16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING
THESSALONIKI
18 - 21 JUNE 2018

SEISMIC RETROFIT OF RC BUILDINGS WITH NONLINEAR VISCOUS DAMPERS: DESIGN METHOD AND CASE STUDY

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ABSTRACT

Seismic performance enhancement using updated seismic design maps is necessary for existing RC buildings that have been designed using older versions of seismic design codes. In this study, a new methodology is proposed to calculate the characteristics of additional nonlinear viscous dampers that are needed, to achieve an enhanced seismic performance of existing RC buildings considering the current earthquake hazard level. The maximum viscous damper forces are calculated in terms of the story shear forces along the height of the unretrofitted building. The proposed design procedure is validated by considering 4-, 8-, and 12-story RC buildings. The effectiveness of the distribution of the viscous damping constants along the height of the RC building proportional to story mass, maximum story shear force, and maximum inter-story drift ratio (IDR) is investigated by keeping the total viscous damping force constant.

Keywords: Existing buildings; Methodology; Performance enhancement; Viscous dampers

1. INTRODUCTION

In recent years, seismic design maps have been updated due to large magnitude earthquake events that have occurred in some seismically active areas. New buildings are designed to achieve a higher seismic performance when compared to existing buildings. Hence, seismic performance enhancement of existing buildings is necessary by increasing damping and/or stiffness corresponding to the current earthquake hazard level. Viscous dampers are velocity dependent passive energy dissipation devices that can be used to enhance the seismic performance of existing buildings. The main advantage of nonlinear viscous dampers with a velocity exponent less than unity is that, in the event of high velocity, the force in the viscous damper is controlled to avoid overloading of the damper or the bracing system to which it is connected (Christopoulos and Filiatrault 2006).

Recently, practical design methods have been proposed to calculate the supplemental viscous damper characteristics to retrofit the building. Christopoulos and Filiatrault (2006) estimated the damping constants of the dampers using a set of fictitious springs at the proposed locations of the linear viscous dampers and distributed according to the lateral stiffness of the unretrofitted building and nonlinear viscous damping constants are calculated by assuming the linear and nonlinear viscous dampers dissipate the same energy. Silvestri et al. (2010) developed a five step design procedure to calculate the nonlinear viscous damping constants to achieve the target performance using the equal energy approach of Christopoulos and Filiatrault (2006) and the energy was equated using the actual velocity of the building with linear viscous dampers instead of pseudo-velocity of the building. Zhou et al. (2012) proposed a simplified relationship to calculate peak nonlinear viscous damping forces from the story shear forces of the unretrofitted building and the required additional viscous damping by assuming a simplified parallelogram shape of the force-displacement curve for the nonlinear viscous damper.

The distribution of the viscous damping constants is an issue along the height of the buildings, because only the required equivalent single degree of freedom (SDOF) system viscous damping can be calculated from most

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of the proposed procedures. Whittle et al. (2012) compared the effectiveness of five linear viscous damper placements techniques (uniform and stiffness proportional damping constants distribution are the standard methods and Simplified Sequential Search Algorithm, Takawaki application, and Lavan analysis/redesign applications are three advanced methods) for a constant sum of the damping constants. Landi et al. (2015) also investigated the performance of the building where the distribution of viscous damping constants was taken to be proportional to different story quantities (story mass, story stiffness, story shear, inter-story drift ratio (IDR), story shear strain energy, efficient story shear strain energy) for a constant supplemental viscous damping.

In this study, a new methodology is proposed to calculate the additional viscous damper characteristics necessary to reach the target performance of existing RC buildings at the current earthquake hazard level using the simplified direct displacement based-design (DBD) procedure. The viscous damper characteristics are calculated by estimating the maximum viscous damping forces in terms of maximum story shear forces of the unretrofitted building along the height. In addition, the effectiveness of the distribution of the viscous damping constants proportional to story mass, maximum story shear force, and maximum IDR is investigated by keeping the total viscous damping forces constant along the height.

2. VISCOUS DAMPERS

2.1 Viscous damping force

A viscous damper consists of a piston with an orifice head which can move through the viscous fluid inside a cylinder. The pressure difference across the piston head generates a nonlinear viscous damping force $P^{NL}(t)$, which depends on the velocity of the piston and is given by,

$$P^{NL}(t) = C^{NL}\left|\frac{dx(t)}{dt}\right|^{\alpha} \operatorname{sgn}\left(\frac{dx(t)}{dt}\right), \tag{1}$$

where C^{NL} is the nonlinear viscous damping constant, α is the velocity coefficient, $x(t)$ is the relative displacement between the ends of the damper, and $\operatorname{sgn}[.]$ is signum function. When $\alpha = 1$, the device acts as a linear viscous damper.

