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Fluid Dampers for Seismic Protection of Woodframe Structures

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Abstract

In the recent past, a large number of steel-framed buildings have been constructed or retrofitted with supplemental energy dissipation systems for the purpose of seismic protection. However, the application of such systems to woodframe structures has been essentially non-existent except for a limited number of experimental laboratory studies. This paper presents a numerical study of the application of fluid dampers for seismic protection of wood-framed structures. Such dampers dissipate energy via orificing of a fluid. The seismic response of a wood-framed shear wall with and without dampers is evaluated via nonlinear finite element analyses. The results of the analyses demonstrate that the dampers are capable of dissipating a large portion of the seismic input energy while simultaneously relieving the inelastic energy dissipation demand on the shear wall.

Introduction

Light-framed wood construction has generally been regarded as performing well during moderate to strong earthquakes. Such performance is primarily due to the low mass of light-framed construction combined with its ability to deform inelastically without inducing collapse of the structure. Although light-framed wood structures typically do not collapse during moderate to strong earthquakes, the inelastic response is generally associated with significant structural and non-structural damage that may be very costly to repair. As an example of the magnitude of the damage to light-framed wood buildings during a moderate earthquake, consider the 1994 Northridge Earthquake (Moment Magnitude = 6.8) in which there was in excess of 20 billion dollars worth of damage to such structures (Kircher et al., 1997). Obviously, the 1994 Northridge Earthquake provides clear evidence that conventional light-framed wood buildings are prone to significant damage when subjected to strong earthquake ground motions.

One approach to mitigating the effects of strong earthquakes on light-framed wood buildings is to incorporate an advanced seismic protection system within the building. For example, introducing a supplemental damping system within the framing of a building can reduce its seismic response. The supplemental damping system dissipates a portion of the seismic input energy, thereby reducing the amount of energy dissipated via inelastic behavior within the structural framing. The number of applications of advanced seismic protection systems within buildings has been steadily growing within approximately the past ten years. Nearly all of these applications have been within either steel or concrete structures (e.g., see Soong and Constantinou, 1995). There are a wide variety of supplemental damping systems available for implementation in buildings (Constantinou et al., 1998 and Constantinou and Symans, 1993a). However, the most rapid growth in the application of supplemental damping systems to buildings has occurred for fluid dampers. Since the first experimental studies on a scale-model steel building frame in 1993 (Symans and Constantinou, 1993b), the number of implementations of fluid dampers within major bridge and building structures has grown to 49 with installation pending in 17 additional structures. Although there are many factors that have contributed to this rapid growth, one of the primary reasons is the high energy dissipation density of fluid dampers (i.e., fluid dampers are capable of dissipating a large amount of energy relative to their size).

Relatively few studies have been conducted on the application of supplemental damping systems for seismic protection of wood frame structures. Filiatrault (1990) performed a numerical study to evaluate the seismic response of a woodframed shear wall with friction dampers at the corners of the wall and Dinehart and Shenton (1998) and Dinehart et al. (1999) experimentally evaluated the seismic response of a woodframed shear wall with viscoelastic dampers located at various positions within the wall. The results of these studies clearly demonstrate that supplemental damping systems have the potential for significantly improving the seismic response of wood-framed buildings. Note that Symans et al. (2001) provides a comprehensive literature review on the application of advanced seismic protection systems (both base isolation and supplemental damping systems) to wood-framed structures.

To the knowledge of the authors, the research presented herein represents the first study on the application of fluid dampers within wood-framed structures for seismic energy dissipation.

Description of Finite Element Model

A nonlinear finite element model of a wood-framed shear wall was developed for the numerical analyses using the commercial program ABAQUS (ABAQUS, 1998) (see Figure 1). The dimensions of the shear wall were 2.44 m x 2.44 m (8 ft x 8 ft). The framing of the wall consisted of 38.1 mm x 88.9 mm (nominal 2 in. x 4 in.) lumber. The vertical studs were spaced at 60.96 cm (24 in.) on center. The wall was sheathed with 1.22 m x 2.44 m (4 ft x 8 ft) waferboard sheathing panels having a thickness of 9.53 mm (3/8 in.). The connections between the sheathing and framing consisted of 6.35 cm (2.5 in.) 8d galvanized common nails. The field and perimeter nail spacing was 15.24 cm (6 in.). The weight at the top of the wall was 44.5 kN (10 kips), which is intended to represent the tributary weight if the wall were located at the first story of a three-story building. The weight was distributed at the nodes along the top plate. The bottom plate is assumed to be fixed to the foundation.

