Design of Structures with Dampers per ASCE 7-16 and Performance for Large Earthquakes

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ABSTRACT

An impediment to the use of seismic protection devices has been the difficulty for practicing engineers to design buildings with isolation system or damping devices. ASCE/SEI task committees charged with development of new generation of codes for seismic design and retrofit of buildings have updated the relevant code sections with one goal being to encourage the use of such devices. An effort was undertaken to develop a step-by-step design guideline for such design. Following the preparation of guideline, incremental analysis of four steel SMF building models was undertaken. The benchmark model was designed using the strength and drift requirements of ASCE 7-16. The other models were based on provisions of Chapter 18 of ASCE 7-16. For one model the lower base shear value was used, and for a third model, the drift ratios were further limited to obtain enhanced performance. Lower- and upper-bound analyses as required by ASCE 7-16 were conducted to size the dampers. The models were then subjected to incremental nonlinear analysis and key response parameters were evaluated. In all cases, the use of dampers resulted in reduction in the hinging of SMF members. It was notes that the best performing model was the model designed for 100% of nominal base shear and above minimum effective damping had superior performance, remaining elastic at design earthquake, and having almost no residual displacement at very large earthquakes.

INTRODUCTION

Overview. 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. Figure 1shows the damper cross section. 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. Figure 2 shows the diagonal dampers placed in a reinforced concrete moment frame building.

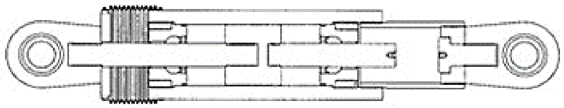


Figure 1. FVD cross section (Taylor 2017)

Figure 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.

ASCE 7-16 design procedure. 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 ASCE (2016) 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 (2016) 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.

When a building is designed according to the Chapter 18 of ASCE 7-16, it is permissible to reduce the base shear demand to as low as 75% of the computed demand to account for the beneficial effect of supplementary damping. The effect of this reduction in strength on the response of the structure to large earthquakes is not well known.

Additionally, currently there are no provisions on the minimum effective damping to be added as part of the design process. Research (Miyamoto and Gilani 2015) 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 (assumed correlated to the plastic hinging and plastic hinge rotations) was investigated. Table 1 summarizes the ley parameters considered as part of this investigation.

Table 1. Key parameters for the models

Demand parameter	B0	B1	B2	B3
V/Vb	100%	100%	100%	75%
SDR no damper	2%	>2%	>2%	>2%
SDR with dampers	--	2%	2%	1%

MODEL PROPERTIES AND DESIGN

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. Figure 3 presents elevation view of the model.

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 (S_a) as a function of period (T) can be obtained for all period ranges of interest. The design spectrum is shown in Figure 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 (PEER 2017). 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 Figure 4; and presented in the same figure. In this investigation, one of the components for each record was used in analysis.

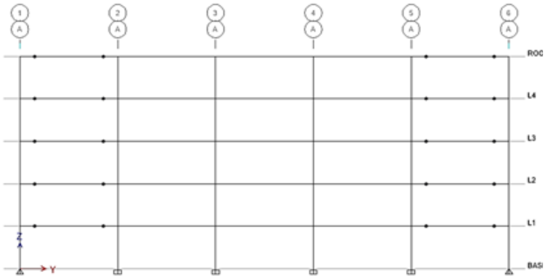


Figure 3. Building geometry

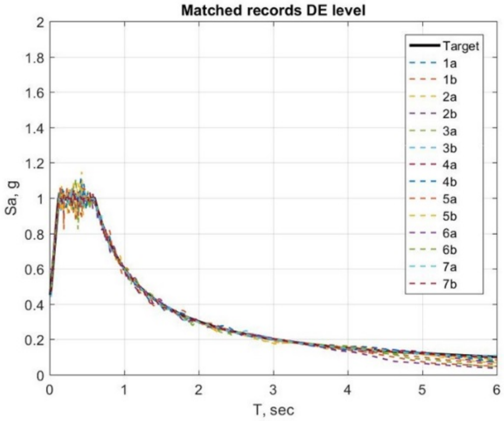


Figure 4. DE response spectrum

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 (2016a and 2016b) 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	B1	B2	B3
Columns	L1-L3	W24x229	W24x146	W24x146	W24x131
	L4-Roof	W24x176	W24x131	W24x131	W24x94
Beams	L1-L3	W24x94	W24x76	W24x76	W24x55
	L4-Roof	W24x76	W24x62	W24x62	W24x55