2.2 Maximum linear viscous damping force in i^th story in terms of the story shear force for a damper aligned horizontally

The maximum nonlinear viscous damping force $P_i^{NL-\max}$ in the i^{th} story is,

$$P_i^{NL-\max} = C_i^{NL} \max_t \left|\frac{dx_i(t)}{dt}\right|^{\alpha}, \qquad (i = 1,..,n), \tag{2}$$

where C_i^{NL} is nonlinear viscous damping constant in the i^{th} story, $x_i(t)$ is the relative displacement between the ends of the damper in the i^{th} story, and n is the number of stories. Using the equivalent pseudo-velocity,

$$P_i^{NL-max} = C_i^{NL}(\omega_1 x_i^{max})^{\alpha}, \qquad (i = 1,..,n), \tag{3}$$

where $x_i^{\max}$ is the maximum relative displacement between the ends of the damper, and ω_1 is the fundamental frequency of the building. The maximum linear viscous damping force P_i^{L-max} is,

$$P_i^{L-max} = C_i^{L}\omega_1 x_i^{max}, \qquad (i = 1,..,n), \tag{4}$$

where C_i^L is linear viscous damping constant which is proportional to the story stiffness K_i at the i^{th} story of the building,

$$C_i^L = \frac{2\xi_1}{\omega_1} K_i, \qquad (i = 1,..,n), \tag{5}$$

where ξ_1 is first mode damping ratio of the building. Therefore, the maximum linear viscous damping force P_i^{L-max} can be approximated with respect to the maximum story shear force of the unretrofitted building V_i^{max} as,

$$P_i^{L-max} = 2\xi_1 K_i x_i^{max} = 2\xi_1 V_i^{max}, \qquad (i = 1,..,n). \tag{6}$$

2.3 Maximum nonlinear viscous damping force in i^th story in terms of the story shear force for a damper aligned horizontally

To determine the maximum nonlinear viscous damping force, the energy dissipated per cycle for a linear viscous dampers E^L and nonlinear viscous dampers E^{NL} are equated,

$$E^L = E^{NL}. \tag{7}$$

For a nonlinear viscous damper subjected to a harmonic relative displacement between the ends of the dampers, the energy dissipated per cycle is obtained from the area under the force-displacement curve as,

$$E^{NL} = \frac{\pi}{\lambda\omega} C^{NL} (\omega x^{\max})^{\alpha+1}, \tag{8}$$

where, $\lambda = \frac{\sqrt{\pi}}{2}\Gamma\left(\frac{\alpha+3}{2}\right) \Big/ \Gamma\left(\frac{\alpha+2}{2}\right),$ (9)

Γ is gamma function, and ω is the frequency of the harmonic relative displacement (Christopoulos and Filiatrault 2006). Eqn. 8 can be re-written as,

$$E^{NL} = \frac{\pi}{\lambda} P^{NL-\max} x^{\max}. \tag{10}$$

From Eqn. (10) the energy dissipation of a linear viscous dampers is,

$$E^L = \pi P^{L-\max} x^{\max}. \tag{11}$$

Substituting Eqns. (10) and (11) into Eqn. (7),

$$\frac{P^{NL-\max}}{P^{L-\max}} = \lambda. \tag{12}$$

Therefore, the maximum nonlinear viscous damping force $P_i^{NL-\max}$ in terms of the maximum story shear force $V_i^{\max}$ of the unretrofitted building is,

$$P_i^{NL-\max} = 2\lambda\xi_1 V_i^{\max}, \qquad (i = 1,..,n). \tag{13}$$

3. PROPOSED DESIGN PROCEDURE

The design procedure consists of four steps.

Step 1: Determine the maximum IDR and maximum story shear forces along the height of the unretrofitted building for the current earthquake hazard level

The maximum IDR and maximum story shear forces $V_i^{\max}$ along the height of the unretrofitted building are calculated from NLRHA for the current earthquake hazard level, by scaling the ground motions to the current design response spectrum (FEMA 356, 2000).

Step 2: Define the displacement profile for the corresponding allowable IDR at the enhanced performance level

The displacement profile along the height of the building is based on the drift limit to design a new building in the DBD procedure. If the building is to remain elastic at the drift limit, the displacement profile can be taken as the elastic first mode shape, otherwise, the inelastic first mode shape can be used for the design displacement profile, however, the inelastic and elastic first mode shapes are often very similar (Priestley et al. 2007). In the proposed procedure, the inelastic first mode displacement shape is used to define the displacement profile along the height of the building for the allowable IDR by considering higher mode effects and the empirical relationship is,

$$\Delta_i^R = \omega_\theta \theta_c h_i \frac{(4H - h_i)}{(4H - h_1)}, \qquad (i = 1,..,n), \tag{14}$$

$$\omega_\theta = 1.15 - 0.0034H \le 1, \tag{15}$$

where Δ_i^R is the retrofitted (target) displacement in i^{th} story, h_i is the height of the i^{th} story, ω_θ is the reduction factor to account for the higher mode, θ_c is the allowable IDR, and H is the height of the building (Sullivan et al. 2012, Sullivan and Lago 2012).

