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A practical method for the design of Friction-Based Passive Control Wall Damper for RC Frame Buildings

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Abstract

This paper aims to introduce an innovative and cost-effective friction-based wall damper to improve the seismic performance of substandard RC structures. The proposed passive control system consists of a non-structural concrete wall panel that is connected to frame elements by two vertical panel-to-column supports in the lateral sides, one horizontal panel-to-beam connection at the bottom, and a friction mechanism at the top. The suggested system is designed to prevent transferring shear forces to the connected beam and column elements and, therefore, to avoid brittle shear failure modes under severe earthquakes. The friction device can be adjusted and tuned independently at each floor to achieve the best seismic performance under design earthquakes. However, obtaining the optimum design slip load distribution can be a challenging task due to nonlinearity of the system and high computational costs. To develop a practical design method, this study investigates the effects of using a wide range of different slip load distributions on the efficiency of the proposed friction-based damper. Extensive non-linear dynamic analyses are performed on 3, 5, 10, 15 and 20-storey substandard RC frames under seven real and synthetic spectrum compatible earthquakes. The results indicate that, irrespective of the height-wise slip load distribution, there is an optimum range for the slip forces which on average leads to a better seismic performance. It is also shown that, in general, using a uniform cumulative slip load distribution pattern leads to the highest energy dissipation in the friction-based dampers and, hence, less damage in the structural elements during strong earthquakes. The results of this study are then used to develop a practical design methodology for optimum performance-based design of friction wall systems by suggesting an empirical equation to estimate optimum slip loads at each storey. The efficiency of the proposed method is demonstrated through several design examples.

Keywords: Passive Control; Friction Wall Damper; RC Frames; Nonlinear Dynamic Analyses

1. Introduction

Much of the existing RC building structures in developing countries are designed primarily to sustain gravity loads with little or no seismic detailing. These substandard structures have high seismic vulnerability that may lead to collapse and failure in primary structural elements during strong earthquakes. To reduce earthquake-induced responses of structural systems either for new building design or strengthening purposes, friction-based passive control systems have shown more efficiency compared to other supplemental passive dampers in terms of simplicity, reliability, energy dissipation capacity and cost-efficiency. In one of the earliest efforts towards using friction energy dissipation devices, Pall and Marsh [1] developed Limited Slip Bolted (LSB) joints for seismic protection of structures with large panels. Their proposed friction joints have been proved to dissipate seismic energy and reduce permanent deformations through a limited slippage in the joints of the panels. Pall friction dampers were the first generation of friction dampers for braced steel frames offered by Pall and Marsh [2]. Pall dampers were designed in two configurations to be used in both single diagonal and X-braced frames. In 2005, Wu et al. [3] developed an improved Pall friction damper by using a T-shaped core plate, which was easier to manufacture and assembly. The analytical and experimental analyses of the improved model showed identical frictional forces as those resulted by the conventional dampers.

Another type of friction-based dampers are Slotted Bolted Connections (SBCs) introduced by Fitzgerald et al. [4], which can dissipate earthquake input energy to avoid buckling of brace elements in concentrically braced frames. In a more recent study, Nikoukalam et al. [5] suggested shear slotted bolted connections (SSBC) to extend the application of SBCs in the members with shear-dominated behaviour. Mualla [6] developed a Rotational Friction Damper (RFD) incorporating three steel plates rotating over circular friction pad discs. In 2015, Mirzabagheri et al. [7] compared the efficiency of one-unit and multi-unit RFDs to improve the seismic performance of multi-storey buildings. They showed that the energy dissipation capacity of RFDs is increased by increasing the amount of relative rotation between the central and side plates over the connection hinge.

All the aforementioned supplemental energy dissipative devices were attached to the original steel or RC frame structures using different types of bracing elements; however, the brace-type dampers are more appropriate for steel frame structures rather than RC frames. Using bracing systems in RC frames can cause high stress concentrations in the connection zones, which can in turn lead to extensive damage in the connection region between the RC member and the brace-type damper. To address this issue, a number of wall-type friction dampers have been proposed for RC structures in the past two decades. In 1997, Sasani and Popov [8] experimentally and analytically investigated the seismic behaviour of a lightweight concrete panel that was fixed to the lower floor beam and connected with three friction energy dissipaters on the top. In a follow-up study conducted by Petkovski and Waldron [9], the effectiveness of a similar concrete wall system with a friction device was evaluated on improving the seismic performance of multi-storey RC structures. To assess the efficiency of the friction wall panels, they considered the slip load at each storey level to be proportional to the corresponding storey shear strength. The effect of concrete panel stiffness on the seismic performance of the selected frames was also investigated in their study by considering different panel thicknesses and opening sizes. Cho and Kwon [10] proposed another kind of wall-type friction damper for RC structures using Teflon sliding sheets in contact with steel plates to ensure an efficient friction mechanism.

None of the above mentioned studies were aimed to find the best height-wise slip load distribution pattern for seismic design of multi-storey RC structures. In most of the cases, a constant slip load distribution was considered mainly for simplicity and practical convenience. However, using a uniform slip load distribution pattern may not necessarily lead to the best seismic performance under a design earthquake. In this study the efficiency of five different predefined slip load distributions are evaluated on the seismic performance indices of 3, 5, 10, 15, and 20-storey RC frames with friction wall dampers. To achieve the best slip load values and height-wise distribution, extensive nonlinear dynamic analyses are conducted for a set of seven spectrum compatible earthquake records. Subsequently, the results are used to develop an empirical equation for more efficient design of friction-based wall dampers to maximum their energy dissipation capacity.

