Optimum Distribution of Slip Load of Friction Dampers Using Multi- Objective Genetic Algorithm

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SUMMARY:
This paper deals with the optimization of slip load of friction dampers using fast and elitist non-dominated Genetic Algorithm (NSGAII) in order to mitigate structure responses. Due to this, two 2-dimensional 5-storey and 10-storey shear frames are considered and the equations of motion of frames for both friction-damped and blank frame are solved using Newmark's method in MATLAB software. Then the slip load value of friction damper is determined in 2 cases: in the first one, the optimum slip load of each friction damper is computed using NSGAII according to simultaneous minimization of three objective functions related to frame responses. After that in second case the total slip load of friction dampers from the first case is distributed among dampers, uniformly. The frames responses are evaluated in these 2 cases and compared with the ones of uncontrolled frames. The results show that optimum distribution of slip load of friction dampers improves the performance of dampers in seismic response.

Keywords: Vibration Control, Friction damper, Slip load, NSGAII

1. INTRODUCTION

In the last two decades, many control algorithms and devices have been proposed in order to reduce the seismic responses of structures and enhance the structural seismic protection without modifying the existing structural strength, rigidity and ductility. Structural control systems, including passive, semi-active, active and hybrid control are being used in civil engineering widely and each of them has their own advantages depending on specific application. There are various types of devices which can dissipate energy passively such as friction dampers, metallic dampers, viscous fluid dampers and viscoelastic dampers and they have several advantages of low cost, easy installation and less maintenance. Friction dampers are so efficient because of simple mechanism and strong instant effect of friction on suppressing earthquake energy. Two proposed types of friction dampers are the Limited Slip Bolted (LSB) joint and pall friction damper. The LSB has been proposed by Pall et al for seismic control of large panel structures [1]. It consists of brake lining pads between steel plates. The Pall friction damper which has been proposed by Pall and Marsh is positioned in the intersection of 'X' braces and it includes rigid diagonal bars with friction hinges at their intersection points connected together by means of horizontal and vertical elements [2]. Filiatrault and Cherry determined the optimum slip load distribution for the friction devices by minimizing a relative performance index derived from energy concepts and proposed slip load spectrum for evaluation of optimum slip load [3]. Pall's friction devices have been installed at different buildings such as library of the Concordia University and building of headquarters of the complex of Canadian space agency.

2. FRAME MODELING AND EQUATION OF MOTION

In this study, two 5-storey and 10-storey steel shear frames have been considered for evaluating the efficiency of different height-wise distribution of slip loads on the seismic performance of friction dampers. The mass and stiffness matrices are determined and the damping matrix is obtained using Rayeileh method with the assumption of 5% for damping ratio of first and middle mode to ensure contributing all effective modes in analysis [4]. Two degrees of freedom, corresponding to the horizontal displacement of the storey and the brace with device has been considered for each storey [5]. The total number of degrees of freedom varies from N when all dampers are in stick phase to 2N when all dissipators slide simultaneously. During the numerical solution process, the equations of motion are separated into two subsets in which the sub-indices *st* and *sl* represent the stick phase and the sliding phase, respectively. The equations of motion are solved using Newmark's method in which the displacement, velocity and acceleration at time step *i+1* are computed from known displacement, velocity and acceleration at time step *i* [4].

The equations of motion of structures under the earthquake excitation can be derived as follows:

$$M\ddot{u}_{st+sl} + C\dot{u}_{st+sl} + Ku_{st+sl} = -Mr\ddot{u}_g(t) - F_{st+sl} \tag{2.1}$$

$$M = \begin{bmatrix} M_f & 0 \\ 0 & M_d \end{bmatrix},\ C = \begin{bmatrix} C_f + C_{d2} & C_{d3} \\ (C_{d3})^T & C_{d1} \end{bmatrix},\ K = \begin{bmatrix} K_f + K_{d2} & K_{d3} \\ (K_{d3})^T & K_{d1} \end{bmatrix},\ u_{st+sl} = \begin{Bmatrix} u_{f,st+sl} \\ u_{d,st+sl} \end{Bmatrix},$$
$$r = \begin{Bmatrix} r_f \\ r_d \end{Bmatrix},\ F = \begin{Bmatrix} +F_{st+sl} \\ -F_{st+sl} \end{Bmatrix},\ r_f = 1,\ r_d = 1 \tag{2.2}$$

