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Seismic behavior of structural and non-structural elements in RC building with bypass viscous dampers

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Abstract. During the last few decades, fluid viscous dampers have been significantly improved in terms of performance and reliability. Viscous dampers dissipate the input energy into heat and the increased temperature may damage internal seals of the damper. As a result, thermal compensation is crucial for almost all fluid viscous dampers. In this study, while referring to the main working principles of the recently developed bypass viscous damper in Iran, a comprehensive case study is conducted on a RC building having diagonal braces equipped with such viscous dampers. Experimental results of a small-scale bypass viscous damper is presented and it is shown that the currently available simplified Maxwell models can simulate behavior of the bypass viscous damper with good accuracy. Using a case study, contribution of bypass viscous dampers to seismic behavior of structural and non-structural elements are investigated. A designed procedure is adopted to increase damping ratio of the building from 3% to 15%. In this way, reductions of 25% and 13% in the required concrete and steel rebar materials have been achieved. From nonlinear time history analyses, it is observed that bypass viscous dampers can greatly improve seismic behavior of structural elements and non-structural elements.

Keywords: viscous damping; bypass viscous damper; energy dissipating device; numerical analysis; seismic behavior; non-structural Elements

1. Introduction

During the last decades, significant efforts have been made to improve seismic behavior of building structures with supplemental energy dissipating devices (Soong and Dargush 1997, Zahrai and Mousavi 20012, Bayat and Bayat 2014, Zahrai *et al.* 2015, Farahi Shahri and Mousavi 2018). Viscous dampers are among the most recognized and reliable passive energy dissipating devices which performed quite satisfactory during laboratory tests (Constantinou and symans 1992, Seleemah and Constantinou 1997, Kasai and Matsuda 2014, Constantinou *et al*. 2001, Zhang *et al.* 2012, Yamamoto *et al*. 2016, Mousavi *et al*. 2018) and earlier strong seismic events (Kasai *et al*. 2012, Taylor Devices Inc 2002). Unlike displacement-dependent energy dissipating devices, viscous dampers have commonly negligible stiffness and they are able to increase effective damping without violating lateral/torsional stiffness of the structure. As a result, viscous dampers have great contribution to mitigating story accelerations and subsequently improving seismic performance of non-structural elements (Seleemah and Constantinou, Mousavi *et al*. 2018, Kasai *et al.* 2012).

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A typical viscous damper works based on the principle of flow of a viscous fluid through one or more orifices with or without pressure relief valves. Although the working principles of viscous dampers are quite simple, the process of design and construction of a modern viscous damper is a multidisciplinary task and requires significant expertise in different branches of science. Modern commercial viscous dampers have many unpublished high-tech details which highly improve their performance and reliability, compared to their predecessors. In other words, most manufacturers, if not all, have their own proprietary technical details which are confidential and cannot be found in open literatures.

A typical viscous damper has four main characteristics, as follow,

I. Damping coefficient: damping coefficient highly depends on the geometrical parameters of the damper and its orifice.

II. Velocity exponent: This parameter defines shape of the force-velocity curve of the damper. Linear and nonlinear viscous dampers have velocity coefficients of 1 and less than 1, respectively. Velocity exponent of the damper depends on details of the damper orifice and the relieve valves, if present. For seismic or even wind applications, velocity exponents of 1 or less are desirable (Seleemah and Constantinou 1997).

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III. Stroke: Damper stroke determines displacement capacity of the damper during load reversals.

IV: Force capacity: Depending on the maximum fluid pressure that can be developed in the damper, force capacity of the damper can be estimated. High-tech viscous dampers can sustain significant pressures, in the range of 600 bar to 1000 bar. Considering a specific sealing technology, force capacity of the damper can be increased by increasing diameter of its main cylinder.

Damping coefficient and velocity exponent of the damper can be highly affected by details of the damper orifice. As shown in Fig. 1, linear or nonlinear behaviors with velocity exponents of 1 or less can be achieved by using fluidic control orifices (Seleemah, and Constantinou 1997), relief valves (Yamamoto *et al.* 2016, KYB Corporation 2018) or other pressure-responsive valves (Seleemah and Constantinou 1997).

A patented new viscous damper, called bypass viscous damper, has been recently developed in Iran by Behsazan Larzeh Davam Co. As illustrated in Fig. 1(c), bypass viscous damper has an external high pressure hose to act as an external flexible orifice. Among other parameters, velocity exponent of the damper can be adjusted by radial flexibility of the hose.

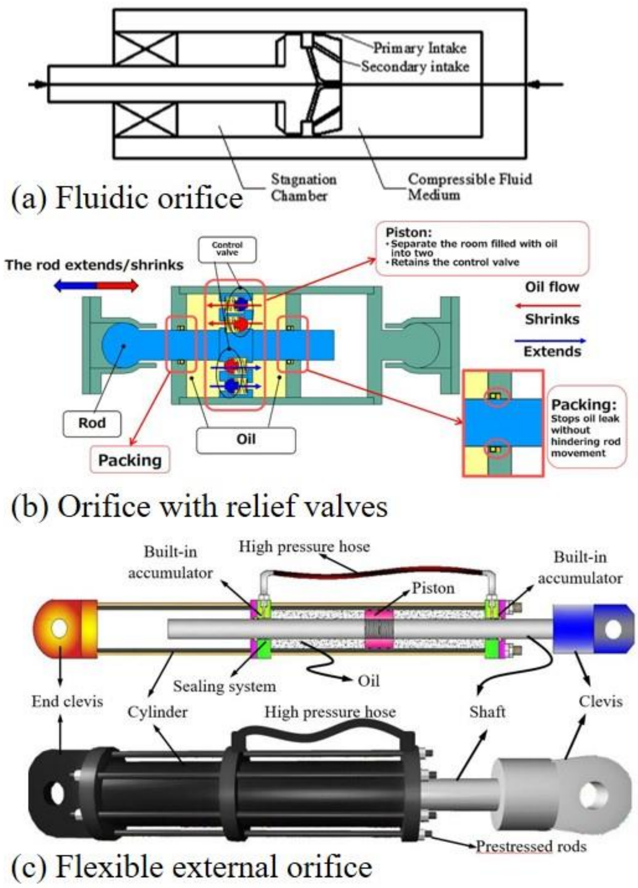

Fig. 1 Different orifice details that are able to lead to velocity exponents of 1 or less. (a) Fluidic orifice (Seleemah and Constantinou 1997), (b) Relief valve orifice (Black and Markis 2006) and (c) Flexible external orifice (Mousavi *et al.* 2018)

As mentioned earlier, viscous dampers dissipate the input energy into heat. Consequently, temperature of the damper can be significantly increased, especially during high duration loads (Mousavi *et al*. 2018, Black and Markis 2006). As measured by Black and Makris (2006), in the case of viscous dampers with internal orifices under high duration loads, temperature of the oil can be increased up to 200 Celsius degrees, especially at the regions close to the orifice. Although compared to early devices, modern viscous dampers are less sensitive to temperature, some of their internal components, such as seals, can still degrade during extremely high temperatures. It is believed that viscous dampers with external orifice have better thermal compensation characteristics.