1.1 Reference Frames

To investigate the efficiency of the proposed friction-based wall damper, five RC frames with 3, 5, 10, 15 and 20 storeys were selected with the typical geometry shown in Fig. 1. The frames were assumed to be placed on a soil type D of the IBC-2015 [11] category. The bare frames were designed based on an earthquake with the PGA of 0.2g to represent substandard RC structures in developing countries. Frame members were designed to support gravity and lateral loads based on IBC-2015 (and ASCE/SEI 7-10) to satisfy the minimum requirements of ACI 318-14 [12]. Pushover and nonlinear time-history analyses were carried out using computer program DRAIN-2DX [13]. A Rayleigh damping model with a constant damping ratio of 0.05 was used for the first mode and the mode at which the cumulative mass participation exceeded 95%. Nonlinear moment rotation (M-□) and axial-moment (P-M) plastic hinges were assigned to the both ends of RC beam and column elements, respectively.

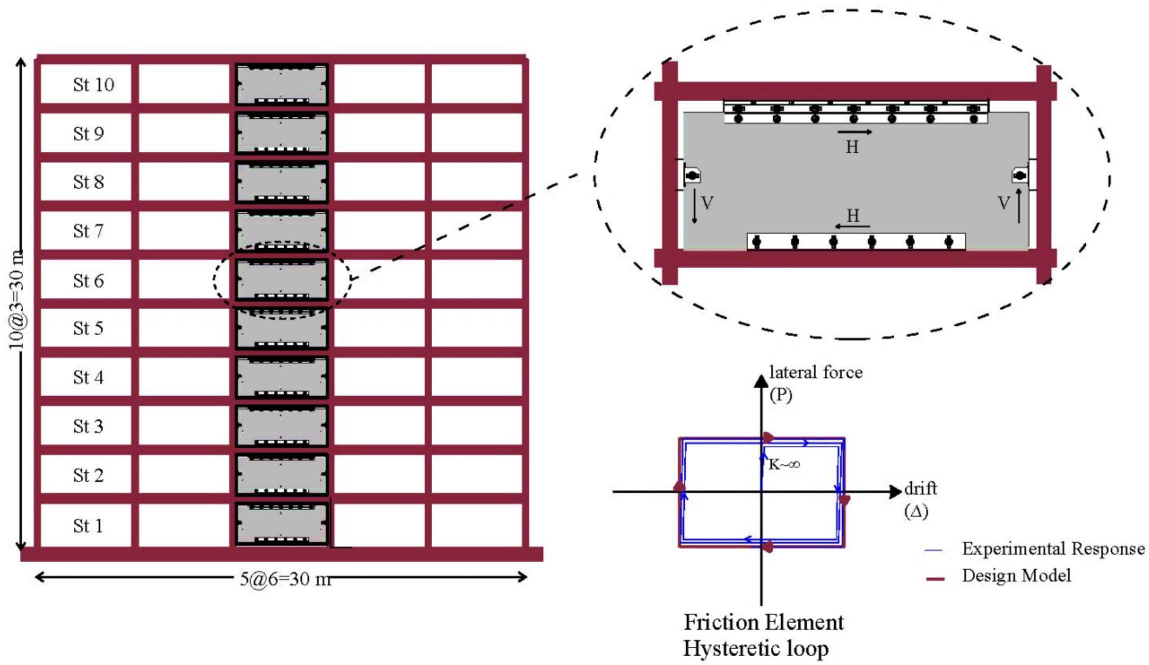

Fig. 1– Typical geometry of RC frames with friction-based wall dampers

1.2 Proposed Friction Wall Damper

The proposed friction-based wall damper incorporates a friction device and a non-structural concrete panel, which is connected to the RC beam and column elements using three connections at the lateral sides (see Fig. 2). The friction device consists of two external steel plates bolted at the top of the panel and clamped together over a T-shaped stainless steel plate. The horizontal slots on the external steel plates provide the possibility of relative horizontal movement of the upper floor beam with respect to the concrete panel. The other supports are designed so as the displacement of the friction mechanism is equal to the inter-storey drift and vertical movement of the panel are prevented. Transferring shear forces to the connected beam and column elements are also avoided by using horizontal slots for the column supports and vertical slots for the lower beam connections. The proposed friction mechanism has been proved to provide an ideal rectangular hysteretic behaviour as shown in Fig. 1.

1.3 Slip Load Distribution Patterns

One of the main features of the friction passive control systems is the feasibility of adjusting the slip forces (F_s) of the friction connections independently at individual storey levels by controlling the clamping forces of the bolts. Such capability provides the possibility of using different patterns for height-wise slip load distributions to improve the seismic performance of the controlled structure. As shown in Fig. 3, to obtain the best slip load distribution, five different distribution patterns are considered, including uniform, uniform cumulative, triangular cumulative, inverted triangular cumulative and a distribution pattern proportional to the storey shear strengths. It is worth mentioning that in practical applications a uniform height-wise slip load distribution is usually employed for the design of passive friction dampers. However, this may not necessarily lead to an optimum seismic performance as will be discussed in the following sections.

