

# A Practical Design Method for Seismic Strengthening of RC Frames Using Friction-Based Passive Energy Dissipation Devices

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## ABSTRACT

In this paper, a practical design solution for more efficient design of friction-based passive control systems is suggested, by considering the selected design earthquakes. In general, the effectiveness of the friction-based supplemental dampers is limited to a narrow range of slip loads. In addition, height-wise slip load distribution pattern can notably affect the overall seismic performance of the structures controlled with friction devices. In this study, the efficiencies of five different height-wise slip load distribution patterns for friction-based passive dampers are first compared; and accordingly, a practical solution for slip load distribution is proposed. The studied system consists of a non-structural concrete panel with a friction connection at the top and three more peripheral supports to provide appropriate boundary condition for the concrete wall panel. To assess the effectiveness of the supplemental friction wall system, extensive nonlinear dynamic analyses have been conducted on 3, 5, 10, 15, and 20-storey RC frames subjected to seven real and synthetic spectrum compatible earthquakes. Subsequently, an empirical equation is suggested to design RC frames with friction wall dampers. The preliminary results show that using the proposed equation can significantly improve the seismic performance of the controlled structures.

**Keywords:** *Passive damper; Structural optimization; Non-linear analysis; Seismic performance*

## 1 INTRODUCTION

An extensive research on friction-based passive control systems to decrease earthquake-induced response of structural systems either for new building designs, or strengthening purposes approves the popularity of such systems among engineering community. In addition to brace-type friction devices, a number of wall-type friction dampers have been also proposed during the last two decades. In the brace-type control devices, there are the possibility of bracing failure under earthquake loads and also cracking or crushing of the concrete in the RC frames' connection zones due to stress concentration.

A limited number of friction-based wall-type systems has been developed so far. In 2001, Sasani and Popov [1] experimentally and analytically investigated the seismic performance of a lightweight concrete panel equipped with three friction-based energy dissipaters at the top and fixed supports at the bottom. The impact effects of the steel bolts and the corresponding expansion of the concrete holes were investigated on the hysteretic behaviour of the device. In a similar study conducted by Petkovski and Waldron [2], the efficiency of another friction-based wall system, but with different boundary condition were evaluated. Petkovski and Waldron assessed the effect of

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using their proposed system on improvement of the seismic responses of multi-storey RC frame structures by taking into account different stiffness characteristics for the frame and the concrete panel. The results of their study on three different frames under four real earthquake records confirmed that, in general, irrespective to the excitation record, there is an optimum range for slippage threshold of the friction connection so as better seismic performance is achieved. In a follow up study by Cho and Kwon [3], a new wall-type friction damper incorporating Teflon plate in the friction connection were proposed to improve the performance of the RC structures under severe earthquakes. They employed Teflon plate in contact with steel plates to ensure more efficient friction mechanism; and a pressure cell to control the clamping forces on the Teflon sliders.

It has been proved by other researchers [4, 5, 6, 7] that there are two crucial design parameters affecting the efficiency of the supplemental friction energy dissipating devices; (1) the location of the damper within the building structure and (2) the slip load of the friction device at each floor level. Filiatrault and Cherry [4] suggested a particular algorithm to obtain the optimum slip load values by minimizing an energy derivation parameter denoted as relative performance index (RPI). Moreover, they generated a general slip load spectrum for quick evaluation of the optimum slip load. Their results displayed that the frequency and amplitude of the ground motions have considerable effect on the optimum slip load values, and hence it is not a structural property. In a research performed by Patro and Sinha [6], the optimal design of friction forces with uniform distribution was carried out by considering different seismic performance indices, ground motion records and soli types.

None of the studies above has evaluated the effects of different height-wise slip load distributions on the seismic performance of the controlled structures. In most of the studies and experimental applications, uniform height-wise distribution of slip loads are assumed for simplicity, however, this may not be the most efficient design solution for all the frame structures.