The framing members and sheathing panels were modeled as 2-D isoparametric beam elements and 2-D isoparametric quadratic plane stress elements, respectively. The connection model for each nail was based on the hybrid Stewart-Dolan connector model, as depicted by the hysteretic loop shown in Figure 2. The parameters of the connection model were obtained from experimental test data provided in Dolan (1989). Note that, as a simplification, the stiffness degradation indicated in Figure 2 was not included in the analyses presented in this paper.

System identification of the wall model was performed via eigenvalue analysis wherein the damping matrix of the wall (without dampers) was assembled using a Rayleigh damping formulation. As obtained from the eigenvalue analysis, the natural frequency and damping ratio in the fundamental mode were 4.18 Hz and 2.1%, respectively. The fundamental mode shape is shown in Figure 3.

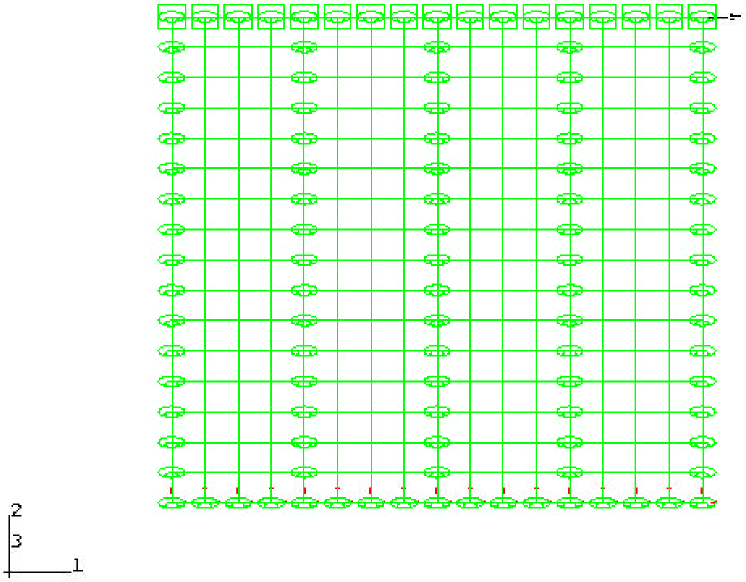

Figure 1 Finite Element Model of Wood-Framed Shear Wall.

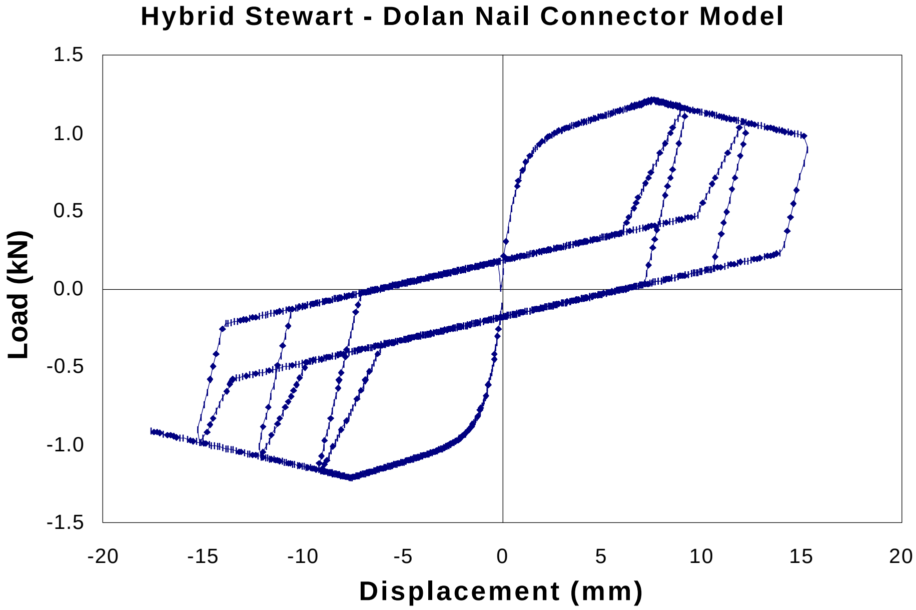

Figure 2 Hysteretic Behavior of Nonlinear Connection Element.