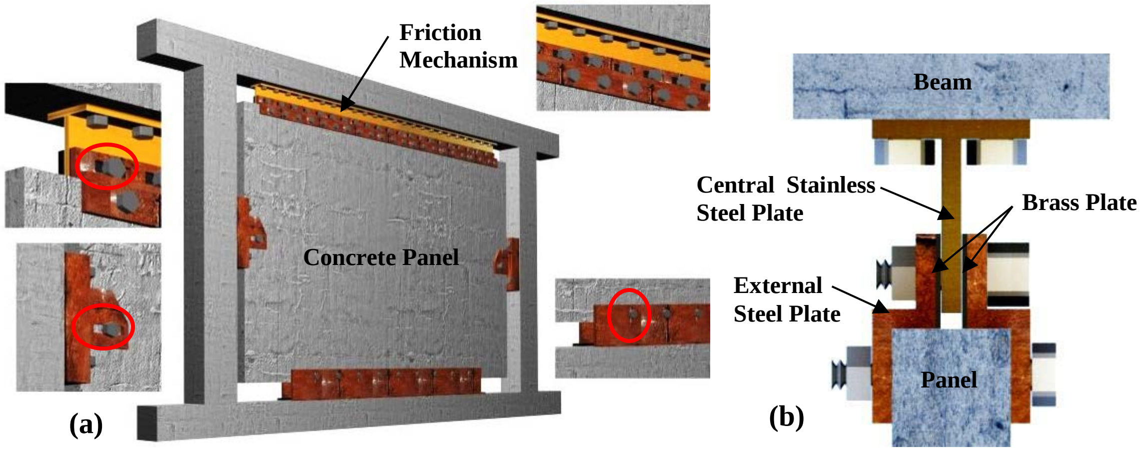

Fig. 2– Details of the (a) proposed friction wall panel, (b) friction device (based on Petkovski et al. [9])

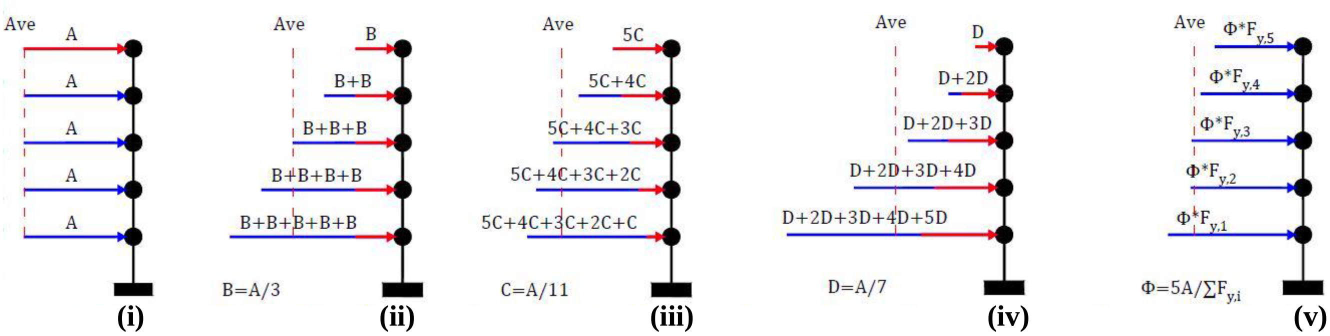

Fig. 3– Schematic model of the selected slip load distribution patterns: i) Uniform, ii) Uniform Cumulative, iii) Triangular Cumulative, iv) Inverted Triangular Cumulative, v) Proportion to the Storey Strength

To investigate the efficiency of the proposed friction-based wall damper, extensive non-linear dynamic analyses are performed on the reference structures and their corresponding bare frames subjected to six real strong ground motions (namely Cape Mendocino 1992, Duzce 1999, Superstitn Hills 1987, Imperial Valley 1979, Loma Prieta 1989 and Northridge 1994) as well as a synthetic earthquake representing the IBC-2015 design spectrum with PGA= 0.4g.

2. Seismic Efficiency of the Proposed Friction Wall Dampers

In this section, first the effectiveness of using five different slip load distribution patterns is investigated on the seismic performance of the selected 3, 5, 15, 15 and 20-storey frames equipped with friction wall dampers. Different structural response parameters such as inter-storey drift and cumulative energy dissipation are discussed to evaluate the seismic efficiency of the reference frames. The slip load ratio (F_SR) is defined as the average of the slip loads at all storey levels normalised to the average of the storey shear strengths as follows:

$$F_{SR} = \frac{\sum_{i=1}^{n} F_{s,i}}{\sum_{i=1}^{n} F_{y,i}} \tag{1}$$

where n is the number of storeys; and $F_{s,i}$ and $F_{y,i}$ are the slip force and the storey shear strength of the i^{th} storey, respectively. Using this parameter helps to compare the effects of employing different slip load distributions, while the total slip load remains constant. For comparison purposes, the response parameters of the frames with friction wall dampers are also normalised to the responses of the corresponding bare frames.

