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Reliability-based Design Optimization for Inelastic Frame Structures with Viscous Dampers

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ABSTRACT: This study aims to establish a framework of dynamic reliability based design optimization to minimize the cost of retrofitting of viscous dampers for structures located in the near-fault region. In the framework, the cost of dampers is considered as objective function to be minimized, which is taken to be proportional to the designed force to sustain, and the locations of dampers are taken as design variables. The dynamic reliability of the structure is considered as the performance constraint. Firstly, a stochastic model of near-fault ground motions is established, and the corresponding near-fault impulsive ground motions are synthesized. Then, the probability density evolution method (PDEM) is employed to solve the dynamic reliability of structures by means of equivalent extreme event method. Because the design variables, namely, the locations of viscous dampers are integer variables, the computational effort will increase with the number of design variables. Accordingly, material interpolation technique in topological optimization of continuum is adopted to transform the integer variables into continuous ones. Finally, numerical example demonstrate the efficiency of design optimization of inelastic frame with viscous dampers in given reliability performance constraint.

Keywords: inelastic frame; viscous dampers; reliability-based design optimization; near-fault ground motions; probability density evolution method

1. INTRODUCTION

Near-fault ground motions have different characteristics compared to far field ground motions, such as rupture directivity effect, fling-step effect, etc. Both rupture directivity effect and fling-step effect may result in distinct velocity pulse in the velocity time history (Bray and Rodriguez-Marek 2004). Those velocity pulses having a larger amplitude and shorter duration play extensively an important role on the damages of building structures in earthquake events. On the other hand, the near-fault ground motions present strong randomness. At a specific site, the occurrence of velocity pulse is random (Baker, 2007). Therefore, the reliability of building structures subject to near-fault ground motions needs to be taken into account for seismic design of structures.

In the near-fault region, the existing structures need to be redesigned so as to resist the potential near-fault ground motions in the future. The retrofitting of energy devices, such as viscous dampers, can effectively reduce nonlinear responses and damages of the structures (Constantinou and Symans, 1992; Lavan and Dargush, 2009). However, the cost of retrofitting is an important factor considered by engineers.

Currently, the topic of reliability based design optimization (RBDO) has drawn more attention (Aoues and Chateauneuf, 2010; Altieri, Tubaldi, et al., 2017). RBDO aims to seek for the best compromise between cost and safety by considering stochastic uncertainties of the system. The stochastic uncertainties of the system may come from either the structural parameters or the excitations acted on the system. In the classical framework of RBDO, the stochastic uncertainties can be expressed by the reliability or failure probability of the system (Kuschel and Rackwitz, 2000; Chun, Song, et al., 2019). Generally, there are different methods for estimating the reliability or failure probability in the time-invariant and time-variant system. For the time-invariant system, the first-order reliability method (FORM) and second-order reliability method (SORM) are commonly used for estimating reliability. In the time-variant system, the method for assessing dynamic reliability based on first-passage failure criteria is different from time-invariant one (Chun, Song, et al., 2019). However, the method based on the level-crossing theory is hardly available for complex excitation, such as the near-fault ground motion.

In the past fifteen years, Li and Chen (2005; 2012; 2016) proposed and developed the probability density evolution method (PDEM) for stochastic dynamic analysis and dynamic reliability analysis of general stochastic system, which is suitable for time-invariant system and time-invariant system. In addition, PDEM can also be uniformly applied for the system with stochastic parameters and stochastic excitations.

This study aims to achieve optimal layout of the dampers by considering the constraint of dynamic reliability of building structures under near-fault ground motions. For this purpose, a stochastic model with nine random variables for near-fault impulsive ground motion and PDEM is employed to assess the dynamic reliability of buildings. Then, an optimization scheme is established to obtain the optimal layout of viscous dampers in potential locations.