Dynamic behavior of full-scale bypass viscous dampers has been experimentally investigated by Mousavi *et al.* (2018). However, due to actuator limitations, the maximum imposed speed was limited to 150 mm/s. To address this problem, a small-scale bypass viscous damper is tested with a much faster actuator to investigate dynamic behavior of bypass viscous dampers in wider range of velocities.

Testing procedure and obtained results are discussed in the subsequent section. The study is followed by investigating a simplified Maxwell model to simulate behavior of the bypass viscous damper. This model is available in many analytical software and has been widely used to simulate behavior of viscous dampers. Finally, considering a case study, contribution of bypass viscous dampers to seismic performance of structural and non-structural elements is investigated. Although such contribution has been extensively studied by earlier researchers, many of the carried out studies (Seleemah, and Constantinou 1997, Domenico and Ricciardi 2019, Liu *et al.* 2019), have compared moment frames without viscous dampers to exactly the same frames with viscous dampers. The authors believe that this may not be a fair comparison as a frame with viscous dampers should have less material compared to its un-damped counterpart. This issue is addressed in this study by independently designing the buildings with and without viscous dampers.

2. Experimental study

2.1 Specimen

The small-scale bypass viscous damper has the following characteristics:

Damping coefficient: 1.25 kN.(s/mm)0.55
Velocity exponent: 0.55
Stroke: ±80 mm
Force capacity: 50 kN

The specimen was manufactured and tested by Behsazan Larzeh Davam Co. The carried out experimental program and the main results are reviewed in the following subsections.

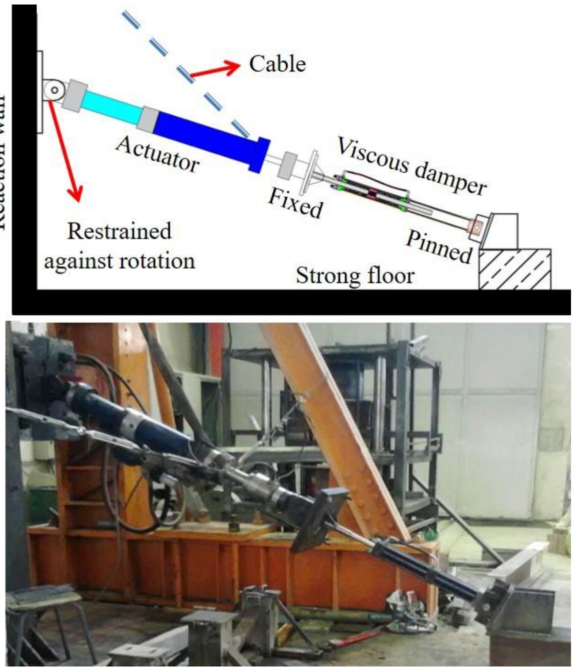

Fig. 2 Adopted set-up for dynamic testing of bypass viscous damper

2.2 Set-up and loading protocols

As shown in Fig. 2, a unique inclined set-up was used to test the damper. Many dampers are tested in a pined-pined configurations [11-13, 15]. However, a pinned-fixed configuration was selected as in some practical applications, minor flexural demands might be imposed to the damper shaft.

Cyclic displacement-controlled loads with different frequencies and amplitudes were applied to the damper. Frequencies from 0.33 Hz to 2 Hz and amplitudes from 10 mm to 70 mm were imposed to the damper and each frequency-amplitude pair was repeated in 5 cycles. Totally 140 cycles with different amplitudes and frequencies were applied to the damper. Due to the superior thermal compensation characteristics of the bypass viscous damper, no time gap was considered between different protocols and the total experimental program was finished in less than 12 minutes.

2.3 Results

Cyclic behavior of the bypass viscous damper in different frequencies and amplitudes are illustrated in Fig. 3. It can be observed that the damper demonstrates quite stable behavior. It is also evident that the damper has some hardening effects during higher amplitude protocols. As mentioned before, one end of the damper was pinned and the other end was fixed. Accordingly, the shaft of the damper experienced minor flexural moments which was also observed during the tests. It is believed that the hardening effect of the damper in higher amplitude protocols, is mainly due to the imposed flexure. Such minor flexural moments may be inevitable in some diagonal damper-brace configurations.

Force-velocity curve of the specimen is depicted in Fig. 4. According to ASCE 7-16 (ASCE 7 2016), recommended values for specification tolerance of velocity-dependent dampers are typically ranging from ±10% to ±15%. From Fig. 4, it is clear that the specification tolerance of the specimen is less than 15%. As a result, it is expected that behavior of the damper can be simulated with its specified properties.