Where:

$$M_d = \begin{bmatrix} m_{d1} & 0 & \dots & 0 \\ 0 & m_{d2} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & m_{dN} \end{bmatrix},\ C_{d1} = \begin{bmatrix} c_{d1} & 0 & \dots & 0 \\ 0 & c_{d2} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & c_{dN} \end{bmatrix},\ C_{d2} = \begin{bmatrix} c_{d2} & 0 & \dots & 0 \\ 0 & c_{d3} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & 0 \end{bmatrix},$$
$$C_{d3} = \begin{bmatrix} 0 & -c_{d2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ \vdots & 0 & \ddots & -c_{dN} \\ 0 & \dots & 0 & 0 \end{bmatrix},\ K_{d1} = \begin{bmatrix} k_{d1} & 0 & \dots & 0 \\ 0 & k_{d2} & 0 & \vdots \\ \vdots & 0 & \dots & 0 \\ 0 & \dots & 0 & k_{dN} \end{bmatrix},\ K_{d2} = \begin{bmatrix} k_{d2} & 0 & \dots & 0 \\ 0 & k_{d3} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & 0 \end{bmatrix},$$
$$K_{d3} = \begin{bmatrix} 0 & -k_{d2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ \vdots & 0 & \ddots & -k_{dN} \\ 0 & \dots & 0 & 0 \end{bmatrix} \tag{2.3}$$

In the above equations, M_f , C_f , and K_f are respectively, the $N \times N$ dimensional mass, damping and stiffness matrices of the frame without the bracing members, M_d , C_{d1} , C_{d2} , C_{d3} , K_{d1} , K_{d2} and K_{d3} are $N \times N$ mass, damping and stiffness matrices of the braces with friction dampers, respectively. $u(t), \dot{u}(t)$ and $\ddot{u}(t)$ represent the displacement, velocity and acceleration vectors of the system. $\ddot{u}_g(t)$ denotes the ground acceleration, *r* is the unit vector and F is the vector of control forces.

The motion of each storey of the structure consists of two phases [6]:

1) Stick or non-sliding phase wherein the frictional force (F_{st}) is less than the maximum frictional resistance of damper. During the stick phase the following conditions are satisfied:

$$\begin{aligned} &\ddot{u}_{f,st} = \ddot{u}_{d,st} \\ &\dot{u}_{f,st} = \dot{u}_{d,st} \\ &u_{f,st} - u_{d,st} = \text{constant} \\ &\left|F_{st}\right| < \mu N_{pre} \\ &F_{st} = M_{d,st}\ddot{u}_{d,st+sl} + (C_{d3,st})^T \dot{u}_{f,st+sl} - C_{d1,st}\dot{u}_{d,st+sl} + (K_{d3,st})^T u_{f,st+sl} \\ &+ K_{d1,st}u_{d,st+sl} + M_{d,st}r\ddot{u}_g(t) \end{aligned} \tag{2.4}$$

In the Eqn. 2.4, μ is the friction coefficient and N_{pre} is the normal force on the sliding surfaces.

2) Sliding or slip phase in which the above conditions are not satisfied and the frictional force exceeds the maximum frictional resistance. Due to the sliding at each floor, the brace degree of freedom related to the floor is taken into account in the equations of motion, also the frictional force acts opposite to the direction of the relative velocity between the floor and the damper.

The stick and sliding conditions are investigated in each time step for each storey. At the first instant, the structure is assumed to be in stick phase and when the conditions of stick phase become unbalanced, the brace with device at that storey enters to the sliding phase, this phase may return to stick phase when the relative velocity $(\dot{u}_f - \dot{u}_d)$ becomes zero or its sign changes during motion and corresponding to these conditions, the equation of motion is converted to accurate status before calculating responses during the next time step. A code has been written in MATLAB environment for solving the equation of motion of frame under different earthquake accelerations. Fig. 2.1 represents the frames model with dampers installed on braces.

