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Seismic performance assessment of steel moment-resisting frames equipped with linear and nonlinear fluid viscous dampers with the same damping ratio

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ABSTRACT

This manuscript presents a comparative study between the seismic collapse performances of steel moment-resisting frames (MRFs) with the same additional damping ratio while equipped with linear and nonlinear viscous dampers. Three steel moment-resisting frames of 6, 8 and 12 stories were designed based on ASCE 7–10 with and without dampers. The characteristics of the linear ($\alpha = 1$) and nonlinear ($\alpha = 0.5$) dampers were then assigned while assuming equal damping ratios (20% for the models of 6 and 8 stories, and 25% for the model of 12 stories). The sophisticated nonlinear model of the structures was then developed in Opensees considering both cyclic strength and stiffness deterioration with lumped plasticity as well as the linear and nonlinear dashpot for dampers while nonlinear geometry was included in all the models. The collapse probability was calculated using well-known incremental dynamic analysis (IDA) under far-field records. The paper demonstrates that the use of damper improves the performance of the steel MRFs and reduces the collapse probability in comparison with the conventional steel MRFs. Moreover, it was observed that steel MRFs with linear dampers have better collapse performance than steel MRFs with nonlinear dampers for the same damping ratio.

1. Introduction

Supplemental passive damping systems can considerably improve the seismic performance of structures by decreasing drifts and inelastic deformation demands on the fundamental lateral load resisting system [1]. The fluid viscous damper is one type of passive energy dissipation systems that is used in the absorption and dissipation of the earthquake input energy. For the past few decades, the use of fluid viscous dampers has become increasingly prevalent in new and retrofit constructions excited by wind and earthquake loads because these devices have the ability to dissipate earthquake-induced energy into structures [2,3]. These dampers are made up of a cylinder and a stainless steel piston. The cylinder is filled with incompressible silicone fluid that is divided into two compartments by a piston. The damper is activated by the stream of silicone fluid between the chambers at the opposite ends of the unit through small orifices. By limiting the velocity with which the fluid can move (via the valve), a velocity-dependent-resisting force is developed. The force, F, in an FVD, is computed as:

$$F = C \times |v|^{\alpha} \times \mathrm{sgn}(v) \tag{1}$$

where F is the damping force, v is the velocity, C is a damping coefficient, α is a damping exponent that adopts the value of 1.0 for linear viscous dampers and a value between 0.1 and 2 for nonlinear viscous dampers and sgn is the signum function [4].

Experimental and analytical studies have shown that the use of viscous dampers inside the structures or between adjacent structures can control and improve the performance of structures such as the motion amplitude, interstory drifts and absolute accelerations generated by earthquake actions [5–11]. Constantinou and Symans [5,6] and Tsai et al. [9] have carried out experimental and analytical research on the seismic performance of steel buildings with FVDs. Uriz and Whittaker [11] found that the use of FVDs with the equivalent viscous damping of 40% of critical damping caused a decrease in the displacement of the frame. Dicleli and Mehta [12] compared the seismic performance of steel chevron braced frames (CBFs) with and without fluid viscous dampers (FVDs) in terms of intensity and frequency characteristics of the ground motion and FVD parameters. Choung-Yeol Seo et al. [13] designed a steel structure with 100% and 75% of design base shear using linear damper; then, it was compared with a structure without dampers. They found that the use of linear damper could improve the performance of the structure and reduce the probability of collapse. Some studies have been conducted using new configurations

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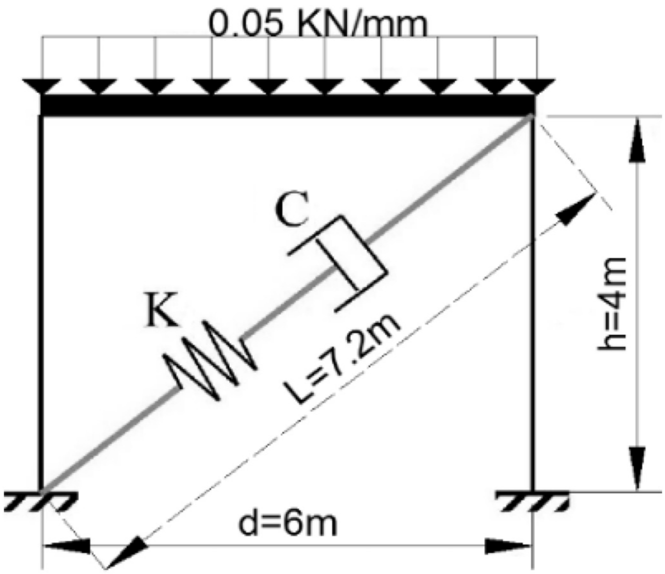

Fig. 1. Details of the verification model.

to amplify velocity across the device, such as scissor–jack systems, toggle brace systems, amplifying brace systems, seesaw energy dissipation system and lever arm systems [1,14–17]. Also, Mansoori and Moghadam [18] studied the possibility of using a linear FVD to control both accelerations and displacements of asymmetric buildings simultaneously.