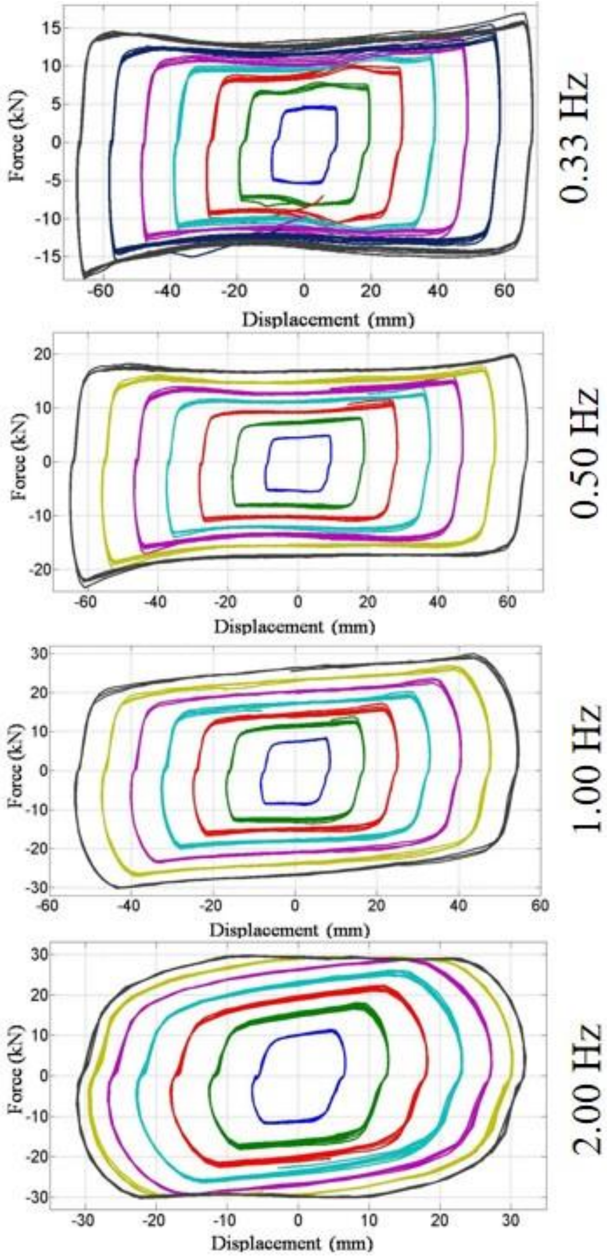

Fig. 3 Obtained cyclic behaviors of the bypass viscous damper under different frequencies and amplitude (each amplitude-frequency is repeated in 5 cycles)

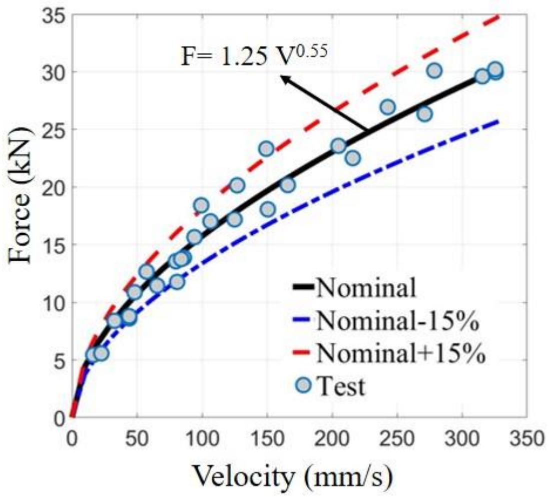

Fig. 4 Force-velocity curve of the tested bypass viscous damper

3. Numerical simulation

Considering a simplified Maxwell model, cyclic behavior of the bypass viscous damper is simulated and compared to those obtained from the carried out tests. As mentioned earlier, the model is available in different analytical software. In this study, SAP2000 (SAP2000 2015) is used for the numerical simulations. Fig. 5 shows that the model is able to simulate behavior of the bypass viscous damper with good accuracy. Due to page number limitations, numerical and experimental results are compared only for excitations with frequency of 1 Hz.

4. Case study

In this section, adopting a 7-story Reinforced Concrete (RC) building and 10 pairs of ground motions with return periods of 50 years and 475 years (two hazard levels), contribution of bypass viscous dampers to seismic behavior of structural and non-structural elements is investigated. Table 1 represents the selected earthquakes. Earthquakes No. 6 to 10 are pulse-type near-field ground motions.

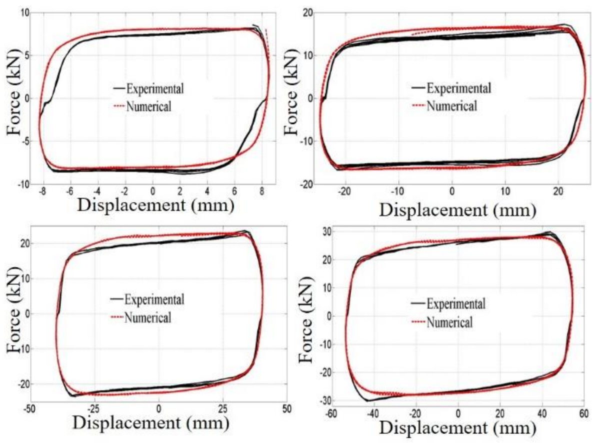

Fig. 5 Accuracy of the simplified Maxwell model to simulate behavior of the bypass viscous damper under different amplitudes and frequency of 1Hz

The building is designed in two different cases, i.e., with and without viscous dampers. Details of the adopted building, design procedure and obtained results are presented in the following subsections. Inelastic behavior of RC shear walls and columns are simulated with fiber plastic hinges, considering the confinement effect of stirrups and crossties. Localized plastic hinges based on ASCE 41-17 (ASCE 41 2017) are used for RC beams considering strength and stiffness degradations. During all simulations, the gravity load (Dead + 0.25 Live) is imposed first and then ground motion pairs are imposed to the building. P-delta effect is also considered in the carried out analyses and inherent damping ratio of 3% is considered for the buildings. Soil-structure interaction is neglected in the numerical models. It should be noted that the building with and without dampers are independently designed and thus they do not have the same beam and column cross sections.

4.1 Case I: Building without damper

As illustrated in Fig. 6, considered structure is a 7-story RC residential building. The building without damper has intermediate RC Moment Resisting Frames (MRFs) along the X direction and dual system of intermediate RC MRFs and special RC shear walls along the Y direction. Seismic performance-based procedure is used to design the building satisfying life safety acceptance criteria for a seismic hazard with return period of 475 years based on the nonlinear static procedure and acceptance criteria of ASCE 41-17.