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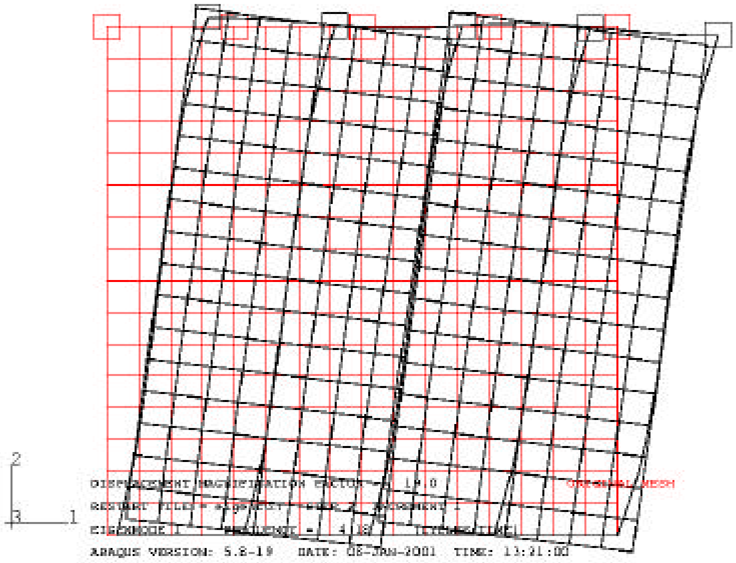


Figure 3 Fundamental Mode Shape for Shear Wall.

Description and Configuration of Fluid Dampers

Fluid viscous dampers offer considerable promise for application within wood-framed buildings due to their high energy dissipation density. The high energy dissipation density allows the dampers to be conveniently located within the walls of a wood-framed structure. For example, in this study, the damper was positioned along the diagonal of the wall (see Figure 4). In this configuration, dual let-in rods are used to connect the lower corner of the wall to the end of the damper. One rod is located on each side of the wall and small plates are used to prevent the rod from buckling outward. One advantage to this configuration is that the damper force lies within the plane of the wall and thus there are no bending moments applied to the wall at the corner connections. In contrast, a disadvantage to this configuration is that the effectiveness of the damper is reduced by 50% (for a square wall) due to the diagonal orientation.

In addition to their high energy dissipation density, the behavior of fluid dampers is quite unique in that they are incapable of developing appreciable restoring forces for the frequencies of motion expected during an earthquake (Symans and Constantinou, 1998). Thus, the dampers behave essentially as pure energy dissipation devices. The design of structures that incorporate such dampers becomes simplified since the dampers may be regarded as simply adding additional energy dissipation capacity to the structure. Of course, one must recognize that the installation of supplemental dampers will alter the load path for the transfer of forces within the structure.

