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DOWNSIZING OF MEMBERS THROUGH NUMERICAL ANALYSIS OF STEEL MULTI-STORIED FRAME WITH PASSIVE FRICTION DAMPERS AT BASE

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Abstract. *In this paper, the vibration control systems using passive dampers settled at the base of steel buildings with the effect of reducing the total steel weight of multi-storied frames with sliding bearings is investigated. The passive friction is one of the vibration control device that is important to use the technology to prevent or minimize damage to buildings[1], and the device can dissipate the seismic energy by sliding during an earthquake excitation. This research address vibration control system permits the downsizing of members of the steel super-structure, which reduces the total steel weight. The first story of the building could contribute to base-isolation because of the passive friction dampers at the bottoms of some columns. Two steel frames were simulated for the research by using OpenSees. The first consisted of large-sized columns and beams while the other utilized smaller member sizes. Both steel frames used columns in the first story equipped with passive friction dampers, which were connected at the base with side-by-side columns. A series of numerical simulations was conducted and the results were compared regarding the inter-story drift angle, slide deviation and seismic energy under earthquake excitations. Finally, results from the numerical analyses of the effect of the base-isolation on the total weight reduction of the multi-storied steel frame were summarized.*

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1 INTRODUCTION

Friction dampers are generally used as a member of vibration control in architectural buildings. In recent, study on friction dampers is making steady progress because the device performance is not only highly controlled and maintained, but also the mechanical property of the device is rather simple. Although there are many experimental analyses[2] and numerical analyses[3] of friction dampers and application for equipment into structures, the study on the flexible use of the friction damper is sparse. Therefore, the objective of this research is to investigate the practical properties of weight reduction of steel frame, which equipped with friction dampers at the base of a building. For designing the weight reduced frame the seismic response of frame equipped with friction dampers has been investigated for determine the coefficient of friction dampers equipped into weight reduced frame.

In this research, friction dampers settled at the bottom of a building frame without connection at the column bases can act as vibration controls for the building. These passive friction dampers can decrease the seismic energy absorbed by the building by sliding motions, thus decreasing the maximum inter-story drift angle of the building. A base-isolation system can be realized by incorporating friction dampers at all column bases in a frame[4]. In order to distribute the slip load uniformly across all dampers, each column base in the building framework can be connected with tying beams. Therefore, all bases of the frame with friction dampers can be restored for spring-back[5]. This permits the flexible use of the reduction of the total steel weight, achieved by downsizing the members of the steel frame equipped with passive dampers[6]. The indices describing the seismic responses of the frameworks and friction dampers are the inter-story drift angle and slide deviation, which must be characterized prior to implementing the described base-isolation system. In this study, the seismic response of the frames and friction dampers are examined by means of analytical simulations.

In this paper, friction dampers are modeled and analyzed by means of OpenSees that is one of multi-purpose structural analysis program. Friction elements are settled at the bottom of a frame. Incorporating friction dampers into the steel frame influences the seismic response of the steel frame. Indexes for the grasp of seismic responses of the frame and friction elements are inter-story drift angle and slide deviation of friction elements, and they were examined by comparing with respect to the indexes by means of analytical parameters.