4.2 Case II: Building with viscous dampers

Current seismic codes provide no straightforward procedure for design of buildings with supplemental energy dissipating devices. However, for buildings with supplemental energy dissipating devices, many design

Table 1 Adopted ground motions in the nonlinear time-history analyses

No.	Name	Station	Mag.	d (km)
1	Northridge	Beverly Hills-Mulhol	6.7	17.2
2	Duzce	Bolu	7.1	12
3	Kobe	Nishi-Akashi	6.9	19.2
4	Manjil	Abbar	7.4	12.6
5	Cape Mendocino	Rio Dell Overpass	7.0	14.3
6	Kocaeli	Izmit	7.5	7.2
7	Loma Prieta	Saratoga-Aloha	6.9	8.5
8	Erzincan	Erzincan	6.7	4.4
9	Landers	Lucerne	7.3	2.2
10	ChiChi	TCU065	7.6	0.6

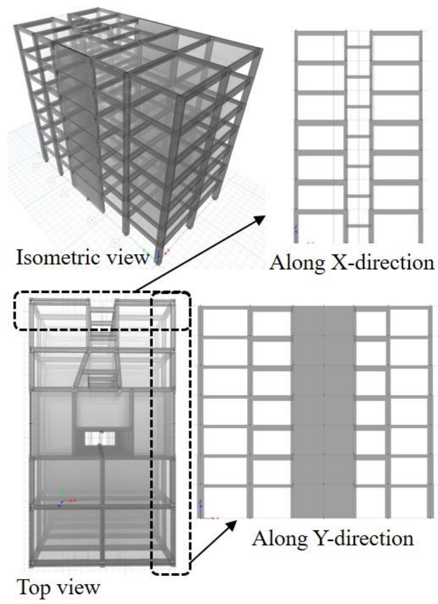

Fig. 6 Adopted building-Case I: Design without damper Fundamental periods of the building without viscous dampers along the X and Y directions are 1.59 s and 0.58 s, respectively

procedures have been proposed by different researchers (Mousavi and Ghorbani-Tanha 2012, Kim *et al*. 2017, Weng *et al*. 2012). As a result, the procedure proposed by Mousavi and Ghorbani-Tanha (Mousavi and Ghorbani-Tanha 2012) is adopted to design the building with viscous dampers. In this procedure optimum placement and characteristics of linear viscous dampers would be obtained to achieve a target damping ratio. The procedure is based on minimizing an optimization index (OI), defined as (Mousavi and Ghorbani-Tanha 2012),

$$OI = \sum_{s=1}^{q} \sum_{j=1}^{n} \left|B_j(\omega_s)\right|^2 \tag{1}$$

where s is the mode number and q represents the maximum number of mode that has a noticeable effect (commonly the first three or four modes are enough). The parameter n stands for the number of stories and Bj is the inter-story transfer function of the jth floor which is the jth element of the inter-story transfer vector B defined as (Mousavi and Ghorbani-Tanha 2012)

$$\boldsymbol{B}(\omega) = -\boldsymbol{A}^{-1}\boldsymbol{\Lambda}_2 \tag{2}$$

$$\mathbf{A} = -\omega^2\boldsymbol{\Lambda}_1 + \mathbf{K}_{\mathbf{db}} + i\omega\mathbf{C}^*_{\mathbf{db}} \tag{3}$$

$$\boldsymbol{\Lambda}_1 = \begin{bmatrix} \lambda_1 & \lambda_2 & \cdots & \lambda_n \\ \lambda_2 & \lambda_2 & \cdots & \lambda_n \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_n & \lambda_n & \cdots & \lambda_n \end{bmatrix} or\, \Lambda_1(r,s) = \begin{cases} \lambda_s\ , & for\, s \geq r \\ \lambda_r\ , & for\, s < r \end{cases} \tag{4}$$

$$\boldsymbol{\Lambda}_2 = \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{Bmatrix} \tag{5}$$

In Eqs. (4) and (5) the parameter λ is the mass index which describes cumulative distribution of mass along the height of the building. According to (Mousavi and Ghorbani-Tanha 2012), the mass index is defined as

$$\lambda_j = \frac{1}{M}\sum_{r=j}^{n} m_r \tag{6}$$

where M is the total seismic mass of the building and m_r is the seismic mass at the rth floor. Moreover, in Eq. (3) C^*_{db} and K_{db} are modified damping and stiffness matrices of the drift-base equation of motion which are defined as (Mousavi and Ghorbani-Tanha 2012)

$$\mathbf{C}^*_{\mathbf{db}} = \frac{1}{M}\left\{\mathbf{T}^*\mathbf{c}\mathbf{T}^{-1} + \mathbf{c}_{\mathbf{d}}\right\},\ \mathbf{K}_{\mathbf{db}} = \frac{1}{M}\left\{\mathbf{T}^*\mathbf{k}\mathbf{T}^{-1} + \mathbf{k}_{\mathbf{d}}\right\} \tag{7}$$

Inherent damping and stiffness matrices of the structure are denoted by c and k, respectively. c_d and k_d are diagonal matrices of added damping and stiffness of the viscous dampers such that each diagonal element denotes the added damping and stiffness in its corresponding story. Moreover, in Eq. (7), T and T^* are defined as

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ -1 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & -1 & 1 \end{bmatrix} or\, T_{rj} = \begin{cases} 1\,, & for\ \ r = j \\ -1\,, & for\ \ r = j+1 \\ 0\,, & otherwise \end{cases} \tag{8}$$

$$\mathbf{T}^* = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 0 & 1 & \cdots & 1 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 1 \end{bmatrix} or\, T^*_{rj} = \begin{cases} 1 & , j \geq r \\ 0\ , & otherwise \end{cases} \tag{9}$$

In the incremental procedure proposed by Mousavi and Ghorbani-Tanha, a predefined damping increment is placed in a specific story and the corresponding value of the parameter OI would be obtained. As a result for each damping increment placed at each story, a value for the OI can be calculated. The story which leads to the minimum OI would be selected as the optimum place for that damping increment. This procedure is repeated for the next damping increment, until the minimum OI reaches its target value. It should be noted that the target OI value can be obtained by assuming the target damping ratio as the inherent damping ratio of the building with no additional energy dissipating device. Further details about this incremental procedure can be found elsewhere (Mousavi and Ghorbani-Tanha 2012).

