Seismic investigation of multi-storey RC frames retrofitted using a friction panel with different slip load distributions

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ABSTRACT. The research focuses on the seismic performance of moment resisting reinforced concrete frames, retrofitted using friction-based passive control systems. To conduct the research, five different RC frames with different storeys (3, 5, 10, 15 and 20) were selected and their seismic responses with and without friction panels were investigated using non-linear dynamic analyses performed by DRAIN-2DX software. Selected frames were analyzed under six real and one synthetic spectrum compatible earthquake. The ratios of the inter-storey drift and roof displacement of the controlled system to the corresponding values in the bare frame were calculated for each case. To assess the overall behaviour of the proposed friction panels, two energy dissipation parameters, which are the main indicators of the efficiency of the system, were considered. In this study, five different lateral load patterns, including uniform, cantilever, triangular, inverted triangular, and storey strength proportional distribution were applied to the friction devices. To achieve the optimum design of friction panels, optimum values of slip load ratio (the ratio of the slip load to the storey strength) have been determined. The results indicated that, in general, up to a particular point increasing the slip load improves the behaviour of the controlled system, while further increase may reduce the efficiency of the proposed passive control system. It was shown that uniform and triangular distributions of the slip load were more effective than other distribution patterns in controlling the seismic responses of the selected RC frames. Using friction panels in RC frames has been proved to be an effective solution in terms of reducing the inter-storey drift and roof displacement regardless the size of the frame and seismic excitation characteristics.

KEYWORDS. Friction panels; Slip load; Distribution patterns; RC frames; Energy dissipation.

INTRODUCTION

Passive energy dissipaters have been considered as one of the most efficient and cost effective solutions in terms of concentrating damage in non-structural elements. In other words, the major part of the seismic energy input is damped through passive dampers, without any serious defects in the structural members. Passive dampers, which slip independently from any external sources of energy, are considered as displacement-dependent elements, and they can be easily replaced after severe earthquakes. Based on previous studies on different types of passive control systems, passive dampers are categorized in six major groups, including 1) Viscous fluid dampers, 2) Viscoelastic dampers, 3)

Metallic yield devices, 4) Tuned Mass Dampers (TMD), 5) Tuned Liquid Dampers (TLD), and 6) Friction dampers [1, 2, 3].

In general, Friction dampers are the most appropriate compared to the others in terms of damping capacity, which is used to improve the seismic performance of substandard systems. In other words, friction dampers have shown sustained performance under large number of cycles, which leads to rectangular hysteretic loops, and higher energy dissipation compared to other passive control devices. However, self-centering or energy dissipating damper is the only exception to this trend (Fig.1). In addition, friction devices are superior to other passive dampers in terms of being velocity and temperature-independent, low cost, ease of construction, and ability to be tuned to the characteristic of the structure.

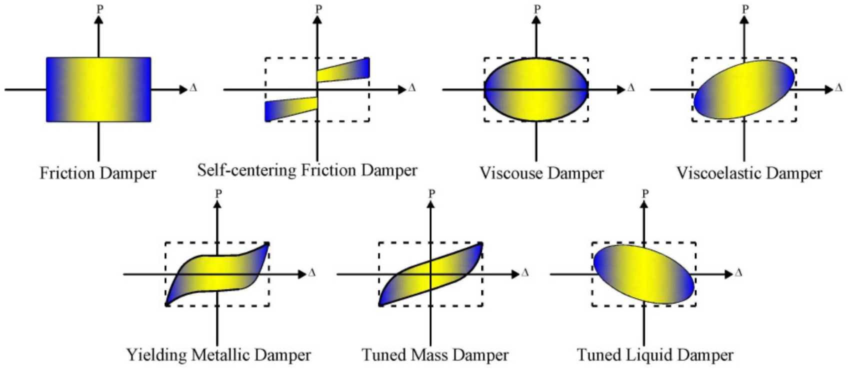


Figure 1: Force-displacement diagrams for passive control devices [4, 5, 6]

Friction-based control systems are classified as 1) Pall friction dampers, 2) Sumitomo dampers, 3) Slotted Bolted Connections (SBC) 4) Energy Dissipating Restraint (EDR) or self-centering dampers, 5) Limited Slip Bolted joints (LSB).