2.1 Maximum Inter-Storey Drift

Maximum lateral inter-storey drift is widely used to measure level of damage to structural and non-structural elements and to evaluate P-delta effects [14]. Since the seismic performance of the proposed friction-based wall damper is directly related to the design slip load values at different storey levels, it is important to obtain a design solution that can efficiently control the lateral displacement demands of the structures during earthquake events. Fig. 4 shows the variation of maximum inter-storey drift ratios (normalised to the bare frames) for the 3, 5, 10, 15 and 20-storey frames using five different slip load distribution patterns with a wide range of slip load ratios. The results are the average of the response parameters obtained for the six selected real earthquakes. It should be noted that the RC frames with friction wall panels using very small slip load ratios can be representative of bare frames, since the energy dissipation capacity of the friction connections will be negligible.

Fig. 4 demonstrates a general trend for different slip load distribution patterns as the maximum inter-storey drift ratios reduce by increasing the friction slip load values up to a certain limit. This is followed by a constant or an ascending trend in short-to-medium (i.e. 3 and 5 storey frames) and high-rise buildings (i.e. 10, 15 and 20 storey frames), respectively.

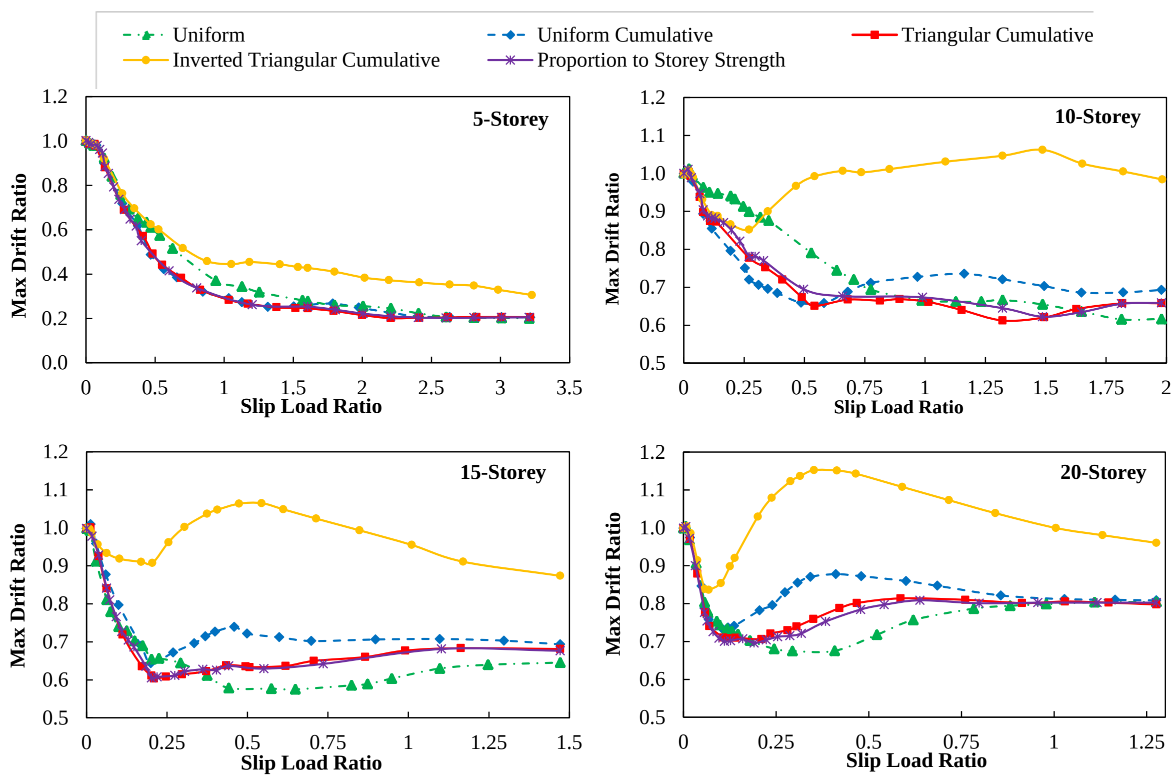

Fig. 4– Variation of maximum inter-storey drift ratios of 5, 10, 15 and 20-storey RC frames as a function of slip load ratio, average of the six selected earthquakes

The presented results indicate that, on average, there is an optimum range for slip load ratios that leads to minimum inter-storey drifts and, therefore, a better seismic performance under design earthquakes. Similar conclusions have been made by Pall et al. [15], Filiatrault and Cherry [16], Marsh [17], Petkovski & Waldron [9] Honarparast and Mehmandoust [18]. Although the optimum range of the slip load ratios varies with the slip load distribution pattern, it is shown in Fig. 4 that, in general, the optimum range decreases by increasing the number of storeys.

Among all the selected slip load distribution patterns, the inverted triangular cumulative slip load pattern seems to be less efficient in reducing the maximum inter-storey drifts, while other distribution patterns can lead to almost similar reduction levels. By ignoring the results of the inverted triangular cumulative slip load distribution, on average, the maximum inter-storey drift of the 3, 5, 10, 15, and 20-storey frames can be reduced up to 85%, 75%, 38%, 40%, and 30%, respectively, by using optimum slip load ratios. It is shown that the reduction in maximum drifts is more noticeable in low-rise buildings.