Although the aforementioned procedure is an effective way to optimally design and place viscous dampers, but this technique is not directly applicable to nonlinear viscous dampers. As a result, nonlinear viscous dampers should be linearized in the preliminary design phase. This can be done by the procedure proposed by Lin and Chopra (Lin *et al.* 2002) where damping coefficient of a nonlinear viscous damper can be obtained from its linear counterpart through the following formulation

$$c_\alpha = \frac{(\omega u_0)^{1-\alpha}}{\beta_\alpha} c_l \qquad (10)$$

where, c_l is the damping coefficient of the linear viscous damper and c_α is damping coefficient of its nonlinear counterpart. Velocity exponent of the nonlinear viscous damper is denoted by α and the constant β_α is

$$\beta_\alpha = \frac{2^{2+\alpha}\Gamma^2(1+0.5\alpha)}{\pi\Gamma(2+\alpha)} \qquad (11)$$

In Eq. (11), Γ (.) is the gamma function. For a linear viscous damper (α=1), β_α=1 and for a nonlinear viscous damper with α=0.55, from Eq. (11) β_α=1.1. Note that in Eq. (10) ω is the fundamental natural frequency along the considered direction and u_0 is the maximum displacement of the damper.

The bare building, i.e., without viscous dampers, are first designed for the gravity loads and the reduced seismic loads as suggested by ASCE 7-16. Target damping ratio of the building selected to be 15% as a result the reduced seismic load would be about 0.75 E, in which, E is the seismic load per ASCE 7-16. After designing the bare building, viscous dampers are designed and placed according to the aforementioned procedure. Obtained results are summarized in Table 1. Totally 28 ND30 viscous dampers are required to increase damping ratio of the building from 3% to 15%. Note that ND30 is a viscous damper with damping coefficient of 30 kN.(s/mm)0.55 and velocity exponent of 0.55. Fig. 7 shows the building with viscous dampers. In the numerical simulations, nonlinear viscous dampers are modeled with link elements which their accuracy has been verified in the previous section.
Fundamental periods of the building with viscous dampers along the X and Y directions are 1.69 s and 1.67 s, respectively. Note that in both directions, the building with viscous dampers has larger natural periods. This is more pronounced along the Y direction due to the fact that the shear wall is removed in the building with viscous dampers.

Table 1 Placement of the viscous dampers

Story	X-direction	Y-direction
7	-	-
6	2 × ND30	2 × ND30
5	4 × ND30	4 × ND30
4	4 × ND30	4 × ND30
3	4 × ND30	4 × ND30
2	-	-
1	-	-

ND30: viscous damper with damping coefficient of 30 kN.(s/mm)0.55 and velocity exponent of 0.55

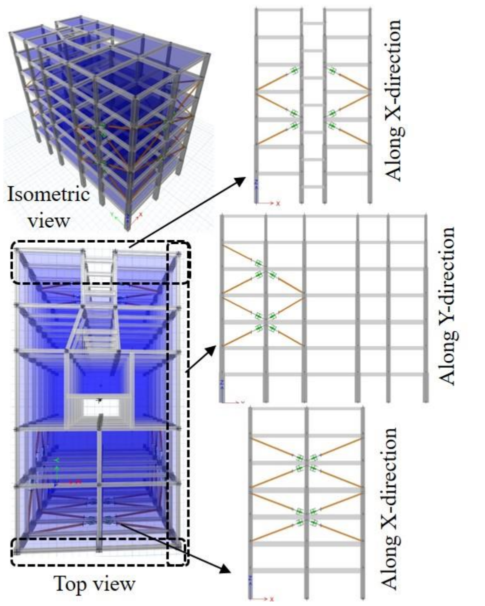

Fig. 7 Adopted building-Case II: Design with damper

4.3 Inter-story drift

Average maximum inter-story drifts of the buildings along different directions and under different seismic hazard levels (return periods of 50 years and 475 years) are illustrated in Fig. 7. It can be seen that along the X direction, the building with viscous damper experienced lower story drifts, except for the 7th story during hazard level of 475 years. However, along the Y direction, the building without damper experienced less maximum story drifts due to presence of RC shear walls along Y direction of the building without dampers.

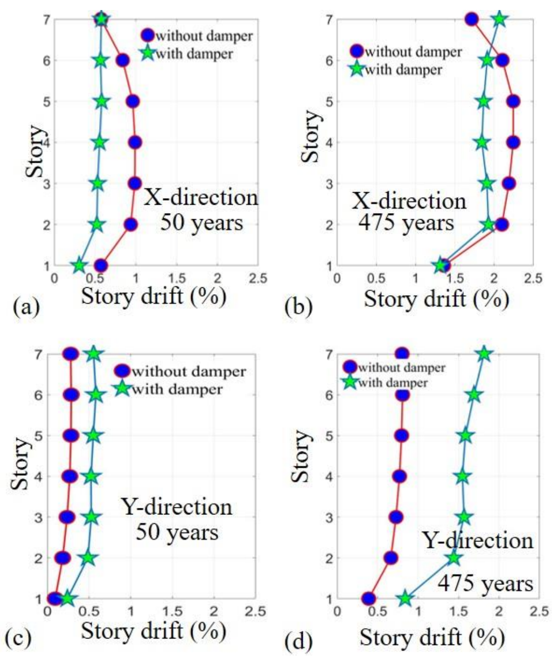

Fig. 8 Maximum inter-story drift of buildings with and without viscous dampers- average of 10 pairs of ground motions

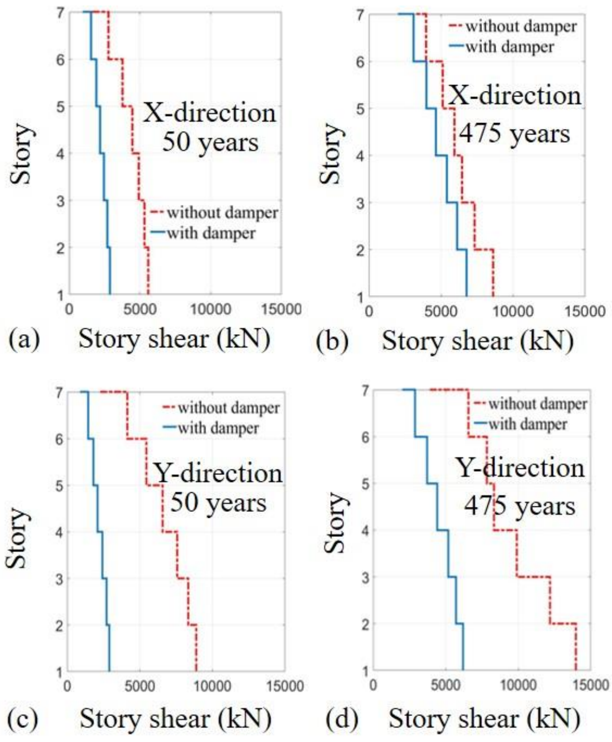

Fig. 9 Maximum story shears of the buildings with and without viscous dampers - average of 10 pairs of ground motions

However, as would be discussed in the following subsections this does not mean that the building without damper experienced less damage along Y direction. The building without damper experienced significant lateral forces, accelerations, and plastic demands along the Y direction due to the shear wall. As a result, focusing only on inter-story drifts may be misleading.

