SEISMIC PERFORMANCE OF STEEL SPECIAL MOMENT FRAMES AND DAMPED FRAMES SUBJECT TO LARGE EARTHQUAKES

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Abstract

Fluid viscous dampers can be used to provide seismic protections to buildings and other structures. To date, over 650 structures, including nearly 500 buildings, have either been designed or retrofitted with viscous dampers. Both through analysis and by performance in recent earthquakes, structures designed with dampers have shown to have excellent seismic performance and meet and/or exceed the seismic requirements of modern building codes. To promulgate the use of seismic protection devices in the U.S., the task committee responsible for the seismic energy dissipation, which is also part of the working group charged with the development of the new seismic building standards (ASCE 7), has updated the relevant code sections with one goal being to encourage the use of such devices. To accomplish this goal, the pertinent sections of the standard were re-organized and re-written to streamline the design process and provide guidance to practicing engineers. In this paper, an analytical investigation was conducted using the provisions of the standard. Three models of building designs were considered; one building was designed without dampers and served as the benchmark, whereas the second building utilized seismic dampers, and a third structure used steel yielding devices. Analyses showed that all three structures met the code requirements and performed well. However, when energy dissipation was used in design, the performance was improved significantly. The improvement in performance was amplified as the models were subjected to larger levels of ground shaking.

Keywords: Seismic dampers, Seismic risk analysis, Steel moment frames, Large earthquake, Residual displacement,

1 Introduction

Fluid viscous dampers (FVDs) were originally developed as shock absorbers for the defense and aerospace industries. FVDs consist of a cylinder and a stainless-steel piston. The cylinder is filled with incompressible silicone fluid. The damper is activated by the flow of silicone fluid between chambers at opposite ends of the unit, through small orifices. Fig. 1 shows the damper cross section [1]. In recent years, they have been used extensively for seismic application for both new and retrofit construction. During seismic events, the devices become active and the seismic input energy is used to heat the fluid and is thusly dissipated. Subsequent to installation, the dampers require minimal maintenance. They have been shown to possess stable and dependable properties for design earthquakes. Fig. 2 shows the diagonal dampers placed in a reinforced concrete moment frame building recently retrofitted in Sacramento, California [2].

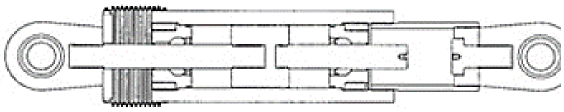


Fig. 1 –FVD cross section

Fig. 2 –Diagonal FVD in a building

The combination of fluid viscous dampers and steel or reinforced concrete special moment resisting frames (SMF) provide an attractive option for the design of new buildings in the regions of high seismicity. The resulting building is a highly damped, low-frequency building that limits seismic demand on structural and nonstructural components. FVDs can be incorporated into new construction to produce large equivalent viscous damping thus reduce the demand on the structural system.

The main advantage of this design is the reduction in the steel or concrete tonnage. Since the design of SMF is generally governed by the story drift ratios (SDRs), larger steel or concrete sizes would be required to meet this requirement. However, since in this design, FVDs are used to control SDR, smaller member sizes can be used, and this saving in material would compensate for the cost of the dampers.

2 ASCE 7-16 design procedure

2.1 Overview

The general approach is to design the SMF members for the strength requirements of the building code only. Such building would then meet all the relevant requirements of ASCE7-16 [3] except the limitations for the SDRs. FVDs are then added to design to reduce the SDRs and provide compliance with all the code requirements. Since the force in FVDs is primarily out-of-phase with the inertial forces, the demand on the existing members of foundation is not significantly increased. However, a second design check for the model with the dampers in necessary to assure that the design is still satisfactory.

The provisions in the ASCE 7-16 [3] provide information on the bounding analysis. For viscous dampers it is anticipated that the property modification factors (λ factors) to be in the range of +/-15%. The upper bound analysis would govern the requirement for the damper force, whereas the lower bound analysis will determine the damper constant necessary to meet the SDR requirements. Currently there are no provisions on the minimum effective damping to be added as part of the design process. Research [4] has shown that enhanced performance with a reduced SDR can be archived for the design by using larger dampers. While the larger (or more) dampers will add slightly to the initial cost, both the seismic performance and the life-cycle cost are significantly improved.