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	B1	B2	B3
Roof	1.6%	1.9%	1.9%	2.3%
L4	2.0%	2.3%	2.3%	2.0%
L3	2.0%	2.5%	2.5%	3.0%
L2	2.0%	2.6%	2.6%	3.2%
L1	1.4%	1.8%	1.8%	2.1%
Period, sec	1.5	2.1	2.1	2.4

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 2% (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. Computed SDR, %

			B0			B2			B3			B4	
	λ	--	--	--	85%	Nom.	120%	85%	Nom.	120%	85%	Nom.	120%
Story	Roof	--	--	--	1.3%	1.2%	1.2%	0.3%	0.3%	0.2%	1.2%	1.0%	0.8%
	L4	--	--	--	1.7%	1.6%	1.4%	0.6%	0.5%	0.5%	1.5%	1.4%	1.3%
	L3	--	--	--	1.9%	1.8%	1.7%	0.9%	0.8%	0.7%	1.9%	1.8%	1.6%
	L2	--	--	--	2.0%	1.8%	1.7%	1.0%	1.0%	0.9%	2.0%	1.9%	1.7%
	L1	--	--	--	1.3%	1.3%	1.1%	0.7%	0.7%	0.7%	1.3%	1.2%	1.1%

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	B1	B2	B3
C (k,in units)	--	20	110	30
α	--	0.5	0.5	0.5
K diver brace, k/in	--	2000	2000	2000
Damper force, kips	--	70	300	100
Damper displacement, in	--	2.6	1.3	2.7

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		B1		B2		B3	
λ	85%	120%	85%	120%	85%	120%	85%	120%
Damper force, kips	--	--	50	80	260	340	80	110
Damper displacement, in	--	--	2.8	2.5	1.5	1.2	2.8	2.5
Damper capacity, kips	--		100		420		135	
Damper stroke, in.	--		4.5		2.5		4.5	

ASCE 7-16 requires that the dampers be sized to resist forces, displacements, and velocities from MCER 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	B1	B2	B3
Damper capacity, kips	--	100	420	135
Damper stroke, in.	--	4.5	2.5	4.5

ANALYSIS PROGRAM

Overview. In this section, the response of the four models to large earthquakes is investigated. For analyses, the following assumptions were made: a) for incremental analysis, epsilon effect is usually used to account for the variation on the spectral shape of ground motion for larger intensities (Vamvatsikos and Cornell, 2004). This factor was not included in analysis; b) since the model is representative of new construction, it was assumed that ductile beam-to-column connections were used. As such hinge properties for compact sections from Table 9.6 of ASCE 41-17 (2018) were used for the beams and columns (see Figure 5); c) the panel zone was not explicitly modeled, however, the centerline dimensions without rigid end offsets were used; d) research (Miyamoto and Gilani 2015) has shown that reaching the damper force and stroke capacities can have significant effect on the response of structures with dampers. This effect was not explicitly modeled, however, the damper forces were monitored, and a limit state was considered when the force in the dampers reached its capacity; e) Damper manufacturers (Taylor 2017) typically use a larger factor of safety for the damper force than required by ASCE 7-16. . However, since the objective of analysis was to strictly comply with the ASCE 7-16 requirements, such increase in capacity was not accounted for in analysis; and f) 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. Figure 6 presents the response from individual seven records normalized to the average response at each level. The record with the least deviation is identified with a solid line and used hereafter.