4.4 Story shear

Average maximum story shears of the buildings with and without viscous dampers are compared in Fig. 9. As expected, the building with viscous dampers experienced substantially less story shears in all stories and both 50 years and 475 years hazard levels. It should be noted that, compared to the building with viscous dampers, the building without dampers is more rigid in both directions further increasing the seismic-induced shears.

4.5 Beam plastic rotation

According to the current state-of-the-practice, seismic performance of a building is commonly judged based on its maximum plastic demands (ASCE 41 2017). Fig. 10 compares maximum plastic rotation of the beams in the buildings with and without viscous dampers. It can be seen that in most cases, beams of the building with viscous dampers experienced less plastic rotations. This is the case even for beams along the Y direction where the building without damper has shear walls and experienced lower story

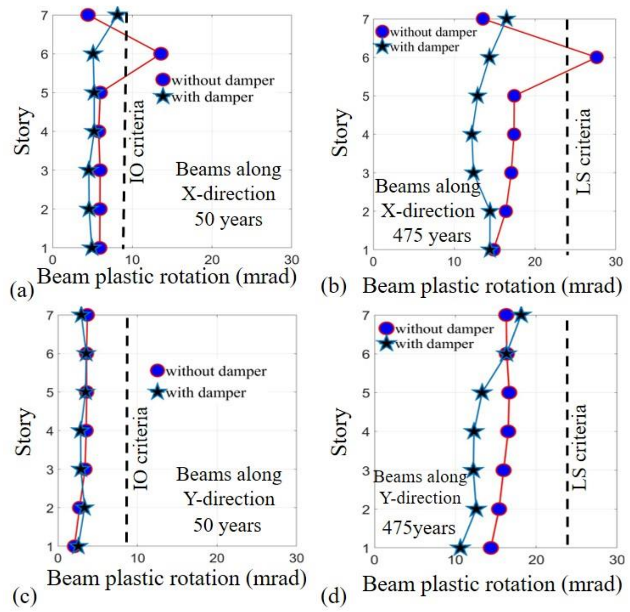

Fig. 10 Maximum plastic rotations of beams- average of 10 pairs of ground motions

drifts. As a result, lower story drifts does not necessarily correspond to lower beam rotations or even better seismic performance.

Fig. 10 indicates that the building without damper failed to satisfy Immediate Occupancy (IO) and Life Safety (LS) criteria for earthquakes with return periods of 50 years and 475 years, respectively.

4.6 Story acceleration

Many non-structural elements are acceleration-sensitive and reduction of absolute acceleration of stories could improve seismic performance of non-structural elements/components. Fig. 11 illustrates absolute story accelerations of the buildings with and without dampers along both directions and under both considered seismic hazards. It is clear that the building with viscous damper experienced significantly lower level of accelerations in all stories.

As a result, seismic demands on non-structural elements including, partition walls, claddings, façade, suspended ceilings, etc. would be lower in the building with viscous dampers.

4.7 Sample time history responses

In this subsection sample response histories of both buildings are compared to illustrate how they have responded. Presenting all results in the form of time history is not possible due to the page number limitation. Fig. 12 shows rotation and hysteretic behavior of a specific beam at the 6th story in the buildings with and without damper. It can be observed that the beam in the building with viscous dampers experienced less rotational demands and subsequently better seismic performance.

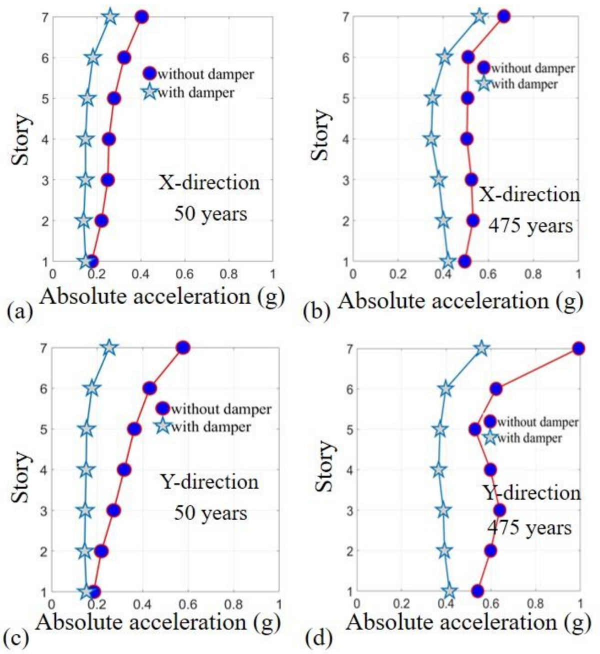

Fig. 11 Maximum story absolute accelerations- average of 10 pairs of ground motions

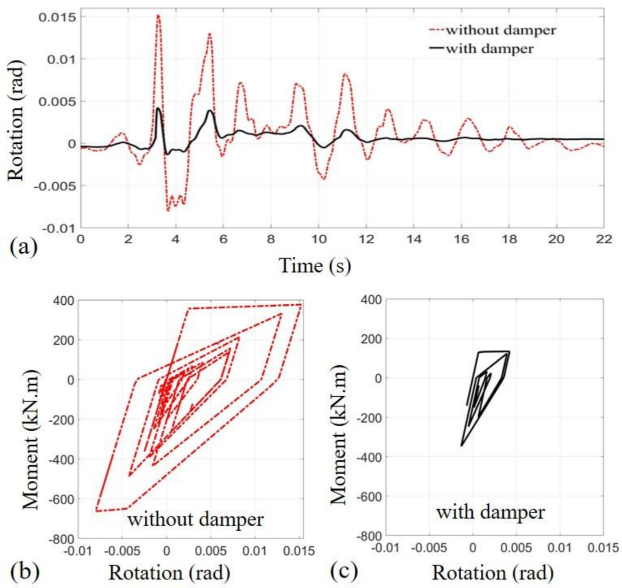

Fig. 12 (a) Rotation time-history of a specific beam at the 6th story of the buildings with and without damper, (b) hysteretic behavior of the beam in the building without damper and (c) same case in the building with damper; all under the Erzincan earthquake with return period of 475 years