In this paper, analytical investigation of an example steel SMF with dampers is presented. The models were designed per ASCE 7-16 for the design earthquake (DE) and then subjected to larger earthquake and key responses and level of expected damage was investigated. Table. 1 summarizes the ley parameters considered as part of this investigation.

Table. 1 Key parameters for the models

Demand parameter	B0	B2
V/Vb	100%	100%
SDR no damper	2%	>2%
SDR with dampers	--	1%

2.2 Building Model

The five-story building is square in plan measuring 150 ft on side consisting of five 30-ft long bays. Typical stories are 13 ft tall. The gravity system consists of 4-in thick concrete slab supported by steel gravity beams and columns. The lateral force resisting system (LFRS) comprises three bays of steel SMF placed on the perimeter. The building seismic mass is approximately 10,000 kips. A typical frame on the perimeter was selected for analysis. The dead load and inertial mass tributary to this frame were included in the model. Fig. 3 presents elevation view of the model.

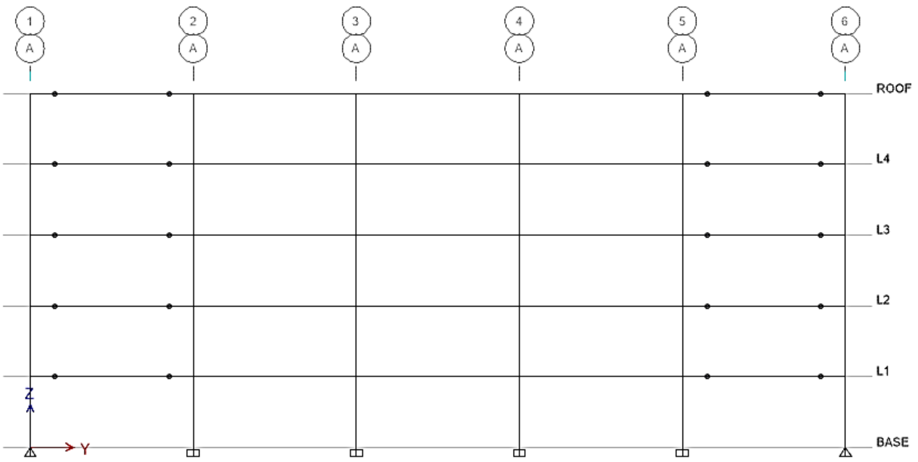


Fig. 3 –Building geometry

2.3 Seismic demand

The seismic demand was based on a typical location in Los Angeles, California, with mapped short-period (Ss) and 1-second (S1) spectral accelerations of 1.5g and 0.6g, respectively. The structure was classified as Risk Category II (I = 1.0) and located on Site Class D. Thus, the design earthquake (DE) short- and 1-second spectral accelerations were equal to 1.0g and 0.6g, respectively. This value placed the structures in Seismic Design Category (SDC) D, according to the ASCE/SEI 7 definition, for both short- and 1-second spectral intensities. The spectral acceleration (Sa) as a function of period (T) can be obtained for all period ranges of interest. The design spectrum is shown in Fig. 4.

Following the design of moment frames according to ASCE/SEI 7 requirements for strength, dampers were sized to limit story drift ratios for models B1 through B3. For new structures that use energy dissipation devices, the engineers can use either the nonlinear response history analysis (NLRHA) procedure or other methods such as equivalent lateral force or response spectrum analysis. The use of methods other that NLRHA are subject to certain limitations. The NLRHA requires that the dampers be modeled as nonlinear elements to capture their force-velocity response. However, the structural members in most cases can be modeled as linear. This approach was used to size the dampers.

