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Multi-criteria performance-based optimization of friction energy dissipation devices in RC frames

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Abstract. A computationally-efficient method for multi-criteria optimisation is developed for performance-based seismic design of friction energy dissipation dampers in RC structures. The proposed method is based on the concept of Uniform Distribution of Deformation (UDD), where the slip-load distribution along the height of the structure is gradually modified to satisfy multiple performance targets while minimising the additional loads imposed on existing structural elements and foundation. The efficiency of the method is demonstrated through optimisation of 3, 5, 10, 15 and 20-storey RC frames with friction wall dampers subjected to design representative earthquakes using single and multi-criteria optimisation scenarios. The optimum design solutions are obtained in only a few steps, while they are shown to be independent of the selected initial slip loads and convergence factor. Optimum frames satisfy all predefined design targets and exhibit up to 48% lower imposed loads compared to designs using a previously proposed slip-load distribution. It is also shown that dampers designed with optimum slip load patterns based on a set of spectrum-compatible synthetic earthquakes, on average, provide acceptable design solutions under multiple natural seismic excitations representing the design spectrum.

Keywords: multi-criteria optimisation; seismic performance; friction damper; slip load distribution; energy dissipation.

1. Introduction

Supplemental passive control devices have been widely utilised as a viable cost-effective approach to enhance the seismic performance of existing and newly designed buildings by modifying the dynamic characteristics and increasing the energy dissipation capacity of the structures. As current design codes do not generally provide guidelines for optimising the configurations of passive control devices, this can be a challenging task due to complexity and high nonlinearity of these systems under earthquake excitations (Whittle *et al*. 2012, 2013). Several optimisation methods have been adopted for optimum design of energy dissipation devices such as: Linear Quadratic Regulator (LQR) (Gluck *et al*. 1996, Agrawal and Yang 1999), Simulated Annealing (SA) (Milman and Chu 1994), Gradient-based Optimisation (Singh and Moreschi 2001; Uetani *et al*. 2003, Park *et al*. 2004, Fujita *et al*. 2010), Genetic Algorithm (GA) techniques (Moreschi and Singh 2003, Lavan and Dargush 2009, Apostolakis and Dargush 2010, Hejazi *et al*. 2013), Fully Stressed Design Optimisation (Levy and Lavan 2006) and a procedure using Sensitivity Analysis and Redesign (Takewaki 2011, Adachi *et al*. 2013, Murakami *et al*. 2013). The concept of performance-based seismic design was also adopted for optimisation of structures with supplemental energy dissipation devices. Liu *et al*. (2005), Lavan and Levy (2010), Lavan and Amir (2014) developed a performance-based optimal design methodology to obtain the best sizing and allocation of viscous dampers in regular and irregular building structures. Similarly, Kim and Choi (2006) proposed a displacement-based design procedure to obtain an optimum number of velocity-dependent supplemental dampers for existing steel structures to satisfy a given performance limit state. In one of the early studies on optimum performance-based design of frames with friction dampers, Daniel *et al*. (2013) adopted a Fully Stressed Design (FSD) optimisation method to obtain the brace stiffness if added damping devices under a constant predefined slip displacement. However, in their study the frame system was considered to be linear, which may not be the case for most structures under strong earthquakes.

In an early attempt, Kasai *et al*. (1998) proposed a simplified theory to predict the seismic performance of passive control systems, and to demonstrate their ability to protect structures during major seismic events. It was shown that reasonably uniform drift distributions can be obtained by using different damper sizes through the building height. Takewaki (2011) introduced criteria-based and sensitivity-based design algorithms for optimal quantity and placement of passive energy dissipation devices, where displacement, acceleration, and earthquake input energy were regarded as the main performance-based design

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indices. A direct performance-based design procedure was proposed by Guo and Christopoulos (2013) using Performance-Spectra (P-Spectra) design tools for nonlinear low to medium-rise frame structures with supplemental dampers. The results of their study indicate that while using the P-Spectra generally leads to very good predictions of the displacement and base shear of damped systems, the acceleration and residual drift predictions may not be very accurate due to higher mode effects and interactions of inelastic elements in the multi-degree of freedom (MDOF) structure. In a more recent study by Kasai *et al*. (2018), a new design method was proposed for vibration control of inelastic multi-storey frames using nonlinear viscous dampers. The method could determine the damper properties required to satisfy a predefined target storey drift at each storey level even for the frames having undesirable storey stiffness/strength distributions. It should be noted that majority of the above mentioned studies have been limited to the optimum design of velocity dependent passive control systems such as viscose and viscoelastic dampers.

Gidaris *et al*. (2018) proposed a multi-criteria framework for cost-effective design of seismic protective devices (mainly viscous dampers) by considering the mean total lifecycle cost and the repair cost as design objectives. Similarly, Saitua *et al*. (2018) presented a multi-objective optimisation approach for height-wise distribution of supplemental viscous dampers in multi-storey buildings by considering the cost and performance as two main optimisation objectives. They considered relationships between cost and damper force capacity, strengthening of columns, and maximum feasible damper force capacity. They concluded that consideration of the cost of column strengthening may have a significant impact on the optimum distribution of dampers, when compared to the approaches that only minimize the cost of the dampers.

Friction-based dampers are considered as one of the appropriate passive energy dissipative systems due to their high adjustability and high energy dissipation capacity resulting from Coulomb dry friction (Aiken 1996). To avoid high stress concentrations at the connection zones in RC frames, wall-type friction-based wall dampers have been proposed by several researchers (Sasani and Popov 2001, Petkovski and Waldron 2003, Cho and Kwon 2004, Nabid *et al*. 2017). In general, the efficiency of friction energy dissipation devices is highly sensitive to the dampers' location and height-wise distribution of slip loads (the loads at which the friction devices start slipping and dissipating energy). In one of the early attempts, Filiatrault and Cherry (1990) developed an optimisation algorithm to obtain the best slip load distribution by minimising an energy performance index. They showed that the optimum slip load values are more dependent on the frequency and amplitude of the earthquake input than the structural features. A Genetic Algorithm (GA) was employed by Moreschi and Singh (2003) for optimum height-wise placement of friction dampers in steel braced frames when satisfying a predefined performance objective. Using a similar approach, Miguel *et al*. (2014) utilised the GA technique for multi-objective optimisation of friction dampers in shear-buildings subjected to seismic loading. In a follow-up study, Miguel *et al*. (2016) adopted a Backtracking Search Algorithm (BSA) for simultaneous optimisation of the slip forces and locations of the friction dampers in shear-buildings subjected to earthquake ground motions. More recently, a practical optimisation methodology was developed by Nabid *et al*. (2018) for seismic design of RC frames with friction dampers. It was shown that the method can increase the energy dissipation capacity of the dampers, while preventing damage concentration and soft storey failure in the frames. However, their proposed method is based on redistributing constant total slip load values (sum of slip loads in all dampers), and hence cannot be directly used to achieve a specific target for performance-based seismic design purposes. Moreover, their optimisation algorithm is not capable of satisfying multiple performance objectives simultaneously. In a follow-up study, Nabid *et al*. (2019a) improved the efficiency of their optimisation method by using an adaptive convergence factor which is modified based on the level of performance violation at each step.

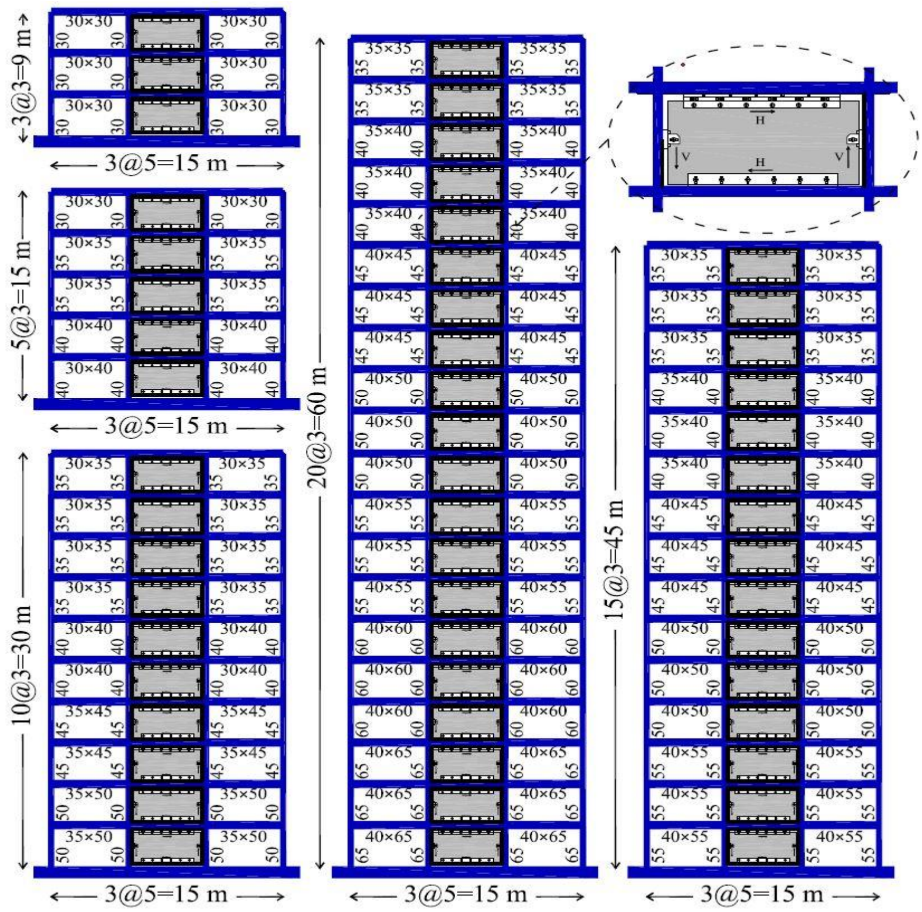
It should be noted that most of the aforementioned optimisation techniques have at least one of the following limitations: (a) they are only adopted for viscous and viscoelastic dampers and may not be appropriate for optimum design of friction energy dissipation devices; (b) they assume a linear behaviour for the main structural system, and thus, do not capture the damage of the structural elements which is generally unavoidable during strong earthquakes; (c) they use equivalent earthquake static loads or non-linear push over analyses and therefore do not take into account the effects of dynamic loads; (d) they are computationally expensive and/or require complex mathematical calculations and are not suitable for practical applications. Consequently, there is a need for developing a computationally efficient methodology for optimum design of non-linear structural systems with friction-based dampers under seismic excitations.