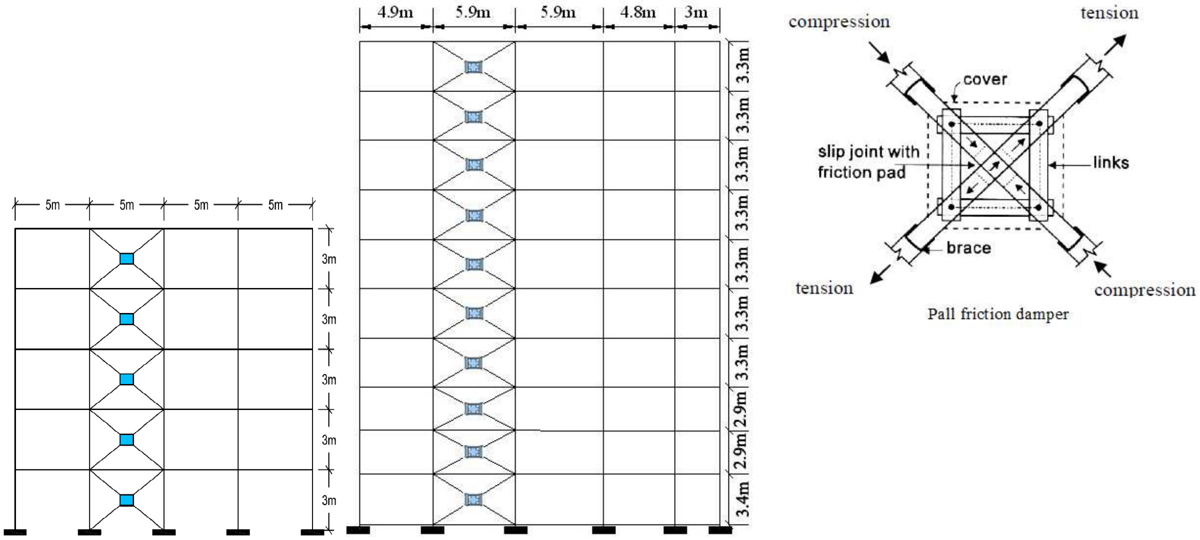

Figure 2.1. Frames model and Pall friction damper

The mass and stiffness data of 5 and 10-storey frames are shown in Table 2.1 and Table 2.2, respectively.

Table 2.1. Properties of 5-stroey frame and bracings + dampers

Storey	1	2	3	4	5
Mass(ton)	6.73	6.73	6.73	6.73	5.93
Stiffness(MN/m)	65.69	45.84	34.93	22.8	15.66
Brace Stiffness (MN/m)	111.3	111.3	111.3	111.3	111.3

Table 2.2. Properties of 10-stroey frame and bracings + dampers

Storey	1	2	3	4	5	6	7	8	9	10
Mass(ton)	10.1	9.9	10	10.2	10.2	10.2	10.2	10.2	10.2	10.4
Stiffness(MN/m)	111.6	179.9	157.4	106.8	60.1	60.1	36.6	36.6	28.5	11.4
Brace Stiffness(MN/m)	159.8	179.7	179.7	163.7	163.7	130	130	105.9	105.9	105.9

In order to determine the frame responses 10 earthquake acceleration records with different properties have been selected and according to Iranian Code of Practice for Seismic Resistant Design of Buildings are scaled to 0.42g [8]. Table 2.3 represents the properties of earthquake excitations which are used in this study.

Table 2.3. Properties of earthquake acceleration records

Num	Earthquake name	Date	Duration (s)	PGA (g)
1	Victoria	1980/06/09	15.57	0.101
2	Zangiran	1994/06/20	26.875	0.0232
3	Friuli	1976/09/11	38.84	0.041
4	Northridge	1994/01/17	39.98	0.34
5	Loma prieta	1989/10/18	39.6	0.244
6	Kocaeli	1999/08/17	29.995	0.318
7	Tabas	1978/09/16	32.82	0.852
8	Coyote lake	1979/08/06	28.455	0.108
9	Sanfernando	1971/02/09	29.99	0.324
10	N.palm spring	1986/07/08	20.13	0.129

3. MULTI-OBJECTIVE OPTIMIZATION

Many real-world problems especially engineering problems involve simultaneous optimization of several different and competing objectives. Two goals of multi-objective optimization are: (i) convergence to the pareto-optimal set, and (ii) maintenance of diversity in solutions of pareto-optimal set. Evolutionary algorithms have been proved to be appropriate for multi-objective optimization problems due to their ability to capture a set of solutions in a single simulation, unlike the traditional mathematical programming methods. Additionally, evolutionary algorithms are less sensitive to the shape of the pareto front which consists of pareto optimal solutions that are non-dominated solutions and no other solutions in the search space are superior to them, considering all objectives. Among evolutionary algorithms, Fast and Elitist Non-Dominated Sorting Genetic Algorithm (NSGAII) is a suitable method that can satisfy the goals of multi-objective optimization [7]. NSGAII uses elitism and a crowded comparison operator that ranks the population based on both pareto dominance and region density. This crowded comparison makes the NSGAII considerably faster and the convergence and ability to find a diverse set of solutions are better with NSGAII in comparison with other methods. In this approach the best solutions are chosen in each generation. So, the optimum solutions can be found using NSGAII with defining the objective functions and main genetic algorithm operators including selection, crossover and mutation.

4. DETERMINATION OF OPTIMUM SLIP LOAD OF FRICTION DAMPERS

The most important parameter in design of friction dampers is determination of optimum slip load that causes better responses of the structure under earthquake accelerations. In order to determine the optimum bound of slip load of friction dampers, a range beginning from 30KN is considered for 5-storey frame and increases as much as the structure responses are reduced, simultaneously. The frame responses are obtained for each value of slip load under different earthquake excitations using non linear time history analysis. In this study the maximum roof displacement and acceleration and also the maximum base shear have been investigated for evaluating the optimum range of slip load. Fig 4.1 represents the maximum roof displacement and acceleration and maximum base shear of 5-storey frame subjected to Victoria and Kocaeli earthquake records, as an example. According to these figures, simultaneously, it is observed that the responses are reduced appropriately in a slip load range between 190KN and 240KN for Victoria excitation and a range of 130 to 160KN for Kocaeli record.