Taking advantage from friction brake pads in automotive and mechanical engineering, Dr. Avtar Pall (1979) first proposed Pall friction_dampers, which are appropriate for slender X brace steel frames, single diagonal and chevron bracing [7, 4]. Pall friction devices comprise of a series of steel plates clamped together using high strength bolts, which prevent compression bending at braces, and slip under predetermined load. Pall dampers have been proved to dissipate almost 80% of the input earthquake energy [8]. Later, an improved model of Pall dampers equipped by a T-section core plate was suggested by Wu (2005). The improved model made the first model cheaper and easier to be analysed because of simplicity of the construction [9]. Sumitomo metal industry proposed a uniaxial friction device made of stainless steel casing with pre-compressed internal springs and friction pads, which has been developed by Aiken and Kelly in 1990 in Japan. Results of testing a ¼ scaled-down 9-storey building controlled with these dampers showed a consistent and ideal Cloumb behaviour accompanied by 60% dissipated input earthquake energy. Afterwards, Constantinou and Reinhorn (1991) applied Sumitomo devices to seismic isolation systems of bridges to form the sliding interface [10]. The other friction devices, which apply Slotted Bolted Connections (SBC) in concentric braced frames, were proposed by Fitzgerald in 1989. The friction was defined based on steel sliding interface, however, a more stable steel-brass frictional behaviour was introduced by Grigorian and Popov (1993) [11, 1].

Flour Daniel Corp. proposed a more sophisticated friction device named Energy Dissipation Restraint (EDR) with self-centering capabilities provided by internal springs and end gap similar to Sumitomo devices [10]. EDRs are the only exception in friction-based control systems without a rectangular hysteresis loops. Their hysteretic behaviour depends on the characteristics of the device such as spring constant, gap size, core configuration and initial slip force [11, 1]. Pall and Marsh (1980) invented Limited Slip Bolted (LSB) joints based on brake lining pads for seismic controlling of large panel concrete structures. LSB joints are embedded in the contact lines of precast concrete walls in which they move relative to each other during earthquake, and the energy is dissipated through friction joints [12].

Concrete wall panels were first proposed by Nabih Youssef and Associates in order to seismic retrofit of a Rivera Library at the University of California at Riverside (UCR) [13]. Each precast concrete wall was connected to the lower beam with the bolted steel connectors and to the beam of the upper floor by three dampers bolted at the top of the panel. The energy was dissipated through the relative displacement of the adjacent floors due to seismic excitation. Afterwards, more valuable research was performed by Petkovski (2001) and Sasani and Popov (1997) on lightweight concrete panel equipped with friction dampers. Petkovski assessed the effectiveness of the friction panels on reducing some seismic responses of the controlled structures with different panel's characteristics (with opening, without opening and different thicknesses). In addition, he has proposed an optimum range for the ratio of the slip forces in the connections to the storey shear strength of the base frames [14, 15].

The intended goals of the current studies are to investigate the most appropriate slip load distribution pattern in terms of improving seismic behaviour, and to ascertain the optimum ranges for slip load ratios applied to 3, 5, 10, 15, and 20-storey RC frames. Studied frames are subjected to six real earthquake records including El-Centro, Imperial Valley, Cape Mendocino, Loma Prieta, Duzce, Northridge and one synthetic IBC spectrum compatible earthquake. For non-linear dynamic analyses using DRAIN-2DX software, three different element types, including inelastic beam and column (type 2), friction connection (type 4), and elastic panel (type 6) have been considered. Panel element is assumed to have eight displacement degrees of freedom, which account for five uncoupled deformation modes, and three rigid body modes at its four nodes [16]. The seismic responses, optimum range of slip load ratio, and the most appropriate slip force distribution pattern in terms of improving the seismic behaviour of the 10-storey RC frame with the characteristics shown in Fig.2 have been discussed in this research.