2.2 Energy Dissipation Capacity

Considering fairly small amount of inherent viscous damping in normal building structures, much of the energy dissipated under strong earthquakes is due to the work done by non-linear deformations of the structural and non-structural elements. The proposed friction-based wall damper, if designed properly, can reduce the inter-storey drifts without increasing the storey shear forces by dissipating a significant amount of the imparted earthquake input energy through the friction mechanism. In this study, to assess the overall structural performance and the efficiency of the added friction-based passive control systems, the following two energy dissipation parameters are defined:

2.2.1 Energy dissipated in the structural elements

To estimate the energy dissipated in the structural elements, R_{w1} is defined as the ratio between the deformation work of the structural members in the controlled structure (W_{cs}) to the work of the members in the corresponding bare frame (W_{bf}) [9].

$$R_{w1} = \frac{(W_{sb} + W_{sc})_{cs}}{(W_{sb} + W_{sc})_{bf}} \tag{2}$$

where W_{sb} and W_{sc} indicate the static work of the structural beam and column elements, respectively.

As presented in Fig. 5 (a), the static work of the structural members in the controlled structure tends to be minimised in a slip load ratio around 0.85, 0.75, 0.35, 0.20, and 0.10 for 3, 5, 10, 15, and 20-storey controlled frames, respectively. The R_{w1} values then increase until a steady state is achieved at higher slip load ratios. The trend seems to be independent of the number of storeys, input seismic excitation and slip load distribution pattern. This confirms that there is an optimum range for the slip load ratios which leads to less deformation work, and hence, less damage in the main structural elements. It is also shown that using the optimum slip load ratios, on average, results in a maximum reduction of about 90% and 60% in R_{w1} values for low-rise and medium to high-rise buildings, respectively.

2.2.2 Energy dissipated in the friction wall panels

The amount of energy dissipated through the friction device is one of the main factors to evaluate the efficiency of the proposed friction wall dampers. This can be quantified by introducing R_{w2} parameter which is denoted as the ratio between the friction work of the friction device (W_{sf}) and the deformation work of the main structural members in the controlled structure (W_{cs}).

$$R_{w2} = \frac{(W_{sf})_{cs}}{(W_{sb} + W_{sc})_{cs}} \tag{3}$$

It should be noted that R_{w1} is a measure to assess the effect of the proposed friction wall dampers on the energy dissipation demand of the structural elements, while R_{w2} mainly represents the energy dissipation capacity of the friction devices.