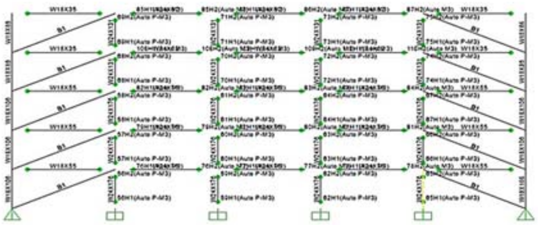


Figure 5. Nonlinear analysis model

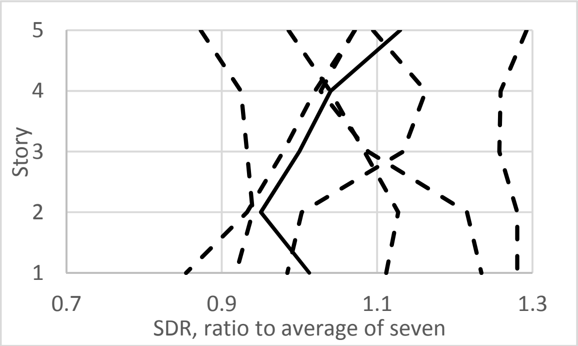


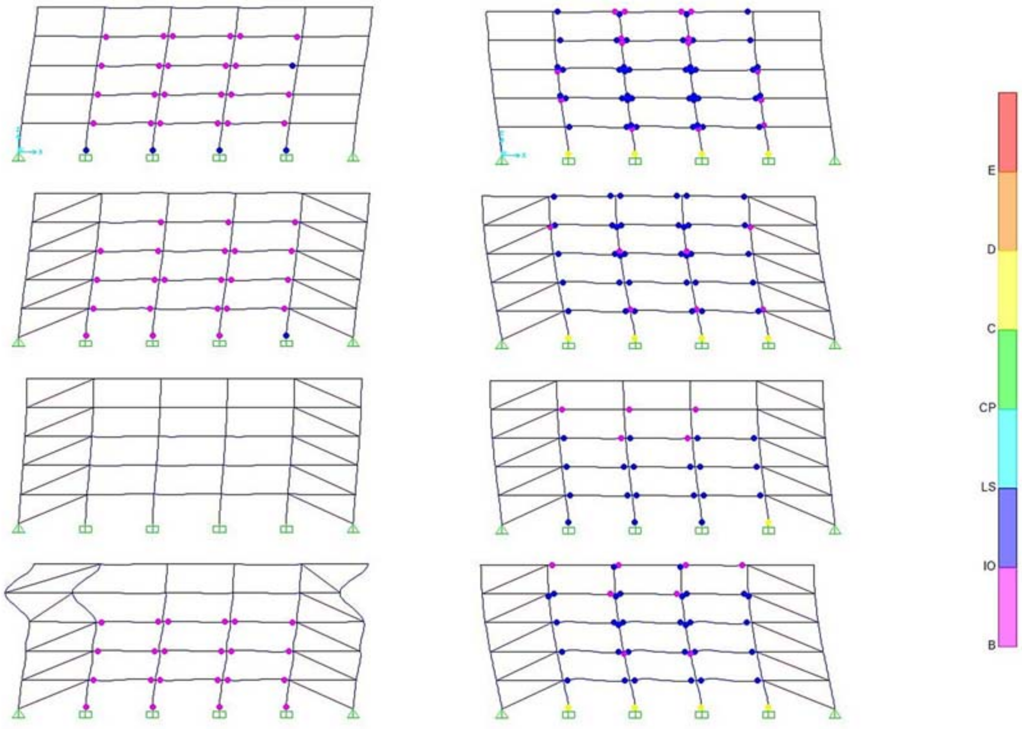
Figure 6. Response normalized to average

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); MCER (Collapse prevention performance); 1.5, 2.0, 2.5, and 3.0 times MCER (investigate response to large earthquakes).