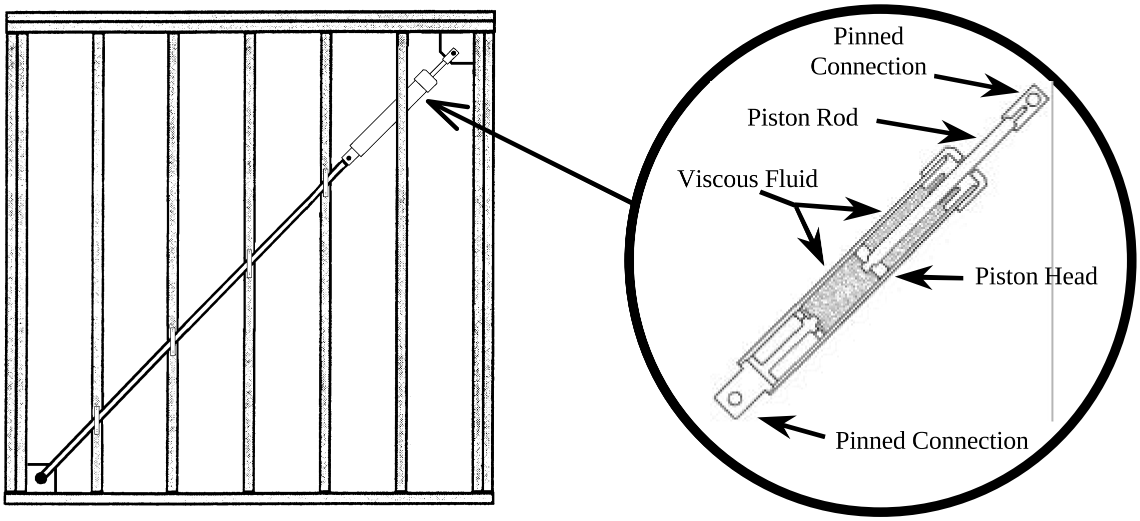


Figure 4 Schematic of Fluid Damper and Orientation within Shear Wall.

Seismic Excitation

The mathematical model of the shear wall was subjected to the following earthquake ground motions: 1) 1952 Kern County Earthquake, Taft record – Lincoln School Tunnel (S69E component) and 2) 1994 Northridge Earthquake, Newhall record – LA County Fire Station (90^o component). These two records were selected since they are so disparate (i.e., the Taft record is a weak, far-field motion while the Newhall record is a strong, near-field motion). The fluid dampers proved to be beneficial for both types of ground motions. For the weak, far-field motion, the structure remained essentially elastic with little to no permanent damage. For the strong, near-field motion, the structure was damaged but much less so than without the dampers. In this paper, results are presented for the near-field motion.

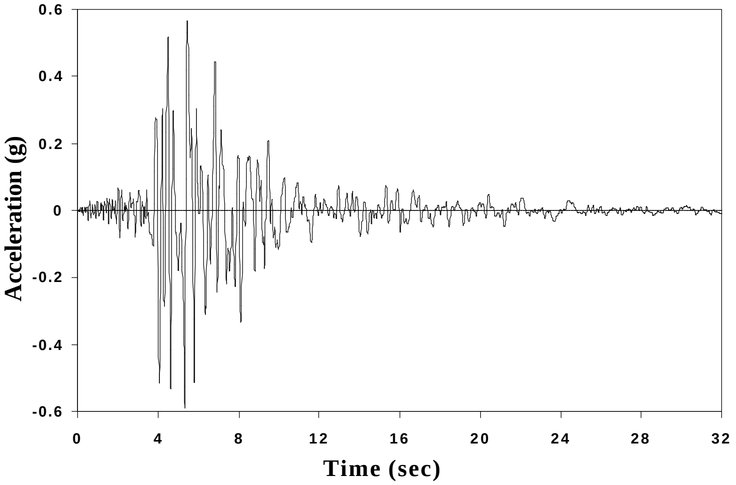
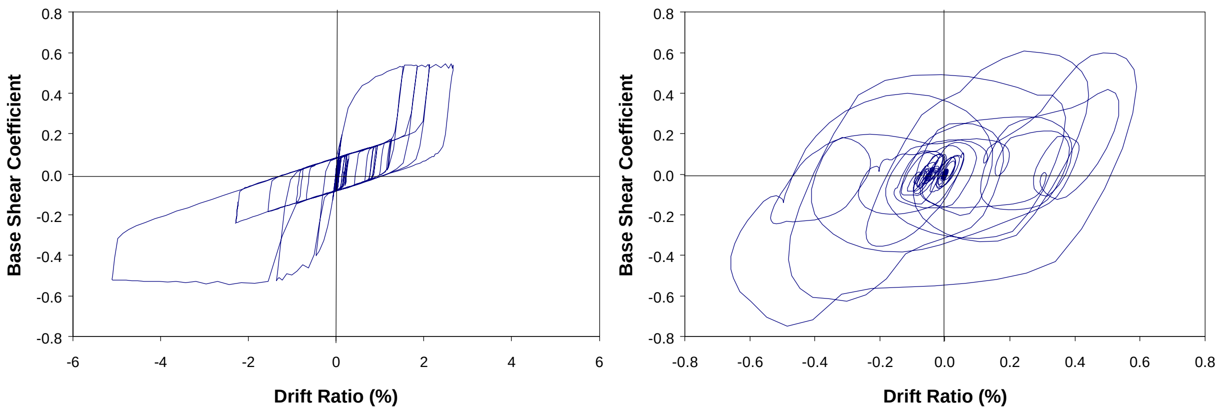


Figure 5 Ground Acceleration Record for Newhall Record (90^o comp.) of 1994 Northridge Earthquake.