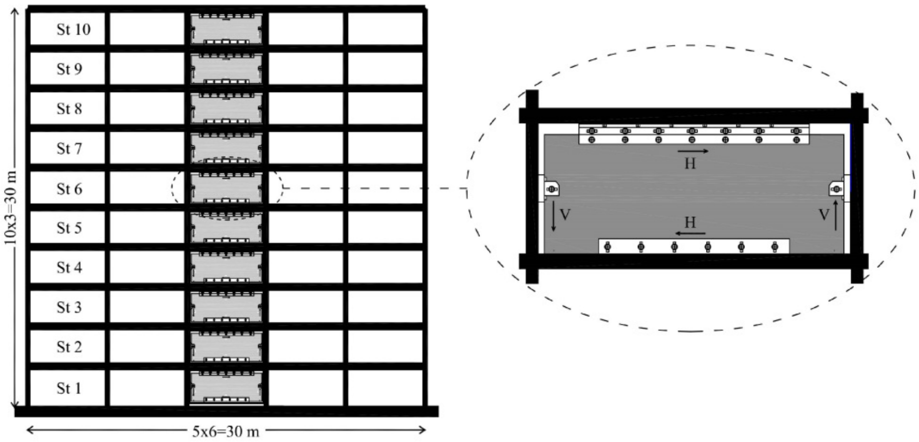


Figure 2: 10-storey RC frame with friction panels

FRICTION PANEL MECHANISM

As shown in Fig.3, friction damper consist of a concrete panel with four connections at its four sides. The friction mechanism is a simple panel-to-frame connection. It consists of two steel plates bolted at the top of the panel (external plates) and clamped together over a slotted steel plate anchored in the beam (central plate). Brass plates used at the friction surface (between the external plates and the central plate) were chosen on the basis of experimental evidence. A better slip/friction performance is obtained by steel-to-brass contact than by steel-to-steel [14]. The other panel-to-frame connections were designed to prevent both vertical and lateral movement of the panel with respect to the floor. Vertical support of the panel was provided by panel-to-column connections with horizontal slots, while horizontal support was supplied by connections between the panel and the floor. The latter connections have vertical slots to secure the movement in the friction connection, which is equal to the inter-storey drift [14].

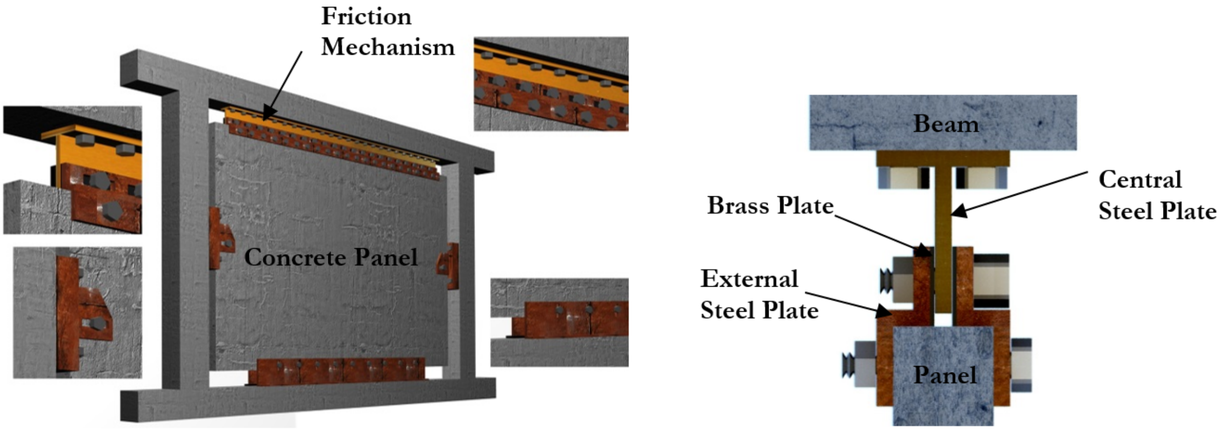
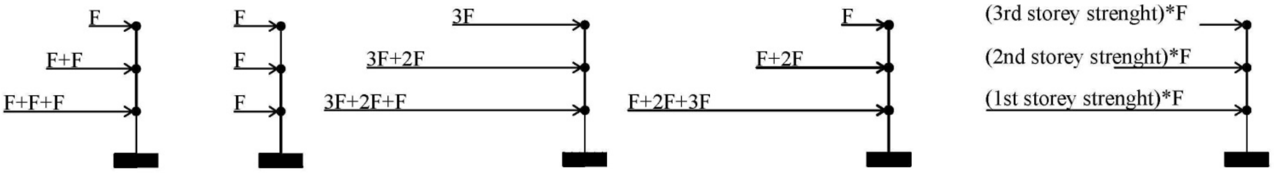


Figure 3: Friction panel and friction mechanism detailing.