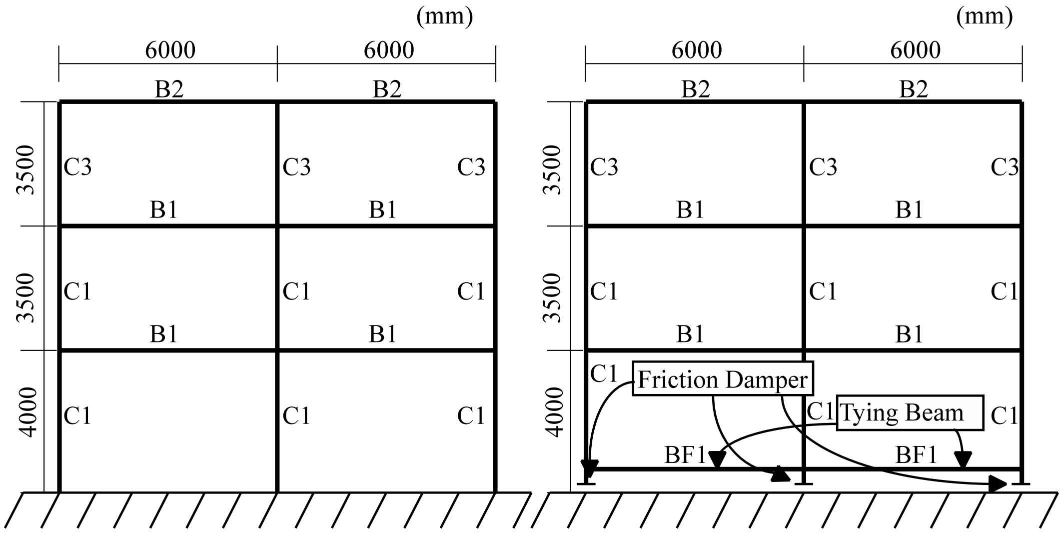
2 ANALYTICAL MODEL

Analytical model in numerical analysis of this research is described in this chapter.

2.1 Analytical Frame

In this chapter, the outline of the analysis frame shown in Fig. 1. The two-bay three-story steel frame, designed based on Japanese building codes, was prepared for a series of numerical analyses. The original frame that the base is fixed on a foundation is depicted in Fig. 1(a). The original frame equipped with friction dampers is shown in Fig. 1(b).

The columns and beams of the original frame both with and without friction dampers are steel hollow sections and steel side-flange sections, respectively, while the friction dampers are represented as special mechanical elements. The hysteretic behavior of the columns and beams include isotropic and kinematic hardening. The size of the cross-sections of the beams and columns of the original frame and steel weight of every story of original frame are shown in Table 1. The size of a cross section of the tying beam is same with the first story. The material property of each member is summarized in Table 2.



(a) Without fiction damper (b) With friction damper

Figure 1: Original frame models.

Story	Column (mm)	Beam (mm)	Steel Weight (t)
1	RHS - 300 x 300 x 16	H - 400 x 200 x 8 x 13	6.06
2	RHS - 300 x 300 x 16	H - 400 x 200 x 8 x 13	5.64
3	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	4.30

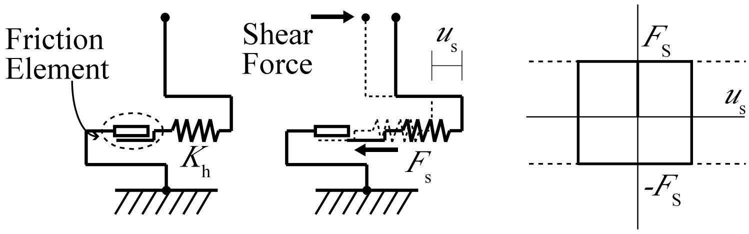
Table 1: Cross sections of members and steel weight of original frame.

Young's modulus	Poisson's ratio	Strain hardening factor	Yield stress
205000N/mm^2	0.3	0.006	258.72 N/mm^2

Table 2: Material property.

2.2 Friction Damper

The analytical model and corresponding mechanical system describing the friction dampers under sliding conditions are shown in Fig. 2.



(a) Friction damper (b) Hysteretic behavior

Figure 2: Analytical and mechanical models of friction damper.

K_h is the stiffness of the friction dampers has infinity values. The hysteretic behavior of the friction dampers is based on the Coulomb model of friction as expressed in Equation (1):

$$F_s = \mu \cdot W \tag{1}$$

where
F_s: slip load
μ: coefficient of friction
W: contact force on the friction damper

The value of F_s is determined by μ and W. When the frictional force approaches the slip load value, the friction damper starts to slide. The characteristics of the sliding of the friction dampers and its deterioration under dynamic loading must be closely related. However, it is assumed that the surface of the friction damper experiences on deterioration throughout the analyses in this research.

3 PARAMETER AND METHOD OF ANALYSIS

This chapter describes analytical parameter of sliding coefficient and analytical method.

3.1 Coefficient of Friction

The contact force of the friction damper that is considered a vertical load, keeps constant value through the analysis as the above mention. The slip load changes with sliding coefficient. Therefore, the numerical works were conducted with the sliding coefficient as the analytical parameters. When the coefficient of friction takes large value, the friction damper does not slide, the effect of energy dissipation can not give play to energy dissipation. As this reason, the sliding coefficient varied from 0.1 to 0.5.

