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Seismic design for enhanced building performance using rocking steel braced frames

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ABSTRACT

Performance-based seismic design has brought about innovative rocking and self-centering structural systems such as rocking steel braced frames (RBF). This lateral force resisting system has recently received focused attention in academic research however has seen limited application in practice to date. This may be due in part to the unconventional load path, plastic mechanisms, and unique dynamic characteristics of the system. The transfer of forces through a RBF with passive energy dissipating devices (steel yielding and viscous) is described and a simplified approach proposed to quantify peak dynamic deformation and force response. Enhanced performance can be achieved by including viscous damping devices over hysteretic devices and post-tensioning (proposed in previous research). The dynamic response of RBF are evaluated through nonlinear transient finite element seismic analyses with ground motion sets. Additionally, the demands placed on non-structural components contained on each building floor was investigated through the computational model by calculating critical response quantities such as inter-story drift, peak floor acceleration, and floor spectra. Structural and non-structural demands are compared with a buckling-restrained braced frame (BRBF) to illustrate the differences in seismic behavior and potential benefits of a well-designed rocking steel braced frame.

1. Introduction

Rocking braced frames (RBF) are a new, developing seismic lateral force resisting system capable of enhanced seismic performance that can minimize or prevent damage to structural components, re-center following an earthquake event, and potentially limit demands on non-structural components. The primary structural components (beams, columns, braces) are designed to remain elastic while passive energy dissipating devices are implemented at the uplifting location to control the response. The RBF system investigated in this paper utilizes both steel yielding and viscous damping devices in parallel for response control. While well-designed conventional ductile steel seismic systems (SCBF, EBF, BRBF, etc.) perform adequately from a life-safety standpoint, damage and residual drift imparted on a structure even in a design basis earthquake might require extensive repairs or demolition following the earthquake.

The behavior and design of a 3-story RBF building including both primary rocking mode and higher mode response are discussed. The forces generated from higher mode response can be significantly larger than the forces to form the 1st mode rocking plastic mechanism but must be accounted for to ensure elastic frame response. Additionally, the higher mode response has significant impact on the floor spectra. Nonlinear transient analysis is performed to calculate response for three sets of 10 ground motions representing far-field DBE and MCE and near-field events at a southern California site.

This paper discusses the behavior and a seismic design approach for rocking steel braced frame buildings and advances knowledge on this next-generation seismic LFRS by: (i) investigating behavior of a more beneficial combination of passive energy dissipating devices that can eliminate the need for post-tensioning, (ii) proposes a design approach to predict both dynamic deformations and force response including higher mode effects, (iii) quantifies demands on both structural and non-structural components, and (iv) compares RBF performance with a similarly designed BRBF building.

2. Background

Seismic steel lateral force resisting systems (LFRS) for building structures currently adopted in the AISC Seismic Design Provisions [1] have been developed with the intent of allowing structural damage even under design-basis seismic events. All current

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seismic steel LFRS use a design approach that sizes protected zones for forces below the elastic force level by accounting for the actual overstrength and ductility of the LFRS and then sizes all surrounding non-protected zones for the ultimate force of the protected zone, a capacity design approach. From a life-safety standpoint, this may provide acceptable structural response. However, from an economic, operational, and sustainability standpoint the behavior is undesirable since damage in the protected zones requires costly repairs of the protected zone members and likely also of the surrounding members, connections, and floor slabs. Additionally, the plastic deformations induced on the protected zones results in permanent deformations and residual drift in the structural system following an earthquake.

A structural system that allows a braced frame or wall to uplift and rock can potentially provide damage-resistant behavior with enhanced performance and can provide a restoring force mechanism through gravity loads and/or post-tensioning forces capable of self-centering (eliminating residual drift). Energy dissipating devices can then be added to control the rocking response to within allowable limits. The performance of this next-generation LFRS is much improved from currently adopted seismic steel LFRS however further investigation of system level structural response, implementation details, and development of analysis and design tools amenable to implementation in practice are needed to advance these systems into common practice. Additionally, the demands placed on non-structural components using these seismic systems need to be assessed for operationally critical structures. Non-structural components may be sensitive to both deformations and floor accelerations therefore it is desirable to control both of these response quantities to limit damage.