Fig. 13 compares hysteretic behaviors of a specific column at the 5th story of the buildings with and without damper. Again in the case of building with viscous dampers, the column is subjected to lower moment and rotation demands. Finally Fig. 14 illustrates hysteretic behavior of the shear wall at the first story of the building without damper and cyclic behavior of one of the dampers in the 4th story in the building with viscous dampers. Although these two behaviors cannot be compared, but it should be noted that energy dissipation in the shear wall is proportional to its damage. However, modern viscous dampers can dissipate significant amount of energy with no damage. As a result post-earthquake damages and repair costs are expected to be lower in the case of building with viscous dampers.

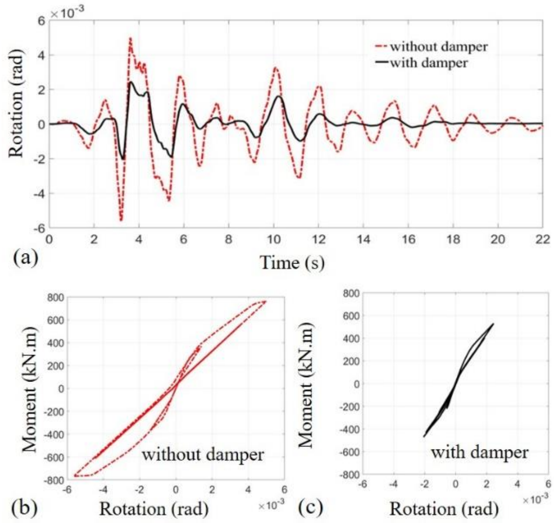

Fig. 13 (a) Rotation time history of a specific column at the 5th story of the buildings with and without damper. Hysteretic behaviors of the column (b) in the building without damper and (c) in the building with damper- under the Erzincan earthquake with return period of 475 years.

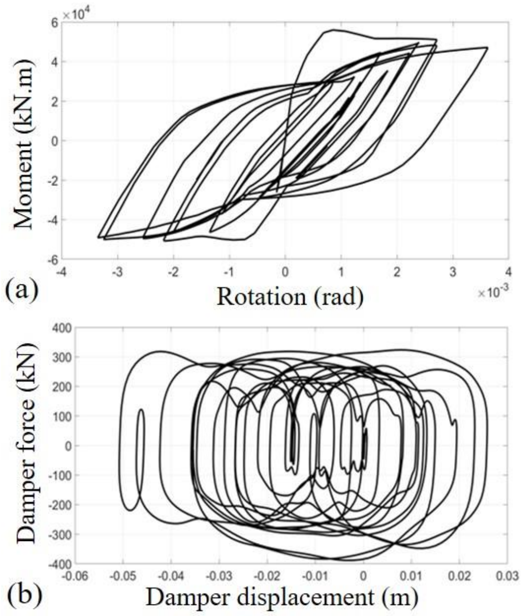

Fig. 14 (a) Hysteretic behavior of the shear wall at the first story of the building without damper. (b) Cyclic behavior of one of the viscous dampers in the building with viscous dampers- under the ChiChi earthquake with return period of 475 years

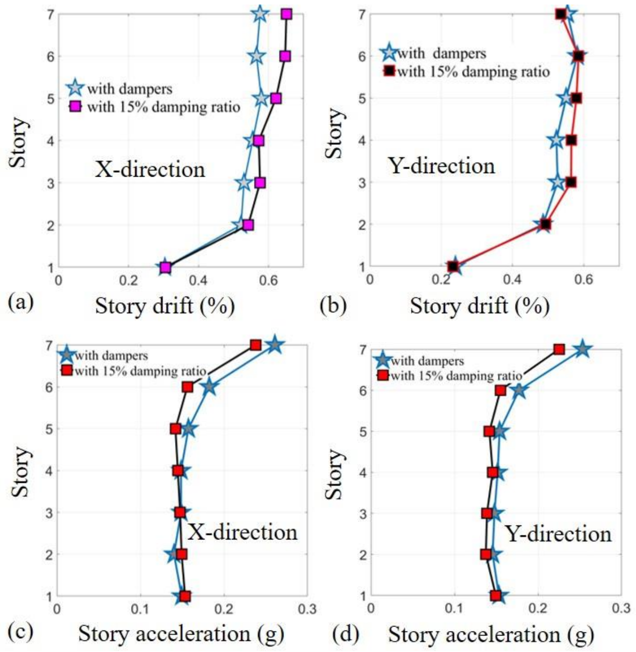

Fig. 15 Seismic responses of building with viscous dampers and the same building without damper but with damping ratio of 15% in terms of (a) story drift along X direction, (b) story drift along Y direction, (c) story acceleration along X direction and (d) story acceleration along Y direction - average of 10 pairs of ground motions

4.8 Verification of achieving the target damping ratio

As mentioned in Sec. 4.2, the building with viscous dampers is designed to reach a target damping ratio from 3% to 15%. In this subsection response of the building with viscous dampers are compared to the same building without viscous dampers but with inherent damping ratio of 15%. The results are illustrated in Fig. 15 in terms of story drifts and story accelerations. The comparisons are made only for ground motions with return period of 50 years to minimize contribution of plastic hinges in the dissipated energy. Fig. 15 indicates that the adopted design procedure is able to increase damping ratio of the building to its target value with good accuracy.

4.9 Non-structural elements

It is seen that the building without viscous dampers experienced significantly higher story accelerations. In this subsection, the consequence of higher story accelerations is assessed in seismic performance of a non-structural masonry wall located at the 6th story. Detail of the considered masonry wall is illustrated in Fig. 16. It is an unreinforced 150 mm thick wall with hollow concrete masonry units with masonry cement mortar type N with rupture modulus of 0.21 MPa, per ACI 530 (ACI 530 2013). Weight of the wall is 2.5 kN/m2 and it has out-of-plane restrainers at the top, left and right edges. The story acceleration is imposed to the restrainers.