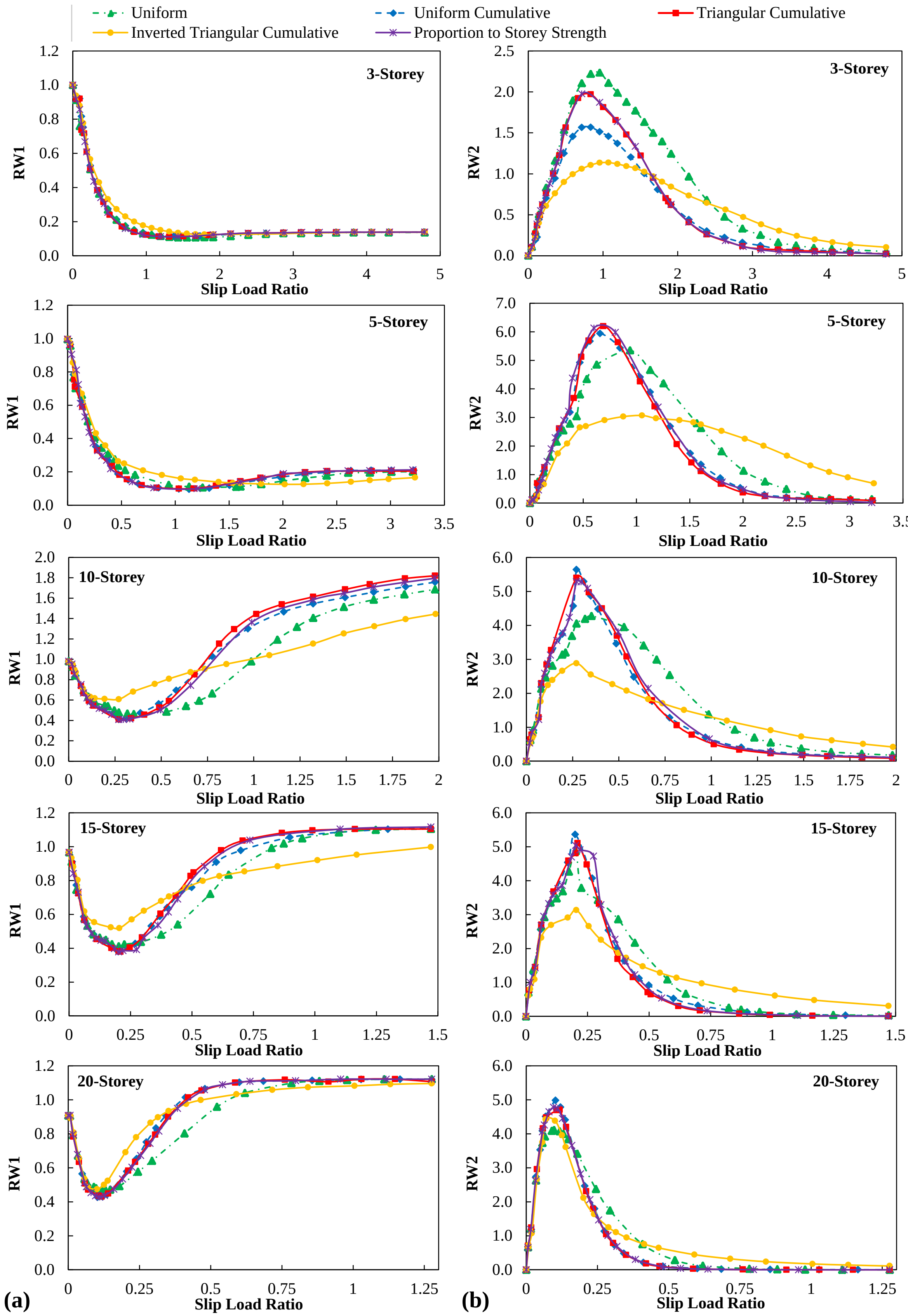

Fig. 5– Energy dissipation parameters R_{w1} and R_{w2} for reference frames, average of the six selected earthquakes

As illustrated in Fig. 5 (b), the R_{w2} factor tends to zero for very low and very high slip load values as the energy dissipations in the friction devices are negligible in both cases. The results indicate that the overall trend is the same for all the reference frames irrespective to the number of storeys and the design ground motion record. However, the optimum slip load ratios, in which the dissipated energy in the friction dampers is maximum, change for the frames with different number of storeys.

It is evident that the uniform cumulative slip load pattern is usually the most effective pattern in terms of increasing the energy dissipation capacity of the friction-based wall dampers (except for the 3-storey frame), while the inverted triangular cumulative pattern has the least efficiency. Although the effectiveness of the uniform cumulative pattern is only slightly better than the triangular cumulative and proportional to the storey shear strength distributions, from the practical point of view it is more convenient to use this slip load pattern due to its simplicity.

3. More Practical Design Method for Friction Wall Dampers

As shown in previous sections, the uniform cumulative distribution pattern, in general, leads to a more energy dissipation in the friction-based wall dampers and a better overall seismic performance. By considering the energy dissipation capacity as the key performance parameter to identify the optimum design solutions, the uniform cumulative distribution is considered as the optimum pattern for the height-wise distribution of slip loads. Based on the results in Fig. 5, the optimum range of the slip load ratios for 3, 5, 10, 15, and 20-storey frames with uniform cumulative slip load distribution is within 0.65-0.95, 0.55-0.85, 0.25-0.45, 0.10-0.30, and 0.05-0.15, respectively.

Fig. 6 plots the optimum range of the slip load ratios as a function of number of storeys. It is shown that an exponential curve can efficiently represent the average values. An equivalent empirical equation is then proposed to achieve the most appropriate slip load ratios by considering the maximum energy dissipation capacity as follows:

$$R = 1.12e^{-0.11n} \tag{4}$$

where n is the number of storeys. It is shown in Fig. 6 that the optimum slip load ranges (solid lines) for the selected reference frames are overlaid by the proposed exponential equation (dashed line).

The slip load ratio R calculated from Eq. (4) is the ratio between the average of the slip loads in uniform cumulative distribution and the average of the storey shear strengths. Therefore, to acquire the slip load values for each storey level, the proposed ratio R should be multiplied by the average of the storey shear strength, and then distributed using the uniform cumulative pattern. Using simple calculations, the following formula can be obtained to calculate the slip load values:

$$F_{si} = \frac{\sum V_{si} \times R}{n(n+1)/2} \times \left(n+1-i\right) \tag{5}$$

By substituting R:

$$F_{si} = \frac{\sum V_{si} \times 1.12e^{-0.11n}}{n(n+1)/2} \times \left(n+1-i\right) \tag{6}$$

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

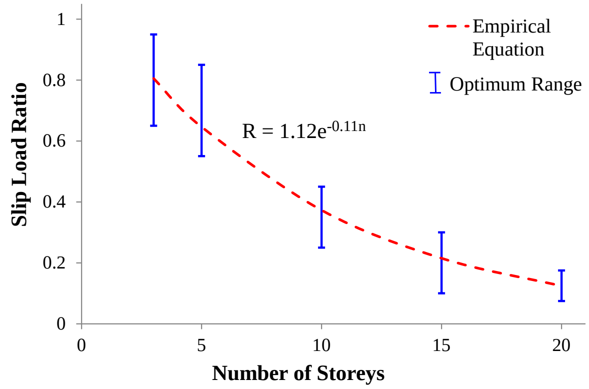

Fig. 5– Compatibility of the proposed equation with the analytical slip load ratio ranges

4. Efficiency of the Proposed Practical Design Method

The synthetic earthquake compatible with the soil type D of IBC-2015 elastic design spectrum is used to evaluate the efficiency of the optimum slip load distributions to improve the seismic performance of the proposed friction wall dampers in the reference frames. For comparison purposes, the overall seismic performances of the reference frames designed using the proposed equation are compared with the reference frames designed based on the uniform slip load distribution (i.e. conventional design) and those with fixed panel-to-frame connections. It should be noted that the energy dissipation capacity of the friction devices in the fixed wall system is zero as there is no friction work and relative movement between the steel plates. The optimum slip load values at different storeys are calculated by using Eq. (4). For a better comparison, the slip load values are scaled in the frames with uniform slip load distribution (without changing the distribution pattern) to have a similar average value as the corresponding optimum design solutions.