In this paper, the efficiency of five different height-wise slip load distribution patterns for low- to high-rise frame structures under seven real and synthetic earthquake records are investigated; and accordingly, a straightforward practical design methodology is proposed aiming at more efficient design of friction-based passive energy dissipation devices.

## 2 REFERENCE FRAMES

Five different RC frame structures with 3, 5, 10, 15 and 20 storeys were picked to evaluate the efficiency of the proposed friction-based passive control wall system on the seismic behaviour of the structures. The typical geometries of the selected frames are shown in Fig. 1. The reference frames are nominated as the existing bare frames strengthened with the proposed friction wall systems in their middle spans in all storey levels. Each frame has six equal bays with the span length of 6m and the floor height of 3m. The gravity and lateral loads are considered based on IBC-2015 [9] in accordance with the minimum requirements of ACI 318-14 [10]. The bare frames are assumed to be located on a soil type D of the IBC-2015 site classifications.

For strengthening purposes, the bare frames are designed based on the earthquake with the peak ground acceleration (PGA) of 0.2g, which represents low-to-medium seismic hazard areas. The frame structures are then strengthened with the proposed friction wall systems and their efficiencies are evaluated under six real severe earthquakes. The selected excitation records are Cape Mendocino 1992, Duzce 1999, Superstition Hills 1987, Imperial Valley 1979, Loma Prieta 1989 and Northridge 1994. All of these earthquakes have almost the same distance ranges from the epicentre, and rather high local magnitudes (i.e.,  $M > 6.5$ ). To estimate the seismic performance of the selected reference frames, extensive nonlinear time-history analyses were performed using computer program DRAIN-2DX [11].