In this paper, for the first time, the optimisation methodology based on the concept of Uniform Distribution of Deformation (UDD) is further developed for multi-criteria performance-based design of friction-based energy dissipation devices in RC frames. To simplify the complex optimisation problem, the proposed method aims to obtain the optimum slip load of friction dampers by using multiple performance targets under Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) earthquakes directly as objective functions, rather than design constraints. The computational efficiency and reliability of the method is then demonstrated through several design examples using single and multi-criteria optimisation scenarios.

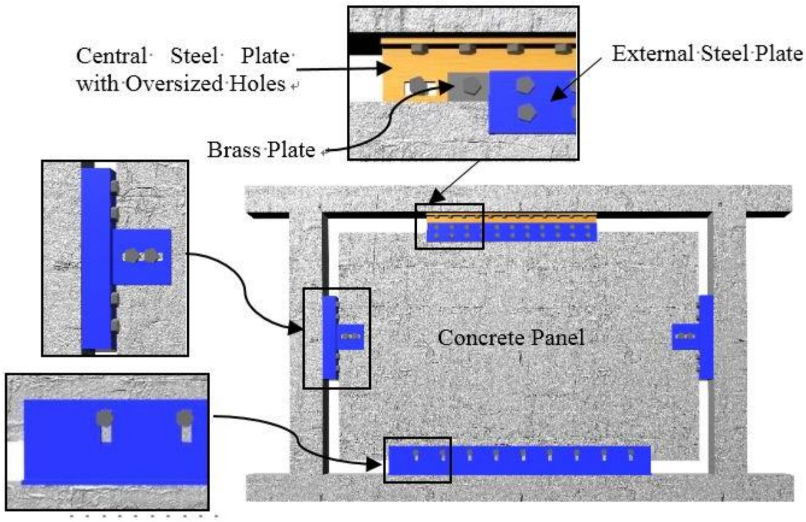
2. Analytical modelling and design assumptions

2.1 RC frames with friction wall dampers

In this study 3, 5, 10, 15, and 20-storey RC frames were selected with the typical geometry shown in Fig. 1(a). The schematic view of the utilised friction damper (Fig. 1(b)) comprises a reinforced concrete wall panel connected to the frame through a friction device at the top, a horizontal



(a)



(b)

Fig. 1(a) Geometry of the reference RC frames equipped with friction wall dampers, (b) schematic view of the friction wall damper (adopted from Nabid *et al*. (2017))

connection at the bottom, and two vertical supports in the sides. The connections are designed to transfer the loads to the beam-column connection, thus avoiding extra shear forces in the middle of the adjacent columns and beams.

The friction device is a Slotted Bolted Connection (SBC) using two steel plates over a central T-shape slotted steel plate anchored to the top floor beam (Fig. 1(b)). By using over-sized holes in the central steel plate of the adopted friction device, the largest friction forces will occur between the central and the brass plates (as shown in Fig. 1 (b)). The size of these holes in the horizontal and vertical directions should be calculated to accommodate the expected maximum lateral drift and vertical deformations of the beam, which would prevent transfer of large stresses on

Table 1 Properties of the selected natural ground motions

No.	Earthquake	*Ms*	Station/Component	Duration (s)	PGA (g)	PGV (cm/s)	PGD (cm)
1	1979 Imperial Valley	6.5	IMPVALL/H-E04140	39	0.485	37.4	20.23
2	1979 Imperial Valley	6.5	IMPVALL/H-E07230	37	0.469	113	46.94
3	1979 Imperial Valley	6.5	IMPVALL/H-EDA360	39	0.481	40.9	16.37
4	1979 Imperial Valley	6.5	IMPVALL/H-BCR230	38	0.777	44.9	15.10
5	1979 Imperial Valley	6.5	IMPVALL/H-E11230	39	0.379	44.6	21.32
6	1987 Superstition Hills (B)	6.7	SUPERST/B-ICC000	60	0.358	46.4	17.50
7	1989 Loma Prieta	6.9	LOMAP/G03000	40	0.555	35.7	8.21
8	1992 Cape Mendocino	6.9	CAPEMEND/PET000	36	0.590	48.4	21.74
9	1994 Northridge	6.7	NORTHR/NWH360	40	0.590	97.2	38.05
10	1994 Northridge	6.7	NORTHR/STC180	30	0.459	60.1	21.89
11	1999 Duzce, Turkey	7.2	DUZCE/DZC270	26	0.535	83.5	51.59
12	1976 Friuli, Italy	6.5	TOLMEZZO/TMZ270	36	0.315	30.5	5.21

the central plate around the slotted holes. More detailed information about the adopted friction wall damper can be found in Nabid *et al*. (2017).

The frames were assumed to be located on a soil type C of Eurocode 8 (EC8, CEN 2004a) category and were designed for low-to-medium seismicity regions, using PGA of 0.2 g to represent typical substandard buildings in developing countries with high seismic risk. The bottom of the concrete panels in the studies models was fixed to the base at the ground level to transfer the imposed loads directly to foundation, and therefore, reduce the maximum column axial loads. The uniformly distributed permanent and non-permanent loads were considered to be 5.5 kN/m^2 and 2.5 kN/m^2 for interior floors, and 5.3 kN/m^2 and 1.0 kN/m^2 for the roof. The reference frames were initially designed to resist the seismic loads based on EC8 (CEN, 2004a) and in accordance with the minimum requirements of Eurocode 2 (EC2, CEN, 2004b) for moment-resisting RC frames with medium ductility (DCM). The concrete compressive strength (f'_c) and the yield strength of steel reinforcement bars (f_y) were assumed to be 35 and 400 MPa, respectively.

The pushover and nonlinear time-history analyses were conducted using the OpenSees software (McKenna 1997, McKenna *et al*. 2000, McKenna 2017). Concrete and reinforcing steel bars were modelled using a uniaxial constitutive material with linear tension softening (Concrete02) and a Giuffre-Menegotto-Pinto model (Steel02) with 1% isotropic strain hardening, respectively. Beam and column members were modelled using displacement-based nonlinear beam-column elements. It should be noted that for displacement-based elements, increasing the number of elements within the length of a member plays a more important role than providing more integration points along the length of the element (Neuenhofer and Filippou 1997, Terzic 2011). Therefore, in this study each column and beam member was divided into three elements, while four Gauss–Lobatto integration points were considered for each element. *P*-Delta effects were taken into account in the analyses. A classical Rayleigh damping model proportional to both mass and stiffness matrices (i.e., $C=\alpha M+\beta K$) was adopted. Based on the results of a modal analysis, a constant damping ratio of 0.05 was assigned to the first mode and to the mode at which the cumulative mass participation exceeds 95%.

Based on the results of preliminary studies, it was assumed that the strength of the concrete wall panels (15 cm thickness) is always higher than the maximum loads transferred from the friction device, and therefore, they were modelled using equivalent elastic elements. A nonlinear spring with an elastic-perfectly plastic uniaxial material, representing an ideal Coulomb friction hysteretic behaviour, was used to model the friction device. The beam-to-column connections were assumed to be fully rigid with no shear failure in the panel zones. A computer code in MATLAB (2014) was developed and linked to the OpenSees (McKenna 1997, McKenna *et al*. 2000, McKenna 2017) program to calculate the energy dissipation in the beam and column elements and friction devices under earthquake loads. The soil-structure interaction (SSI) effects were not taken into account in this study. However, previous studies demonstrated that ignoring the SSI effects generally leads to conservative design solutions, especially in tall buildings (Lu *et al*. 2016).

2.2 Earthquake ground motions

To demonstrate the efficiency of the proposed performance-based optimisation framework, a set of twelve natural ground motions obtained from Pacific Earthquake Engineering Research Center online database (PEER NGA) was used in the non-linear dynamic analyses in this study. Table 1 shows the characteristics of the selected natural ground motions. All earthquake excitations had high local magnitudes (i.e., Ms>6.5) and were recorded on soil class C of EC8 with less than 45 km distance from the epicentre. In addition, the TARSCTHS program (Papageorgiou *et al*. 2002) was used to generate synthetic earthquakes to be matched with the EC8 design response spectrum for the high seismicity regions (i.e., PGA=0.4 g) with soil class C. While there are different methods available for the selection of design earthquake ground motions in the literature, it is very common to utilise spectrum-compatible earthquakes for design and assessment purposes (e.g., Kim and Choi 2006, Apostolakis and Dargush 2010, Kasagi *et al*. 2016).