2. STOCHASTIC SYNTHESIS MODEL OF NEAR-FAULT GROUND MOTIONS

2.1. *Long-period Velocity Pulse*

A stochastic pulse model with the Gabor wavelet established by Yang and Zhou (2015) to fit the strongest velocity pulse is utilized in this work, and expressed as follows

$$\begin{aligned} & V_p(t;T_p,N_c,T_{pk},\varphi,\sigma_{\ln PGV}) \\ & = PGV\cdot\exp\left[\sigma_{\ln PGV}-\frac{\pi^2}{4}\left(\frac{t-T_{pk}}{N_cT_p}\right)^2\right] \\ & \quad\times\cos\left(2\pi\frac{t-T_{pk}}{T_p}-\varphi\right) \end{aligned} \tag{1}$$

where T_p, N_c, T_{pk} and φ represent the pulse period, number of circles in the pulse, the location and phase of the pulse, respectively; $\sigma_{\ln PGV}$ is the standard deviation of the regression residuals, which can be considered as random variable; the attenuation of *PGV* is fitted by using the regression formula presented by Bary and Rodriguez-Marekis (2004)

$$\ln\left(PGV\right)=c_1+c_2M_w+c_3\ln(R^2+c_4^2)+\sigma \tag{2}$$

where M_w is the moment magnitude; R is the fault distance; and c_1, c_2, c_3 and c_4 are the regression parameters; and σ represents the regression residual of Eq. (2), respectively.

2.2. *High-frequency Components*

The residual acceleration time series can be generated by extracting the domain pulse and differentiating the residual velocity history. In this study, a random variable based spectral representation method in Liu *et al.* (2016) is employed to simulate the residual stochastic nonstationary high-frequency components of near-fault ground motion, which is written as

$$\begin{aligned} a_{\text{res}}(t) &= \sum_{k=0}^{N}\sqrt{S(t,\omega_k)\Delta\omega} \\ &\quad\times\left[\cos(\omega_k t)X_k+\sin(\omega_k t)Y_k\right] \end{aligned} \tag{3}$$

where $S(t, \omega_k)$ is the nonstationary power spectral density function of residual acceleration time history; $\Delta\omega=(\omega_u-\omega_l)/N$ denotes the frequency step size; $\omega_k=\omega_l+k(\omega_u-\omega_l)/N$ means the discrete frequency; X_k and Y_k are the orthogonal random variables, which can be defined as a random function with one elementary random variable γ as follows

$$X_k = \sqrt{2}\cos(k\gamma + \frac{\pi}{4})$$
$$Y_k = \sqrt{2}\sin(k\gamma + \frac{\pi}{4}) \tag{4}$$

in which the elementary random variable γ is uniformly distributed within $[-\pi, \pi]$. In Eq. (3), a modified K-T (Kanai-Tajimi) spectrum with high-pass filter modulated by a random variable based envelope function in Yang and Zhou (2015) is used to express the nonstationary spectral function, namely

$$S(t,\omega) = |e(t)|^2 G(\omega) S_{\text{K-T}}(\omega) \tag{5}$$

where $e(t)$, $G(\omega)$ and $S_{\text{K-T}}(\omega)$ indicate the envelope function, Butterworth filter, K-T spectrum, respectively. To present the variability of envelope function, the following stochastic envelope function with three random parameters in Yang and Zhou (2015) is also adopted

$$e(\alpha,\beta,\tau;t) = \begin{cases} 0 & t \le t_0 \\ \left(\dfrac{t-t_0}{\tau}\right)^{\alpha} & t_0 \le t \le t_0+\tau \\ e^{-\beta(t-t_0-\tau)} & t \ge t_0+\tau \end{cases} \tag{6}$$

In Eq. (6) the parameter t_0 describes the initial instant of non-zero ground motion, and the envelope parameters τ, α and β are considered as random variables.

As a result, the stochastic velocity time history $V_s(t)$ of ground motion scaled by the peak of residual velocity history V_{res}, and the high-frequency acceleration $a_s(t)$ of the near-fault ground motion can then be obtained by differentiating the scaled velocity time series. Finally, the acceleration time series with the strongest pulse can be generated by the superposition of the high-frequency acceleration and the low-frequency counterpart $a_p(t)$ achieved from the velocity pulse function shown in Eq. (1).