4.1. Determination of optimum slip load using Non-Dominated Sorting Genetic Algorithm

Due to optimization of slip load of friction dampers using NSGAII, two different cases are considered: in first case, the slip load value of each damper is considered as an independent variable which can have different value from other damper’s slip load and its optimum value is determined via NSGAII. Actually in this case the total slip load is distributed non-uniformly in height of the frame. In the second case the total slip load is distributed uniformly among dampers and all dampers have the same

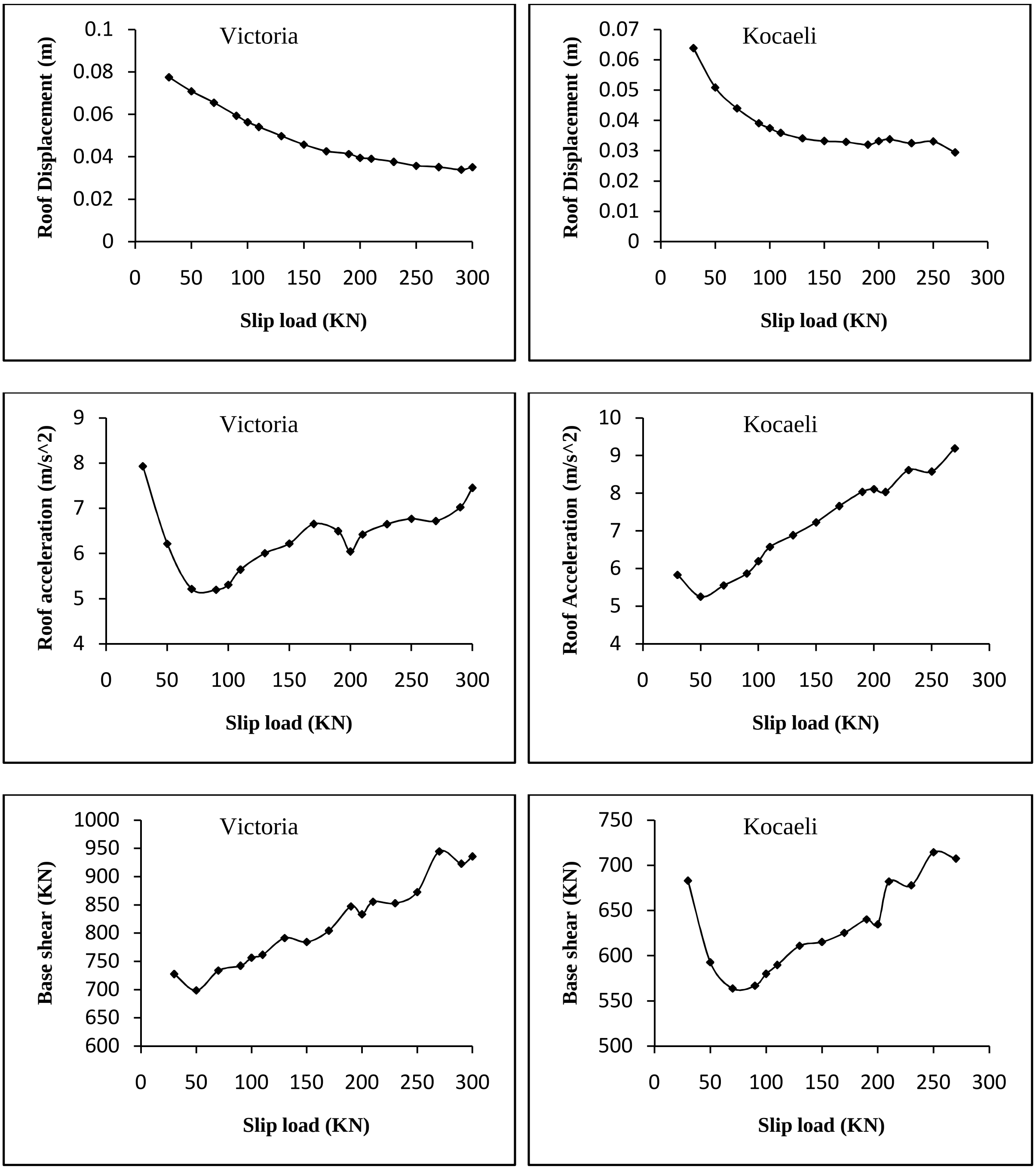

Figure 4.1. Maximum roof displacement, acceleration and maximum base shear obtained for different slip load values subjected to Victoria and Kocaeli earthquakes

slip load value. It is mentioned that the total slip load in both cases is equal. Due to use of NSGAII an m-file has been provided to define the variables and objective functions. In this study, the following objective functions are minimized simultaneously using NSGAII in MATLAB.