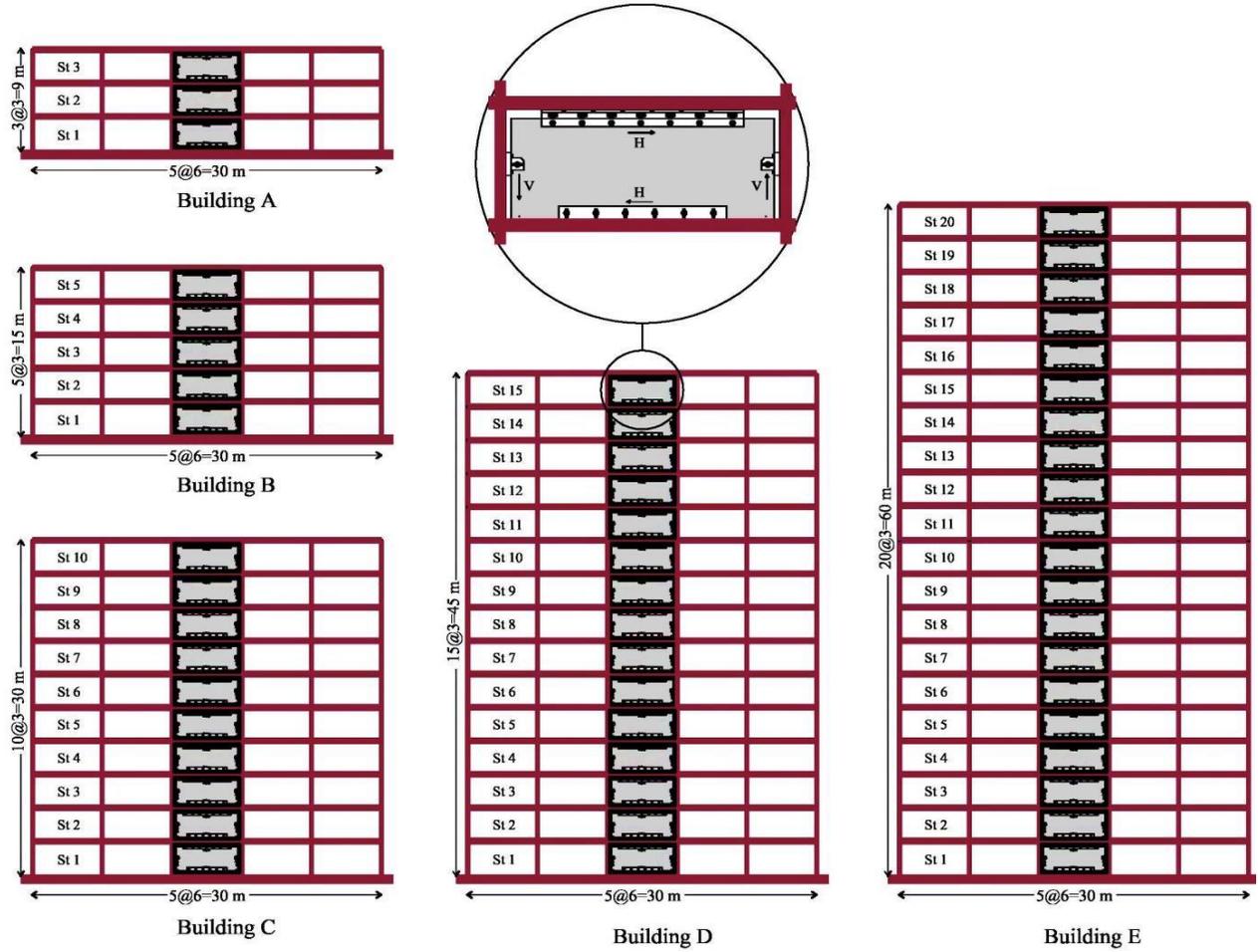


Figure 1 - Typical geometries of the reference frames

### 3 WALL-TYPE FRICTION-BASED PASSIVE CONTROL SYSTEM

The proposed wall-type friction-based system incorporates a non-structural concrete wall panel with the thickness of 15cm attached to the surrounded beam and column elements using four connections at the four sides [2]. Fig. 2 depicts the details of the proposed friction wall panel and how it is connected to the frame elements. The panel-to-frame connection is provided through two vertical supports in the lateral sides between the panel and the adjacent columns, one horizontal connection between the bottom of the panel and the lower floor beam, and a longitudinal steel-brass connection at the top to ensure the desired dry friction mechanism. The panel-to-column connections account for preventing the vertical movement and rotation of the panel with respect to the floor, while allow for horizontal displacement by using horizontal slots (see Fig. 2). This supports prevent transferring shear forces to the connected columns, and thus avoid brittle shear failure of the columns, however, they can increase the column axial loads. Likewise, the bottom support inhibits transferring shear forces to the lower floor beam through vertical slots.

The friction connection is a simple panel-to-frame connection incorporating two z-shape external steel plates clamped to the top of the panel and a T-shape central stainless steel plate anchored to the upper floor beam and sandwiched between the external plates [2]. The horizontal slots in the external plates allow for the movement of the central plate (i.e. upper floor) without moving the panel. In this situation, the displacement of the friction connection is exactly equal to the inter-storey drift. It should be noted that more stable frictional characteristics has been exhibited by sliding interface of steel and brass compared with the steel on steel contact interface [12]. Therefore, two additional brass plates are placed between the central and the external steel plates to

enhance the frictional characteristics of the mechanism. The proposed mechanism displays ideal elasto-plastic behaviour (Coulomb behaviour) with rectangular hysteretic loop.