3. OPTIMIZATION SCHEME OF INELASTOC STRUCTURE WITH VISCOUS DAMPERS

3.1. Equilibrium equation

The differential equation of motion of the structure subjected to stochastic ground motions can be descripted as follows

$$\mathbf{M}\ddot{\mathbf{X}} + [\mathbf{C}_s + \mathbf{C}_d]\dot{\mathbf{X}} + \mathbf{F}(\mathbf{X},\mathbf{Y}) = -\mathbf{M}\mathbf{I}\ddot{u}_g(\boldsymbol{\theta}_{\text{f}}, t) \tag{7}$$

where $\mathbf{M}$=diag(m_1, m_2,…, m_n) denotes the mass matrix; $\mathbf{K}$ indicates initial stiffness matrix; $\mathbf{C}_s$ means inherent damping of the structure, Rayleigh damping, i.e., $\mathbf{C}_s=a\mathbf{M}+b\mathbf{K}$ is adopted in this study; $\mathbf{C}_d$ denotes the added damping matrix; $\ddot{\mathbf{X}}$, $\dot{\mathbf{X}}$ and $\mathbf{X}$ are the acceleration, velocity and displacement vector, respectively; $\mathbf{I}$ indicates the $n\times1$ unit column vector; $\ddot{u}_g(\boldsymbol{\Theta},t)$ is the acceleration of near-fault impulsive ground motion described in Section 1; $\boldsymbol{\Theta}$=(T_p, N_c, T_{pk}, φ, σ_{lnPGV}, α, β, τ, γ) denotes the random parameters vector of near-fault ground motion; $\mathbf{F(X,Y)}$ indicates inelastic stiffness of the structure, which can be expressed with modified Bouc-Wen hysteretic model

$$\mathbf{F}(\mathbf{X},\mathbf{Y}) = \alpha\mathbf{K}\mathbf{X} + (1-\alpha)\mathbf{K}\mathbf{Y} \tag{8}$$

in which $\mathbf{Y}=(Y_1, Y_2, \ldots, Y_n)^{\text{T}}$ denotes the hysteretic displacement, where Y_i is expressed as the following first-order nonlinear differential equation with respect to the relative displacement between floors $u_{\text{i}} = x_i - x_{i\text{-}1}$

$$\dot{Y}_i = h(Y_i)\frac{A\dot{u}_i - \nu\left(\beta\left|\dot{X}_i\right|\cdot\left|Y_i\right|^{N-1}Y + \gamma\dot{X}_i\left|Y_i\right|^{N}\right)}{\eta} \tag{9}$$

where α, β, γ, A, N, d_v, d_η, ζ_s, ψ, d_ψ, λ, p, q are parameters of Bouc-Wen model.

The considered system is subjected to near-fault ground motions, and has the deterministic initial condition $\mathbf{X}(t)\big|_{t=0} = \mathbf{X}_0$, $\dot{\mathbf{X}}(t)\big|_{t=0} = \dot{\mathbf{X}}_0$.

3.2. Objective function

In structural engineering, the energy dissipation devices, such as viscous dampers etc., have been widely used for reducing inelastic responses and damage of structures. Mounts of researches have shown that the distribution of damper may remarkably affect its efficiency (Constantinou and Symans, 1992; Lavan and Dargush, 2009). On the other hand, the great number of dampers will bring the more cost of retrofitting. Therefore, the optimization method plays an important role for performance-based design of structures.

Generally, the cost of a viscous damper can be taken as a function of the designed force, the stroke, and the damping coefficient. Although the damping coefficient has a limited direct effect on the cost, it affects the designed force. The cost of a damper can be taken to be proportional to its designed force. Thus, the cost of retrofitting can be presented by multiplying the number of dampers of each size group by the cost of a single damper of that size group (Lavan and Amir, 2014), namely

$$J = \sum_{i=1}^{N_c} N_i c_i \tag{10}$$

where N_c indicates the number of size groups of adopted dampers; N_i means the number of dampers of size group i; c_i denotes the damping coefficient of size group i.

The existence of damper in certain potential location is a discrete variable, which can be taken as 0 or 1. Thus, the damping coefficient at a certain location j is formulated as follows

$$c_{d,j} = \sum_{i=1}^{N_c} x_{ij} c_i, \quad x_{ij} \in \{0,1\}, \quad j = 1,\ldots,N_d \tag{11}$$

In practice, the number of size group of adopted dampers is small. For the two size groups, the damping coefficient can be alternatively rewritten as

$$\mathbf{c}_d = diag(\mathbf{x}_1)\left[c_1\mathbf{I} + (c_2 - c_1)\mathbf{x}_2\right] \tag{12}$$

where $\mathbf{x}_1$ determines the existence of the damper at N_d locations; $\mathbf{x}_2$ determines which size group damper is selected at these locations. The discrete variables form the integer-programming problem, which may bring the computational effort.