It should be noted that most seismic performance-based

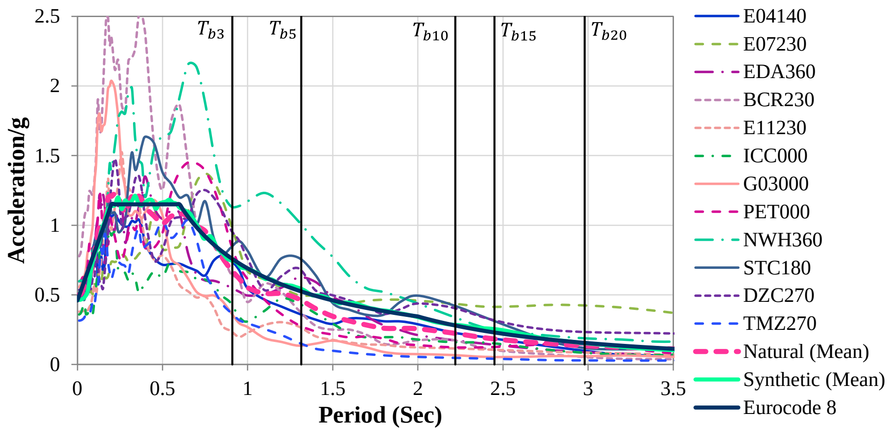


Fig. 2 Comparison between the elastic acceleration response spectra of the selected natural and synthetic earthquake records and the EC8 design spectrum, 5% damping ratio

design guidelines (e.g., ASCE/SEI 41-17 2017) aim to control the seismic response of the buildings under two different earthquake levels: (a) Design Basis Earthquake (DBE) with 10% probability of exceedance in 50 years, and (b) Maximum Considered Earthquake (MCE) with 2% probability of exceedance in 50 years. In this study, it is assumed that the DBE and MCE design spectra match with the EC8 design response spectrum for soil class *C* with PGA levels equal to 0.4 g and 0.6 g, respectively. This means that in this study the MCE events are taken to be 1.5 times of the DBE events. Fig. 2 compares the elastic acceleration response spectra of the selected natural earthquake records, the EC8 design spectrum and the spectrum of the generated synthetic earthquakes. It is observed that both the average spectrum of the synthetic earthquakes and the average spectrum of the natural ground motions can represent the EC8 design spectrum with a good accuracy, and therefore, can be efficiently utilised to evaluate the seismic performance of the designed frames.

3. Optimum slip load range for maximum energy dissipation

One of the main advantages of friction energy dissipation devices in general is the capability to adjust the height-wise distribution of slip forces (F_s) to achieve predefined performance targets. Nabid *et al.* (2017) studied the efficiency of friction wall dampers designed with different slip load distribution patterns in improving the seismic performance of substandard RC structures. Based on the results of their study, the following empirical formula was proposed to obtain an efficient height-wise distribution of slip loads for buildings with different number of storeys

$$R = 1.12e^{-0.11n} \tag{1}$$

where n is the number of storeys (representing the fundamental period of the building), and R is the slip load ratio defined as the ratio between the average of slip loads and the average of storey shear strengths at all storey levels. By considering the uniform cumulative pattern for height-wise slip load distribution (as suggested by Nabid *et al.* 2017), the slip load values at each storey level can be calculated using the equation below

$$\begin{aligned} F_{s,i} &= \frac{\sum_1^n F_{y,i} \times R}{n\dfrac{(n+1)}{2}} \times (n+1-i) \\ &= \frac{\sum_1^n F_{y,i} \times 1.12e^{-0.11n}}{n\dfrac{(n+1)}{2}} \times (n+1-i) \end{aligned} \tag{2}$$

where $F_{(s,i)}$ and $F_{(y,i)}$ are the slip load and the storey shear strength of the i^{th} storey, respectively. The shear strength of each storey ($F_{(y,i)}$) can be calculated from a non-linear pushover analysis. To avoid the effects of lateral load patterns on the results, for each storey a single lateral load is applied, while the lateral degrees of freedom for all lower level storeys are constrained. This implies that for each structure, n (=number of storey) individual push over analyses are required to calculate the shear strength values at all storey levels. The same approach has been successfully applied in previous studies to define equivalent modified shear-building models for multi-storey buildings (e.g., Hajirasouliha and Doostan 2010, Hajirasouliha and Pilakoutas 2012). In a more recent study, Nabid *et al.* (2019b) developed new design equations to obtain the optimum range for the friction damper slip loads under near-field and far-field earthquake ground motions.

It should be noted that Eq. (1) may not be directly applicable for the buildings having geometries different with those considered in Nabid *et al.* (2017). Therefore, in this section, the adequacy of this empirical equation in improving the energy dissipation capacity of the friction wall dampers is assessed for the set of RC frames used in this study (see Fig. 1). The seismic performance of the selected RC frames with friction wall dampers is quantified in terms of maximum inter-storey drift, maximum axial load in the columns, base shear, and an energy dissipation parameter (R_w) defined as the ratio between the friction work of the dampers and the plastic deformation work of the structural elements (Petkovski and Waldron 2003, Nabid *et al.* 2018). While the maximum inter-storey drift and energy dissipation (R_w) parameters are used to assess the efficiency of the dampers, the maximum axial load and base

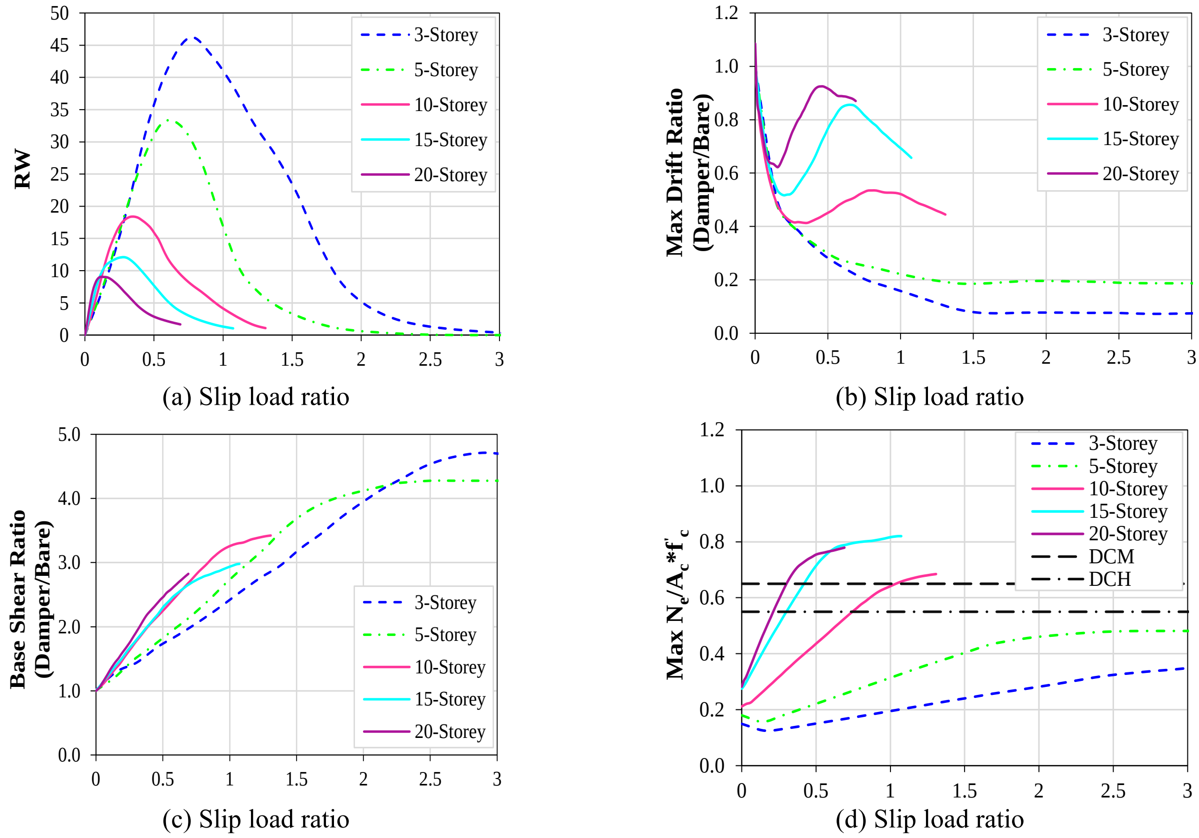


Fig. 3 Variations of (a) R_w, (b) maximum drift ratio, (c) base shear ratio, and (d) maximum $N_e/A_cf'_c$ for the 3, 5, 10, 15 and 20-storey frames as a function of slip load ratio, average of selected natural earthquakes

shear values are considered to control the additional loads imposed by the friction wall system to the existing structural elements. It should be noted that according to EC8 (CEN 2004a), the column axial load ratio (defined as $N_e/A_cf'_c$) should be limited to 0.55 and 0.65 for ductility classes DCH (high) and DCM (medium), respectively, where A_c is the cross section area of the column and N_e is the column axial load under seismic and concurrent gravity actions. This highlights the importance of reducing the additional axial loads imposed by the utilised friction wall system.

Fig. 3 displays the average variations of selected performance parameters versus slip load ratio for the 3, 5, 10, 15 and 20-storey frames under the selected natural earthquakes. For better comparison, the drift and base shear results in this figure are scaled to those of the corresponding bare frames. Similar to the results reported by Nabid *et al.* (2017), it is shown in Fig. 3 that there is always an optimum range of slip load ratios for each selected frame that in general leads to higher energy dissipation capacity and lower displacement demands. The optimum slip load values were in the range of 0.65-0.95, 0.50-0.80, 0.25-0.45, 0.10-0.30, and 0.05-0.15 for the 3, 5, 10, 15, and 20-storey frames, respectively. These results compare very well with the optimum slip load ratios calculated by Eq. (1), irrespective of the difference between the frame geometries used in this study and those in Nabid *et al.* (2017).

It can be seen from Figs. 3 (c) and (d) that the base shear and axial loads imposed by the wall dampers increase by increasing the slip load ratio (up to a maximum limit where the friction devices are all locked). This means that while using the optimum slip range can efficiently increase the energy dissipation capacity of the dampers, it may lead to excessive base shear and column axial load values and, consequently, impart large loads on the foundations. Since the distribution pattern of the slip loads and the storey shear strengths are not identical, to reach the locking stage, the slip load ratio R would naturally exceed 1.

As shown in Fig. 3(d), some higher slip load factors may lead to maximum axial loads which exceed the moderate and high ductility (DCM and DCH) EC8 target limits, and therefore, cannot be used in practical design applications. To address this issue, in the following sections a methodology is proposed for optimum design of friction dampers to satisfy predefined performance targets while minimising the additional imposed loads.