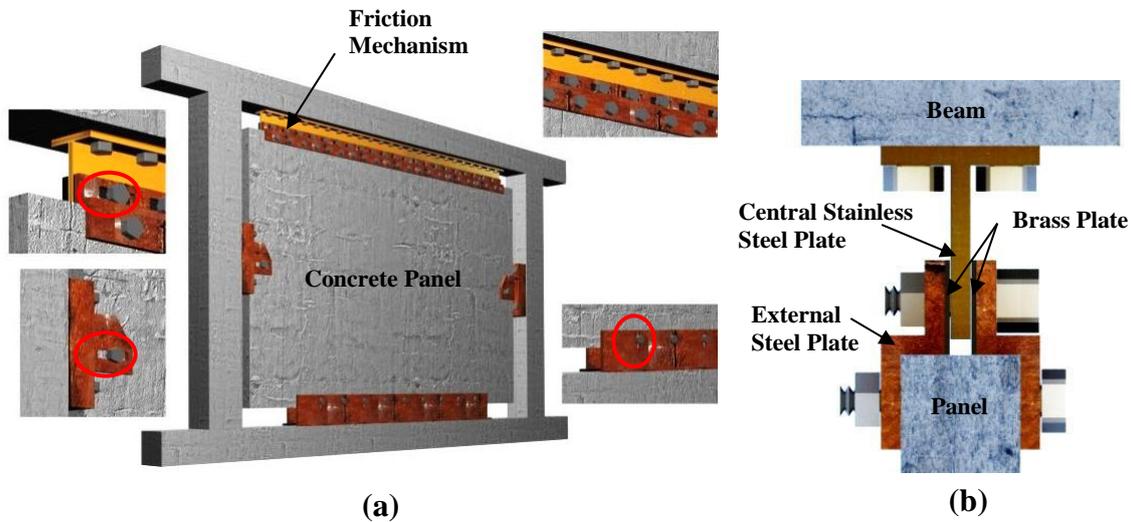


Figure 2 – Wall-type friction system (a) panel-to-frame connection, (b) friction connection

#### 4 SLIP LOAD DISTRIBUTION PATTERNS

Friction-based passive control systems are capable of being adjusted and tuned independently for each individual floor level by changing the clamping forces (torque) of the bolts in the friction connections. Therefore, it is feasible to have different slippage thresholds (slip forces at which the friction connection start moving and dissipating energy) for different levels. Such capability provides the possibility of using different patterns for height-wise slip load distributions, which in turn lead to different seismic performances of the structure. This study aims at comparing five different slip load distribution patterns, and then proposing a simple practical solution to achieve the best seismic performance. As shown in Fig. 3, the selected slip load distribution patterns are; i) uniform, ii) uniform cumulative, iii) triangular cumulative, vi) inverted triangular cumulative and v) a distribution proportional to the storey shear strengths.

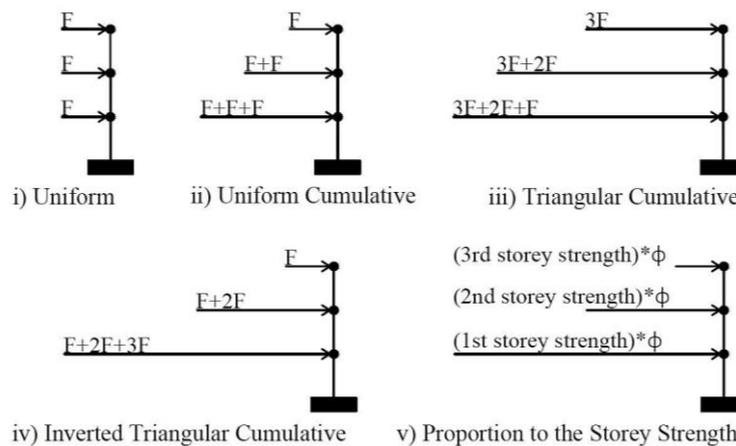


Figure 3 - Five selected slip load distribution patterns

It should be noted that in practical applications and most of the previous researches, the uniform height-wise slip load distribution is usually employed for the design of friction-based passive control systems. However, this may not necessarily lead to the best seismic behaviour for all the frame structures with different properties as will be discussed in the following sections.

To obtain the best range of the slip loads which leads to the most efficient seismic responses, a wide range of friction forces was employed for each individual distribution patterns and each reference frame in nonlinear dynamic analyses. The average seismic responses of the 5 and 15-storey frame structures under six real earthquakes are presented to compare the efficiency of the selected slip load distribution patterns on different performance indices.