Step 3: Determine the equivalent SDOF system displacements

The equivalent SDOF system displacement is used in the DBD procedure to design the building. The retrofitted (target) displacement Δ^R and unretrofitted displacement Δ^{UR} in the equivalent SDOF system are calculated from,

$$\Delta^R = \sum_{i=1}^{n} m_i \left(\Delta_i^R\right)^2 \Big/ \sum_{i=1}^{n} m_i \Delta_i^R, \tag{16}$$

$$\Delta^{UR} = \sum_{i=1}^{n} m_i \left(\Delta_i^{UR}\right)^2 \Big/ \sum_{i=1}^{n} m_i \Delta_i^{UR}, \tag{17}$$

where m_i is the mass of the i^{th} floor, and Δ_i^{UR} is the unretrofitted displacement in i^{th} story (Sullivan et al. 2012, Sullivan and Lago 2012). The unretrofitted displacement in i^{th} story Δ_i^{UR} can be calculated from the IDR profile in Step 1.

Step 4: Calculate the maximum force of viscous dampers and damping constants in each story

The required supplemental viscous damping ξ_{req} is calculated from the ratio between the retrofitted (target) displacement Δ^R and unretrofitted displacement Δ^{UR} in the equivalent SDOF system. An empirical relationship is used in this step, which is used to scale the displacement spectrum by Sullivan and Lago (2012). The viscous damping offered by the retrofitted and unretrofitted building is assumed as 5% (equivalent viscous damping due to inelastic deformation is not taken to account). The period of the equivalent SDOF system is taken as the fundamental period of the building, which is assumed as same for retrofitted and unretrofitted building (effect of the additional damping on the fundamental period of the building is neglected). Hence, the required supplemental viscous damping ξ_{req} is,

$$\xi_{req} = \left(\left(\frac{\Delta^{UR}}{\Delta^{R}} \right)^2 \times 10 \right) - 10. \tag{18}$$

The required maximum damper displacement Δ_i^d is,

$$\Delta_i^d = \Delta_i^R - \Delta_{i-1}^R, \qquad (i = 1,..,n), \tag{19}$$

the maximum viscous damping force $P_i^{NL-\max}$ in the i^{th} story is from Eqn. 13,

$$P_i^{NL-\max} = 2\lambda \xi_{req} V_i^{\max}, \qquad (i = 1,..,n), \tag{20}$$

and using Eqn. 3, the viscous damping constant C_i^{NL} in the i^{th} story is calculated as,

$$C_i^{NL} = \left(\frac{2^{(1-\alpha)} \lambda \xi_{req} T_1^{\alpha}}{\pi^{\alpha}} \right) \frac{V_i^{\max}}{\left(\Delta_i^d\right)^{\alpha}}, \qquad (i = 1,..,n). \tag{21}$$

Finally, the calculated viscous damping characteristics can be modified by considering the geometric amplification factor based on the arrangement (e.g. horizontal, diagonal, upper toggle, reverse toggle, scissor-jack) and number of the viscous dampers in each story of the building.

4. APPLICATION OF THE PROCEDURE

4.1 Building description and modeling

The proposed design procedure is applied to 4-, 8-, and 12-story, three-bay by three-bay RC buildings (Fig. 1). The bay width is 6.1 m in both directions and the story height is 3.9 m. The buildings are designed using the equivalent lateral force (ELF) procedure, following the provisions of IBC 2009 (ICC 2009), ASCE 7-05 (ASCE 2005), and ACI 318-08 (ACI 2008). The design response spectrum is constructed for an arbitrary location in California (33.99 N, 118.162 W) and the soil is characterized as stiff soil (Site class D). The building is intended to be used as an office building (occupancy category III). The design floor dead load (slab, partitions, finishes), live load, and self-weight of the concrete are 8.28 kN/m^2, 2.37 kN/m^2, and 25 kN/m^3, respectively.

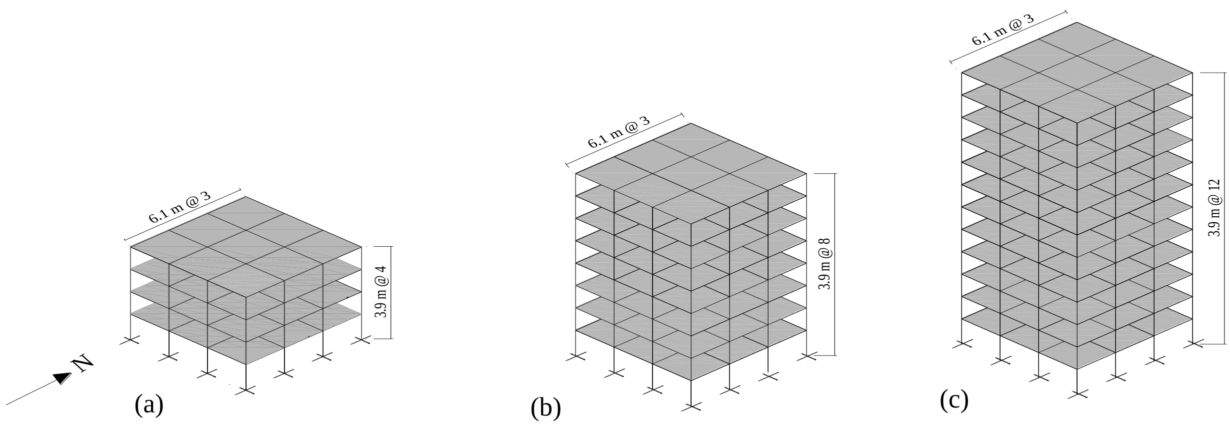

Figure 1. The RC buildings used in this study: (a) 4-story (b) 8-story (c) 12-story.