4. Developing a performance-based optimisation framework

In this study, an efficient performance-based optimisation framework is developed based on the concept of Uniform Distribution of Deformation (UDD) for optimum design of RC frames with friction energy dissipation devices. The objective is to find the best height-wise distribution of slip loads in the friction wall dampers to satisfy a predefined performance level under the design earthquake by using minimum total friction loads. This will reduce the additional loads imposed to the existing structural elements as discussed before. The slip load values of the friction wall dampers are considered to be the key design variables as they have a dominant effect on controlling the seismic response of the system in the nonlinear response range. In the proposed approach, the slip loads of the friction devices are redistributed using an iterative method until all inter-storey drifts reach the target values. It should be mentioned that a similar optimisation concept was previously used by other researchers for optimum seismic design of different types of structural systems such as RC frames (Hajirasouliha *et al.* 2012), shear-buildings (Moghaddam and Hajirasouliha 2008; Ganjavi *et al.* 2016), truss-like structures (Hajirasouliha *et al.* 2011), and viscous dampers (Levy and Lavan 2006). However, this is the first time that the proposed performance-based optimisation method is adopted for seismic design of friction dampers to obtain the best height-wise distribution of the slip loads.

Current performance-based seismic design guidelines such as ASCE-41-17 (2017) and EC8 impose limits on acceptable values of different response parameters (e.g., maximum inter-storey drift, plastic hinge rotation or axial compression stress) to achieve a specific performance level. In general, performance-based seismic design guidelines aim to simultaneously control the structural and non-structural damage during an earthquake event. Structural damage measures are usually considered to be related to maximum and residual inter-storey drifts as well as maximum inelastic deformations in the structural elements. On the other hand, non-structural damage measures are mainly related to performance parameters such as maximum inter-storey drifts and floor accelerations (Karavasilis and Seo 2011). In EC8, the inter-storey drifts are also limited by the displacement ductility capacity, or indirectly, by the curvature ductility capacity of the structural elements, in accordance with the ductility class of the structure.

In this study, maximum inter-storey drift is considered as the performance criterion to assess the efficiency of friction wall dampers in controlling the damage to structural and non-structural elements under earthquake excitations.

Maximum inter-storey drift limits of 1%, 2% and 4% are considered for Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) performance levels, respectively. In the following sections, a practical performance-based optimisation method is developed for optimum seismic design of RC frames with friction wall dampers based on the concept of UDD.

4.1 Single-criteria performance-based optimisation method

As discussed above, in general, increasing the slip loads in the friction wall dampers can reduce the maximum displacement demands during strong earthquakes. However, this may be accompanied by an increase in the based shear and loads imposed to the existing structural elements. This highlights the need for efficient optimum design methods for friction wall dampers that can satisfy the prescribed performance deformation and loading targets under the design earthquake. To this end, the following optimisation algorithm is adopted in this study:

1) A pre-defined slip load distribution is assumed for the initial design of the friction wall dampers. In this study the slip load distribution obtained from Eq. (2) is used as proposed by Nabid *et al.* (2017). It should be mentioned that the final optimum design solution is independent of the initial slip load distribution as will be discussed in the following section.

2) The RC structure with the designed friction dampers is then subjected to the selected design earthquake and the maximum inter-storey drift at each storey is calculated and compared with the target value. The structure can be considered to be practically optimum if all the inter-storey drifts are close to the performance target within an acceptable tolerance. Otherwise, the design algorithm is continued. It should be noted that three dimensional models can be used at this stage to include the effects of adjacent frames and torsional irregularity of the building.

3) To satisfy the performance-based design objective, the friction loads in the storeys with inter-storey drift higher than the predefined performance target should be increased. On the other hand, in the storeys with inter-storey drift less than the target value, the slip loads (and hence the additional imposed loads) can be reduced. To achieve this, the following equation is proposed to obtain a more efficient distribution of slip loads

$$\left(F_{s,i}\right)_{n+1} = \left(F_{s,i}\right)_n \times \left(\frac{\Delta_i}{\Delta_{target}}\right)_n^{\alpha} \tag{3}$$

where Δ_i and Δ_{target} are maximum and target inter-storey drifts of i^{th} storey for n^{th} iteration, respectively. α is the convergence parameter ranging from 0 to 1. Using the proposed equation, the slip load is increased in the storeys where the inter-storey drift exceeded the predefined performance target, and reduced in the storeys with inter-storey drifts below the target value. It will be shown in the following sections that the convergence parameter has a significant effect on the convergence rate of the problem, while it does not affect the final design solution. The results of this study show that α factor of 0.5 always leads to reliable convergence behaviour for the studied frames.

4) The design procedure is then repeated from step 2 until the coefficient of variation of the inter-storey drifts (COV_Δ) decreases to an acceptable level (e.g., less than 0.1). Based on the concept of uniform distribution of displacement demands, the structure at this stage is expected to satisfy the design performance target by using minimum amount of total slip loads. This can minimise the adverse effects of using wall dampers on the foundation and the existing structural elements as discussed before. It should be noted that some of the storey levels in the bare frame usually can satisfy the performance target even without using friction wall dampers; and therefore, it is very unlikely to reach a very uniform inter-storey drift distribution in practical applications.

To ensure that the added axial force demands due to the application of friction wall dampers are within the load bearing capacity of the columns, the moment-axial load

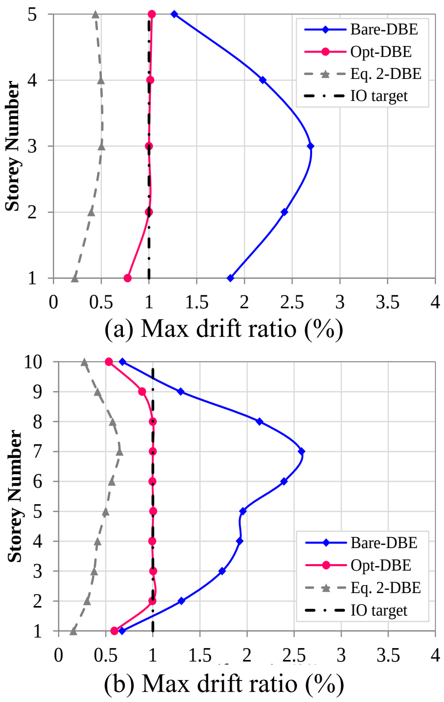


Fig. 4 Maximum drift ratios for (a) 5-storey and (b) 10-storey frames without friction walls (bare frame), with optimised friction walls and those designed based on Eq. (2), DBE event

interaction curves of the column sections were also investigated in the final design solution. Although friction wall dampers impose additional axial loads to the adjacent columns, the results indicated that by using the proposed design method the axial loads generally remain within the capacity of the column sections. Current performance-based design guidelines (such as ASCE/SEI 41-17 2017) usually aim to limit the structural and non-structural damage of ordinary buildings to the LS and CP performance levels during DBE and MCE events, respectively. However, for essential and safety critical facilities (e.g., hospitals) higher performance targets should be satisfied. In this section, the proposed optimisation algorithm is used to obtain the optimum slip load distributions in the 5 and 10-storey frames to satisfy IO performance target under the synthetic earthquake representing the DBE event (see Fig. 2). In this study, 1% target drift ratio (ratio of the storey drift to the storey height) is considered as the IO performance level.

Figs. 4(a) and (b) illustrate the average distribution of the maximum inter-storey drift ratios for the 5 and 10-storey frames, respectively, without friction walls (i.e., bare frame), with friction walls designed based on Eq. (2) and those optimised using the proposed optimisation method. It is shown that the proposed optimisation method could efficiently satisfy the predefined performance target while led to a uniform distribution of maximum inter-storey drifts, which in turn prevents damage localisation and soft storey failure mechanism. Using Eq. (2) for designing the friction wall dampers provided very conservative design solutions with maximum inter-storey drift ratios well below the target value.

Fig. 5 compares average of slip load distributions (scaled to the average of storey strengths), column axial load and base shear ratios (scaled to the corresponding bare frame), and the energy dissipation parameters (*Rw*) for the 5 and 10-storey frames with optimised friction walls and those designed based on Eq. (2). The results indicate that the wall dampers designed based on Eq. (2) could dissipate significantly higher energy levels compared to the

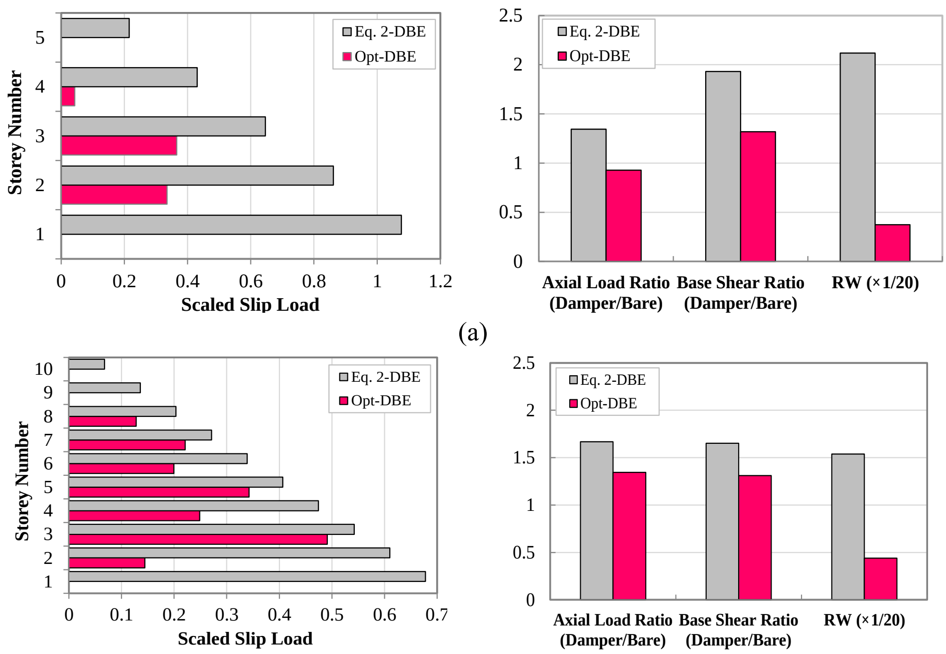
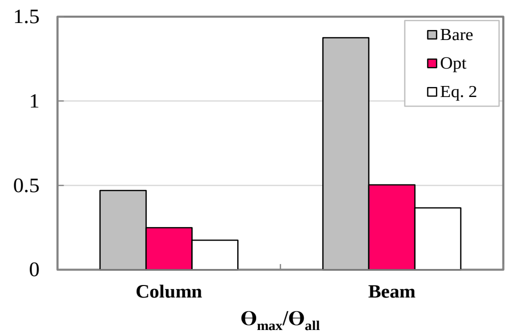
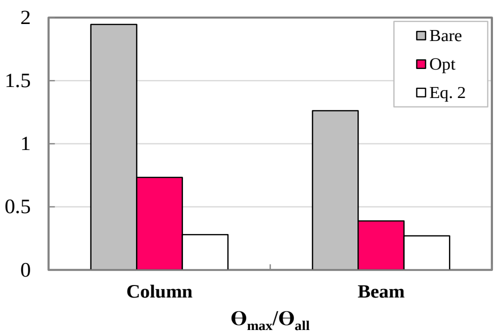