$$F1=\min\left\{\left(\frac{u_{\max,opt}}{u_{\max,uc}}\right)_{roof}\right\} \quad F2=\min\left\{\left(\frac{\ddot{u}_{\max,opt2}}{\ddot{u}_{\max,uc}}\right)_{roof}\right\} \quad F3=\min\left\{\frac{R_{\max,opt}}{R_{\max,uc}}\right\} \tag{4.1}$$

In which $u_{\max,opt}, u_{\max,uc}, \ddot{u}_{\max,opt}, \ddot{u}_{\max,uc}, R_{\max,opt}, R_{\max,uc}$ denote the maximum displacement of roof after and before damper installation, the maximum acceleration of roof after and before damper installation and the maximum base shear after and before damper installation, respectively. The number of variables in first case is 5 and 10 for 5-storey and 10-storey frame according to installment of one damper in each story, and the lower and upper bounds of variables is considered regarding the optimum range resulted from non-linear time history analyses for each slip load value. The genetic algorithm parameters are set according to Table 4.1.

Table 4.1. Genetic algorithm parameters

selection	crossover	mutation	population	generation
Tournament	Two point	Gaussian	30	200

By running genetic algorithm a pareto front is obtained for each earthquake in which each individual represents the slip load value of each damper. Regarding objective values of each individual of pareto front, one of them is selected which causes balance between three objective functions. Figure 4.2 shows the pareto front which is related to Kocaeli earthquake.

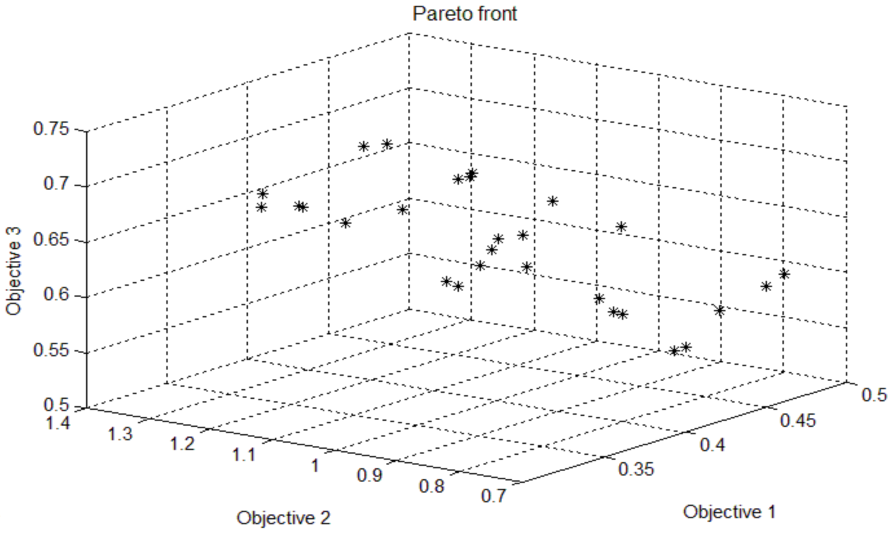

Figure 4.2. Pareto front obtained by running NSGAII under Kocaeli earthquake.

The NSGAII is run for 10 earthquake accelerations and for each of them an optimum individual is selected from pareto front. The final slip load value of each damper is determined in two cases of variable and uniform distribution using Vinzuri average because of the significant difference of slip load value of each damper under some earthquake accelerations in comparison with other records. The slip load of each damper under all earthquakes and their average are shown in Table 4.2. The similar trend has been performed for 10-storey frame and the average slip load of each damper is presented in Table 4.3.

5. NUMERICAL RESULT

5.1. Result of 5-Storey Frame

By applying the final slip load of each damper with uniform and variable distribution, the frame responses such as maximum story displacement, inter-story drift, acceleration and maximum base shear are determined subjected to each of 10 earthquake excitations and the average responses is calculated. The maximum base shear of uncontrolled frame and friction damped frame with uniform and variable distribution of slip load is shown in Table 5.1.