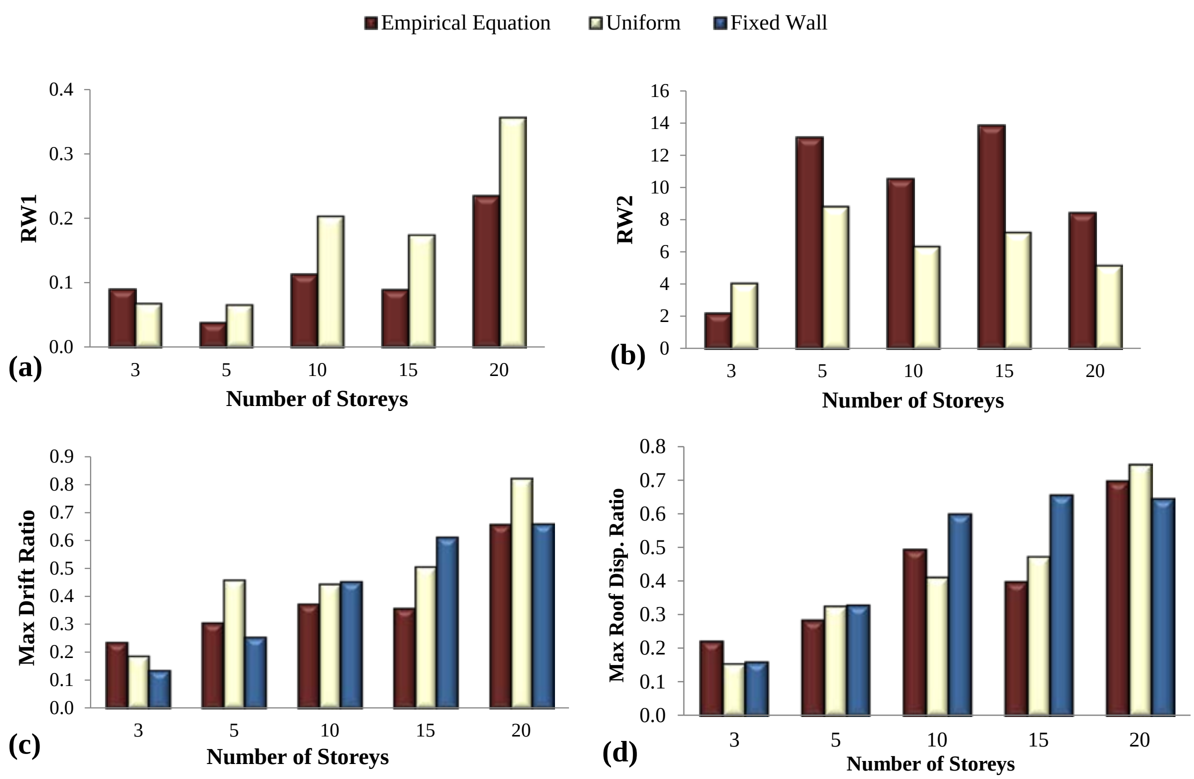

Fig. 6– Seismic responses of the reference frames with different design methods under the synthetic design spectrum compatible earthquake: (a) maximum drift ratio, (b) maximum roof displacement, (c) R_{w1}, (d) R_{w2}

Fig. 7 displays the energy dissipation parameters (R_{w1} and R_{w2}) and the inter-storey and roof displacement demands of the reference RC frames with fixed walls (i.e. no friction device), friction wall dampers designed with the proposed equation and friction wall dampers using the uniform slip load distribution. Figs. 7(a) and (b) show that, except for the 3-storey frame, using the proposed equation (Eq. 6) to design friction-based wall dampers always leads to a lower energy dissipation demand in the structural elements (up to 49% smaller R_{w1} values) and a higher energy dissipation in the friction-based wall panels (up to 48% larger R_{w2} values) compared to the similar frames designed with the conventional uniformly distributed slip loads. Similarly the results in Figs. 7 (c) and (d) show the friction wall systems designed based on Eq. (6) have lower displacement demands (up to 33%) and therefore exhibit less structural damage compared to those designed conventionally.

As illustrated in Figs. 7 (c) and (d), in some cases, using a fixed wall system can lead to less inter-storey drift and roof displacement demands compared to the frames with friction-based wall dampers. However, the results of this study showed that fixed wall systems considerably increase the total base shear and also transfer excessive additional axial loads to the connected columns. In general, it can be concluded that the friction-based wall dampers designed with the proposed slip load distribution pattern provide better design solutions for the frames with more than 5 storeys comparted to the fixed wall systems and conventionally designed wall dampers.