Fig. 5 Slip load, column axial load and base shear ratios for (a) 5-storey and (b) 10-storey frames with optimised friction walls and those designed based on Eq. (2), DBE event



(a)



(b)

Fig. 6 Plastic rotation ratio (maximum to allowable plastic rotation) of the beam and column elements for (a) 5-storey and (b) 10-storey frames without friction wall, with optimised friction walls and those designed based on Eq. (2), DBE event

optimised dampers (see Fig. 5), which is in agreement with the results reported by Nabid *et al*. (2017). However, this is accompanied by imposing considerably higher column axial loads and base shear demands (up to 32%) to the structures compared to the optimum design solutions due to using higher slip load values. This implies that the proposed performance-based optimisation methodology fulfils the desired performance objective with the minimum additional imposed loads to the main structure, while it can also reduce the strengthening cost by removing unnecessary friction wall dampers (with zero slip load values).

It should be noted that by reducing the maximum inter-storey drifts, the local performance parameters such as maximum plastic rotations are also expected to be reduced. This implies that the proposed optimisation algorithm can simultaneously improve both local and global performance parameters. Fig. 6 compares the plastic rotation ratio (maximum to allowable plastic rotation in accordance of ASCE-41-17 (2017)) of the beam and column elements for 5-storey and 10-storey frames without friction wall, with optimised friction walls and those designed based on Eq. (2) under DBE event. Based on the results, the structural elements of the bare frames do not fulfil the ASCE-41-17 performance design criteria, as their maximum plastic rotations exceed their corresponding allowable limit.

However, by using the proposed algorithm, all the beam and column elements could efficiently satisfy the allowable limits. It is also shown that using the empirical equation always leads to more conservative design solutions compared to the optimum designed frames, which is in complete agreement with the previous results

4.2 Multi-criteria performance-based optimisation method

In this section, the proposed optimum design method is extended to achieve an optimum slip load distribution pattern that satisfies multiple performance objectives. To this end, Eq. (3) in the proposed optimisation algorithm is substituted with the following equations

$$\left(F_{s,i}\right)_{n+1} = \left(F_{s,i}\right)_n \times [\Delta R_i]^{\alpha} \tag{4}$$

$$\Delta R_i = Max\left[\frac{(\Delta_i)_1}{(\Delta_{target})_1}, \frac{(\Delta_i)_2}{(\Delta_{target})_2}, ..., \frac{(\Delta_i)_j}{(\Delta_{target})_j}\right] \tag{5}$$

where $(\Delta_i)_j$ and $(\Delta_{target})_j$ are the maximum and target inter-storey drifts of the i^{th} storey for j^{th} performance objective, respectively. Eq. (5) is used to identify the performance objective that governs the design at each storey level. By using ΔR parameter in Eq. (4), multiple performance targets under representative design earthquakes with different probability of occurrence are simultaneously used to obtain the best overall optimum design solution. While a similar concept has been previously adopted by Hajirasouliha *et al*. (2012) and Lavan and Wilkinson (2017) for seismic design of regular and irregular RC frames, respectively, this is the first time that it is used for multi-criteria performance-based optimisation of passive control systems.

To demonstrate the efficiency of the multi-criteria performance-based optimisation algorithm, the 3, 5, 10, 15 and 20-storey RC frames with friction wall dampers were optimised to simultaneously satisfy IO and LS performance limits under DBE and MCE representative spectrum compatible earthquakes, respectively. Figs. 7(a) and (b) show the distributions of the maximum inter-storey drift ratios and slip load ratios for 3, 5, 10, 15 and 20-storey frames without friction walls (bare frames) and with friction wall dampers designed based on Eq. (2) and the proposed optimum design methodology. The results generally show that while the bare frames clearly violated the performance targets with the damage localised in certain storey levels under the design earthquakes, the optimum solutions could efficiently satisfy the required performance levels with rather more uniform inter-storey drift distributions. As illustrated in Fig. 7(b), in the case optimum slip load distributions, the slip load values in certain storeys (here mainly at lower and upper storey levels) tend to zero, and consequently, the corresponded supplemental devices can be removed from the structure, which in turn leads to more cost-effective design of friction wall dampers.

The results shown in Fig. 7 indicate that using the slip load values from Eq. (2) generally leads to acceptable design solutions; however, the lateral inter-storey drifts may be considerably less than the performance targets. As discussed before, this can impose unnecessary additional column axial loads and base shear demands. To quantify this effect, Table 2 compares the axial load and base shear ratios of 3, 5, 10, 15 and 20-storey frames designed using fixed wall (i.e., very high slip load values), optimised

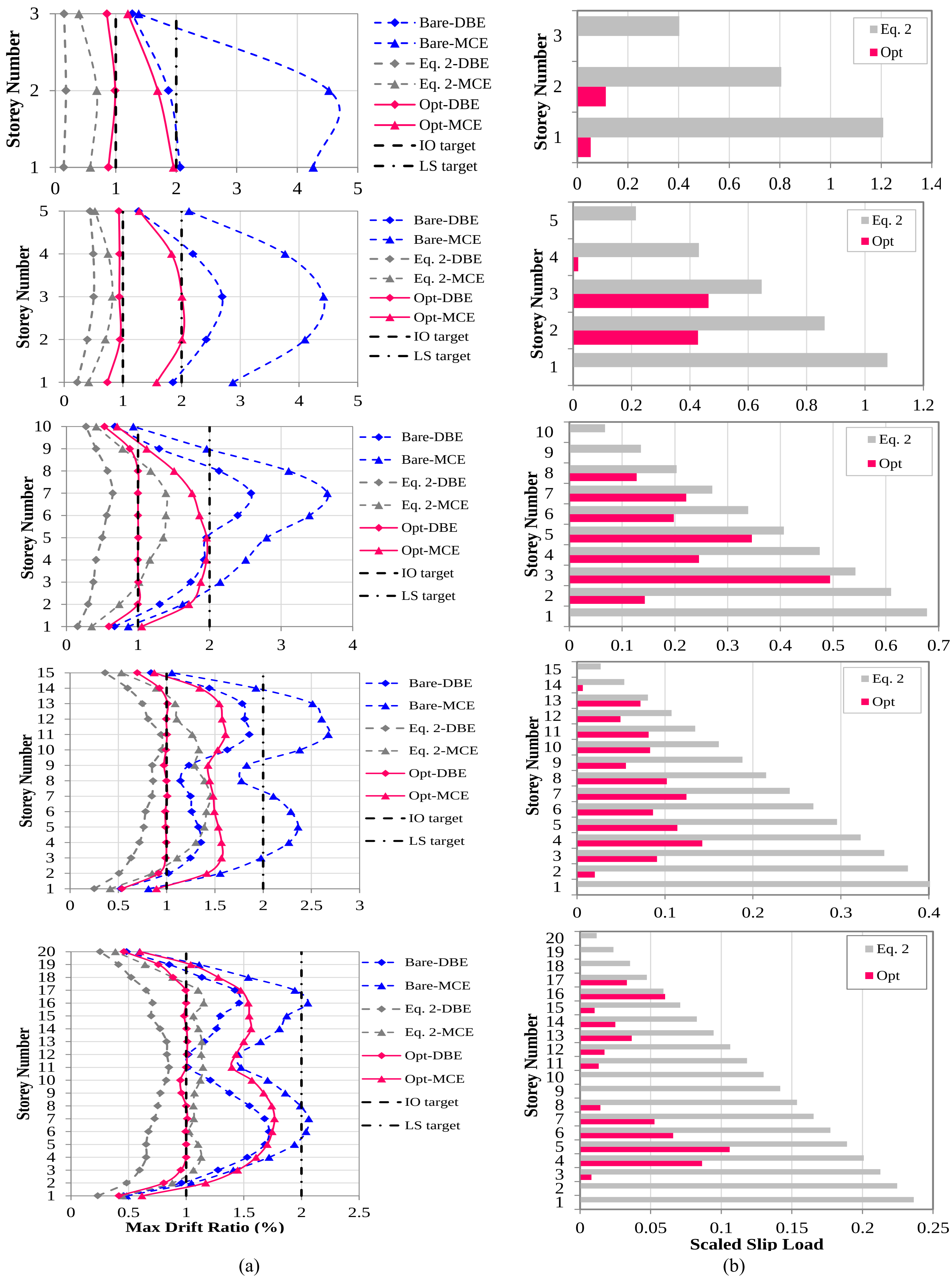


Fig. 7(a) Maximum drift ratios and (b) Slip load ratios for 3, 5, 10, 15 and 20-storey frames without wall and with optimised friction walls and those designed based on Eq. (2), DBE and MCE events

Table 2 Comparison of maximum $N_e/A_cf'_c$ and base shear ratio (scaled to the corresponding bare frame) for 3, 5, 10, 15 and 20-storey frames designed with fixed walls, optimised friction walls and those designed based on Eq. (2), DBE and MCE events