Table 4.2. Optimum value of slip load of dampers of 5-story frame under different excitations

Earthquake	Slip load distribution	Slip load of dampers					Total
		Storey					
		1	2	3	4	5	
Victoria	variable	212	233.5	248	176	168	1037.5
	uniform	207.5	207.5	207.5	207.5	207.5	1037.5
Zangiran	variable	213	207	142	272	246	1080
	uniform	216	216	216	216	216	1080
N.palm springs	variable	308.5	306	307	196	295	1412.5
	uniform	282.5	282.5	282.5	282.5	282.5	1412.5
Friuli	variable	175	232	248	183	222	1060
	uniform	212	212	212	212	212	1060
Sanfernando	variable	347	344	349	190	330	1560
	uniform	312	312	312	312	312	1560
Coyote lake	variable	160	201	223.5	112	206	902.5
	uniform	180.5	180.5	180.5	180.5	180.5	902.5
Northridge	variable	373	374	376.5	344	357.5	1825
	uniform	365	365	365	365	365	1825
Tabas	variable	325	311	274	285	257.5	1452.5
	uniform	290.5	290.5	290.5	290.5	290.5	1452.5
Kocaeli	variable	209	76.5	74	235	163	757.5
	uniform	151.5	151.5	151.5	151.5	151.5	757.5
Loma prieta	variable	236	239.5	211.5	243.5	224.5	1155
	uniform	231	231	231	231	231	1155
Average slip load	variable	257	258	253.5	224	245	1237.5
	uniform	247.5	247.5	247.5	247.5	247.5	1237.5

Table 4.3. Average of optimum value of slip load of dampers of 10-story frame

Slip load distribution	Slip load of dampers										Total
	Storey										
	1	2	3	4	5	6	7	8	9	10	
Variable	331	287	305	258.5	307	278.5	296	268	271.5	272.5	2875
Uniform	287.5	287.5	287.5	287.5	287.5	287.5	287.5	287.5	287.5	287.5	2875

Table 5.1. Average maximum base shear of uncontrolled frame and friction damped frame

		Average maximum base shear (KN)
Bare shear frame		1436.99
Braced frame		2262.637
Controlled frame	Variable distribution	1021.65
	Uniform distribution	1048.5

According to the Table 5.1, it is found that the average maximum base shear in optimum slip load distribution is less than the corresponding value in uniform distribution. Also, the maximum base shear of friction damped frame has reduction equal to 28.77% and 55% compared to bare frame and braced frame, respectively. The ratio of mean responses of friction damped frame to the average responses of braced frame without dampers in two cases of slip load distribution are shown in Fig 5.1. This figure indicates that variable slip load distribution of friction dampers in comparison with uniform distribution provides better performance of friction dampers and causes more reduction of responses especially in reducing maximum story displacement and inter-story drift. It is observed that by variable slip load distribution more reduction equal to 11% and 20% has been achieved in the average maximum roof displacement and inter-story drift, respectively. However, the maximum roof acceleration hasn’t changed in both slip load distribution.

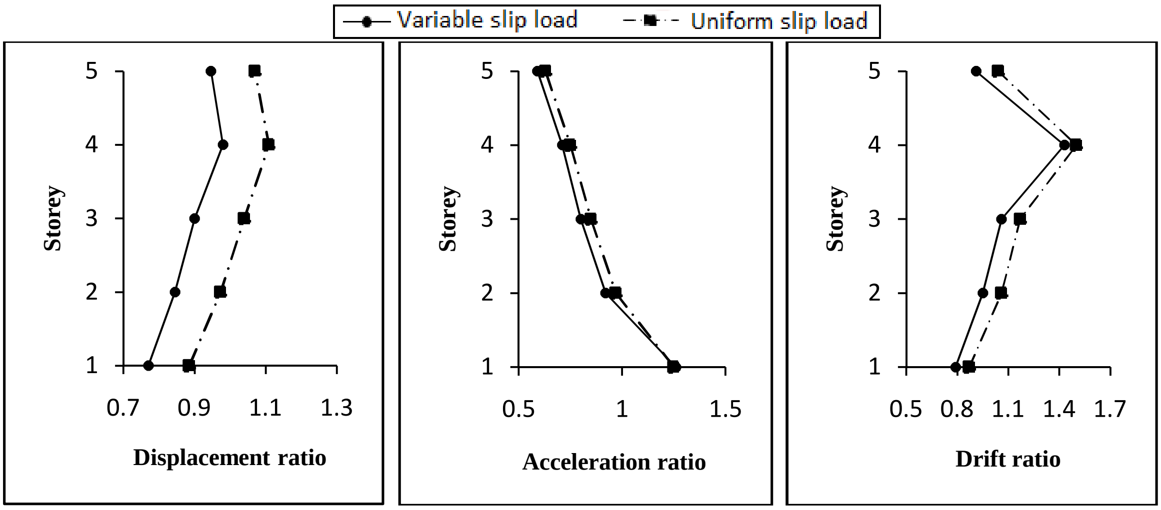

Figure 5.1. Comparison of frame response ratio of friction damped frame with uniform and variable slip load distribution to braced frame for each story

Fig. 5.2 represents the mean of maximum responses of bare and braced frame and friction damped frame with variable slip load distribution. It is observed that in comparison with the bare frame, friction damped frame provides comparable reductions in frame responses especially in the maximum displacement and maximum inter-story drift. The amount of acceleration also decreased. However, the acceleration response is not much affected at the first story. Although, compared to the responses of braced frame, controlled frame has caused noticeable reduction in maximum acceleration. The amount of maximum inter story drift is not always reduced when friction dissipators are used and in some situation the maximum reduction is obtained for braced frames. The amount of response reduction of friction damped frame with variable slip load distribution is shown in Table 5.2.