To perform NLRHA, seven pairs of independent pairs of strong motion data were selected from the PEER NGA West database [6]. Either scaling or spectrum-matching of records is permitted. In this example, the matching procedure is used. The recorded accelerations were spectrally matched to the target spectrum of Fig. 4; and presented in the same figure. In this investigation, one of the components for each record was used in analysis.

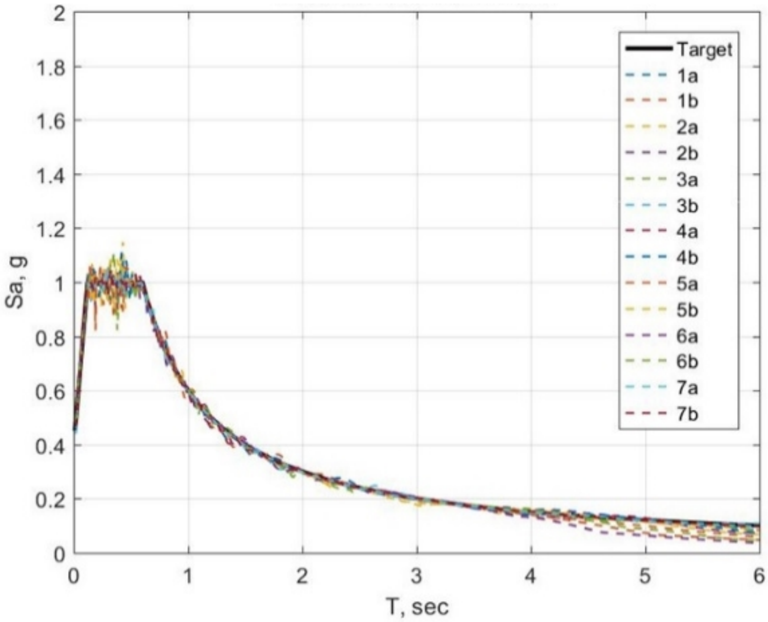


Fig. 4 –DE response spectrum and spectrum-matched motions

2.4 Building design

The equivalent lateral force (ELF) procedure of ASCE 7-16 was used to design the members of the LRFS for the models. The first model was designed for both strength and drift, whereas, the last three models were checked for strength provisions only. The design of the models was based on the current seismic provisions and thus all AISC seismic requirements ([7] and [8]) were met. The requirement for the strong column-weak beam governed the size of a number of columns; especially for B0. As it is common in practice, the same beam or column sizes were used for a give story. In addition, the members were grouped to reduce the number of member sizes for a more efficient design. Table. 2 summarizes the size of LFRS members.

Table. 2 LFRS member sizes

LFRS member sizes		**B0**	**B2**
Columns	L1-L3	W24x229	W24x146
	L4-Roof	W24x176	W24x131
Beams	L1-L3	W24x94	W24x76
	L4-Roof	W24x76	W24x62

Table. 3 presents the SDRs computed for each model. The listed values are the so-called inelastic SDR as defined in ASCE 7-16. For models B1 through B3, FVDs are added to lower the SDR to the 2% threshold value. The fundamental period for each models are also shown in the figure.

Table. 3 SDR, code-based design SDR, %

Story	**B0**	**B2**
Roof	1.6%	1.9%
L4	2.0%	2.3%
L3	2.0%	2.5%
L2	2.0%	2.6%
L1	1.4%	1.8%
Period, sec	1.5	2.1

2.5 Damper property selection

The initial selection of damper size was based on the approximate reductions in the response listed in ASCE 7-16. The damper constant (C) was then optimized to provide a SDR of approximately 1% for B2 for the level with the highest SDR for the lower bound NLRHA; see Table. 4. Since there are only five levels in the building, one size damper was used for all elevations. For all dampers, nonlinear models with a velocity exponent (α) of 0.5 were used.

Table. 4 SDR, damper added

		B0			**B2**		
	λ	--	--	--	85%	Nom.	120%
	Roof	--	--	--	0.3%	0.3%	0.2%
	L4	--	--	--	0.6%	0.5%	0.5%
	L3	--	--	--	0.9%	0.8%	0.7%
	L2	--	--	--	1.0%	1.0%	0.9%
	L1	--	--	--	0.7%	0.7%	0.7%

Table. 5 summarizes the nominal damper properties from analysis. The damper force and displacement correspond to the average value from the seven NLRHA for the damper with the largest response.