		3-Storey		5-Storey		10-Storey		15-Storey		20-Storey	
		$\frac{N_e}{A_cf'_c}$	Base Shear	$\frac{N_e}{A_cf'_c}$	Base Shear	$\frac{N_e}{A_cf'_c}$	Base Shear	$\frac{N_e}{A_cf'_c}$	Base Shear	$\frac{N_e}{A_cf'_c}$	Base Shear
Fixed Wall	DBE	0.40	4.74	0.48	4.15	0.67	3.25	0.87	2.65	0.90	3.41
	MCE	0.46	5.88	0.58	5.46	0.71	3.72	1.04	3.25	1.02	3.63
Equation 2	DBE	0.18	1.859	0.25	1.930	0.38	1.653	0.48	1.404	0.45	1.316
	MCE	0.18	2.300	0.25	2.100	0.38	1.840	0.49	1.547	0.45	1.443
Optimum	DBE	0.11	1.024	0.16	1.310	0.30	1.309	0.35	1.063	0.32	1.109
	MCE	0.15	1.190	0.21	1.179	0.31	1.252	0.35	1.077	0.32	1.120
Reduction (%)	DBE	36.8	44.9	34.0	32.1	19.4	20.8	28.2	24.2	29.7	15.8
	MCE	17.0	48.2	16.7	43.9	20.1	32.0	29.4	30.4	29.2	22.4

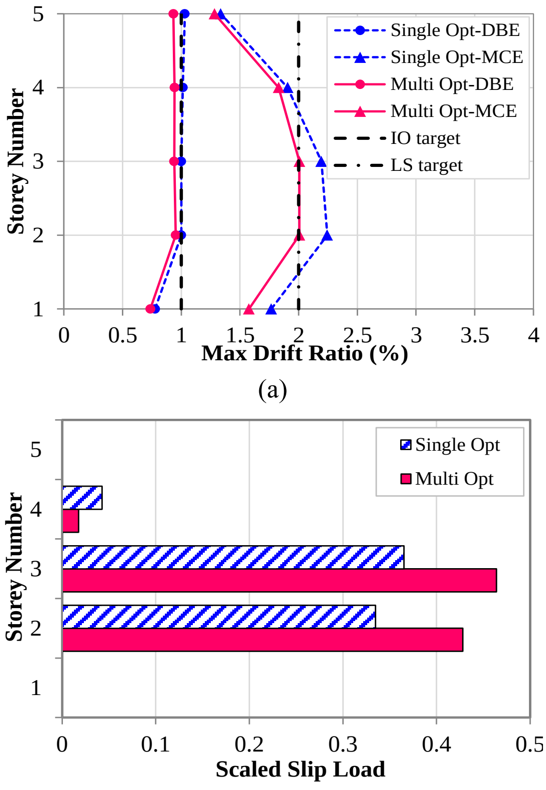


Fig. 8 Distribution of (a) maximum drift ratios, and (b) optimum slip load ratios for 5-storey frames optimised based on single-criteria and multi-criteria optimisation algorithms, DBE and MCE events

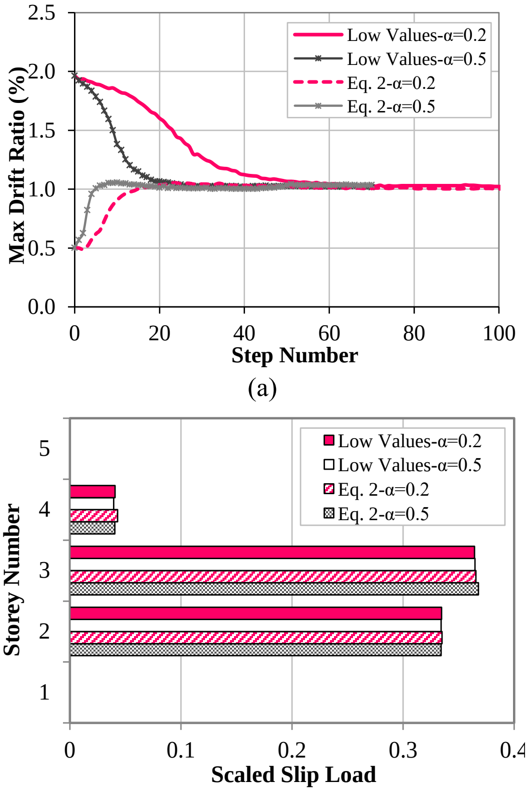


Fig. 9(a) Variation of maximum inter-storey drifts versus iteration steps and (b) distributions of optimum slip loads for 5-storey frames initially designed based on Eq. (2) and very low slip load values at all storey levels, DBE event

friction walls and those designed using Eq. (2) under representative DBE and MCE events. According to the results, using fixed walls leads to excessive column axial load values, and hence, exceeding the DCM ductility class in medium to high-rise frames under both DBE and MCE events. Although, using Eq. (2) resulted in acceptable design solutions, optimum designed wall dampers could reduce the maximum $N_e/A_cf'_c$ and base shear ratio of the studied frames by up to 37% and 48%, respectively. This is in agreement with the results presented in section 4.1.

Fig. 8 compares the distributions of the maximum inter-storey drifts and optimum slip load ratios for the 5-storey frames optimised to satisfy IO performance limit under DBE events (single-criteria optimisation) and the frames optimised to simultaneously satisfy IO and LS performance levels under DBE and MCE events, respectively (multi-criteria optimisation). It is shown that the frames optimised only based on DBE events, did not satisfy the required performance level under MCE events. However, by performing the multi-criteria optimisation, both IO and LS performance targets were satisfied while the total required friction force was increased by 18%.

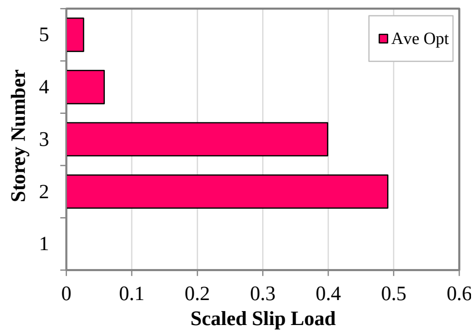
5. Sensitivity of the optimisation method to the initial design and convergence parameter

In previous sections, the slip load values calculated based on Eq. (2) (uniform cumulative distribution) were used for the initial design of the friction wall dampers in the optimisation process. To investigate the effect of the predefined initial slip loads on the final optimum design solution, the optimisation process was also started with the dampers designed based on a uniform distribution of slip loads with very small slip load values (5 kN) at all storey levels. Fig. 9(a) compares the variation of maximum inter-storey drifts versus iteration steps for the 5-storey frames designed with the two selected slip load distributions under the DBE event. While the maximum drift ratios of the initial structures were considerably different, they both converged to the target value (i.e., IO performance limit) at the end of the optimisation process. However, a faster Fig. 9 also shows the effects of using convergence parameters α=0.2 and 0.5 on the convergence rate and the final distribution of slip loads. It can be observed that while the both selected α values can efficiently converge to the same optimum design solution; in general, faster convergence was achieved by using α values of 0.5. Previous studies showed that UDD optimisation methods generally lead to the answers that are close to the global optimum solutions when appropriate values are used for the convergence parameter α (Mohammadi *et al*. 2018).

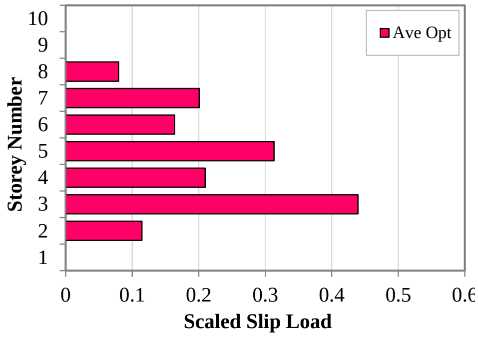
In general, there is also an uncertainty in the slip load values of friction-based devices mainly as a result of inherent creep in sliding interface materials, and wear in the sliding interface due to substantial motions (Constantinou *et al*. 2007). While this uncertainties can be considerably reduced by using appropriate composition of the sliding interface (Housner *et al*. 1997, Symans *et al*. 2008) they should be considered in the seismic design of friction-based devices. However, previous studies on RC frames with friction wall dampers indicated that there is always an optimum range of slip load ratios for the proposed friction wall dampers, and therefore, the optimum design solution is not very sensitive to the small variations of friction forces (Nabid *et al*. 2017, 2019b). On the other hand, some of the above mentioned losses may be addressed by adjusting the clamping forces in the friction dampers after a period of time.

6. Optimum seismic design for an ensemble of earthquakes

While the seismic excitation is the main source of uncertainty in the seismic design of structures, there is a concern that this may affect the efficiency of the optimum structures designed based on a single earthquake event. One of the most important limitations of the adaptive method is the sensitivity of the optimal frame to the selected design ground motion. Therefore, the optimum design solution under a specific earthquake may not be optimum for a different design earthquake. Previous studies by Hajirasouliha and Pilakoutas (2012) on shear type buildings showed that, to overcome this limitation, a set of synthetic spectrum-compatible earthquakes can be used in the optimisation process. In this section, the efficiency of their proposed design concept is investigated for optimum design of RC structures with friction wall dampers subjected to an ensemble of EC8 spectrum-compatible natural earthquakes.