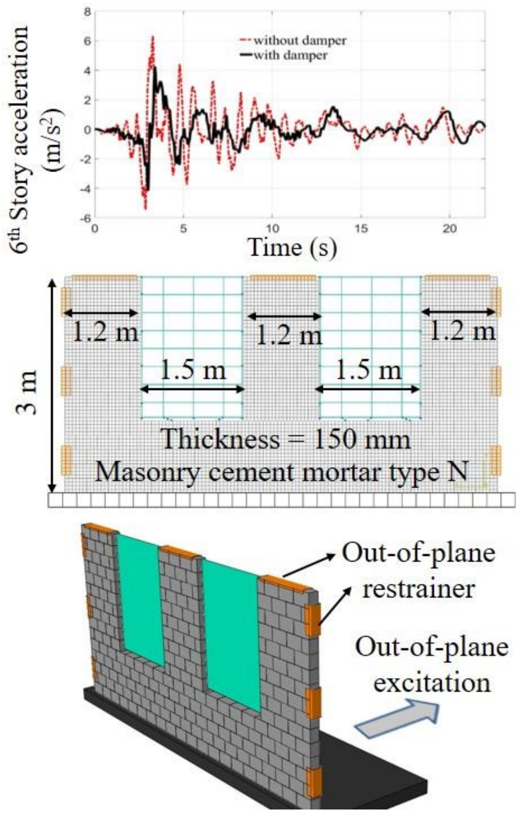

Fig. 16 Details of the considered non-structural masonry wall and the imposed excitations

The finite element model of the wall is constructed in Abaqus (2016). Bonding of the masonry blocks are simulated by contact and cohesive interactions. The wall is subjected to the 6^{th} story acceleration from the Erzincan earthquake with return period of 475 years. Obtained results are depicted in Fig. 17. It is clear that the wall in the building without dampers would collapse along its out-of-plane direction. Therefore, it can be concluded that viscous dampers can improve seismic performance of non-structural elements by reducing story accelerations.

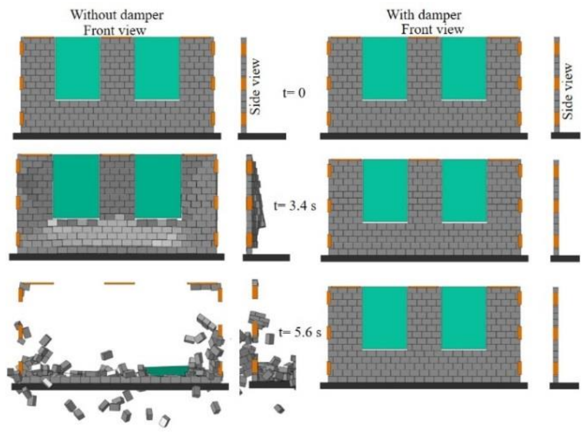

Fig. 17 Behaviors of the non-structural masonry wall at the 6^{th} story of the building with and without viscous dampers under the Erzincan earthquake.

Table 2 Concrete and steel weights of the buildings with and without dampers- excluding floor materials (all units are in ton-1ton=10 kN)

Story	without dampers		With dampers		
	concrete	rebar	Concrete	rebar	brace
7	164	10.7	87.9	9.3	0
6	164.8	11.3	110.3	10.6	0.7
5	173.9	12.4	118	11.9	1.3
4	189.8	13.7	130.4	12.6	1.3
3	196.3	14.5	141.1	13.5	1.3
2	203.2	15.9	145.4	14	0
1	207.9	17.9	161.1	16.3	0
Footing	880	34.2	739.2	25.8	0
Total	**2179.9**	**130.6**	**1633.4**	**114**	**4.6**

4.10 Material saving

As stated earlier, the building with viscous damper is more flexible and needs less material compared to that without damper. Table 2 represents concrete and steel reinforcement weights in both buildings. The last column in Table 2 shows weights of the steel braces required for dampers placement. It can be seen that, considering foundation materials, the building with viscous dampers is about 560 ton lighter than the building without dampers. In other words, the building with viscous required 25% less concrete material (excluding floor concrete) and about 13% less rebars (excluding floor rebars). However, price of the required 28 viscous dampers and the required steel braces should be accounted in the construction cost estimation of the building with viscous damper. No quantitative comparison in terms of construction costs is made in this study as price of concrete and rebars may significantly differ among different countries.

5. Conclusions

- A recently developed bypass viscous damper is briefly introduced and seismic behavior of a RC building equipped with nonlinear bypass viscous dampers is numerically investigated under different earthquakes. It is also shown that the commonly used simplified Maxwell model is applicable for the bypass viscous dampers. As a result behavior of the damper can be simulated by the currently available link/spring elements.
- Using a case study, contribution of the bypass viscous damper to seismic behavior of a 7-story RC building is examined. Obtained results can be summarized as follow.
- Viscous dampers can greatly reduce material usage of the building. In the carried out case study reduction of concrete and steel rebar weights are 25% and 13%, respectively. However, in other buildings the material saving may be different from the abovementioned values.
- Compared to conventional buildings, buildings with viscous dampers would be more flexible. A MRF with viscous dampers can experience less inter-story drifts compared to its more rigid counterpart without viscous dampers, due to higher damping involved.
- RC shear walls are more effective in reducing inter-story drifts than viscous dampers. However, this would be achieved at the expense of significant story shears, plastic demands and story accelerations. As a result, inter-story drift may not be a reliable demand parameter in seismic assessment of different buildings with different energy dissipation mechanisms.
- The Building with viscous dampers experienced less story shears and story accelerations. The reductions are more pronounced in the more frequent earthquakes with return period of 50 years. This is due to the fact that during the higher seismic hazard, some energy dissipation would be provided from post-yield behavior of the elements, regardless of presence of viscous dampers.
- Viscous dampers are effective in reducing moment and rotation demands of beams and columns. As a result, the building with viscous damper experienced lower level of plastic demands compared to the conventional building without damper.
- The building with viscous damper satisfied IO and LS performance criteria under seismic hazards with return periods of 50 years and 475 years, respectively. In contrast, the building without damper, although had more materials, failed to satisfy both of the abovementioned performance criteria.
- Non-structural elements of the building with viscous damper performed better due to the reduced story accelerations.

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