3.2 Method of analysis

OpenSees (the Open System for Earthquake Engineering Simulation) is an object-oriented open-source software framework incorporating the finite element method (FEM). The numerical analyses of the building schematics here were performed using this framework. In this research, the dynamic analyses were conducted. In the dynamic analyses, ground motion was applied to the frames in the lateral direction. The ground motion followed the vibration data are shown in Table 2. Eventually, the maximum velocity of the ground motion was set to 0.50 [m/s], representing an unexpected major earthquake. The numerical work was performed using the Newmark-β method in which β takes the value of 1/4. The Rayleigh damping model was used with both the first and the second damping constants take the value of 0.02.

Ground motion	Acceleration [m/s^2]	Velocity [m/s]	Duration time [s]
El Centro NS 1940	5.11	0.50	20.0
JMA Kobe NS 1995	4.92		20.0
NTT Kobe NS 1995	1.90		20.0
Taft EW 1952	4.97		20.0

Table 3: Input earthquake wave.

4 DYNAMIC ANALYSIS OF ORIGINAL FRAME

4.1 Sliding coefficient

The contact force on the friction damper, defined as the total weight of the frame, is approximately constant throughout the analysis. The slip load changes with the coefficient of friction. Therefore, numerical simulations were conducted using the coefficient of friction as the analytical parameter varied from 0.1 to 0.5. Equal horizontal ground motion was applied to the frame for all analyses, using data from the wave of Table 2. Because the various possible magnitudes of earthquakes can cause very different results, the maximum velocity of ground motion was set to 0.50 [m/s], representing an earthquake of medium intensity. The step time of the numerical integration of the seismic response analysis was 0.002 [s], and the duration of the analysis was 20.0 [s].

4.2 Maximum inter-story drift angle

The maximum inter-story drift angle $R_{i\,\max}$ for each story in the original frame and the original frame with damper are shown in Fig. 3. When the coefficient of friction takes the value smaller than 0.3, the values of $R_{i\,\max}$ for the original frame with friction dampers are smaller than that of the original frame for all stories. However, larger coefficients of friction decrease the effect of vibration control, which is why the sliding displacement of the friction damper is decreased for large coefficient of friction.

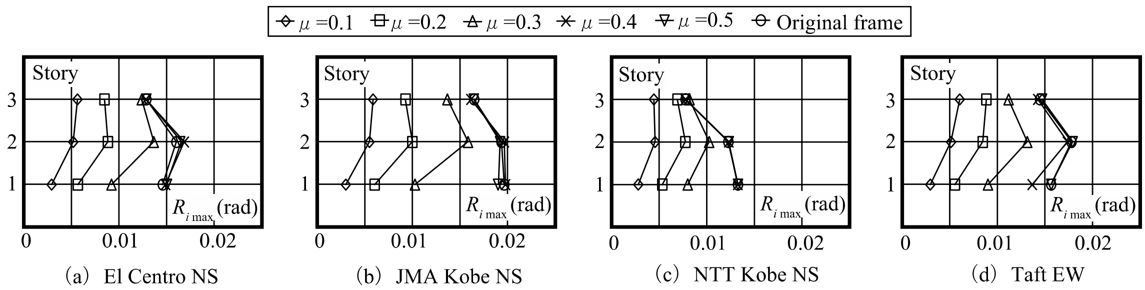


Figure 3: Maximum drift response

4.3 Slide deviation

The relationship between the absolute value of the maximum slide deviation ($u_{s\,\max}$) and the coefficient of friction for the original frame and the original frame with damper are shown in Fig. 4 (a). The maximum slide deviations are similar when the coefficient of friction is set between 0.1 and 0.3. However, the slide deviation is almost zero when the coefficient of friction is set to 0.4 or 0.5, because the friction damper does not slide when the coefficient of friction is enough large.