Three-dimensional finite element modelling is carried out using PERFORM-3D (CSI 2011). Beam and column members are divided into three elements along the length and each element is modeled usinginelastic fiber segments. A section is discretized into unconfined concrete fibers, confined concrete fibers, and steel fibers. Uniaxial material models with a nonlinear constitutive relationship are assigned to the fibers. Mander model (Mander et al. 1988) and Manegotto and Pinto model (Mangetto et al. 1973) are used for concrete and steel, respectively. Rigid diaphragms are used for floors to constrain all nodes located in a horizontal plane to have same horizontal displacement and rotation about the vertical axis. The viscous damper and supporting brace are connected in series and modeled as a Maxwell spring-dashpot system.

4.2 Nonlinear Response History Analysis (NLRHA)

The current design response spectrum is defined from U.S. Seismic design maps based on the provisions of IBC 2015 (ICC 2015) at the same location of the building. A total of seven far-fault ground motions (Table 1) are selected from the Pacific Earthquake Engineering Research Centre database (PEER 2017). In the selection process, the following criteria are employed: (i) magnitude of the earthquake $M_W \geq 6.5$; (ii) closest distance to the fault rupture $10 < R_{rup} < 100$ km; (iii) site class for recording station is D. The selected ground motions are scaled to the current earthquake design spectrum in the period range of $0.2T_1$ to $1.5T_1$ (Fig. 2). For the buildings considered in this study, the period range is 0.18 s to 3.38 s (the fundamental period T_1 of the

Table 1. Ground motions used in this study.

No	Event	Year	Station	M_w	Source-site distance (km)	Shear wave velocity (m/s)	Scaling factor
1	Imperial Valley-06	1979	Delta	6.53	22.03	242.05	2.29
2	Corinth_ Greece	1981	Corinth	6.60	10.27	361.40	2.61
3	Taiwan SMART1(45)	1986	SMART1 O02"	7.30	57.13	285.09	3.20
4	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	18.20	192.05	2.01
5	Northridge-01	1994	Canyon Country - W Lost Cany	6.69	12.44	325.60	1.56
6	Kobe_ Japan	1995	Sakai	6.90	28.08	256.00	3.42
7	El Mayor-Cucapah_ Mexico	2010	RIITO	7.20	13.00	242.05	1.62

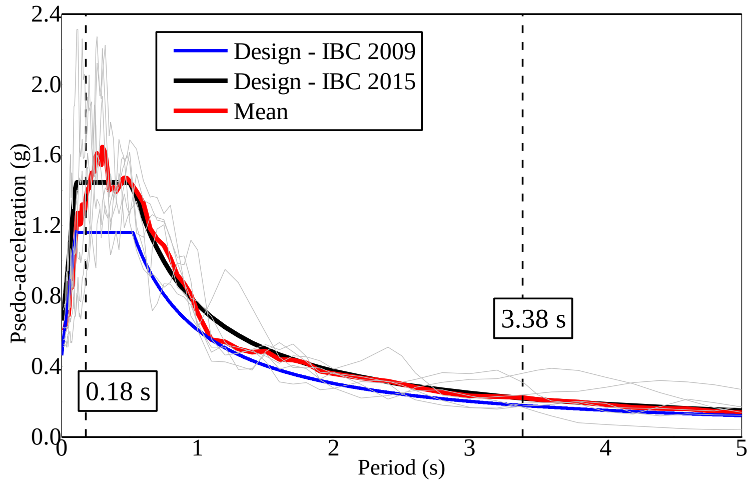

Figure 2. Comparison of 5%-damped response spectra for scaled ground motions and their mean with design acceleration response spectra.

4-, 8-, and 12-story buildings are 0.89 s, 1.74 s, and 2.25 s, respectively). The ground motions are applied in the N-S direction of the building.

4.3 Verification of the proposed procedure

The mean values of the peak IDR and peak story shear forces along the height of the unretrofitted building is calculated from the NLRHA in Step 1 of the design procedure. The structural performance level for the retrofitted building is assumed to be Immediate Occupancy (IO) level corresponding to an allowable IDR $\theta_c = 1\%$ (FEMA 356, 2000). The velocity coefficient of the nonlinear viscous dampers is assumed as $\alpha = 0.2$. The viscous damper is connected diagonally with a supporting brace in series as shown in Fig. 3. Two viscous dampers with the same mechanical characteristics are assigned to each story. The required maximum damper displacement Δ_i^d, maximum nonlinear viscous damping force $P_i^{NL-\max}$, and nonlinear viscous damping constant C_i^{NL} in i^{th} story are,

$$\Delta_i^d = (\Delta_i^R - \Delta_{i-1}^R)\cos\theta, \qquad (i = 1,..,n), \tag{22}$$

$$P_i^{NL-\max} = \frac{\lambda \xi_{req}}{\cos(\theta)} V_i^{\max}, \qquad (i = 1,..,n), \tag{23}$$

$$C_i^{NL} = \left(\frac{\lambda \xi_{req} T_1^{\alpha}}{(2\pi)^{\alpha} \cos(\theta)} \right) \frac{V_i^{\max}}{(\Delta_i^d)^{\alpha}}, \qquad (i = 1,..,n), \tag{24}$$

where θ is the inclination of the viscous damper.