Table. 5 Nominal damper sizes, DE

Damper property	**B0**	**B2**
C (k,in units)	--	110
α	--	0.5
K diver brace, k/in	--	2000
Damper force, kips	--	300
Damper displacement, in	--	1.3

Table. 6 presents the computed damper force and displacements from the upper bound and lower bound analyses. Note that the increase in the damper force from upper bound analysis is somewhat mitigated because nonlinear dampers are used.

Table. 6 Upper and Lower bound results, DE

Damper property	**B0**		**B2**	
λ	85%	120%	85%	120%
Damper force, kips	--	--	260	340
Damper displacement, in	--	--	1.5	1.2

ASCE 7-16 requires that the dampers be sized to resist forces, displacements, and velocities from MCE_R ground motions. Table. 7 presents the expected displacement and force capacity of dampers based on the ASCE 7-16 requirements.

Table. 7 Nominal damper capacities

Damper property	**B0**	**B2**
Damper capacity, kips	--	420
Damper stroke, in.	--	2.5

3 Response subjected to large earthquakes

In this section, the response of the four models to large earthquakes is investigated using program SAP [5] . To simplify analysis, the following assumptions were made: a), epsilon effect [9] was ignored, ductile beam-to-column connections were assumed (hinge properties for compact sections from ASCE 41-17 [10]); the panel zone was not explicitly modeled; damper limit states were ignored; and to expedite analysis and data processing, incremental analysis was performed using only one of the seven records. The selection of the record was based on how close an individual record represented the average response.

3.1 Ground motion intensities

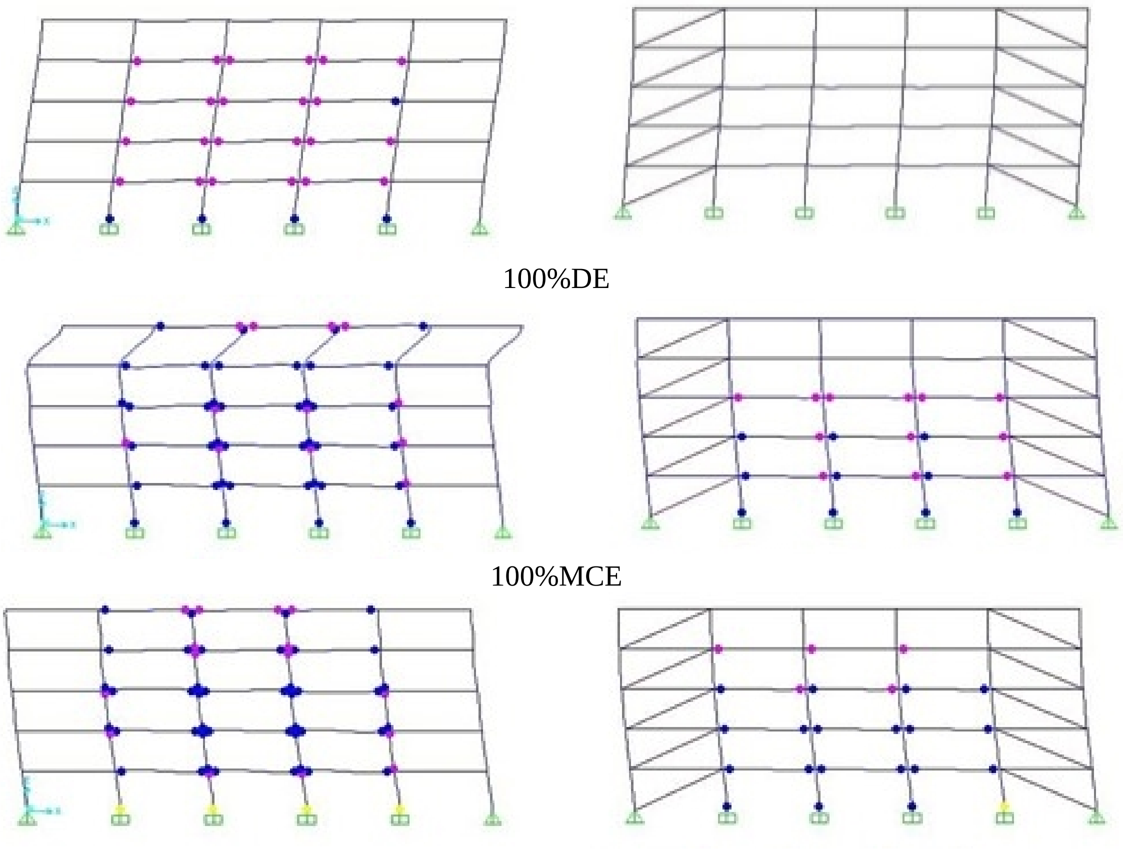
The models were subjected to incrementally increasing ground motion amplitudes and the responses of the models were monitored. The following intensities were selected: 2/3DE (typical value used for allowable stress design and for which members are expected to remain elastic); DE (life safety performance); MCE_R (Collapse prevention performance); 1.5, 2.0, 2.5, and 3.0 times MCE_R (investigate response to large earthquakes).