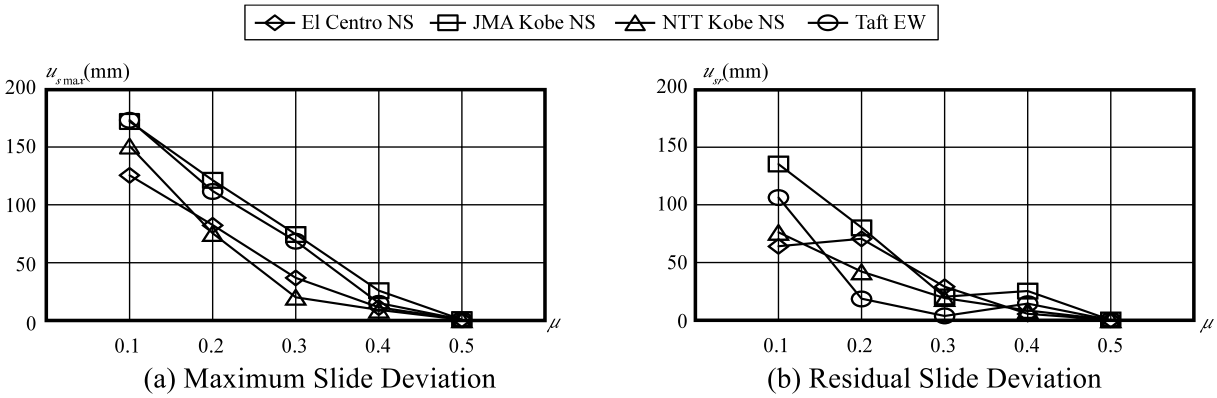


Figure 4: Maximum slide deviation

Therefore, the residual slide deviation is also important. Because of the friction damper that is related to the weight of the frame at the base of all first column of the frame, the restoring force of the damper cannot work for sliding back to the original position. According to this reason, a decrease in residual slide deviation by elastically returning it of the frame after ground motion disappeared cannot be expected. The relationship of the residual slide deviation (u_{Sr}) and the coefficient of friction is shown in Fig. 4 (b). According to this graph, the residual slide deviation decreases with the coefficient of friction increase. The prediction of the residual slide coefficient of friction is difficult, although the residual slide deviation can be greatly restrained by a suitable coefficient of friction when design the weight reduced frame.

4.4 Energy calculation

The energy dissipation is the amount of dynamic energy absorbed by sliding of the friction elements. Variations in the amount of energy dissipation influence the hysteric behaviour of the frame. When subjected to lateral force, the frame and friction elements absorb dynamic energy. To evaluate this energy, the amount of energy dissipation by friction elements (E_p) and the amount of strain energy absorbed by the frame (E_c) are compared. The amount of the accumulated strain energy that is obtained with the inter-story drift angle and the story shear, is expressed by Equation (2):

$$E_c = \sum_{i=1}^{N} E_{ci} = \sum_i \sum_j \{\frac{1}{2} \cdot (Q_{i,j+1} + Q_{i,j}) \cdot (R_{i,j+1} - R_{i,j}) \cdot h_i\} \tag{2}$$

where

i: story number

j: step number in calculation

N: number of stories

E_{ci}: ith story's strain energy

Q_i: ith story's shear

R_i: ith story's drift angle

h_i: ith story's height

The amount of the energy dissipation is obtained using the frictional force and thesliding displacement as expressed by Equation (3):

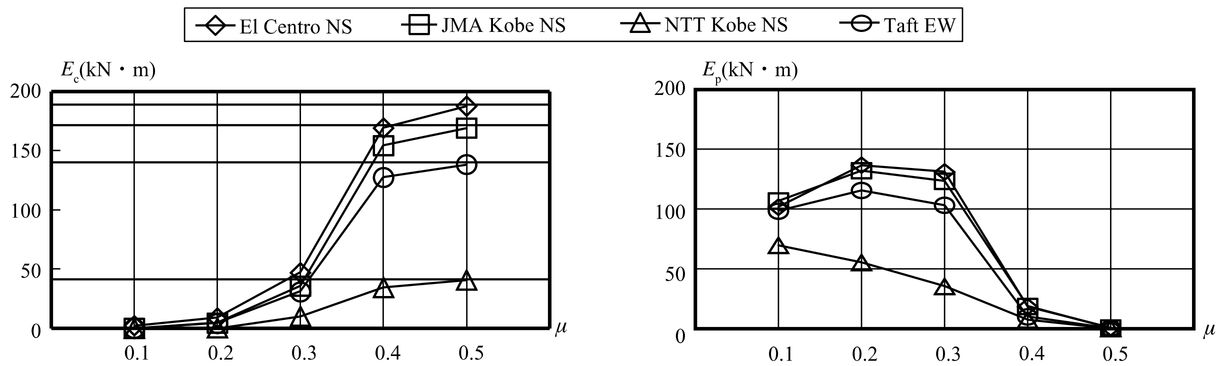
$$E_p = \int F(u_s) du_s \tag{3}$$

where

F: friction force of friction damper
u_s: slide deviation

The relationship between the energies of the original frame with damper and the coefficient of friction is shown in Fig. 5. In the graphs, the horizontal lines are the accumulate strain energy of the original frame in four earthquake waves.