Lavan and Amir (2014) proposed a novel continuous variables method by introducing the material interpolation technique widely applied in topology optimization design of structures. The discrete variables $\mathbf{x}_1$ and $\mathbf{x}_2$ are expressed by the rational approximation of material properties (RAMP) as follows

$$x_{ij} = \frac{x_{ij}'}{1 + p(1 - x_{ij}')}, \quad i = 1,2;\ j = 1,\ldots,N_d \tag{13}$$

in which x_{ij}' denotes the continuous variable with values between 0 and 1; p presents a penalization effect resulting in a preference of 0–1 for x_{ij}. Thus, the problem is transformed into a mix-integer programming. In order to transform all of the design variables into continuous ones, Lavan and Amir also presented a continuous approach of damping coefficient c_1 and c_2 by multiplying the maximum nominal damping coefficient $\bar{c}_d$ by two continuous variables y_1 and y_2, i.e., $c_1 = \bar{c}_d y_1$, $c_2 = \bar{c}_d y_2$, where y_1 and y_2 lie on the interval [0,1].

For convenience, the superscript (’) of continuous variables in Eq. (13) is ignored hereafter.

3.3. Constraint function

The inter-story drift is an important performance index of structural damage of the structure. The hysteretic energy devices, such as viscous dampers, can effectively reduce nonlinear responses and damages. In this work, the dynamic reliability or failure probability is evaluated based on the inter-story drift of the structure.

3.4. Optimization problem

This study focuses on the layout optimization design of dampers in building structures. By adopting the continuous variable technique proposed by Lavan and Amir (2014), the total dynamic reliability of structures subjected to stochastic near-fault pulse-like ground motions is considered as the constraint function to minimize the cost of retrofitting of dampers. The optimization problem can be formulated as

$$
\begin{aligned}
\text{min} \quad & J = \overline{c}_d \mathbf{x}_1^{\mathrm{T}} [y_1 \mathrm{I} + (y_2 - y_1)\mathbf{x}_2] \\
\text{s.t.} \quad & P_f(t) \le [P_f] \\
& 0 \le x_{1,j}, x_{2,j} \le 1 \\
& 0 \le y_1, y_2 \le 1 \\
\text{with} \quad & \mathbf{M}\ddot{\mathbf{X}} + [\mathbf{C}_s + \mathbf{C}_d]\dot{\mathbf{X}} + \mathbf{F}(\mathbf{X},\mathbf{Y}) = -\mathbf{MI}\ddot{u}_g(\boldsymbol{\theta}_f, t) \\
& \frac{\partial p_{Z\boldsymbol{\Theta}}(z,\boldsymbol{\theta},t)}{\partial \tau} + \dot{Z}(\boldsymbol{\Theta},\tau)\frac{\partial p_{Z\boldsymbol{\Theta}}(z,\boldsymbol{\theta},t)}{\partial z} = 0 \\
& p_{Z\boldsymbol{\Theta}}(z,\boldsymbol{\theta},\tau) = 0, \quad z \notin \Omega_s \\
& p_{Z\boldsymbol{\Theta}}(z,\boldsymbol{\theta},\tau)\big|_{\tau=0} = \delta(z - z_0) P_q \\
& P_f(t) = 1 - \int_{-\infty}^{b} p_{\mathbf{Z}}(\mathbf{z}, \tau = 1)\mathrm{d}\mathbf{z}
\end{aligned}
\tag{14}
$$

where $P_f(t)$ denotes the failure probability, which is easily expressed by total the dynamic reliability of structures; $[P_f]$ is admissible failure probability.

In this work, the method of moving asymptotes (MMA) is used to solve the optimization problem described in Eq. (14). Due to the objective function is explicitly expressed by design variables, i.e., $[\mathbf{x}_1, \mathbf{x}_2, y_1, y_2]$, the calculation of the gradient of the objective function is straightforward. However, the constraint function is implicit with respect to design variables. The calculation of constraint function is time-consuming. Thus, the first-order derivatives are solved in this work. The sensitivities of constraint with respect to design variables are evaluated by semi-analytical method.