## 5 NON-LINEAR DYNAMIC RESPONSES OF THE STRENGTHEND FRAMES

To investigate the effect of different slip load distribution patterns on the seismic performance of the reference structures, six performance indices are considered, including maximum inter-storey drift, maximum roof displacement, maximum axial force of the connected column to the panel, overall base shear, and two energy dissipation parameters. For comparison purposes, the response parameters of the frames with friction wall dampers are normalised to those of the corresponding bare frames. Moreover, the average of the slip loads at all storeys was calculated and normalised to the average of the storey shear strengths, denoted as slip load ratio.

### 5.1 Displacement Demands

Maximum lateral inter-storey drift and roof displacement are excellent value measures to estimate the level of damage to the structural and non-structural elements under strong earthquakes. Fig. 4 shows the variation of maximum inter-storey drift ratios for 5, and 15-storey frames using five different slip load distribution patterns with a broad range of slip load ratios. Fig. 4 exhibits a similar descending trend of the displacement demands for different slip load distribution patterns. The maximum inter-storey drift and roof displacement ratios generally reduce by increasing the friction slip loads up to a certain range. This is followed by a constant and an ascending trend in 5 and 15-storey frames, respectively. The presented results indicate that, on average, there is an optimum domain for slip load ratios in which the inter-storey drift ratios and, therefore, structural damage are minimized under design earthquakes. It can be seen in Fig. 5 that the optimum range for the 5-storey frame is higher than the optimum range in 15-storey framers.

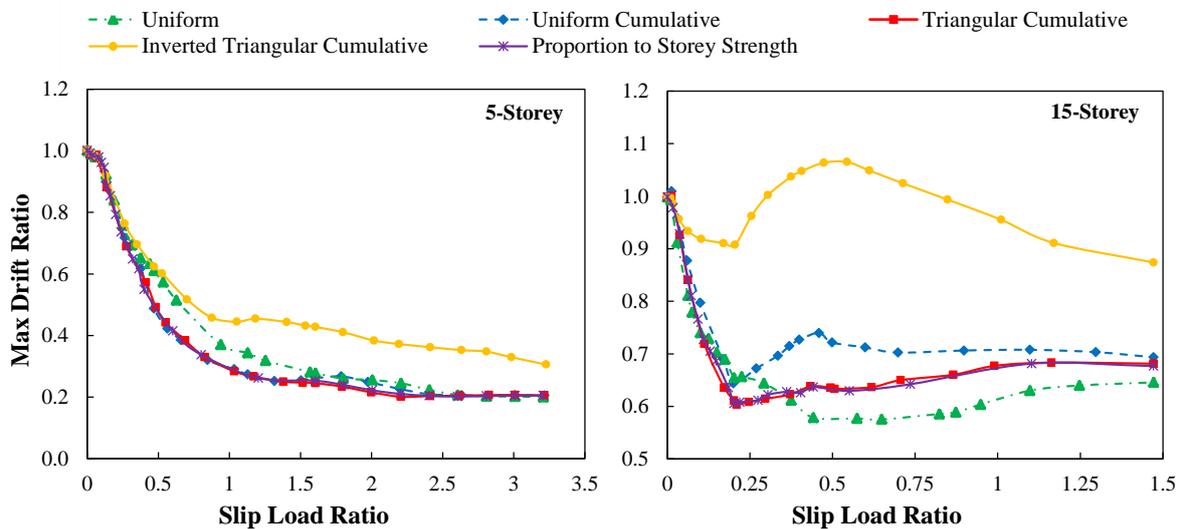


Figure 4 - Envelopes of the maximum drift ratio for the 5 and 15-storey frames as a function of slip load ratio, average of six earthquakes

Among all the selected slip load distribution patterns, inverted triangular cumulative pattern seems to be the least effective in reducing the displacement demands, while other distribution patterns can lead to almost similar reduction levels. As disclosed by the results, the seismic performance of the reference frames designed based on the triangular cumulative pattern and the distribution proportional to the storey shear strength are strictly similar. The conventional uniform pattern leads to more improvement in displacement demands of the 15-storey frame. By neglecting

the results of the inverted triangular cumulative slip load distribution, on average, the maximum reductions of 75% and 40% of displacement demands can be obtained for 5 and 15-storey frames, respectively, by considering optimum slip load ratios. This implies that the reduction in maximum drift ratios is more prominent in low rise buildings.