By changing the coefficient of friction, the value of energy dissipation is reduced and the value of strain energy is enhanced. However, the value of energy dissipation increases when the coefficient of friction changed from 0.1 to 0.3. Through the dynamic analysis, when the coefficient of friction is set between 0.1 and 0.5, the sliding bearing accommodates energy absorption by sliding. When the coefficient of friction takes the value between 0.1 and 0.3, the effect of energy dissipation is the most efficient.



(a) Strain Energy (b) Energy Dissipation

Figure 5: Relationship between coefficient of friction and energy

5 DESIGN OF WEIGHT REDUCED FRAME

According to Figs. 3 and 4, when the coefficient of friction exceeds 0.3, the maximum inter-story drift angle approximately are same as that of the original frame, because the larger coefficient of friction leads the sliding displacement decreased, the effect of vibration control also decreased. In addition, according to Fig. 5, when the coefficient of friction takes larger values, the strain energy rapidly increases. On the other hand, the energy dissipation was reduced. Because of these reasons, and the base on the experimental analysis[2], the design goal of the weight reduced frame is the maximum inter-story drift angle of each story falls within 0.02 rad when the coefficient friction takes the value of varying from 0.2 to 0.3.

The weight reduced frame that consisted of smaller member sizes is shown in Fig. 6. The columns and beams of the weight-reduced frame are also the steel hollow sections and the steel wide-flange sections. The summary of the size of the cross-sections of the beams and the columns in the weight-reduced frame, the steel weight of each story and the ratio of the weight reduction of the weight-reduced frame are shown in Table 4.

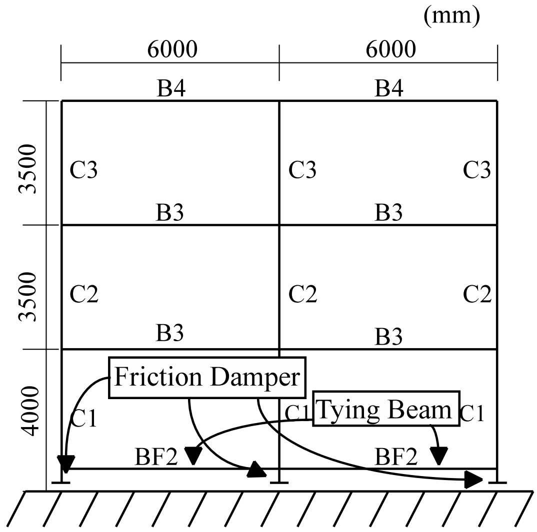


Figure 6: Model of weight reduced frame.

Coefficient of friction	Story	Steel weight (t)	Column (mm)	Beam (mm)	Ratio of weight reduction (%)
0.20	1	9.83	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	20.41
	2	9.19	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	
	3	7.17	RHS - 250 x 250 x 12	H - 300 x 150 x 6.5 x 9	
0.22	1	9.83	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	16.71
	2	9.19	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	
	3	8.39	RHS - 250 x 250 x 12	H - 350 x 175 x 7 x 11	
0.24	1	11.37	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 13	12.04
	2	9.19	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	
	3	8.39	RHS - 250 x 250 x 12	H - 350 x 175 x 7 x 11	
0.26	1	11.37	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 13	7.37
	2	10.73	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 13	
	3	8.39	RHS - 250 x 250 x 12	H - 350 x 175 x 7 x 11	
0.28	1	11.37	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 13	4.92
	2	10.73	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 13	
	3	9.19	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	
0.30	1	12.23	RHS - 300 x 300 x 12	H - 350 x 175 x 7 x 11	2.30
	2	10.37	RHS - 300 x 300 x 12	H - 354 x 176 x 8 x 11	
	3	9.19	RHS - 350 x 350 x 12	H - 354 x 176 x 8 x 13	

Table 4: Cross section of members of weight reduced frame.

6 EFFECT OF WEIGHT REDUCTION

6.1 Maximum inter-story drift angle

The comparisons of the maximum inter-story drift angle distribution of the original frame, the original frame with damper and the weight-reduced frame are shown in Fig. 7. According to Fig. 7, in dynamic analysis, the maximum inter-story drift angle of the weight-reduced frame is approximately 0.02 rad, and is almost the same as the result of the original frame.