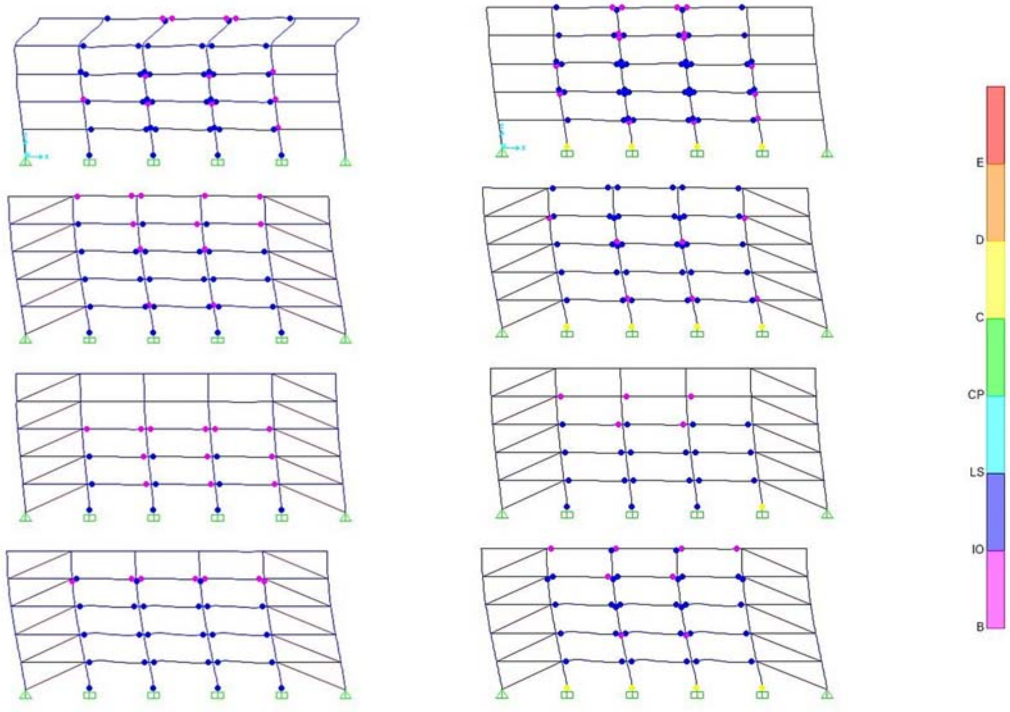
ANALYSIS RESULTS

Deformed shapes. Figure 7 depicts the displaced shape of the model at maximum deflection (not concurrent for all models) at four selected levels of incremental ground motion. In the figures, the models correspond to B0 through B4 from top to bottom respectively. The following is noted:

- At 67%DE intensity, all models remained elastic and thus comply with the assumptions used in the allowable stress design methodology
- At 100%DE, B2 the model with enhanced design, remained elastic and thus damage free. For the other three models, plastic hinges formed. The hinges for all the models met the life safety requirement, which is the implied performance level for the new buildings. The models with minimum supplemental damping (B1 and B3) underwent less nonlinearity and met a higher performance
- At 100%MCE, all models met the collapse prevention criteria or better whereas; B2 met the higher immediate occupancy performance.
- At 200%MCE, except for B2, large plastic hinge rotations beyond collapse prevention are noted.