(a)

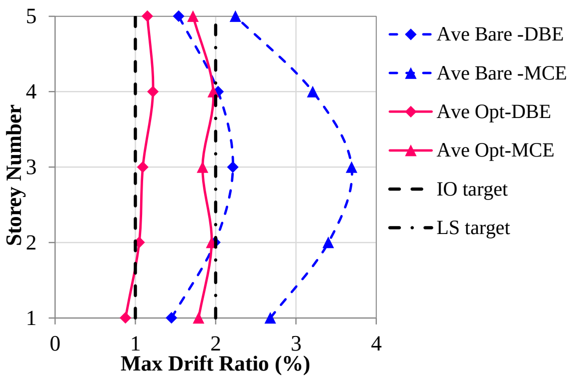


(b)

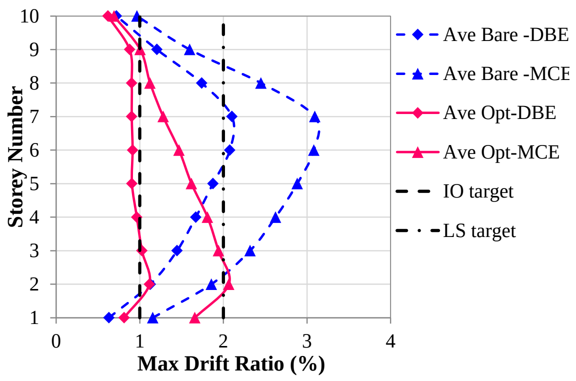
Fig. 10 Average optimum slip load values for (a) 5-storey and (b) 10-storey frames, Average of six synthetic DBE and MCE events

The 5- and 10-storey frames were optimised for IO and LS performance objectives under the six spectrum-compatible synthetic DBE and MCE events. The average of the optimum slip load values was then used to design the frames (see Fig. 10) and their seismic performance was assessed under the twelve natural earthquakes listed in Table 1. As discussed in section 2.2, the average response spectrum of these natural earthquake records compares well with the selected EC8 DBE. Similar to the simulated earthquakes, a scale factor of 1.5 was used to obtain MCE natural events used in this section. Fig. 11 compares the average height-wise distribution of the maximum drift ratios for the frames without friction walls (bare frames) and those with optimised friction walls subjected to the selected natural earthquakes. Based on the results, the optimum design frames, on average, could satisfy the target performance levels under both DBE and MCE events with a very good accuracy (less than 5% error on average). It can be also noted that the optimum design frames exhibited significantly lower maximum drift ratios (up to 51%) and a relatively more uniform distribution of maximum drift ratios compared to the corresponding bare frames.

The proposed approach is general and can be used for any set of earthquake records representing a design spectrum. Considering the low computational costs and simplicity of the proposed performance-based optimisation method, the results of this study should prove useful in



(a)



(b)

Fig. 11 Maximum drift ratios of (a) 5-storey and (b) 10-storey frames with optimised friction walls obtained for six synthetic DBE and MCE events, Average of twelve natural DBE and MCE events

practical design of RC frames with friction-based dampers. However, the efficiency of the method should be further investigated for other structural systems and types of dampers.

7. Conclusions

In this paper is presented a computationally efficient (low computational cost) multi-criteria optimisation method developed for performance-based seismic design of RC frames with friction wall dampers. The method is based on the concept of Uniform Distribution of Deformation (UDD), in which the height-wise distribution of slip loads is modified until multiple predefined performance objectives are simultaneously satisfied with minimum additional imposed loads to the base structure. The efficiency of the proposed optimisation method was demonstrated through the optimum design of 3, 5, 10, 15, and 20-storey RC frames with friction wall dampers subjected to DBE and MCE representative spectrum-compatible earthquakes using single- and multi-criteria optimisation scenarios. According to the results, the following conclusions can be drawn:

• Using the slip load range suggested by Nabid *et al.* (2017) could efficiently increase the energy dissipation capacity of friction wall dampers under a set of twelve natural spectrum-compatible earthquakes. However, it was shown that the designed dampers may lead to excessive base shear and column axial load values.

• The proposed multi-criteria optimisation method was shown to be efficient to satisfy multiple performance objectives under DBE and MCE representative earthquakes, leading to rather uniform distribution of lateral deformations. Compared to the dampers designed to have maximum energy dissipation capacity, the proposed optimisation method resulted in design solutions with less number of required dampers and up to 37% and 48% lower column axial load and base shear demand, respectively.

• Based on the results, the proposed low computational-cost method generally leads to optimum design solutions in only a few steps. It was shown that the final optimum solution is independent of the selected initial slip loads and convergence parameter; however, a considerably faster convergence can be achieved by using an appropriate convergence parameter and slip load distribution pattern as the starting point.

• The uncertainty in the design earthquake excitation was taken into account by optimising the frames based on the average of a set of synthetic spectrum-compatible earthquakes. The results indicated that the optimised frames could satisfy the performance targets under multiple natural seismic excitations representing DBE and MCE design spectra, while exhibited significantly lower maximum drift ratios (up to 51%) compared to their bare frame counterparts.

References

Adachi, F., Yoshitomi, S., Tsuji, M. and Takewaki, I. (2013), "Nonlinear optimal oil damper design in seismically controlled multi-story building frame", *Soil Dyn. Earthq. Eng.*, **44**, 1-13. https://doi.org/10.1016/j.soildyn.2012.08.010.

Agrawal, A.K. and Yang, J.N. (1999), "Design of passive energy dissipation systems based on LQR control methods", *J. Intel. Mater. Syst. Struct.*, **10**(12), 933-944. https://doi.org/10.1106%2FFB58-N1DG-ECJT-B8H4.

Aiken, I. (1996), "Passive energy dissipation - hardware and applications", *Proc., Los Angeles County and SEAOSC Symposium on Passive Energy Dissipation Systems for New and Existing Buildings*, California, U.S.A.

Apostolakis, G. and Dargush, G.F. (2010), "Optimal seismic design of moment-resisting steel frames with hysteretic passive devices", *Earthq. Eng. Sturct. Dyn.*, **39**(4), 355-376. https://doi.org/10.1002/eqe.944.

ASCE/SEI 7-16 (2016), Minimum Design Loads for Buildings and Other Structures, Am. Soc. Civil Eng., Virginia, U.S.A.

ASCE/SEI Standard 41-17 (2017), Seismic Rehabilitation of Existing Buildings, Am. Soc. Civil Eng., Virginia, U.S.A.

ATC-58-1 (2008), Guidelines for Seismic Performance Assessment of Buildings, 50% Draft, Applied Technology Council, Washington D.C, U.S.A.

British Standards Institution (1990), Steel, Concrete and Composite Bridges. Part 9. Bridge Bearings, Section 9.1 Code of Practice for Design of Bridge Bearings, BS5400, Section 9.1:1983, London, U.K.

CEN (Comité Européen de Normalization) (2004a), Eurocode 8: Design of Structures for Earthquake Resistance-Part 1: General

Rules, Seismic Actions and Rules for Buildings, EN 1998-1-1, Brussels, Belgium.

CEN (Comité Européen de Normalization) (2004b), Eurocode 2: Design of Concrete Structures -Part 1-1: General Rules and Rules for buildings, EN 1992-1-2, Brussels, Belgium.

Cho, C.G. and Kwon, M. (2004), "Development and modelling of a frictional wall damper and its applications in reinforced concrete frame structures", *Earthq. Eng. Struct. Dyn.*, **33**(7), 821-838. nhttps://doi.org/10.1002/eqe.379.

Constantinou, M.C., Whittaker, A.S., Kalpakidis, Y., Fenz, D.M. and Warn, G.P. (2007), "Performance of seismic isolation hardware under service and seismic loading", Report No. MCEER-07-0012, Multidisciplinary Center for Earthquake Engineering Research, N.Y., U.S.A.

Daniel, Y., Lavan, O. and Levy, R. (2013), "A simple methodology for the seismic passive control of irregular 3D frames using friction dampers", *Seismic Behav. Des. Irreg. Compl. Civil Struct.*, **24**, 285-295. https://doi.org/10.1007/978-94-007-5377-8_19.

Filiatrault, A. and Cherry, S. (1990), "Seismic design spectra for friction-damped structures", *J. Struct. Eng.*, **116**(5), 1334-1355. https://doi.org/10.1061/(ASCE)0733-9445(1990)116:5(1334).

Fujita, K., Moustafa, A. and Takewaki, I. (2010), "Optimal placement of viscoelastic dampers and supporting members under variable critical excitations", *Earthq. Struct.*, **1**(1), 43-67.

Ganjavi, B., Hajirasouliha, I. and Bolourchi, A. (2016), "Optimum lateral load distribution for seismic design of nonlinear shear-buildings considering soil-structure interaction", *Soil Dyn. Earthq. Eng.*, **88**, 356-368. https://doi.org/10.1016/j.soildyn.2016.07.003.

Gidaris, I. and Taflanidis, A.A. (2015), "Performance assessment and optimization of fluid viscous dampers through life-cycle cost criteria and comparison to alternative design approaches", *Bull. Earthq. Eng.*, **13**(4), 1003-1028. https://doi.org/10.1007/s10518-014-9646-5.

Gidaris, I., Taflanidis, A.A. and Mavroeidis, G.P. (2018), "Multiobjective design of supplemental seismic protective devices utilizing lifecycle performance criteria", *J. Struct. Eng.*, **144**(3), 040147225. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001969.

Gluck, N., Reinhorn, A.M., Gluck, J. and Levy, R. (1996), "Design of supplemental dampers for control of structures", *J. Struct. Eng.*, **122**(12), 1394-1399. https://doi.org/10.1061/(ASCE)0733-9445(1996)122:12(1394).

Guo, J.W.W. and Christopoulos, C. (2013), "Performance spectrabased method for the seismic design of structures equipped with passive supplemental damping systems", *Earthq. Eng. Struct. Dyn.*, **42**(6), 935-952. https://doi.org/10.1002/eqe.2261.

Hajirasouliha, I. and Doostan, A. (2010), "A simplified model for seismic response prediction of concentrically braced frames", *Adv. Eng. Softw.*, **41**(3), 497-505. https://doi.org/10.1016/j.advengsoft.2009.10.008.

Hajirasouliha, I. and Pilakoutas, K. (2012), "General seismic load distribution for optimum performance-based design of shear-buildings", *J. Earthq. Eng.*, **16**(4), 443-462. https://doi.org/10.1080/13632469.2012.654897.

Hajirasouliha, I., Asadi, P. and Pilakoutas, K. (2012), "An efficient performance-based seismic design method for reinforced concrete frames", *Earthq. Eng. Struct. Dyn.*, **41**(4), 663-679. https://doi.org/10.1002/eqe.1150.

Hajirasouliha, I., Pilakoutas, K. and Moghaddam, H. (2011), "Topology optimization for the seismic design of truss-like structures", *Comput. Struct.*, **89**(7-8), 702-711. https://doi.org/10.1016/j.compstruc.2011.02.003.

