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Seismic structural and non-structural performance evaluation of highly damped self-centering and conventional systems

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ABSTRACT

This paper evaluates the seismic structural and non-structural performance of self-centering and conventional structural systems combined with supplemental viscous dampers. For this purpose, a parametric study on the seismic response of highly damped single-degree-of-freedom systems with self-centering flag-shaped or bilinear elastoplastic hysteresis is conducted. Statistical response results are used to evaluate and quantify the effects of supplemental viscous damping, strength ratio and period of vibration on seismic peak displacements, residual displacements and peak total accelerations. Among other findings, it is shown that decreasing the strength of nonlinear systems effectively decreases total accelerations, while added damping increases total accelerations and generally decreases residual displacements. Interestingly, this work shows that in some instances added damping may result in increased residual displacements of bilinear elastoplastic systems. Simple design cases demonstrate how these findings can be considered when designing highly damped structures to reduce structural and non-structural damage.

1. Introduction

An important requirement of performance-based seismic design is the simultaneous control of structural and non-structural damage [1]. Structural damage measures are related to story drifts, residual drifts and inelastic deformations. Non-structural damage measures are related to story drifts, total floor accelerations and floor response spectra. Earthquake reconnaissance reports highlight that injuries, fatalities and economical losses related to failure of non-structural components far exceed those related to structural failures [2]. Explicit consideration of non-structural damage becomes vital in the design of critical facilities such as hospitals carrying acceleration-sensitive medical equipment which should remain functional in the aftermath of earthquakes [3].

Conventional seismic-resistant structural systems, such as steel moment resisting frames (MRFs) or concentrically braced frames (CBFs), are currently designed to experience significant inelastic deformations under the design seismic action [4]. Significant inelastic deformations result in damage and residual drifts, and hence, in economic losses such as repair costs, costly downtime during which the building is repaired and cannot be used or occupied, and, perhaps, building demolition due to the complications associated with straightening large residual drifts [5]. In addition, conventional seismic-resistant systems cannot provide harmonization of structural and non-structural damage since reduction of drifts or deformations and reduction of total floor accelerations are competing objectives, i.e., adding stiffness and strength to the structure decreases drifts and inelastic deformation demands but increases total accelerations [6].

Residual drift is an important index for deciding whether to repair a damaged structure versus to demolish it. McCormick et al. [7] reported that repairing damaged structures which had experienced residual story drifts greater than 0.5% after the Hyogoken-Nanbu earthquake was no financially viable. MacRae and Kawashima [8] studied residual displacements of inelastic single-degree-of-freedom (SDOF) systems and illustrated their significant dependence on the post-yield stiffness ratio. Christopoulos et al. [9] studied residual displacements of five SDOF systems using different hysteretic rules and showed that residual displacements decrease with an increasing post-yield stiffness ratio. An extensive study by Ruiz-Garcia and Miranda [10] showed that residual displacements are more sensitive to changes in local site conditions, earthquake magnitude, distance to the source range and hysteretic behavior than peak displacements. Pampanin et al. [11] studied the seismic response of multi-degree-of-freedom (MDOF) systems and highlighted a significant sensitivity of residual drifts to the hysteretic rule, post-yield

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stiffness ratio and global plastic mechanism. Recently, Pettinga et al. [12] examined the effect of stiffness, strength and mass eccentricity on residual displacements of one story buildings and suggested that a proper inclusion of orthogonal elements close to the building plan perimeter can result in reduced differences in permanent drifts across the building plan.

Rate-dependent passive dampers (viscous, viscoelastic, elastomeric; referred to herein as passive dampers) have been extensively used in seismic-resistant design and retrofit [13]. Lin and Chopra [14] studied highly damped elastic SDOF systems and showed that supplemental viscous damping is more effective in reducing displacements than total accelerations. Ramirez et al. [15] studied inelastic SDOF systems for a wide range of periods of vibration and showed that added damping has no significant effect on the relation between peak elastic and peak inelastic displacements and also, confirmed the technical basis of FEMA 450 [16] to allow a 25% reduction in the minimum design base shear of damped buildings. Pavlou and Constantinou [17] showed that inelastic steel MRFs with passive dampers designed to achieve similar drifts with conventional MRFs experience lower total floor accelerations than conventional MRFs. Lee et al. [18] designed steel MRFs with elastomeric dampers and showed that design criteria that allow some inelastic behavior, but limit drift to 1.5% under the design earthquake lead to the most effective damper design. Vargas and Bruneau [19] studied the effect of supplemental viscous damping on the seismic response of inelastic SDOF structural systems with metallic dampers for three periods of vibration. Their results showed that viscous dampers increase total accelerations of systems whose original frame still behaves inelastically under strong earthquakes. A recent paper showed that retrofitting a building with viscous dampers improves both structural and non-structural fragilities [20]. Occhiuzzi analyzed different examples of frames with passive dampers found in literature and showed that values of the 1st modal damping ratio higher than 20% seem to trade off a minor reduction of interstorey drifts with a significant increase of total floor accelerations [21]. Compressed elastomer dampers with viscoelastic behavior under small amplitudes of deformation and friction behavior under large amplitudes of deformation were designed and tested by Karavasilis et al. [22,23]. When combined with flexible steel MRFs of reduced strength, these dampers were found capable of significantly reducing drifts and inelastic deformations without increasing total floor accelerations.