## 5.2 Force Demands

As described earlier, panel-to-column connections in the friction-based passive wall dampers are designed to avoid transferring shear forces to the columns, however, they can apply extra axial loads to the connected columns. The variation of the column shear force ratios for the 5 and 15-storey frames (i.e. medium and high-rise frames) with different slip load distributions are shown in Fig. 5 as a function of slip load ratio.

It is shown that, irrespective to the selected slip load distribution pattern, the axial load in the connected columns increases by increasing the slip load ratios up to a certain domain in which the slippage is prevented at all storey levels (i.e. fixed wall condition). As plotted by Fig. 5, the maximum column axial load ratios can increase to the maximum of 7 and 4.5 for the 5-storey and the 15-storey reference frame, respectively. Such significant increase in force demands of the reference frames highlights the importance of obtaining optimum slip load ratios that can both minimize the lateral displacement demands of the structures and control the base shear and axial loads applied to the connected columns.

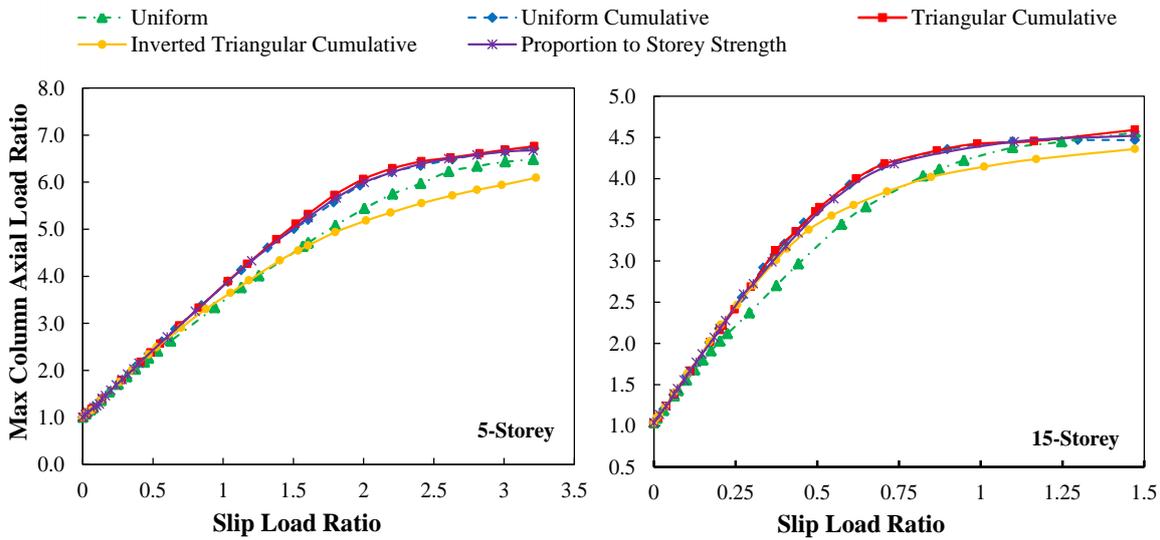


Figure 5 - Envelopes of the column axial load ratio for the 5 and 15-storey frames as a function of slip load ratio, average of six earthquakes

It is worth mentioning that among all the distribution patterns, conventional uniform slip load distribution pattern leads to less increase in force demand; however, this normally happens beyond the optimum slip load domain that is not considered in the design purposes.