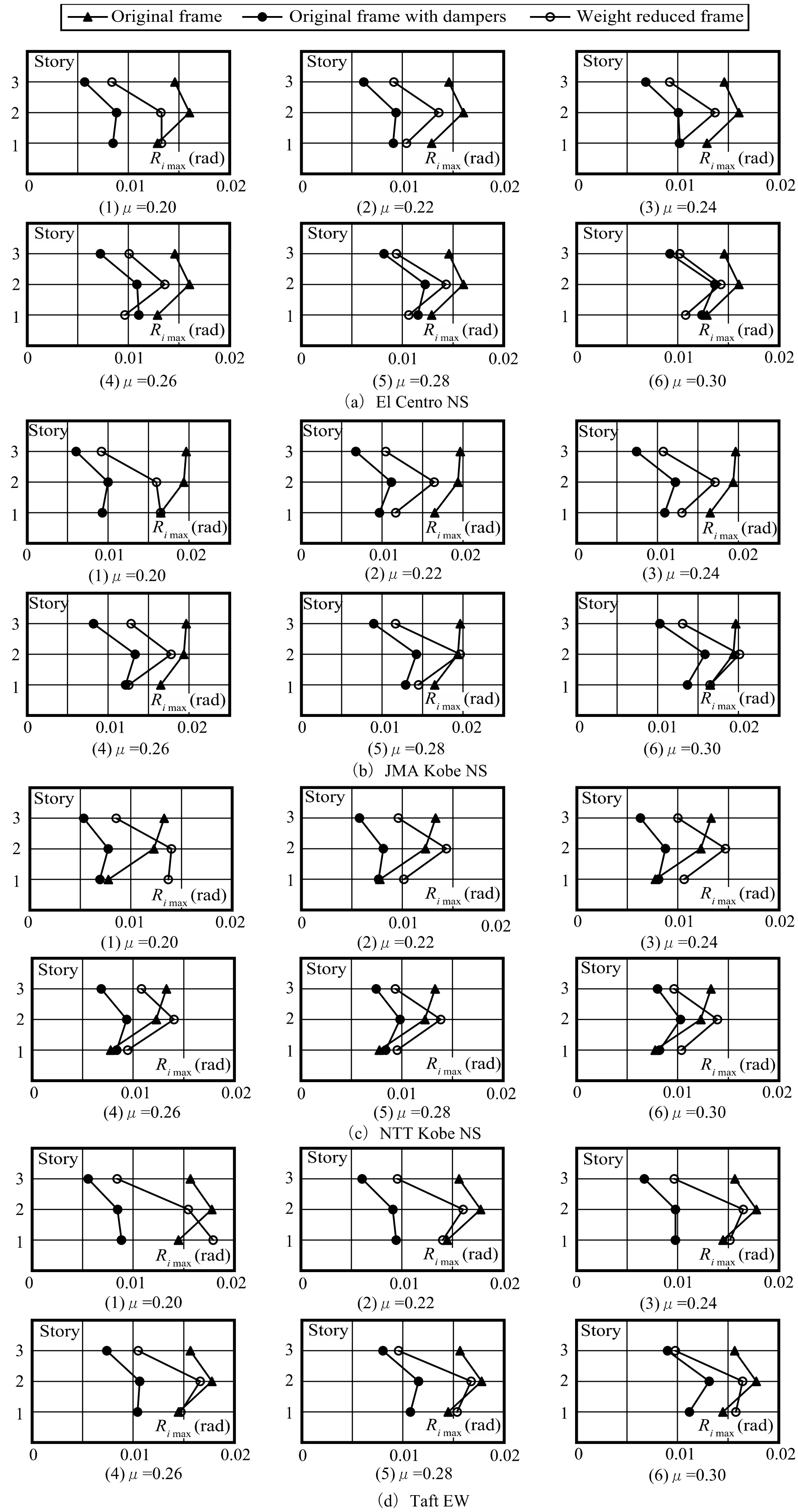


Figure 7: Comparison of maximum inter-story drift angle.

6.2 Strain energy and energy dissipation

The weight reduction effect of the strain energy and energy dissipation are shown in Figs. 8 and 9. According to Fig. 8, the accumulated strain energy of the weight-reduced frame increased more than that of the original frame. Instead, It reduced almost 70% that of the original frame. It is thought the most effect of the frame equipped with friction damper at the base of column. According to Fig. 9, the energy dissipation also decreased almost 50% of the original frame with damper except for earthquakes NTT and Kobe NS. It is thought that the f force decreased by reduction of the contact force, because the weight of the frame reduced.