The viscous damper characteristics calculated from the proposed procedure are given in Tables 2-4. The seismic response indicators of the unretrofitted and retrofitted buildings with linear viscous dampers (LVD) and nonlinear viscous dampers (NLVD) obtained from NLRHA are shown in Figs. 4-5. The mean values of the peak IDR of the unretrofitted buildings (Step 1 of design procedure) and retrofitted buildings are shown in

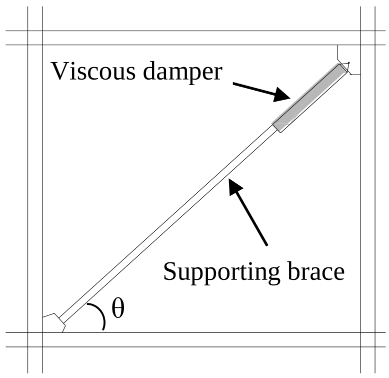

Figure 3. Geometric arrangement of viscous damper and supporting brace.

Table 2. Viscous damper characteristics for the 4-story building.

Story	m_i (t)	$V_i^{\max}$ (kN)	$IDR^{\max}$	Δ_i^{UR} (mm)	Δ_i^{R} (mm)	Δ_i^{d} (mm)	$P_i^{L-\max}$ (kN)	C_i^{L} (kN.s/m)	$P_i^{NL-\max}$ (kN)	C_i^{NL} (kN.s$^{0.2}$/m$^{0.2}$)
1	495	5,401	0.016	64.0	40.0	33.5	2,032	8,587	1,691	2,256
2	470	4,856	0.020	144.9	74.7	29.0	1,827	8,908	1,521	2,088
3	470	4,430	0.017	214.3	104.0	24.6	1,667	9,605	1,387	1,969
4	444	3,149	0.011	258.4	128.1	20.1	1,185	8,345	986	1,457

* θ = 33.024°, Δ^{UR} = 200.3 mm, Δ^{R} = 98.2 mm, and ξ_{req} = 31.5%.

Table 3. Viscous damper characteristics for the 8-story building.

Story	m_i (t)	$V_i^{\max}$ (kN)	$IDR^{\max}$	Δ_i^{UR} (mm)	Δ_i^{R} (mm)	Δ_i^{d} (mm)	$P_i^{L-\max}$ (kN)	C_i^{L} (kN.s/m)	$P_i^{NL-\max}$ (kN)	C_i^{NL} (kN.s$^{0.2}$/m$^{0.2}$)
1	495	6,405	0.017	70.0	39.8	33.3	3,007	24,984	2,503	3,822
2	470	6,043	0.021	163.0	77.0	31.2	2,837	25,199	2,362	3,655
3	470	5,758	0.018	245.5	111.7	29.0	2,704	25,790	2,250	3,532
4	470	5,375	0.016	315.9	143.8	26.9	2,524	25,999	2,100	3,348
5	470	4,913	0.016	380.5	173.4	24.7	2,307	25,833	1,920	3,112
6	470	4,735	0.015	444.5	200.3	22.6	2,223	27,270	1,851	3,055
7	470	4,206	0.012	502.4	224.7	20.4	1,975	26,774	1,624	2,768
8	444	2,773	0.008	541.8	246.6	18.3	1,302	19,727	1,084	1,866

* θ = 33.024°, Δ^{UR} = 403.4 mm, Δ^{R} = 181.5 mm, and ξ_{req} = 39.3%.

Table 4. Viscous damper characteristics for the 12-story building.

Story	m_i (t)	$V_i^{\max}$ (kN)	$IDR^{\max}$	Δ_i^{UR} (mm)	Δ_i^{R} (mm)	Δ_i^{d} (mm)	$P_i^{L-\max}$ (kN)	C_i^{L} (kN.s/m)	$P_i^{NL-\max}$ (kN)	C_i^{NL} (kN.s$^{0.2}$/m$^{0.2}$)
1	527	9,589	0.010	40.0	36.2	32.9	3,898	42,544	3,245	5,233
2	501	8,997	0.017	107.6	76.9	31.5	3,658	41,161	3,044	4,952
3	501	8,410	0.019	183.8	112.8	30.1	3,419	40,784	2,846	4,672
4	501	8,083	0.021	268.2	147.1	28.7	3,286	41,112	2,735	4,533
5	501	7,795	0.017	337.8	179.7	27.3	3,169	41,679	2,637	4,415
6	501	7,321	0.017	405.8	210.6	25.9	2,976	41,262	2,477	4,191
7	501	6,634	0.016	470.5	239.9	24.5	2,697	39,527	2,245	3,840
8	501	5,854	0.016	535.8	267.5	23.1	2,381	36,993	1,981	3,429
9	469	4,559	0.016	601.8	293.4	21.7	2,069	34,241	1,722	3,019
10	469	4,005	0.016	667.6	317.6	20.3	1,854	32,783,	1,543	2,740
11	469	4,005	0.014	726.0	340.2	18.9	1,629	30,937	1,355	2,442
12	444	2,500	0.008	764.8	361.1	17.5	1,017	26,774	846	1,548