SLIP LOAD DISTRIBUTION PATTERNS

Slip force in friction connections (Fs) is a main parameter that can be adjusted and tuned independently for each storey by controlling the clamping force in bolts. Such capability provides the possibility of different patterns for slip load distributions along the height of structures. For the case of cantilever distribution, an identical slip load threshold was considered in all stories, while for other patterns the values varied from one storey to the other. For uniform, triangular, and inverted triangular distributions, the loads increased from the top storey to the bottom based on a cumulative rule. However, for the storey strength proportional pattern, the slip load in each level was a constant coefficient of the same storey strength. Fig. 4 shows the different slip load distribution patterns used in this study.



i) Uniform ii) Cantilever iii) Trianglular iv) Inverted Trianglular v) Proportion to the Storey Strength

Figure 4: Schematic model of slip load distribution patterns

MAXIMUM INTER-STOREY DRIFT AND ROOF DISPLACEMENT RATIO

The maximum drift ratio is defined as the ratio of the maximum drift in a frame with friction panels to the maximum drift in a bare frame with no panels. Therefore, the ratio starts from one for no slip load case (Fs=0), and reduces gradually by increasing the slip load until it remains steady or increases slightly as shown in Fig. 5. Such result was found to be independent from the seismic excitation characteristics, and the overall trend was similar for all seven earthquake records. It was observed that the reduction was more significant up to a certain slip force limit, and after that increasing the slip force did not have a considerable effect. Fig. 5 indicates that, for the 10-storey frame, the maximum decrease in drift ratio (up to 38% decrease) was relevant to the uniform and triangle distribution patterns, which occurred in the slip load ratio between 0.8 and 1.5. Among all, the inverted triangular distribution had the least impact on improving the structural responses of the frame. Similar results were obtained for 3, 5, 15, and 20-storey frames. The maximum roof displacement ratios also decreased considerably for all distribution patterns (up to around 42%) by increasing the slip force.

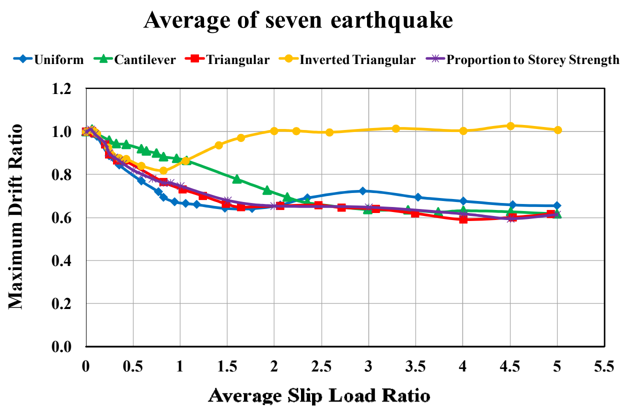


Figure 5: Variation of maximum inter-storey drift ratio

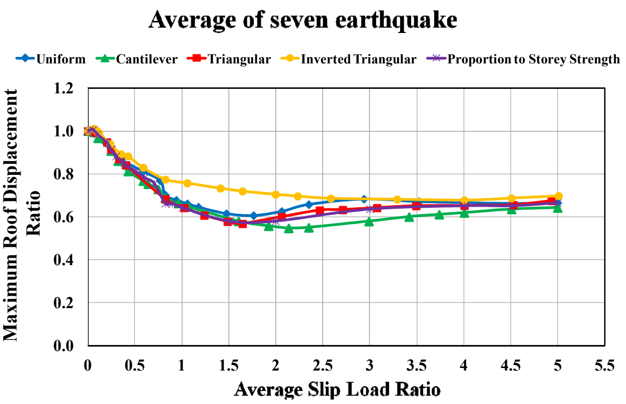


Figure 6: Variation of maximum roof displacement ratio

Fig. 6 illustrates that the most reduction in the 10-storey frame was observed for slip load range of 1.3 to 1.6. In addition, it is depicted that frames designed with the triangle and proportion to the storey strength slip load distributions performed better than others. Although after this slip load ratio range (1.3-1.6) cantilever pattern lead to more reduction, the most effective patterns are those which have the most impact within the optimum range. The overall trend of each seismic response (maximum inter-storey drift and roof displacement) was similar for all size of the buildings and seismic excitations.

ENERGY DISSIPATED IN THE STRUCTURAL ELEMENTS (RW1)

Rw1, the first energy dissipation parameter, is the ratio between the statistic work in the frame structural members equipped with friction dampers to the work in the members of the corresponding bare frame [14, 15]. This parameter represents the energy dissipation in the structural elements. The results indicate that Rw1 starts from one (for Fs=0) and reduces up to an average slip load ratio between 0.8 and 1.4, then it goes up by increasing the slip load and remains almost steady (Fig. 7). This trend implies the fact that the work in the frame elements first decreases by increasing the dissipated energy in friction panel, and it has been observed to be the same for all models regardless the slip load distribution and input earthquake excitation. The maximum drop was usually observed for triangle and uniform distribution (more than 60% drop). Besides, it is clear that proportional to the storey strength pattern has the same effect as the triangular one. Fig. 7 also shows that increasing the slip load ratio more than a limit (here around 1.0) would not lead to a better seismic performance. Although the range of optimum slip load ratio differs for different frame heights (for example, an optimum slip load range of 1.7-2.5 for 5-storey and 0.4-0.8 for 15-storey), similar trend were observed for all frames.