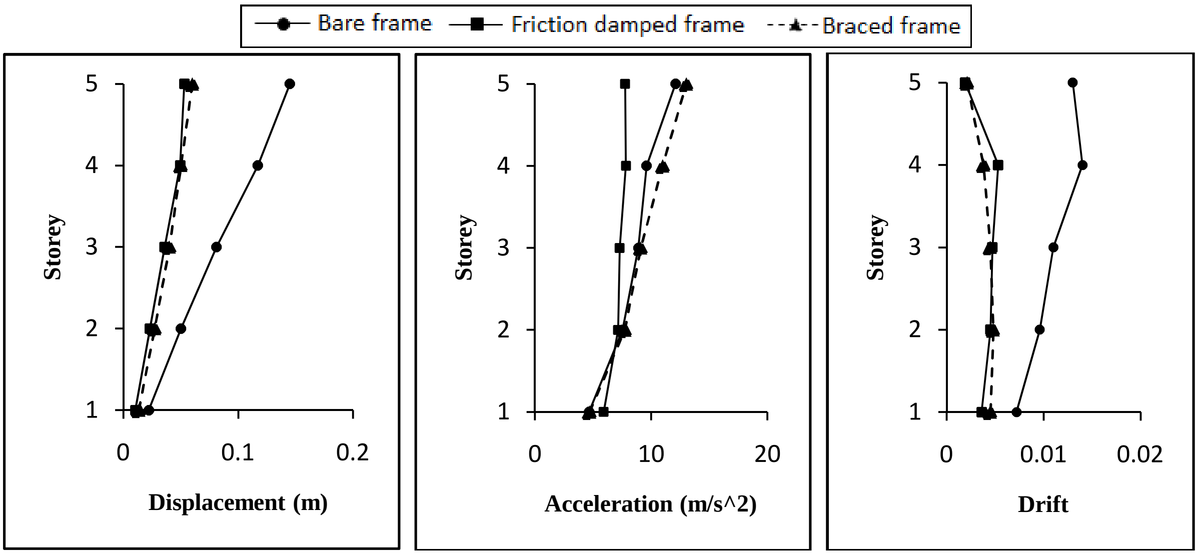

Figure 5.2. The average of maximum responses of bare frame, braced frame and friction damped frame

5.2. Result of 10-Storey Frame

The average responses of 10-storey frame were obtained subjected to 10 earthquake accelerations. According to Fig. 5.3 and Table 5.3 it is concluded that like the 5-storey frame, the optimum slip load distribution of dampers causes more response reductions especially in maximum story displacement and inter-story drift ratio.

Table 5.2. The amount of response reduction of friction damped frame to the response of uncontrolled frame

Maximum response	Controlled frame to	The reduction percent of controlled frame response to braced frame response				
		1	2	3	4	5
Displacement	Bare frame	53.18	54	55.80	57.78	63.45
	Braced frame	22.56	15.44	10.5	1.2	11.67
Acceleration	Bare frame	-26.82	5.05	18.09	18.54	35.87
	Braced frame	-25.74	7.62	19.89	28.91	40.45
Drift	Bare frame	50	53.13	57.27	62.14	85.38
	Braced frame	20	6.25	-4.44	-39.47	9.52