Results of Numerical Analysis

The analyses were performed for the shear wall alone and for the shear wall with one fluid damper installed along the diagonal (see Figure 4). The damper was assumed to exhibit linear viscous behavior with a damping coefficient of 87.6 kN-s/m (500 lb-s/in). Note that experimental testing has shown that such damper behavior can be attained (e.g., see Symans and Constantinou, 1998). The effectiveness of the damper is clearly depicted in the hysteresis loops shown in Figure 6. Note that the two hysteresis loops are not plotted to the same scale on the horizontal axis. For the wall alone (i.e., no damper), the hysteresis loop clearly demonstrates the strongly nonlinear behavior of the wall. For the wall with the damper, the hysteresis loop consists of a combination of damper behavior and wall behavior and thus it is not as readily apparent how well the damper performed. However, a careful examination of the two loops reveals that the peak drift was reduced by 87% when the damper was utilized. This represents a significant reduction in structural damage. Furthermore, one may note the larger forces that develop within the small displacement region of the pinching zone for the case of the wall with the damper. This is the result of the damper force being proportional to velocity, thus leading to large damper forces in the region of the pinching zone where the displacements are small and the velocities are large. The larger forces that develop in the pinching region is one of the reasons that the dampers are so effective.



No Damper

C = 87.6 kN-s/m

Figure 6 Hysteresis Loops of Shear Wall Without and With Fluid Dampers.

The 87% reduction in peak drift may also be observed in the time-history shown in Figure 7. The large pulse-like response that is often associated with strong, near-field ground motions is readily apparent in the response for the wall with no damper. In contrast, the pulse-like response is completely suppressed for the wall with the damper. In addition, Figure 7 shows that the peak base shear *increases* by 37% for the wall with the damper. This is not surprising since the inclusion of supplemental dampers in a building often leads to an increase in the peak base shear (since the base shear has contributions from both the damper force and the wall shear force).

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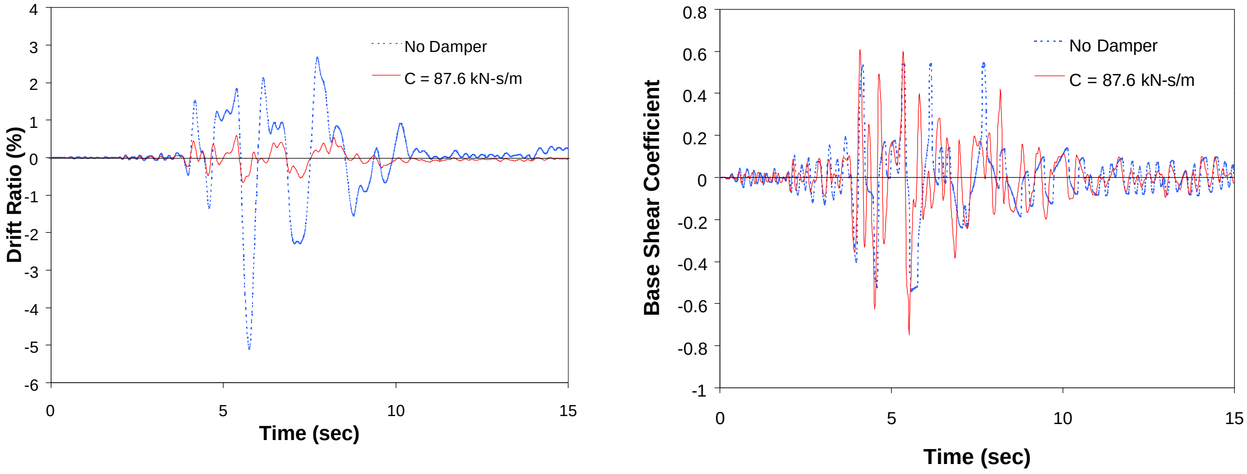
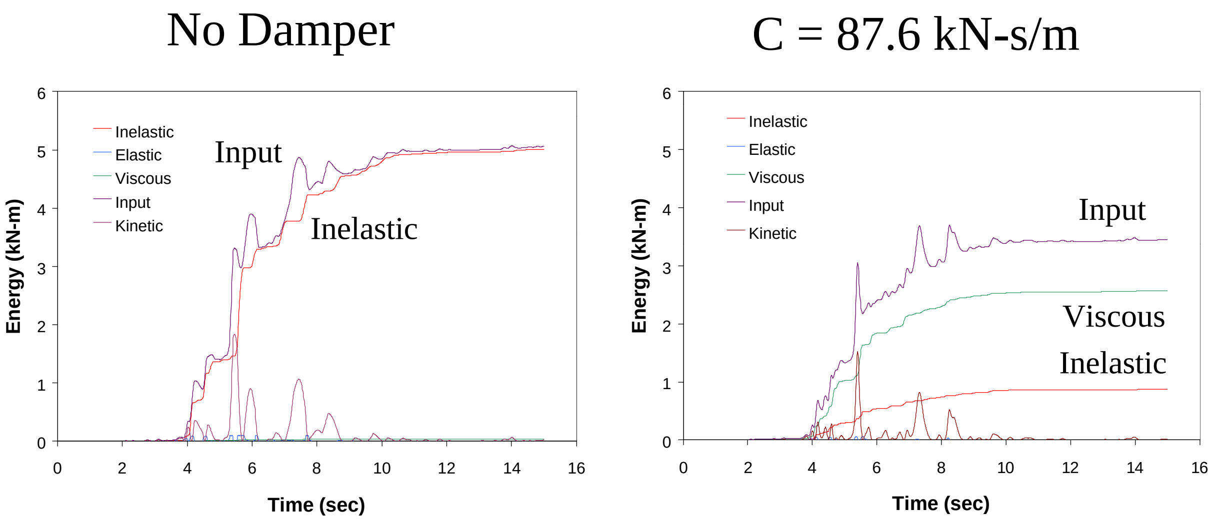