* θ = 33.024°, Δ^{UR} = 546.1 mm, Δ^{R} = 260.1 mm, and ξ_{req} = 34.0%.

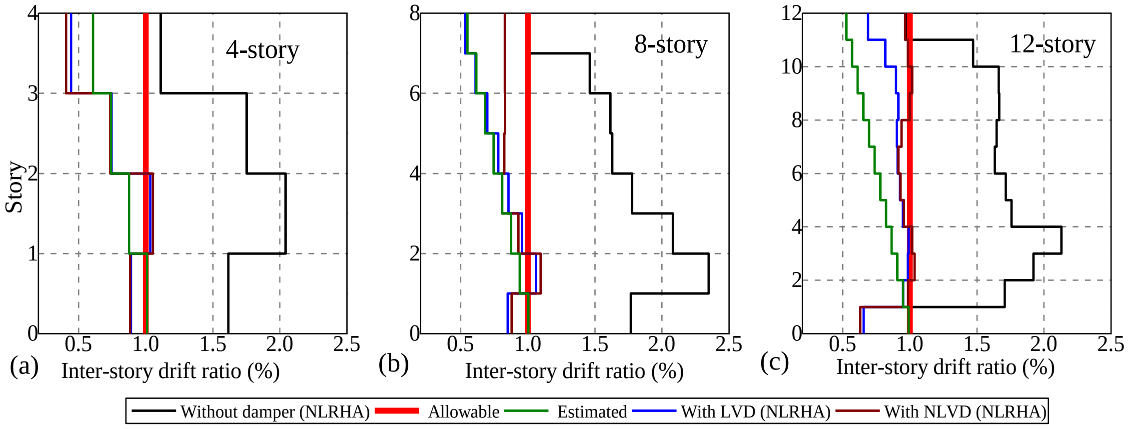

Figure 4. Mean values of the peak IDR of the buildings: (a) 4-Story (b) 8-Story (c) 12-Story.

Fig. 4. The peak IDR of the buildings reduces to 1%, which indicates that the proposed procedure can be used to estimate the required additional viscous damper characteristics to achieve the target performance. The estimated IDR profile based on the first mode inelastic displacement profile (Step 2 of design procedure)is close to the peak IDR of the 4- and 8-story buildings with linear viscous dampers from NLRHA, modification is necessary in the other cases. There is no significant difference in the peak IDR profile shape along the height

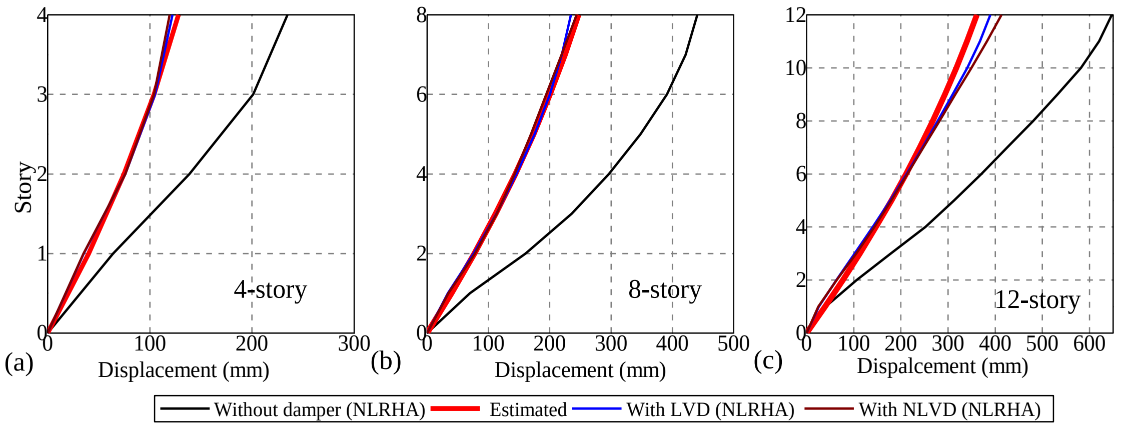

Figure 5. Mean values of the peak floor displacement of the buildings: (a) 4-Story (b) 8-Story (c) 12-Story.

of the building due to the additional linear viscous dampers. Fig. 5 shows that the estimated displacement profile based on the allowable IDR (Step 2 of design procedure) are close to the peak floor displacement profile of the building. However, there is a slight increase in the top floor peak displacement in the 12-story building.