Several sources have described the design of a structure with damper [5,19–27]. In 1993, Structural Engineers Association of Northern California (SEAONC) announced the initial design approaches for new structures with supplemental passive dampers [28]. These standards were developed on the basis that dampers would be placed in a lateral force-resisting system that previously met the strength and drift criteria of the existing seismic code, with the aim of decreasing earthquake damage. The 2010 ASCE/SEI-7 Standard [29], however, summarizes design strategies for structures with supplemental passive damping systems. It permits the use of a decreased design base shear force for the seismic design of structures with passive damper where the demanded performance is similar to or higher than that of the structures with a conventional lateral force-resisting system. This standard proposes the analysis of structures with damper using three methods: (a) response spectrum, (b) equivalent lateral load and (c) nonlinear methods and then describes their design. Moreover, in a comprehensive study, Hwang et al. [30] offered equations to calculate damping ratio and magnification factor for a variety of viscous damper installations. They also amended the existing equation in FEMA 273 and showed that both vertical and horizontal displacements at the ends of dampers were effective for the obtained responses.

Previous studies have demonstrated that the use of both linear and nonlinear viscous dampers could improve the seismic performance of structures. Nevertheless, the comparison between structures with linear and nonlinear dampers and the same damping ratio is scarce. FEMA 451 [31] comprises these dampers and shows that the nonlinear FVD has better performance and could dissipate more energy than the linear FVD (see Fig. 15). In this comparison, only α is changed, and C is kept constant. According to FEMA 273 and Hwang et al. [30], for the same damping ratio, damping coefficient is different for linear and nonlinear FVDs. Thus, we cannot compare the seismic performance of linear and nonlinear FVDs only by changing their damping exponents. Thus, this study aims to compare the seismic performance of SMRFs with linear and nonlinear FVDs. To this end, three steel moment-resisting frames (MRFs) are designed according to ASCE 7–10, equipped with FVDs. Properties of the FVDs are calculated with the same damping ratio for comparison purposes.

2. Modeling procedure of viscous damper and verification of results

To model a damper in SAP 2000, a section of damper type was used and assigned to a Link element. It is noteworthy that to prevent subsequent convergence issues; it is better to assign low mass to the damper. To model a viscous damper in Opensees, viscous damper material proposed by Akcelyan and Lingos was used and, then, it was assigned to a twoNodeLink element [32].

In order to verify the modeling procedure of the viscous damper, a one-story frame with one span was modeled both in SAP and Opensees, and the results were compared. Details of the model are shown in Fig. 1. A box section with the dimensions of 200 ∗ 200 ∗ 20 mm was used for columns, and the IPE 160 section was used for the beams. The model was loaded under the distributed load of 0.05 kN/mm and period of 0.8 s. Finally, the model was analyzed using time history analysis under Kobe earthquake records with the scale factor of 0.5. As shown in Fig. 2, the force-displacement results from SAP and Opensees were in good accordance with both linear and nonlinear fluid viscous dampers, which would verify the results from the modeling procedure in Opensees.

3. Criteria for the design of structures

In this study, three steel structures were modeled with 6, 8, and 12 stories. As shown in Fig. 3, only circumferential frames were SMRF and all the beam-to-column joints of the inner members, which were under gravitational loading, were pinned [note: only two middle spans were SMRF in the circumferential frames; the two others were simple]. In the

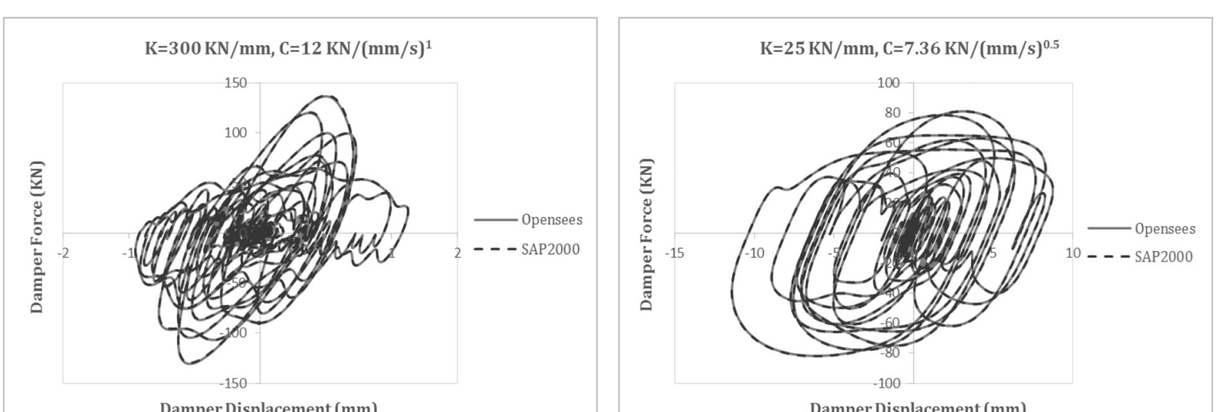

Fig. 2. Comparing force-displacement results from SAP and Opensees for linear and nonlinear viscous dampers.