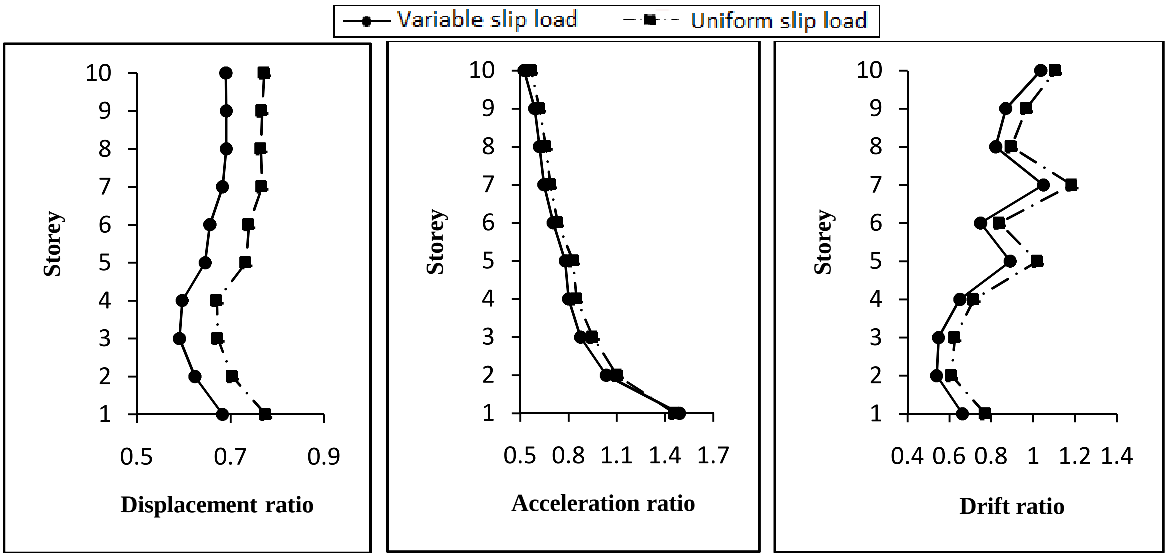

Figure 5.3. Comparison of frame response ratio of friction damped frame with uniform and variable slip load distribution to braced frame for each story

Table 5.3. Average maximum base shear of uncontrolled braced frame and friction damped frame

		Average maximum base shear(KN)
Braced frame		4420.6
Controlled frame	Variable distribution	1718
	Uniform distribution	1741.5

Fig. 5.4 indicates that the maximum roof displacement and acceleration of controlled frame with variable distribution has been decreased 31% and 48%, respectively, in comparison with the uncontrolled braced frame. The amount of reduction of inter-story drift in all stories except in the seventh and tenth floor is quite appropriate and this is equal to 45% in third floor.

6. CONCLUSIONS

In this study, the effectiveness of optimized height-wise slip load distribution of pall friction dampers in reducing the responses of a 5-storey and 10-storey, 2-dimensional shear frame has been investigated. The slip load value of friction dampers has been optimized in two different variable and uniform distribution using NSGAII.

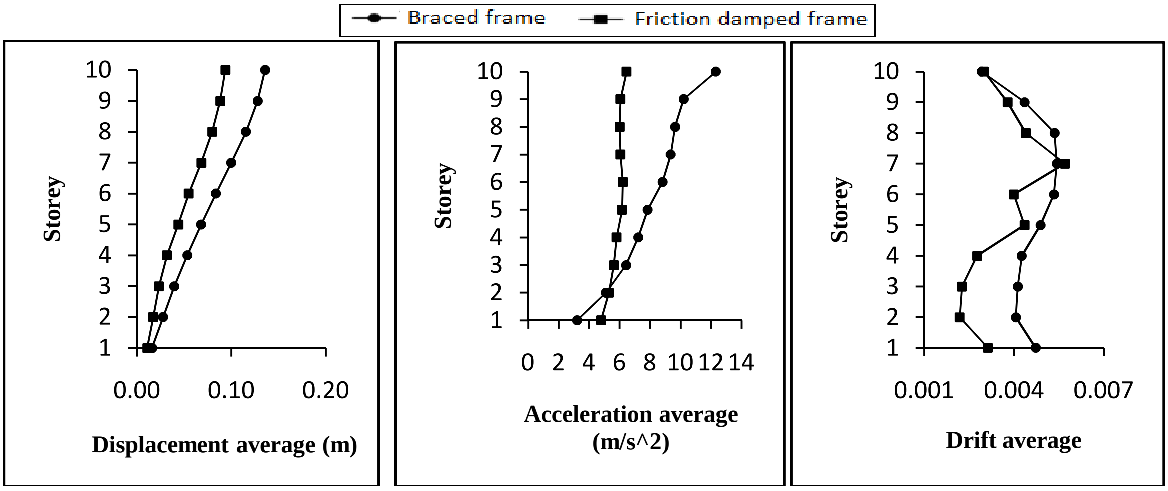

Figure 5.4. The average of maximum responses of braced frame and friction damped frame

Based on this study the following conclusions can be drawn:

1) The optimum height wise of slip load of friction dampers in comparison with uniform distribution of slip load provides better performance of dampers in response reduction especially in storey displacement and inter story drift.
2) The advantage of friction damped frame to braced frame is the significant reduction of base shear and acceleration. However, controlled frame causes appropriate decrease in displacement and inter-storey drift.
3) Incorporation of friction dampers in the 5-storey bare frame causes significant reduction in floor displacement and floor drift ratios.
4) Compared to the response of braced frame, the dynamic response of building is not always reduced by using friction dampers and the maximum reduction may be obtained for braced frames.
5) NSGAII is an appropriate procedure in determination of optimum design parameters. However the objective functions and the genetic algorithm operators have strong effects on optimum variable.

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