Figure 7 Time-Histories of Drift Ratio and Base Shear Coefficient

The performance of the fluid dampers may also be evaluated by considering the energy distribution within the wall during the earthquake. The time histories of various energy quantities are shown in Figure 8 for the wall with and without the fluid damper. Note that the two plots shown are plotted to the same scale. Figure 8(a) indicates that, without a fluid damper, essentially all of the seismic input energy is eventually dissipated via inelastic behavior in the wall. In contrast, Figure 8(b) demonstrates a significant reduction in energy dissipation demand on the wall (i.e., the final inelastic energy demand is approx. 1 kN-m) while the viscous energy dissipated by the fluid damper represents a large portion of the final seismic input energy (approx. 2.7 kN-m). Thus, the fluid damper has effectively provided for a transfer of energy dissipation demand from the wall to the damper. One may also note that the seismic input energy is not the same for the wall with and without the damper. This is the case since the input energy, as defined herein, is the integral of the base shear over the ground displacement. Since the base shear is different for the wall with and without the damper, the input energy is also different.

Practical Implementation Issues

For the wall with the damper, the force, velocity, and stroke demand for the damper are 14.8 kN (3.3 kips), 17.0 cm/s (6.7 in/s), and 1.1 cm (0.43 in), respectively. Such characteristics are readily available in off-the-shelf dampers. However, a number of issues remain to be addressed before fluid dampers will find implementation in buildings. For example, it is recognized that typical light wood-framed structures are primarily constructed in the field. To aid in the installation of fluid dampers in such structures, it is likely that the damper would need to be installed within a pre-fabricated shop-built wall that could be conveniently “dropped-in” to the field-constructed walls. The pre-fabricated walls would be constructed in a controlled manufacturing environment with damper connections that produce minimal slip prior to damper engagement. Minimal slip will be important for controlling the level of damage during earthquakes; particularly for frequent, weak earthquakes that, while producing damage in the structure, generate relatively small wall displacements.



(a) **(b)**

Figure 8 Energy Distribution Within Wall During Earthquake.

Conclusions

Although there has been a steadily increasing growth in the application of supplemental energy dissipation systems within steel structures, the applications within wood structures is essentially non-existent. This is in spite of the fact that light-framed wood structures experienced extensive damage during the 1994 Northridge Earthquake. The numerical analyses presented herein represents the first study on the application of fluid dampers to light-framed wood buildings. The results of the study offer convincing evidence of the potential benefit that fluid dampers offer for seismic protection of light-framed wood structures.

Acknowledgments

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