4. DYNAMIC RELIABILITY ANALYSIS BY USING PDEM

4.1. Generalized Probability Density Evolution Equations

Based on the principle of probability conservation of random event description, Li and Chen (2012) derived the uncoupled generalized probability density evolution equation, and the one-dimensional GPDEE is expressed as follows

$$
\frac{\partial p_{\mathbf{X}\boldsymbol{\Theta}}(\mathbf{x},\boldsymbol{\theta},t)}{\partial t} + \dot{X}(\boldsymbol{\theta},t)\frac{\partial p_{\mathbf{X}\boldsymbol{\Theta}}(\mathbf{x},\boldsymbol{\theta},t)}{\partial x} = 0 \tag{15}
$$

with boundary condition: $p_{\mathbf{X}\boldsymbol{\Theta}}(\mathbf{x},\boldsymbol{\theta},t)\big|_{x\to\pm\infty} = 0$ and initial condition: $p_{\mathbf{X}\boldsymbol{\Theta}}(\mathbf{x},\boldsymbol{\theta},t)\big|_{t=0} = \delta(x - x_0) p_{\boldsymbol{\Theta}}(\boldsymbol{\theta})$, where $\delta(\cdot)$ is the Dirac delta function; x_0 denotes the initial value of the interested physical quantity $X(t)$, which is one component of the $\mathbf{X}_0$; $p_{\boldsymbol{\Theta}}(\boldsymbol{\theta})$ is the joint probability density function of random parameters $\boldsymbol{\Theta}$.

Subsequently, the joint probability density function (PDF) of $\mathbf{X}(t)$ can be achieved by

$$
p_{\mathbf{X}}(\mathbf{x},t) = \int_{\Omega_{\boldsymbol{\Theta}}} p_{\mathbf{X}\boldsymbol{\Theta}}(\mathbf{x},\boldsymbol{\theta},t)\mathrm{d}\boldsymbol{\theta} \tag{16}
$$

where $\Omega_{\boldsymbol{\Theta}}$ is the distribution domain of $\boldsymbol{\Theta}$. For a general structure, the numerical procedure is implemented essentially.

4.2. First-passage Dynamic Reliability Analysis

Based on the first-passage failure criterion, the dynamic reliability of structures is defined as

$$
P_s(t) = \Pr\left\{X(\tau) \in \Omega_s, 0 < \tau \le t\right\} \tag{17}
$$

where Ω_s denotes the safe domain.

By using PDEM, the dynamic reliability in Eq. (17) can be obtained by assuming equivalent extreme value distribution method (Li and Chen 2005). The random process is regarded a series system over the time domain. Once the response crosses the safety margin in certain moment, that is, the maximum of response in whole time domain exceeds the threshold, the failure occurs. In another word. Thus, the dynamic reliability can be expressed as

$$
P_s(t) = \Pr\left\{\bigcap_{1\le i\le m}\left[\bigcap_{0<\tau\le t} X_i(\tau) \in \Omega_s\right]\right\} \tag{18}
$$

By introducing a virtual time τ, a virtual random process can be assumed as follows

$$
Z(\boldsymbol{\Theta},\tau) = \tau \cdot X_{\max}(t) \tag{19}
$$

where $X_{\max}(t) = \max\limits_{1<i\le m}\left\{\max\limits_{0<\tau\le t}[X_i(\boldsymbol{\Theta},\tau) - b]\right\}$, and b is the allowable value of inter-story drift, m denotes the number of floors of structures.

Therefore, another probability conservative system can be formulated by GPDEE

$$
\frac{\partial p_{\mathbf{Z}\boldsymbol{\Theta}}(\mathbf{z},\boldsymbol{\theta},\tau)}{\partial \tau} + \dot{Z}(\boldsymbol{\theta},\tau)\frac{\partial p_{\mathbf{Z}\boldsymbol{\Theta}}(\mathbf{z},\boldsymbol{\theta},\tau)}{\partial z} = 0 \tag{20}
$$

with initial condition

$$p_{\mathbf{Z\Theta}}(\mathbf{z},\boldsymbol{\theta},\tau)\big|_{\tau=0} = \delta(z)\, p_{\boldsymbol{\Theta}}(\boldsymbol{\theta}) \tag{21}$$

where the derivation of virtual stochastic process is expressed as $\dot{Z}(\boldsymbol{\Theta},\tau) = X_{\max}(t)$, when τ=1, $Z(\boldsymbol{\Theta}, \tau)|_{\tau=1} = X_{\max}(t)$.

