buildings [5, 6]. Several experimental [e.g. [7]], analytical [e.g. [7, 8]], and numerical [e.g. [9–12]] studies have been conducted to evaluate the behavior and potential advantages of PT connections. Fig. 1 shows a reduced beam section (RBS) welded moment connection and a PT beam-column connection with top-and-seat angles. PT strands are used in the latter to provide restoring forces or self-centering (SC) capability, while the top-and-seat angles are used to dissipate energy. Other types of energy dissipation mechanisms such as viscous dampers [13] have also been used. As a result, structural damage in the connection is localized at the angles, which can be easily replaced after an earthquake.

To assess the advantages of using self-centering moment resisting frames (SC-MRFs) with PT connections, their seismic performance and potential cost-benefit should be studied. To achieve this goal, a reliable modeling technique that captures the collapse behavior of SC-MRFs with PT connections is needed. However, existing modeling approaches are limited to PT connections with other types of energy dissipation devices, such as web hourglass shape pins [14], friction devices [15], and passive dampers [13]. Therefore, there is a need to develop a reliable, practical and simplified modeling technique for PT connections with top-and-seat angles, which can be used to predict the structural response of SC-MRFs subjected to earthquake loading.

In addition to the structural response, assessing earthquake-induced building economic losses can also be used to quantitatively evaluate the advantages of SC-MRFs. Currently, several methods are available to

* Corresponding author.
E-mail addresses: guanxingquan@ucla.edu (X. Guan), hvburton@seas.ucla.edu (H. Burton), s.moradi@ryerson.ca (S. Moradi).

https://doi.org/10.1016/j.jcsr.2018.07.026

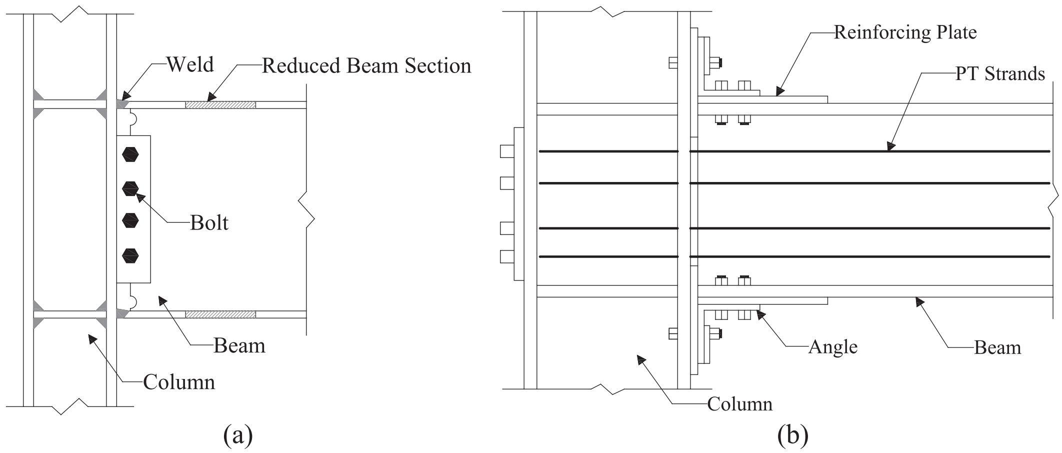

Fig. 1. Schematic illustration of an (a) RBS welded connection and (b) PT connection.

assess earthquake-induced losses of buildings. Porter et al. [16] proposed an approach that involves conducting nonlinear dynamic analyses, prediction of damage at the component level using fragility functions, and estimation of total building repair cost. The approach was further enhanced in the second-generation performance-based earthquake engineering (PBEE) methodology [17]. As part of the PBEE framework development, Ramirez and Miranda [18] demonstrated that excessive residual drifts significantly influence earthquake-induced building losses. The state-of-the-art methodology for earthquake-induced economic loss estimation is described in FEMA P58 [19]. This methodology uses 2nd generation PBEE along with a complete database of damage fragility loss functions for structural and nonstructural components and considers the influence of residual drifts.

In this study, a phenomenological model of top-and-seated angle PT connections is developed in OpenSees [20] and subsequently verified using prior experiments. A prototype building, which has SC-MRFs as its lateral force resisting system, is selected. Using the proposed phenomenological model of the PT connection, a 2D model for the SC-MRF is constructed. To facilitate a comparative assessment, a welded moment resisting frame (WMRF) model with the same member sizes as the SC-MRF but with RBS connections, is created. Nonlinear static and dynamic analyses are performed on both the SC-MRF and WMRF models and their collapse performance is quantified. Finally, the economic seismic losses for both buildings are assessed using the FEMA P58 methodology, which accounts for the influence of residual drifts and the repair costs of structural and nonstructural components. Fig. 2 illustrates the workflow of the study.

2. Model development in OpenSees

2.1. Description of prototype building

A 6-story office building with 6 bays in the E-W and N-S directions, which has been developed by Garlock et al. [21], is selected as the prototype building. The building is located in the Los Angeles metropolitan area and has two identical MRFs in each direction (Fig. 3). A single MRF is considered for the current study. The frame is designed as an SC-MRF with top-and-seat angle PT connections by Garlock et al. [21] using a ten-step procedure. First, the equivalent lateral force (ELF) method is used to determine the seismic story forces. The beam and column

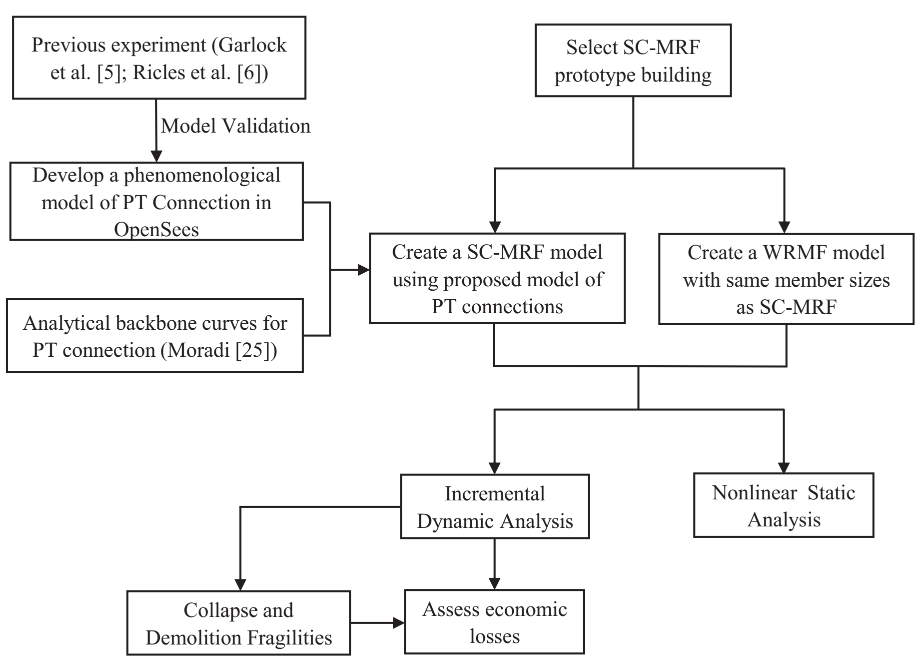

Fig. 2. Overview of study.