4.4 Supporting brace for the viscous damper

The stiffness of the supporting brace can significantly affect the performance of the viscous damper. However, it is necessary that the brace should be as stiff as possible to increase the efficiency of the viscous damper. The braces were assumed as rigid in the proposed design procedure (dynamic effect from supporting braces are neglected). Londoño et al. (2014) proposed a relationship to calculate the required minimum axial stiffness of a supporting brace to provide a specific efficiency by a linear viscous damper,

$$k_i^b = \left(\frac{1}{\varepsilon^2} - 1\right)^{-\frac{1}{2}} C_i^L \quad \omega_1, \qquad (i = 1,..,n), \tag{25}$$

where ε is efficiency and k_i^b is minimum axial stiffness of the brace in i^{th} story of the building. In the present study, the axial stiffness of the supporting brace in the i^{th} story is taken as, $10k_i^b$ with $\varepsilon = 98\%$. In the case of nonlinear viscous dampers, the same values of axial stiffness are used in each story as for the case of linear viscous dampers. Table 5 shows the stiffness of the supporting bars. The peak deformation of the

Table 5. The stiffness of the supporting braces.

Story	**4-Story (kN/m)**	**8-Story (kN/m)**	**12-Story (kN/m)**
1	2,897,202	4,437,232	5,829,918
2	3,005,677	4,475,335	5,713,046
3	3,240,575	4,580,236	5,588,700
4	2,815,673	4,617,407	5,633,603
5		4,587,905	5,711,320
6		4,843,111	5,654,259
7		4,755,008	5,416,481
8		3,503,467	5,069,205
9			4,692,184
10			4,492,400
11			4,239,433
12			2,857,745

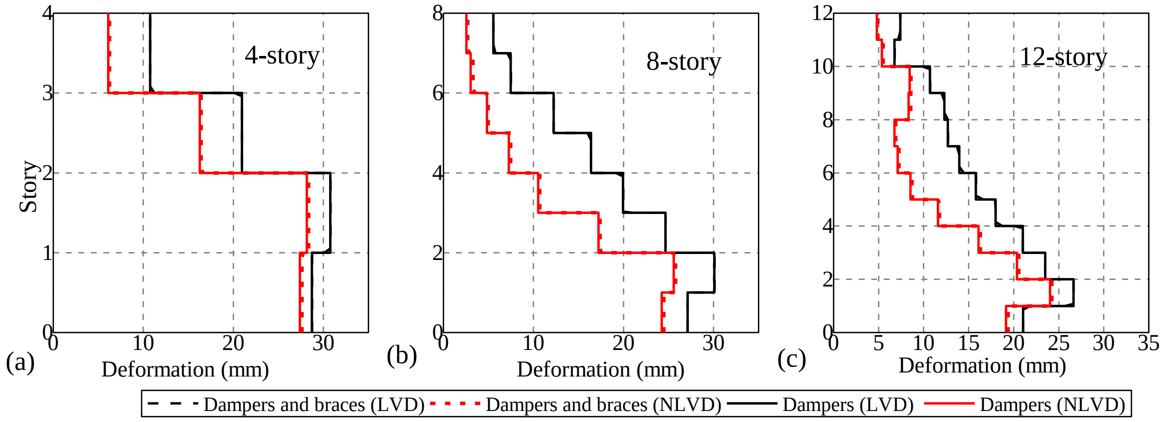

Figure 6. Mean values of the peak deformation of the dampers of the buildings: (a) 4-Story (b) 8-Story (c) 12-Story.

viscous damper is compared with the peak deformation of the viscous damper and brace compound component in Fig. 6. Both deformations coincide with each other, hence, the axial stiffness of the supporting braces can be calculated from $10k_i^b$ in the proposed procedure.

5. EFFECTIVENESS OF THE DISTRIBUTION OF VISCOUS DAMPING CONSTANTS

Keeping the total viscous damping forces calculated in Section 4 constant, the effectiveness of the distribution of viscous damping constants along the height of the building proportional to p_i^s, story mass (SM), maximum story shear force (SS), and maximum IDR is considered in this section. A simplified procedure is used to calculate the viscous damping characteristics based on Landi et al. (2015). The nonlinear viscous damping constant C_i^{NL} is proportional to the story parameter $p_i^S (S = SM,\ SS,\ IDR)$ and is given by,

$$C_i^{NL} = k_S\, p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR), \tag{26}$$

where $k_S (S = SM,\ SS,\ IDR)$ is a constant. Hence, the sum of the viscous damping constants is proportional to the sum of the story parameters,

$$\sum_{j=1}^{n} C_j^{NL} = k_S \sum_{j=1}^{n} p_j^S, \qquad (S = SM,\ SS,\ IDR). \tag{27}$$

From Eqn. 26 and Eqn. 27,

$$C_i^{NL} = \left(\sum_{j=1}^{n} C_j^{NL} \Big/ \sum_{j=1}^{n} p_j^S \right) p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR). \tag{28}$$