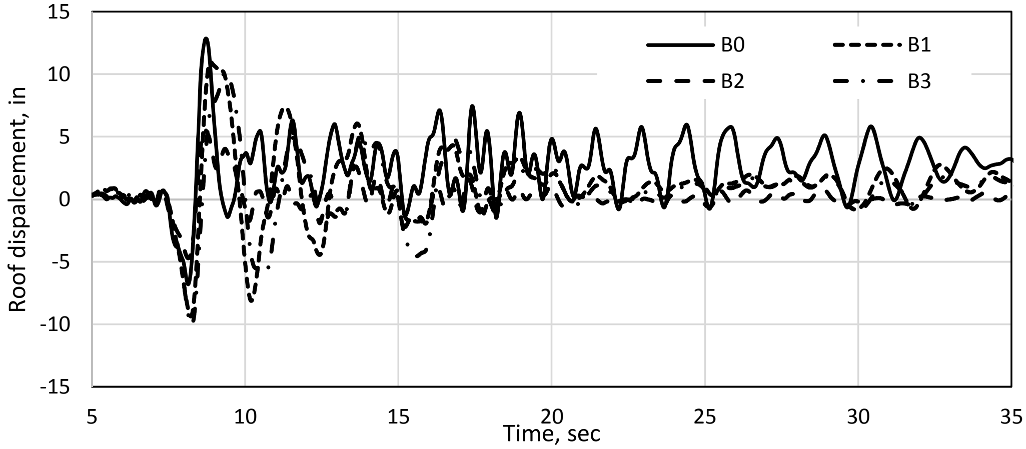
100%DE 100%MCE



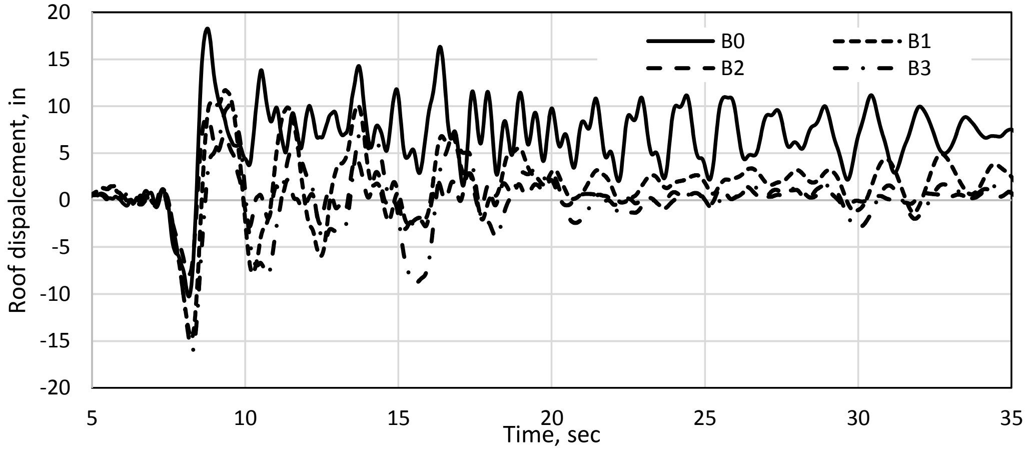
150%MCE 200%MCE

Figure 7. Displaced shape of the models at given intensities

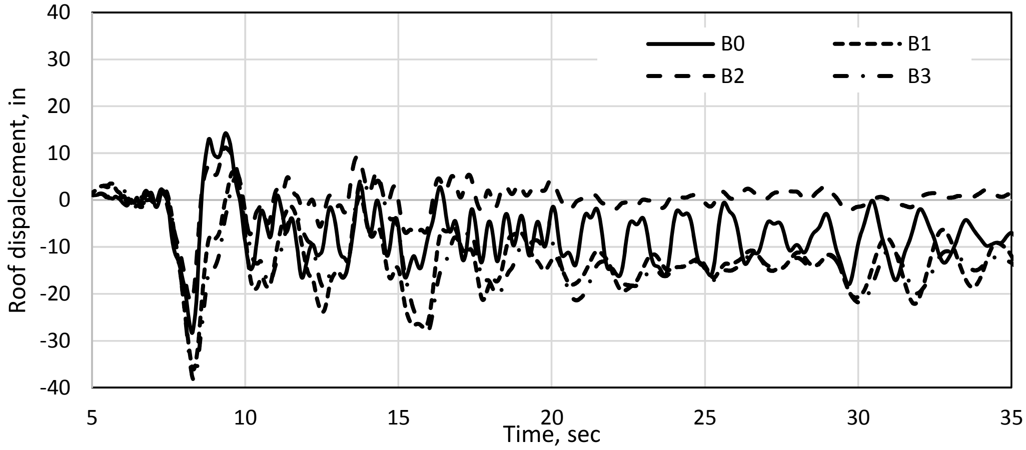
Displacement response. Figure 8 presents the displacement response of the top floor of the models at the selected responses.



100%DE



100%MCE



200%MCE

Figure 8. Key response parameters as a function of incremental intensities

Response evaluation. Key response parameters from analyses are summarized in Table 8. The maximum of responses from analysis are shown. The values correspond to the values at the top floor of the building. The results for B3 are not shown, as they were similar to B1. These response parameters are the key in assessing the seismic risk for the buildings, are indicative of down time, and repair costs. The structures with dampers experience lower accelerations and thus reduce demand on acceleration-sensitive components. For the enhanced model B2, the residual displacement is essentially eliminated. This parameter is critical whether building needs replacement in the aftermath of an earthquake.

Table 8. Maxima of responses

Response	100%DE			100%MCE			200%MCE		
	B0	B1	B2	B0	B1	B2	B0	B1	B2
Displacement, in.	12.9	10.9	5.5	18.3	14.7	8.8	28.3	36.1	21.7
Peak floor acceleration (PFA), g	1.00	0.64	0.44	1.32	0.82	0.57	2.00	1.10	0.81
Residual displacement (RD)	3.2	0.7	0	5.6	1.8	0.3	10.0	14.4	0.3

Damper responses. Table 9 summarizes the damper forces from analysis. As seen, the damper forces at large earthquakes exceed the current ASCE 7-16 requirements. It is recommended that a factor of approximately 2.0 beyond MCE be used for sizing dampers—consistent with the current manufacturer practice (Taylor 2017).

Table 9. Damper response

	Damper force, kips			Force/capacity		
Input level	B1	B2	B3	B1	B2	B3
100%DE	80	350	110	0.8	0.8	0.8
100%MCE	100	440	125	1.0	1.0	1.0
200%MCE	130	580	160	1.3	1.4	1.2

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 three cases used dampers to control the drift ratios. Different targets of base shear and SDR were used. 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.

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