By solving Eq. (7) and (20), the probability density function of virtual stochastic process $Z(\boldsymbol{\Theta}, \tau)$ can be calculated by

$$p_{\mathbf{Z}}(\mathbf{z},\tau) = \int_{\Omega_{\boldsymbol{\Theta}}} p_{\mathbf{Z\Theta}}(\mathbf{z},\boldsymbol{\theta},\tau)\mathrm{d}\boldsymbol{\theta} \tag{22}$$

and the reliability of structure can be achieved by

$$P_s(t) = \int_{-\infty}^{b} p_{X_{\max}}(\mathbf{x},t)\mathrm{d}\mathbf{x} = \int_{-\infty}^{b} p_{\mathbf{Z}}(\mathbf{z},\tau=1)\mathrm{d}\mathbf{z} \tag{23}$$

5. NUMERICAL EXAMPLE

As an example, a 5-story hysteretic frame is considered. The mass and stiffness of floors are listed in Table 1. The probability distribution of random parameters of the stochastic model is estimated by the impulsive records in the Chi-Chi earthquake event, and is shown in Table 2

Table 1 The mass and stiffness of floors

Floor	1st	2nd	3th	4th	5th
Mass m_i (10^5 kg)	2.6	2.4	2.2	2.0	1.8
Stiffness k_i (10^5 kN/m)	3.8	3.6	3.4	3.2	3.0

Table 2. The probability distribution of random parameters for near-fault pulse-like ground motions.

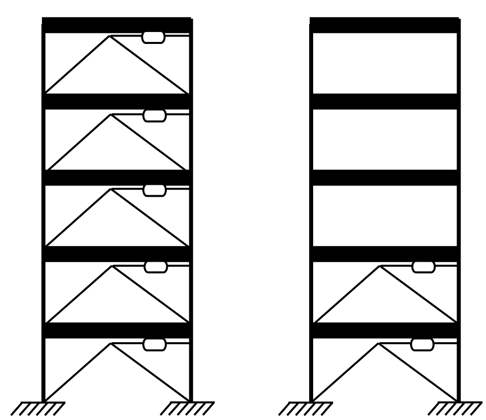
Parameter type	Param-eters	Distribution	Bounds	Mean	Std. D
Pulse parameters	T_p	Normal	[1.5, 15]	6.81	1.62
	N_c	Lognormal	[0.2, 2]	0.01	0.29
	T_{pk}	Normal	[19.29, 54.16]	22.32	6.41
	φ	Normal	[0, 2π]	3.06	1.71
	$\sigma_{\ln PGV}$	Normal	[−0.6, 0.6]	0.00	0.25
Envelope parameters	τ	Normal	[0, 40]	20.43	6.68
	α	Lognormal	[0.5, 4.5]	0.63	0.41
	β	Lognormal	[0.02, 0.17]	−2.56	0.39
High-frequency parameter	γ	Uniform	[0, 2π]	0.00	$\pi^2/3$

In this example, the maximum nominal damping coefficient $\overline{c}_d$ =3000 kN s/m; initial value of design variable $\mathbf{x}_1$ = [0.5, 0.5, 0.5, 0.5, 0.5], $\mathbf{x}_2$ = [0.5, 0.5, 0.5, 0.5, 0.5], y_1 = 0.9, y_2 = 0.1, and the initial layout of viscous dampers is illustrated in Figure 1(a). The initial penalty p = 1. To present original discrete design variables by using continuous design variables, the penalty p is multiplied by 1.5 for every 10 design iterations. The allowable inter-story drift is 0.06 m, and the admissible failure probability $[P_f]$ = 0.005 herein.