Substituting C_i^{NL} from Eqn. 28 into the Eqn. 3 the maximum viscous damping force in the i^{th} story is,

$$P_i^{NL-\max} = \left(\frac{2\pi}{T_1} \right)^{\alpha} \left(\sum_{j=1}^{n} C_j^{NL} \Big/ \sum_{j=1}^{n} p_j^S \right) \left(\Delta_i^d \right)^{\alpha} p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR), \tag{29}$$

The sum of the maximum viscous damper forces is,

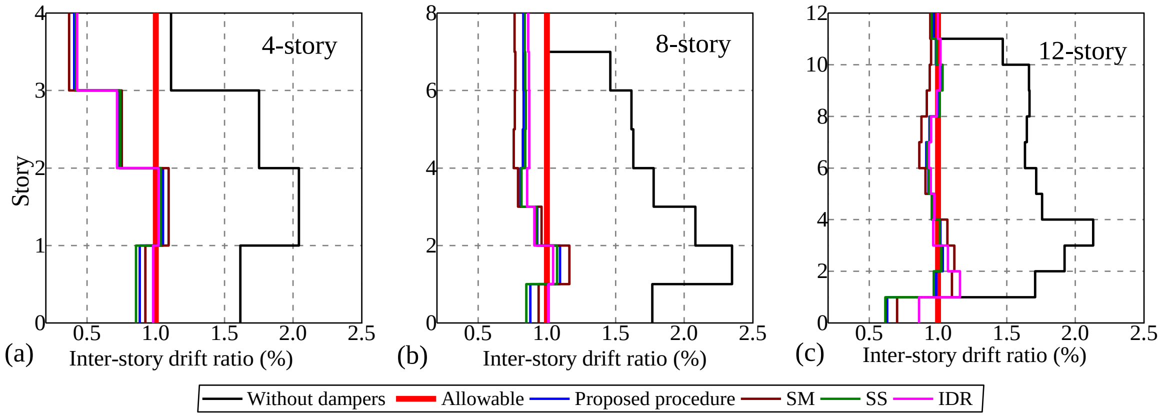

Figure 7. Mean values of the peak IDR of the buildings: (a) 4-Story (b) 8-Story (c) 12-Story.

$$\sum_{j=1}^{n} P_j^{NL-max} = \left(\frac{2\pi}{T_1}\right)^{\alpha} \left(\sum_{j=1}^{n} C_j^{NL} \Big/ \sum_{j=1}^{n} p_j^S\right) \sum_{k=1}^{n}\left[p_k^S \left(\Delta_k^d\right)^{\alpha}\right], \qquad (S = SM,\ SS,\ IDR), \tag{30}$$

Using Eqn. 28 and Eqn. 30, the nonlinear viscous damper constant C_i^{NL},

$$C_i^{NL} = \left(\frac{T_1}{2\pi}\right)^{\alpha} \left(\sum_{j=1}^{n} P_j^{NL-\max} \Big/ \sum_{j=1}^{n} p_j^S \left(\Delta_j^d\right)^{\alpha}\right) p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR). \tag{31}$$

Finally, from Eqn. 20, and Eqn. 31 the nonlinear viscous damping constant C_i^{NL} is,

$$C_i^{NL} = 2\lambda\xi_{req} \left(\frac{T_1}{2\pi}\right)^{\alpha} \left(\sum_{j=1}^{n} V_j^{max} \Big/ \sum_{j=1}^{n} p_j^S \left(\Delta_j^d\right)^{\alpha}\right) p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR), \tag{32}$$

and using Eqn. 3 and Eqn. 32, the maximum nonlinear viscous damping force P_i^{NL-max} is,

$$P_i^{NL-max} = 2\lambda\xi_{req} \left(\frac{T_1}{2\pi}\right)^{\alpha-1} \left(\sum_{j=1}^{n} V_j^{max} \Big/ \sum_{j=1}^{n} p_j^S \left(\Delta_j^d\right)^{\alpha}\right) \left(\Delta_i^d\right)^{\alpha} p_i^S, \qquad (i = 1,..,n;\ S = SM,\ SS,\ IDR). \tag{33}$$

The nonlinear viscous damper characteristics are calculated for each case of the distribution and the seismic performances are compared using NLRHA in Fig. 7. In all cases, the peak IDR satisfy the target performance, there is no significant difference in the seismic performance of the buildings due to different methods of distribution of viscous damping constants.

6. CONCLUSIONS

In this paper, a new methodology is proposed to calculate the characteristics of additional nonlinear viscous dampers needed to enhance the seismic performance of existing RC buildings to correspond to the current earthquake hazard level. The proposed design procedure is applied to 4-, 8-, and 12-story buildings. Results from NLRHA show that the retrofitted buildings satisfy the allowable IDR and that the proposed procedure can be used to estimate the viscous damper characteristics. The estimated displacement profile for the corresponding allowable IDR (Step 2 of design procedure) is close to the peak displacement profile along the height of the buildings from NLRHA.
The effectiveness of the distribution of viscous damping constants proportional to story mass, story shear force, and IDR were investigated. The buildings satisfy the target performance when the different methods of

distribution are used to obtain the damping constants and there is no significant difference in the performance of the buildings.

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