Others ([2–4]) have investigated behavior of rocking steel braced building frames that incorporate vertical post-tensioning strands attached to the rocking braced frame that adds to the restoring force provided by the tributary gravity load carried by the frame and increases the total lateral force resistance of the frame. The post-tensioning strands add large concentrated forces that must be adequately distributed to the frame. Either steel yielding devices or friction devices are incorporated along the height of uplifting columns to dissipate seismic energy. The systems developed the expected response through analytical and experimental verification which focused on displacements and forces. Roke et al. [4] observed that the member forces can be significantly affected not only by the rocking mode response but also by the higher mode effects and developed a set of load factors through probabilistic analysis for the 6-story building and suite of seismic ground motions used in that study. Weibe [5] proposed the inclusion of multiple rocking sections along a wall's height to reduce the demands caused by higher mode force effects in a multi-story building. The approach was shown to reduce force demands from the higher mode effects although requires additional rocking connection details between sections.

Tremblay et al. [6] have investigated a similar rocking braced frame concept for seismic resistance of building structures but have investigated implementation of nonlinear fluid viscous dampers as the energy dissipation device at the base of the rocking frame column. Shake table testing and analytical studies were performed to evaluate and verify response.

Gunay et al. [7] evaluated the use of rocking concrete walls to create a rigid core to attract seismic forces and limit demands on non-ductile framing potentially preventing soft story failures. The rocking wall rehabilitation approach for non-ductile moment frame structures was shown to be cost effective with minimal construction complexity providing potential benefit for developing countries. Pollino et al. [8] proposed a similar rehabilitation technique for sub-standard steel framing utilizing large pin-supported steel columns or trusses.

Pollino and Bruneau [9] investigated a rocking system for the seismic design or retrofit of steel truss bridge piers. The piers represented an essentially SDOF system and was investigated both analytically (using nonlinear transient analyses) and experimentally (using large-scale 6DOF shaking table testing). The restoring force was supplied strictly by the vertical tributary weight in this application. The dynamic behavior of bridge piers is also fundamentally different from that of buildings due to the participation of higher lateral modes in the seismic response of buildings.

Kam et al. [10] investigated the use of various combinations of yielding, friction, and viscous passive energy dissipation devices in series or in parallel for achieving enhanced damage-free performance for structures located in both far-field and near-field earthquakes. The concept was investigated numerically using simple SDOF models.

Other self-centering steel seismic lateral force resisting systems have been proposed in recent years that include post-tensioned moment frames ([11–13], among others) and re-centering bracing devices ([14–16]). While these systems have similar self-centering hysteretic behavior, they generally do not experience the higher mode effects described in this paper which result from the continuous elastic frame introduced over the building height with the rocking braced frame.

3. Rocking braced frame behavior

The rocking braced frame (RBF) seismic lateral force resisting system described here (illustrated in Fig. 1) consists of an elastic braced frame within a building frame which is allowed to uplift from its supports (sliding prevented) prior to diagonal brace yielding and buckling. The frame may or may not be post-tensioned vertically to provide a vertical restoring force (F_{PT}) in addition to the tributary vertical weight (w_D). The static force–deformation behavior of a RBF with displacement-based steel yielding devices (SYD) and post-tensioning has been formulated and described in detail by others [2]. The proposed seismic system described here includes both displacement-based steel yielding devices (SYD) and velocity dependent viscous dampers (VD) implemented at the uplifting location to control the response. The steel yielding devices are considered to provide displacement-based hysteretic behavior with kinematic and isotropic material hardening. The viscous dampers considered have a force output based on:

$$F_{\mathrm{VD}} = c_d \cdot sgn(v_d) \cdot (|v_d|)^{\alpha_d} \tag{1}$$

where c_d = damping constant, v_d = relative velocity across damper ends, and α_d = damping exponent. The addition of viscous damping

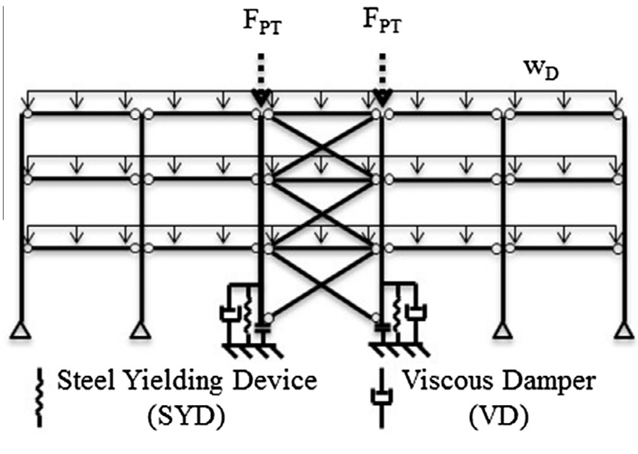

Fig. 1. RBF frame illustration.