Table 3 Optimization results

Floor	x_1	x_2	Selected damper (kN s/m)
1st	0.9933≈1	0.9245≈1	2974.55
2nd	0.9063≈1	0.9999≈1	2974.55
3th	0.0565≈0	0.7368	0
4th	0.0036≈0	0.7507	0
5th	0.0038≈0	0.6517	0

After 180 iterations, the optimization results converge, and are presented in Table 3. The values of $\mathbf{x}_1$ and $\mathbf{x}_2$ indicate the existence of dampers. When these values are larger than 0.8, the damper needs to be added in the corresponding location, not vice versa. The damping coefficient of the location is achieved by $c_1 = \overline{c}_d y_1$, $c_2 = \overline{c}_d y_2$, in which the values of y_1 and y_2 are 0.1887 and 0.9915, respectively. As a result, the two dampers with damping coefficient c_2 need to be installed in first two floors, and the optimal layout is illustrated in Figure 1(b).



(a) (b)

Figure 2. (a) *Initial and* (b) *Optimal layout of dampers.*

6. CONCLUSIONS

In this study, an efficient dynamic reliability based design optimization framework is established to minimize the cost of retrofitting of viscous damper for inelastic frame structure. In order to consider the potential near-fault ground motion, a stochastic model with nine random variables is adopted. The probability density evolution method (PDEM) with equivalent extreme method are employed to evaluate dynamic reliability of structure. In the established framework, the damping coefficient and the layout of dampers are uniformly treated by the rational approximation of material properties (RAMP) widely applied in topology optimization design of structures. Finally, the numerical example demonstrates the effectiveness of established optimization framework.

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8. REFERENCES

Bray, J.D. and Rodriguez-Marek, A. (2004). Characterization of Forward-directivity Ground Motions in the Near-fault Region, *Soil Dyn. Earthq. Eng.*, 24(11), 815−828.

Baker, J.W. (2007). Quantitative Classification of Near-fault Ground Motions Using Wavelet Analysis, *Bull. Seismol. Soc. Am.*, 97(5), 1486−1501.

Constantinou, M.C, Symans M. (1992). Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers, *National Center for earthquake engineering research*: Buffalo, NY.

Lavan, O. and Dargush, G.F. (2009). Multi-objective evolutionary seismic design with passive energy dissipation systems. *J. Earthq. Eng.*, 13(6):758–790.

Aoues, Y. and A. Chateauneuf (2010). Benchmark study of numerical methods for reliability-based design optimization, *Struct. Multidiscip. O.*, 41(2): 277−294.

Altieri, D., Tubaldi, E., et al. (2017). Reliability-based optimal design of nonlinear viscous dampers for the seismic protection of structural systems. *B. Earthq. Eng.*, 16(2): 963−982.

Kuschel, N. and Rackwitz, R. (2000). Optimal design under time-variant reliability constraints. *Struct. Saf.*, 22(2): 113−127.

Chun, J., Song, J., and Paulino, G. H. (2019). System-reliability-based design and topology optimization of structures under constraints on first-passage probability. *Struct. Saf.*, 76: 81−94.

Li, J. and Chen, J.B. (2005). Dynamic Response and Reliability Analysis of Structures with Uncertain Parameters, *Int. J. Numer. Meth. Eng.*, 62(2), 289−315.

Li, J., Chen, J. B., et al. (2012). Advances of the Probability Density Evolution Method for Nonlinear Stochastic Systems, *Probabilist. Eng. Mech.*, 28, 132−142.

Li, J. (2016). Probability density evolution method: Background, significance and recent developments. *Probabilist. Eng. Mech.*, 44: 111−117.

Yang, D.X. and Zhou, J.L. (2015). A Stochastic Model and Synthesis for Near-fault Impulsive Ground Motions, *Earthq. Eng. Struct. Dyn.*, 44(2), 243−264.

Liu, Z.J., Liu, W. and Peng, Y.B. (2016). Random Function based Spectral Representation of Stationary and Non-stationary Stochastic Processes, *Probabilist. Eng. Mech.*, 45, 115−126.

Lavan, O., and Amir, O. (2014). Simultaneous topology and sizing optimization of viscous dampers in seismic retrofitting of 3D irregular frame structures. *Earthq. Eng. Struct. Dyn.*, 43(9): 1325−1342.