Hall, J.F. (2006), "Problems encountered from the use (or misuse) of Rayleigh damping", *Earthq. Eng. Struct. Dyn.*, **35**(5), 525-545. https://doi.org/10.1002/eqe.541.

Hejazi, F., Toloue, I., Jaafar, M.S. and Noorzaei, J. (2013), "Optimization of earthquake energy dissipation system by genetic algorithm", *Comput. Aid. Civil Infr. Eng.*, **28**(10), 796-810. https://doi.org/10.1111/mice.12047.

Karavasilis, T.L. and Seo, C.Y. (2011), "Seismic structural and non-structural performance evaluation of highly damped self-centering and conventional systems", *Eng. Struct.*, **33**(8), 2248-2258. https://doi.org/10.1016/j.engstruct.2011.04.001.

Kasagi, M., Fujita, K., Tsuji, M. and Takewaki, I. (2016), "Effect of non-linearity of connecting dampers on vibration control of connected building structures", *Front. Built Environ.*, **1**, 25. https://doi.org/10.3389/fbuil.2015.00025.

Kasai, K., Fu, Y. and Watanabe, A. (1998), "Passive control systems for seismic damage mitigation", *J. Struct. Eng.*, **124**(5), 501-512. https://doi.org/10.1061/(ASCE)0733-9445(1998)124:5(501).

Kasai, K., Nishijima, M., Tanaka, K., Wang, S. and Mahin, S. (2018), "Simplified design method for frames with nonlinear viscous dampers", *Proceedings of the 11th U.S. National Conference on Earthquake Engineering*, California, U.S.A. June.

Kim, J. and Choi, H. (2006), "Displacement-based design of supplemental dampers for seismic retrofit of a framed structure", *J. Struct. Eng.*, **132**(6), 873-883. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:6(873).

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. https://doi.org/10.1002/eqe.2399.

Lavan, O. and Dargush, G.F. (2009), "Multi-objective evolutionary seismic design with passive energy dissipation systems", *J. Earthq. Eng.* **13**(6), 758-790. https://doi.org/10.1080/13632460802598545.

Lavan, O. and Levy, R. (2010), "Performance based optimal seismic retrofitting of yielding plane frames using added viscous damping", *Earthq. Struct.*, **1**(3), 307-326. https://doi.org/10.12989/eas.2010.1.3.307.

Lavan, O. and Wilkinson, P.J. (2017), "Efficient Seismic Design of 3D asymmetric and Setback RC frame buildings for drift and strain limitation", *J. Struct. Eng.*, **143**(4), 04016205. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001689.

Levy, R. and Lavan, O. (2006), "Fully stressed design of passive controllers in framed structures for seismic loadings", *Struct. Multidiscip. Optim.*, **32**(6), 485-498. https://doi.org/10.1007/s00158-005-0558-5.

Liu, W., Tong, M. and Lee, G.C. (2005), "Optimization methodology for damper configuration based on building performance indices", *J. Struct. Eng.*, **131**(11), 1746-1756. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:11(1746).

Lu, Y., Hajirasouliha, I. and Marshall, A.M. (2016), "Performance-based seismic design of flexible-base multi-story buildings considering soil–structure interaction", *Eng. Struct.*, **108**, 90-103. https://doi.org/10.1016/j.engstruct.2015.11.031.

MATLAB and Statistics Toolbox Release (2014), The Math Works, Natick, Massachusetts, USA.

McKenna, F. (1997), "Object-oriented finite element programming: Frame-works for analysis, algorithms and parallel computing", Ph.D. Dissertation, University of California, Berkeley, California, U.S.A.

McKenna, F. (2017), *Open System for Earthquake Engineering Simulation*, PEER.

McKenna, F., Fenves, G.L. and Scott, M.H. (2000), "Open system for earthquake engineering simulation", University of California, Berkeley, California. http://opensees.berkeley. Edu.

Miguel, L.F.F., Miguel, L.F.F. and Lopez, R.H. (2014), "Robust design optimization of friction dampers for structural response control", *Struct. Control Hlth. Monit.*, **21**(9), 1240-1251.

https://doi.org/10.1002/stc.1642.

Miguel, L.F.F., Miguel, L.F.F. and Lopez, R.H. (2016), "Simultaneous optimization of force and placement of friction dampers under seismic loading", *Eng. Optim.*, **48**(4), 586-602. https://doi.org/10.1080/0305215X.2015.1025774.

Milman, M.H. and Chu, C.C. (1994), "Optimization methods for passive damper placement and tuning", *J. Guid. Control Dyn.*, **17**(4), 848-856. https://doi.org/10.2514/3.21275.

Moghaddam, H. and Hajirasouliha, I. (2008), "Optimum strength distribution for seismic design", *Struct. Des. Tall Spec Build.*, **17**(2), 331-349. https://doi.org/10.1002/tal.356.

Mohammadi, R.K. Mirjalaly, M., Mirtaheri, M. and Nazeryan, M. (2018), "Comparison between uniform deformation method and genetic algorithm for optimising mechanical properties of dampers", *Earthq. Struct.*, **1**(14), 1-10. https://doi.org/10.12989/eas.2018.14.1.001.

Moreschi, L.M. and Singh, M.P. (2003), "Design of yielding metallic and friction dampers for optimal seismic performance", *Earthq. Eng. Struct. Dyn.*, **32**(8), 1291-1311. https://doi.org/10.1002/eqe.275.

Murakami, Y., Noshi, K., Fujita, K., Tsuji, M. and Takewaki, I. (2013), "Simultaneous optimal damper placement using oil, hysteretic and inertial mass dampers", *Earthq. Struct.*, **5**(3), 261-276. https://doi.org/10.12989/eas.2013.5.3.261.

Nabid, N., Hajirasouliha, I. and Petkovski, M. (2017), "A practical method for optimum seismic design of friction wall dampers", *Earthq. Spectra*, **33**(3), 1033-1052. https://doi.org/10.1193%2F110316eqs190m.

Nabid, N., Hajirasouliha, I. and Petkovski, M. (2018), "Performance-based optimisation of RC frames with friction wall dampers using a low-cost optimisation method", *Bull. Earthq. Eng.*, **16**(10), 5017-5040. https://doi.org/10.1007/s10518-018-0380-2.

Nabid, N., Hajirasouliha, I. and Petkovski, M. (2019a), "Adaptive low computational cost optimisation method for performance-based seismic design of friction dampers", *Eng. Struct.*, **198**, 109549. https://doi.org/10.1016/j.engstruct.2019.109549.

Nabid, N., Hajirasouliha, I. and Petkovski, M. (2019b), "Simplified method for optimal design of friction damper slip loads by considering near-field and far-field ground motions", *J. Earthq. Eng.* **2019**, 1-25. https://doi.org/10.1080/13632469.2019.1605316.

Neuenhofer, A. and Filippou, F.C. (1997), "Evaluation of nonlinear frame finite-element models", *J. Struct Eng.*, **123**(7), 958-966. https://doi.org/10.1061/(ASCE)0733-9445(1997)123:7(958).

Papageorgiou, A., Halldorsson, B. and Dong, G. (2002), "TARSCTH (Target Acceleration Spectra Compatible Time Histories)", Engineering Seismology Laboratory, New York, U.S.A.

Park, J.H., Kim, J. and Min, K.W. (2004), "Optimal design of added viscoelastic dampers and supporting braces", *Eng. Struct. Dyn.*, **33**(4), 465-484. https://doi.org/10.1002/eqe.359.

PEER NGA, Online Database. Available from: http://peer.berkeley.edu/nga/search.html.

Petkovski, M. and Waldron, P. (2003), "Optimum friction forces for passive control of the seismic response of multi-storey buildings", *Proceedings of the 40 years of European Earthquake Engineering SE40EEE*, Ohrid, Macedonia, August.

Saitua, F., Lopez-Garcia, D. and Taflanidis, A.A. (2018), "Optimization of height-wise damper distributions considering practical design issues", *Eng. Struct.*, **173**, 768-786. https://doi.org/10.1016/j.engstruct.2018.04.008.

Sasani, M. and Popov, E.P. (1997), "Experimental and analytical studies on the seismic behavior of lightweight concrete panels with friction energy dissipators", Earthquake Engineering Research Centre, Report No. UBC/EERC-97/17, California, U.S.A.

Sasani, M. and Popov, E.P. (2001), "Seismic energy dissipators for RC panels", *J. Eng. Mech.*, **127**(8), 835-843. https://doi.org/10.1061/(ASCE)0733-9399(2001)127:8(835).

Singh, M.P. and Moreschi, L.M. (2001), "Optimal seismic response control with dampers", *Earthq. Eng. Struct. Dyn.*, **30**(4), 553-572. https://doi.org/10.1002/eqe.23.

Symans, M.D., Charney, F.A., Whittaker, A.S., Constantinou, M.C., Kircher, C.A., Johnson, M.W., and McNamara, R.J. (2008), "Energy dissipation systems for seismic applications: current practice and recent developments", *J. Struct. Eng.*, **134**(1), 3-21. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:1(3).

Takewaki, I. (2011), *Building Control with Passive Dampers: Optimal Performance-based Design for Earthquakes*, John Wiley and Sons, Singapore.

Terzic, V. (2011), "Force-based element vs. displacement-based element", Pacific Earthquake Engineering Research Centre, California, U.S.A.

Uetani, K., Tsuji, M. and Takewaki, I. (2003), "Application of an optimum design method to practical building frames with viscous dampers and hysteretic dampers", *Eng. Struct.*, **25**(5), 579-592. https://doi.org/10.1016/S0141-0296(02)00168-2.

Whittle, J.K., Williams, M.S. and Karavasilis, T.L. (2013), "Optimal placement of viscous dampers for seismic building design", *Des. Optim. Act. Pass. Struct. Control Syst.*, 34-49.

Whittle, J.K., Williams, M.S. and Karavasilis, T.L., Blakeborough, A. (2012), "A comparison of viscous damper placement methods for improving seismic building design", *J. Earthq. Eng.*, **16**(4), 540-560. https://doi.org/10.1080/13632469.2011.653864.

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