4 Analysis results

4.1 Deformed shapes

Fig. 5 depicts the displaced shape of the model at maximum deflection (not concurrent for all models) at selected levels of incremental ground motion. The following is noted:

- At 100%DE, B2 the model with enhanced design, remained elastic and thus damage free. For the other model, plastic hinges formed. The hinges met the life safety requirement, which is the implied performance level for the new buildings.
- At 100%MCE, models met the collapse prevention criteria or better whereas; B2 met the higher immediate occupancy performance.
- At 200%MCE, for B0, large plastic hinge rotations beyond collapse prevention were noted.



100%DE

100%MCE

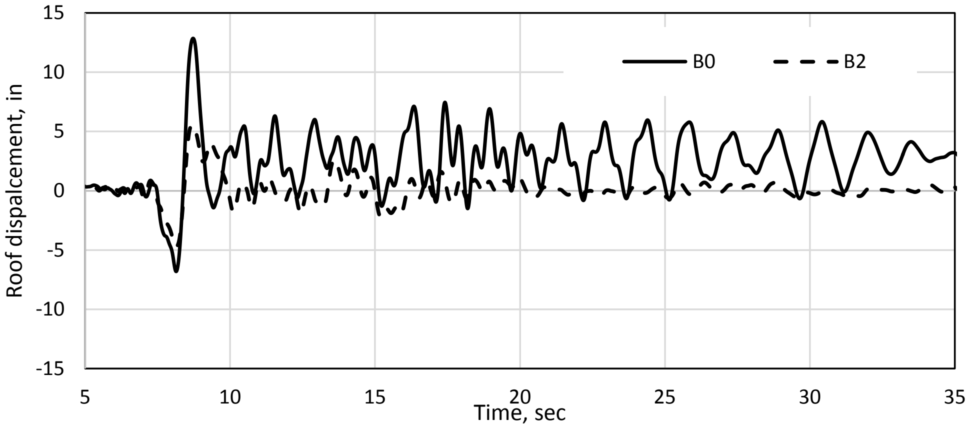
200%MCE

B00 B02

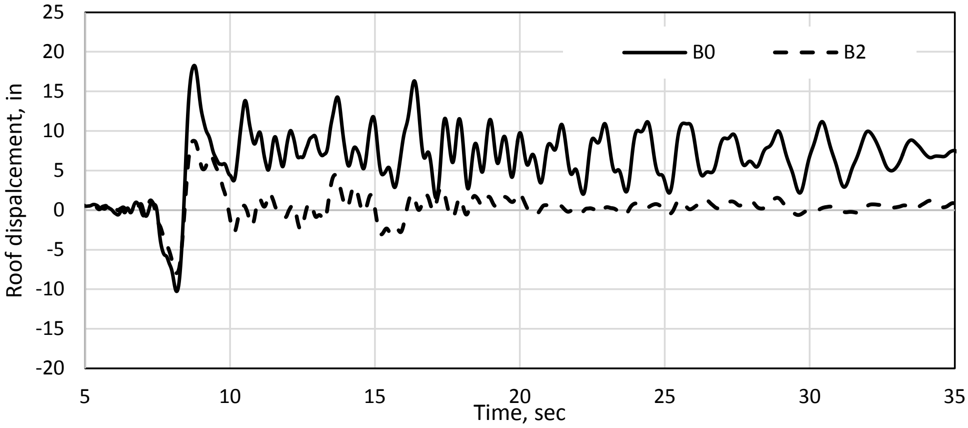
Fig. 5 –Displaced shape of the models at given intensities

4.2 Displacement response

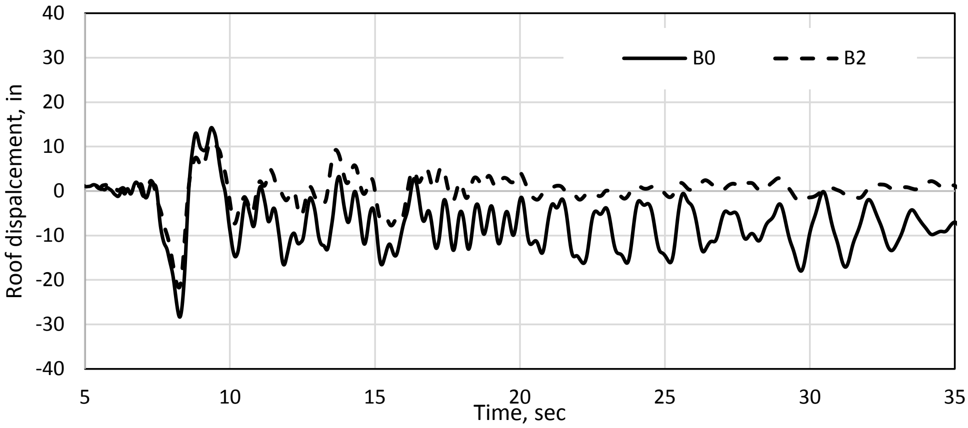
Fig. 6 presents the displacement response of the top floor of the models at the selected responses. As shown, the code-based model has significantly larger displacements and residual displacements.



100%DE



100%MCE



200%MCE

Fig. 6 –Key response parameters as a function of incremental intensities

4.3 Response evaluation