ENERGY DISSIPATED IN THE FRICTION CONNECTION (RW2)

The second parameter, Rw2, is the ratio between statistic work of the friction loads in the upper supports of the panel, and the work carried out by damaging of the main structural members in the controlled structure [14, 15]. The Rw2 factor shows the energy dissipation level in the friction panels. Therefore, maximum Rw2 represents the optimum design solution. Fig. 8 illustrates that the Rw2 factor tends to zero for very low and very high slip forces (i.e. non-active dampers). The results imply that according to the different distribution patterns used for the 10-storey frame, Rw2 factor reaches its maximum value for a slip load ratio range of 0.8-1.4, which considered as the most effective domain to obtain the best control action. Also, Fig. 8 shows that the maximum energy dissipation of friction connections was observed in the frame designed with triangle and uniform distributions, which was in agreement with the previous response parameters (Fig. 5 and Fig. 6). The peaks of the Rw2 ratio indicated that friction connections dissipate the earthquake energy almost 6 or 7 times greater than main structural elements. In other words, friction panels account for increasing the energy dissipation capacity of the structure and, consequently, decreasing damage to the structural elements.

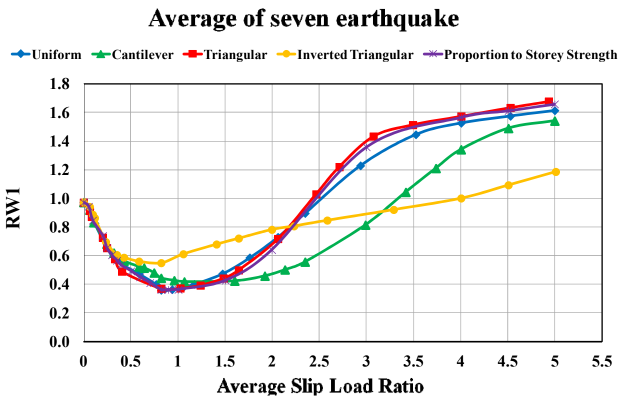


Figure 7: Energy dissipation RW1 for different slip load patterns

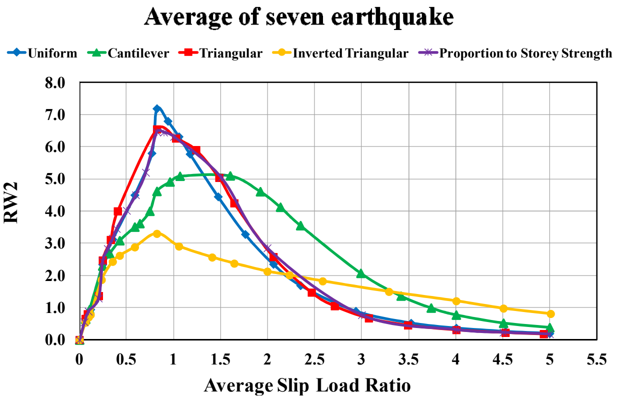


Figure 8: Energy dissipation RW2 for different slip load patterns

The results of this study, in general, show that the optimum designed friction-wall panels can significantly improve the seismic behaviour of deficient RC frames.

CONCLUSION

Using friction panels can lead to a significant improvement in some seismic responses (inter-storey drift and roof displacement) of the studied RC frames (3, 5, 10, 15, and 20-storey) by increasing the energy dissipation capacity of the systems. It was shown that, on average, friction panels can decrease the maximum inter-storey drift and maximum roof displacement of the 10-storey frame by up to 38% and 42%, respectively.

The overall results of all seismic responses, including the inter-storey drift and roof displacement for all studied frames indicated that uniform and triangle distribution patterns, in general, would lead to a considerably better seismic performance compared to the others. Triangle and proportional to the storey strength patterns have been observed to have the same effects on the structural responses. Inverted triangular pattern has shown as the least effective one on the seismic improvement. It was confirmed that, there is an optimum design range for the slip load ratios, which result in higher energy dissipation in the friction panels. This range was ascertained to be between 0.8 and 1.4 for a 10-storey friction-based controlled frame. However, the range would be decreased by increasing the height of the frame (for example, an optimum slip load range of 1.7-2.5 for 5-storey and 0.75-1.0 for 15-storey).

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