Recent research developed self-centering (SC) steel MRFs with post-tensioned (PT) connections [24]. SC steel MRFs have the potential to eliminate inelastic deformations and residual drifts under strong earthquakes as the result of a softening force–drift behavior due to separations (gap openings) developed in beam-to-column connections; re-centering capability due to elastic pretensioning elements (e.g., high strength steel tendons) providing clamping forces to connect beam and columns; and energy dissipation capacity due to energy dissipation elements (EDs) which are activated when gaps open. The parallel combination of tendons and EDs results in self-centering flag-shaped hysteresis. SC steel MRFs experience drift and total accelerations similar to those of conventional steel MRFs of the same strength and stiffness, i.e., they have conventional seismic performance in terms of non-structural damage. A recent work developed self-centering energy-dissipative braces which eliminate residual drifts and provide story drifts lower and total floor accelerations similar to those achieved with buckling restrained braces (BRBs) [25]. Christopoulos et al. [26] showed that self-centering SDOF systems can match the response of elastoplastic SDOF systems in terms of ductility by using physically achievable energy dissipation and post-yielding stiffness. The same work found self-centering systems of high post-yield stiffness ratio to experience higher total accelerations than elastoplastic systems. Seo and Sause [27] showed that self-centering systems develop greater ductility demands than conventional systems when the lateral strength and post-yield stiffness ratio are the same. They also found that ductility demands can significantly decrease by increasing the energy dissipation capacity and the post-yield stiffness ratio of self-centering systems. Recently, Kam et al. [28] showed that a parallel combination of self-centering systems of sufficient hysteretic energy dissipation capacity with viscous dampers can achieve superior performance compared to other structural systems, especially when the peak viscous damper force is controlled by implementing a friction slipping element in series with the viscous damper.

Seismic design for harmonization of structural and non-structural damage has been the topic of few recent works. A new concept of weakening the main lateral load resisting system along with using passive dampers has been proposed [29] and validated with frames employing concrete rocking columns [30]. Recent works proposed design procedures for optimal location and capacities of added passive dampers and weakening structures based on optimal control theory [31] and references therein.

The literature survey shows that more work is needed to evaluate the structural and non-structural performance of highly damped conventional and self-centering structural systems. In particular, the increase in total accelerations of conventional yielding and self-centering systems due to added damping [19,28,29] should be quantified. A detailed evaluation of the effect of added damping on residual displacements of conventional yielding systems is missing. The decrease in total accelerations due to strength reductions should be evaluated [29,30]. Moreover, a comparison of the response of highly damped conventional and self-centering systems is needed.

This paper aims to address the aforementioned research needs as well as to independently verify the findings of earlier investigations. For this purpose, a parametric study on the seismic response of highly damped single-degree-of-freedom (SDOF) systems with self-centering flag-shaped or bilinear elastoplastic hysteresis was conducted. Statistical response results were used to evaluate the effects of supplemental viscous damping, strength ratio and period of vibration on seismic peak displacements, residual displacements and peak total accelerations. Simple design cases demonstrate how the aforementioned effects can be considered when designing highly damped structures to reduce structural and non-structural damage.

It is emphasized that the results and conclusions presented in this paper are based on the response of SDOF systems and cannot be directly extended to MDOF buildings. It has been shown that the distributions of peak story drifts, peak residual story drifts and peak total floor accelerations along the building height depend on the fundamental period of vibration, number of stories and level of inelastic deformation [32,33].

2. Methodology

2.1. Simplified nonlinear structural systems with viscous dampers

Fluid viscous dampers dissipate energy by forcing incompressible fluids to flow through orifices and provide a damping force output, f_D, equal to

$$f_D = c_d \, |\dot{u}_d|^{\alpha} \, \mathrm{sgn}(\dot{u}_d) \tag{1}$$

where c_d is the damping constant; α is the velocity exponent that usually takes values between 0.15 and 1.0 for seismic applications and characterizes damper nonlinearity; $\dot{u}_d$ is the velocity across the damper; and sgn is the signum function [13].

Dampers are placed between successive floors of a building by using supporting braces which are designed to be stiff enough