5. Global Damage Index

The overall damage index is considered as a good performance parameter to evaluate the effectiveness of the proposed design strategies mentioned in the previous section. Linear cumulative damage theory, which has been used in this study, takes into account the changes in the energy dissipation capacity of the structure as a function of displacement demands [19]. In this method, it is assumed that the damage caused by each plastic excursion is independent of the damage induced by any other excursions. To clearly define each excursion, the Rainbow Counting Method is suggested by Powell and Allahabadi [20]. Based on this approach, the cumulative damage index (DI_i) at i^{th} storey, ranging from 0 for absence of damage to 1 for complete failure, is calculated using the following equation:

$$DI_i = \sum_{j=1}^{N} \left(\frac{\delta_{pj}}{\delta_y}\right)^C \tag{7}$$

where N is the total number of plastic excursions, δ_{pj} is the plastic displacement of the j^{th} excursion, δ_y is the ultimate plastic displacement, and c is the structural parameter which accounts for the stability of the hysteretic behaviour. Powell and Allahabadi [20] suggested that for low cycle fatigue, c values vary between 1.6 and 1.8. In this study, c is considered to be 1.5 as suggested by Cosenza and Manfredi [21] for damage detection of reinforced concrete structures.

The global damage index (DI_g) evaluates the damage of the whole structure by considering the weighted average of the storey damage indices. The following equation is used to calculate the global damage index of the structures:

$$DI_g = \frac{\sum_{i=1}^{n} DI_i W_{pi}}{\sum_{i=1}^{n} W_{pi}} \tag{8}$$

where n is the number of storeys, W_{pi} and DI_i are the dissipated energy and the damage index of the i^{th} storey, respectively. To better assess of the efficiency of the proposed design methodology, the global damage indices of the selected reference frames are calculated under the Synthetic earthquake as shown in Fig. 8. The results indicate that in general using friction-based dampers could significantly improve the seismic performance of the bare frames, especially for low-medium rise buildings. With respect to the bare frames, conventionally designed wall dampers with uniform slip load distribution led to negligible reductions in the global damage index of the high-rise structures (i.e. more than 10 storeys). However, using the proposed practical methodology to design friction-based wall dampers is more effective to reduce the global damage of the reference RC frames compared with the conventional design solutions. It is shown in Fig. 8 that friction dampers designed with the proposed empirical equation (Eq. (6)) could reduce the global damage index of the 3, 5, 10, 15 and 20-storey frames with conventionally designed dampers by 83%, 18%, 55%, 49% and 30%, respectively.

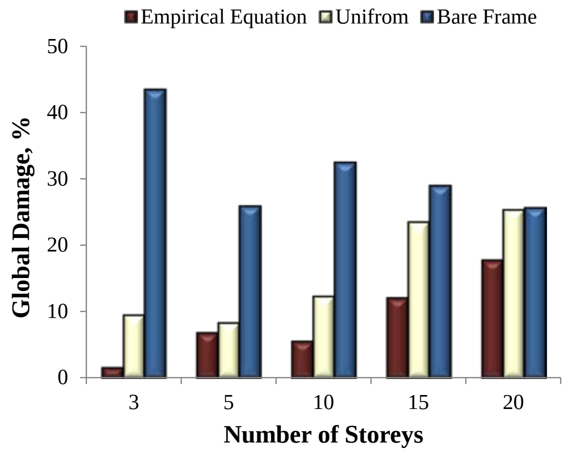

Fig. 7– Global damage index of the bare frames compared to the frames with friction-based wall dampers designed with the proposed equation and uniform distribution under the synthetic earthquake

6. Conclusions

An innovative friction-based wall damper was introduced to improve the seismic performance of multi-storey RC framers. The proposed passive control system incorporates a non-structural concrete panel and a friction device that can be tuned independently at each floor to achieve the best seismic performance. Extensive non-linear dynamic analyses were performed on 3, 5, 10, 15 and 20-storey frames under seven spectrum compatible earthquakes to obtain the best slip load distributions which lead to a maximum energy dissipation in the dampers. Based on the results of this study, the following conclusions can be drawn:

1) Irrespective to the height-wise distribution of the slip loads at the friction devices and the design earthquake, there is always an optimum range for the slip load ratios (normalised to the storey shear strength) that leads to minimum inter-storey drift and roof displacement demands. It was shown that, on average, the optimum range of the slip loads decreases by increasing the number of storeys.

2) To find the most efficient slip load distribution, five different distribution patterns were selected, including uniform, uniform cumulative, triangular cumulative, inverted triangular cumulative and a distribution proportional to the storey shear strengths. In general, the uniform cumulative slip load pattern was usually the most effective pattern in terms of increasing the energy dissipation capacity of the friction-based wall dampers, while the inverted triangular cumulative pattern had the least efficiency.

3) Based on the results of this study an empirical equation was proposed to estimate optimum slip loads at different storey levels. The energy dissipation parameters (R_{w1} and R_{w2}) and inter-storey and roof displacement demands were calculated for the reference frames with fixed walls (i.e. no friction device), friction wall dampers designed with the proposed equation and friction wall dampers with uniform slip load distribution. It was shown that the friction wall systems designed based on the proposed equation have lower displacement demands (up to 33%) and higher energy dissipation capacity (up to 48%) compared to those designed conventionally.

4) To evaluate the effectiveness of the proposed design strategy, the global damage index of the reference frames were calculated and compared. It was shown that the friction dampers designed with the proposed empirical equation can reduce the global damage index of the RC frames with conventionally designed dampers by up to 83%.

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