## 5.3 Energy Dissipation Capacity

To assess the overall structural performance and the efficiency of the added friction-based passive control system, two energy dissipation parameters have been scrutinized. The first energy dissipation parameter ( $R_{w1}$ ) is denoted as the ratio between the deformation work of the beam and column elements in the controlled structure ( $W_{cs}$ ) to that of the structural elements in the corresponding bare frame ( $W_{bf}$ ). The related equation is as follow [2]:

$$R_{w1} = \frac{(W_{sb} + W_{sc})_{cs}}{(W_{sb} + W_{sc})_{bf}} \quad (1)$$

The second energy dissipation parameter,  $R_{w2}$ , is the key parameter in determination of the optimum slip load and the efficiency of the friction-based wall system, as it represents the amount of dissipated energy through the friction mechanism.  $R_{w2}$  is defined as the ratio between the friction work of the friction mechanism ( $W_{sf}$ ) and the deformation work of the main structural members in the controlled structure ( $W_{cs}$ ) [2].

$$R_{w2} = \frac{(W_{sf})_{cs}}{(W_{sb} + W_{sc})_{cs}} \quad (2)$$

Fig. 6 presents the average envelopes of the second energy dissipation parameter as a function of slip load ratio for the 5 and 15-storey reference frames subjected to the six selected earthquakes. Fig. 6 implies that the  $R_{w2}$  factor tends to be zero for very low and very high slip force values. It should be noted that the trend is independent of the input seismic excitation and the slip load distribution pattern. It is evident that the maximum energy dissipated through the friction mechanism occurs in the slip load ratio ranges from 0.70 to 0.90 for the 5-storey and 0.15 to 0.25 for the 15-storey frame.

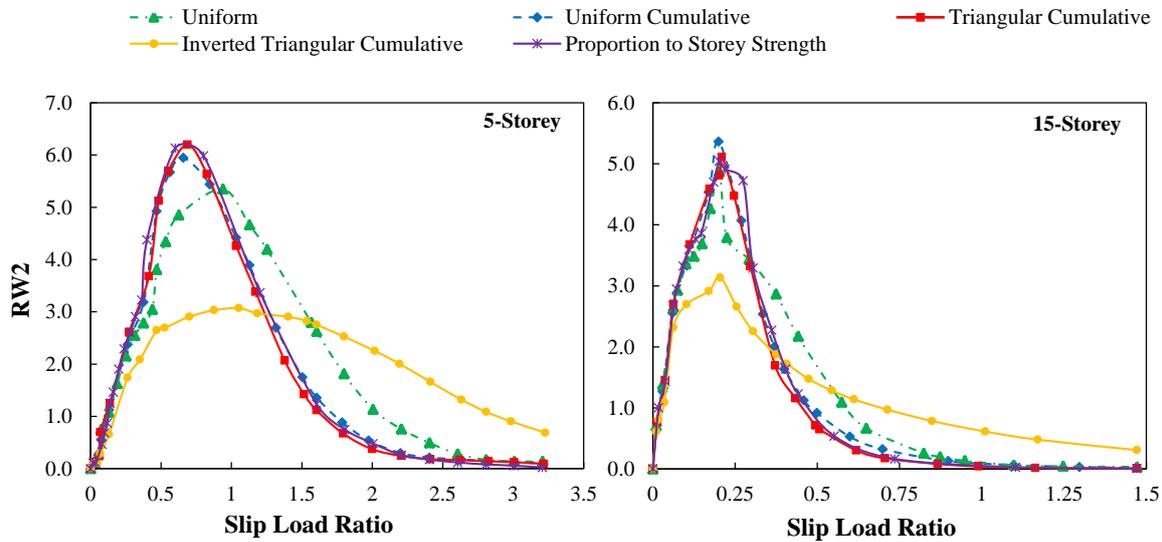


Figure 6 - Envelopes of  $R_{w2}$  parameter for the 5 and 15-storey frames as a function of slip load ratio, average of six earthquakes

Similar to the other performance indices, the inverted triangular cumulative pattern has the least efficiency on energy dissipation of the controlled frames, while the uniform cumulative, the triangular cumulative and the proportional to the storey strength distribution patterns have almost the highest efficiency on the seismic performance of the controlled system. The uniform pattern is usually leads to the optimum performance in the higher slip load ratio, which in turn leads to higher force demands. Since the seismic performance of the friction-based wall dampers is strictly related to the design slip load values, it is important to obtain a design solution that can efficiently control the lateral displacement demands and damage of the structures during earthquake events.