Key response parameters from analyses are summarized in Table. 8. The maximum of responses at the top floor are listed. These response parameters are the key in assessing the seismic risk for the buildings, are indicative of down time, and repair costs. The structure with dampers experienced lower accelerations (reduced demand on acceleration-sensitive components), the residual displacement (critical factor for replacement assessment) was essentially eliminated.

Table. 8 Maxima of responses

Response	**100%DE**			**100%MCE**			**200%MCE**		
	B0		**B2**	**B0**		**B2**	**B0**		**B2**
Displacement, in.	12.9		5.5	18.3		8.8	28.3		21.7
Peak floor acceleration (PFA), g	1.00		0.44	1.32		0.57	2.00		0.81
Residual displacement (RD)	3.2		0	5.6		0.3	10.0		0.3

5 Conclusions

New steel buildings were designed using provisions of ASCE 7-16. A baseline case was designed using the code strength and drift requirements. The other model used dampers to control SDRs. Analysis showed that:

- When subjected to large earthquakes, models with dampers would experience smaller plastic hinge rotations, SDR, floor accelerations, and residual displacement
- The enhanced model based on 100% of nominal base shear and larger effective damping (smaller SDR) has superior performance. This model remained damage free at MCE.
- To utilize the beneficial effect of dampers, it is critical to size the units to have sufficient strength. This is the current manufacturer practice and provides additional margin of safety for very large earthquakes.

6 Acknowledgements

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