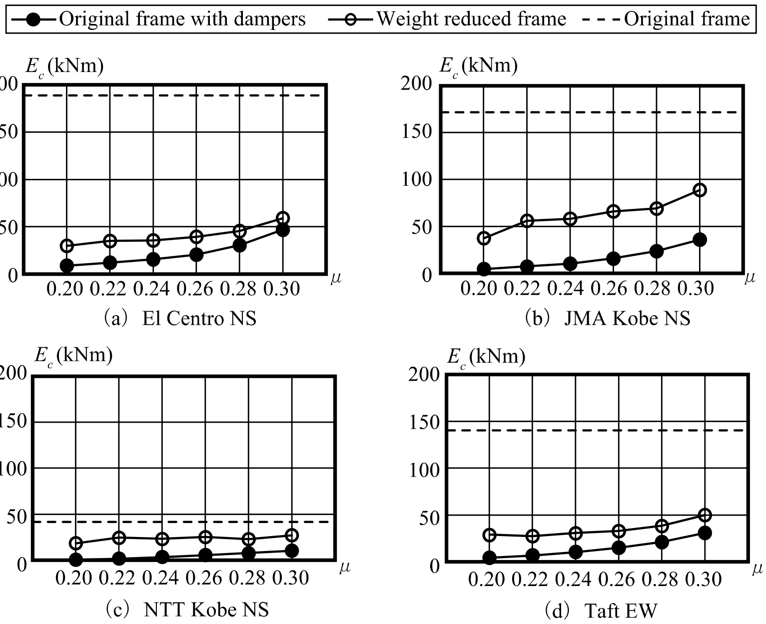


Figure 8: Weight reduction effect of strain energy.

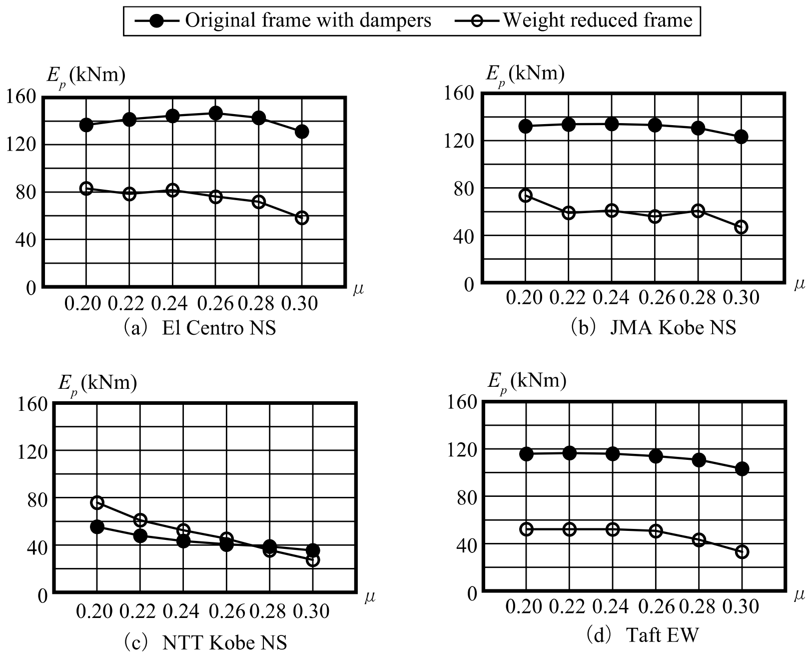


Figure 9: Weight reduction effect of energy dissipation.

7 CONCLUSIONS

This is a basic study on the weight reduction effect of steel multi-storied frame with friction damper. The maximum inter-story drift angle and the slide deviation of a building frame with sliding bearings were investigated regarding the weight reduction of the frame through numerical analyses. The vibration control system was confirmed to have an advantage in reducing the total weight of the steel super-structure by permitting the downsizing of steel structure members. Some trends were observed by the numerical analyses for the frame equipped with the friction dampers, when the friction coefficient varied from 0.2 to 0.3:

1) The weight of the frame can reduced approximately 20% when the maximum drift angle is set to less than 0.02 rad.

2) The energy dissipation of weight reduced frame decreased around 50% than the original frame with friction damper.

3) The strain energy of the weight-reduced frame reduced 70% of the original frame.

4) The passive friction dampers have an advantage of reducing the size of the cross section of members of the steel frame.

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