## 6 A PRACTICAL DESIGN METHODOLOGY FOR FRCITION-BASED ENERGY DISSIPATION DEVICES

As described earlier, the uniform cumulative, the triangular cumulative and the proportion to the storey strength slip load distribution patterns, in general, leads to a better seismic performance as well as more energy dissipation. Considering the easiest way to distribute the slip loads, the uniform cumulative pattern is more practical. Among all the performance indices, the displacement demand and the maximum energy dissipation in the friction connection are more critical for efficient design solution. Therefore, by employing the results of the optimum slip load ratio ranges

for the other reference frames (i.e. 3, 10, and 20-storey frames), an exponential compatible curvature could be suggested.

An empirical equation is subsequently proposed to achieve the most appropriate slip load ratio leading to the most energy dissipation and the lowest structural damage. The results show that the optimum slip load ratios of the reference frames follow an exponential-compatible pattern. The equation of the most efficient slip load ratio is as follow:

$$R = 1.12e^{-0.11n} \quad (3)$$

where  $n$  is the number of storeys.

The proposed ratio is considered as the ratio between the average of the slip load in the uniform cumulative distribution and the average of the storey shear strength. To obtain the most efficient slip load distribution, the ratio should be multiplied by the average of the storey strength, and then uniformly distributed to the storeys. The following formula is suggested to achieve the slip load of each storey in the uniform cumulative pattern:

$$F_{si} = \frac{\sum V_{si} \times R}{n(n+1)/2} \times (n+1-i) \quad (4)$$

By substituting  $R$ :

$$F_{si} = \frac{\sum V_{si} \times 1.12e^{-0.11n}}{n(n+1)/2} \times (n+1-i) \quad (5)$$

where  $F_{si}$  and  $V_{si}$  are the slip load and the storey strength of the  $i^{th}$  storey number respectively, and  $n$  is the number of storeys.

The effectiveness of the proposed empirical equation for all the reference frames is compared with the conventional design of the friction wall system (i.e. using uniform distribution pattern). As shown in Table. 1, using the proposed equation leads to less displacement demand and more energy dissipation in all the reference frames except for the 3-storey frame.

*Table 1: Comparison of the proposed methodology with the conventional design*

	Uniform Cumulative (Eq. 5)					Uniform (Convectional design)				
	3st	5st	10st	15st	20st	3st	5st	10st	15st	20st
<b>Maximum Drift ratio</b>	0.24	0.30	0.37	0.36	.66	0.19	0.46	0.44	0.50	.82
<b><math>R_{w2}</math></b>	2.2	13.0	10.5	13.9	8.4	4.0	8.8	6.4	7.2	5.2

## 7 CONCLUSION REMARKS

The results of the study clarify that there are different specific slip load ratio ranges for the studied reference frames which lead to the best seismic performance under the selected design earthquakes. The efficiency of five slip load distribution patterns is compared in terms of force and displacement demands, and energy dissipation capacity. As resulted by the envelopes of the performance indices, the inverted triangular cumulative pattern is the least efficient pattern to design the controlled frames. However, the uniform cumulative, the triangular cumulative and the proportional to the storey strength distribution patterns have almost the highest efficiency on the seismic behaviour of the controlled system. According to the best slip load ranges, an exponential equation was proposed based on the uniform cumulative distribution for more practical design of the friction-based passive energy dissipation devices. The proposed methodology was confirmed to be more efficient than the conventional uniform pattern to design the medium- to high-rise frame structures strengthened with the friction dampers.

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