Dynamic Behavior of Multi-storied Steel Frame with Passive Friction Dampers under Earthquake

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SUMMARY:
This paper is concerned with dynamic response of a multi-storied steel moment frame with passive friction devices that are settled at the bottom of the frame. It is important to use the technology of seismically isolated structures and the devices that dissipate seismic energy nowadays. Avoiding damage main frame by means of the dampers and keeping building life long by replacing the devices in which damage concentrate in disaster are needed for a new structural design concept. The friction dampers are made by machine-finish, the cost is apt to high. On the other hand, the device performance is not only highly controlled and maintained but also mechanical property of the device is simple. Friction forces arising from the relative motion of two contacting surfaces are a source of energy dissipation.

Keywords: Seismic response, Steel structure, Friction damper

1. INTRODUCTION

Friction dampers are generally used as a member for vibration control in architectural buildings. The study on friction dampers are recently making steady progress because the device performance is not only highly controlled and maintained but also mechanical property of the device is rather simple. Although there are many experimental or analytical studies of friction dampers and application for equipment into structures, the study on the relation between the main structure and the friction damper is sparse. Therefore, the objective of this research is to clarify the dynamic properties of steel frame and friction dampers.

There are hitherto the researches on design of bracing-friction damper systems for seismic retrofitting and the researches on seismic response control of a building complex utilizing the passive friction damper. The object of those studies is dissipation of energy by friction damper in structural response. The friction dampers can play an important role of energy dissipation element because characteristic of friction damper have simple energy dissipation mechanism. In addition, friction damper have easy construction, installation and maintenance. However, in order to take an advantage of energy dissipation effectively, slip loads of a friction damper must be well controlled and kept constant under earthquake excitation. The slip loads actually fluctuate. Therefore, many numerical experiments are required. It is important to explore various tendencies of friction dampers.

In this paper, friction dampers are modelled 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 steel frame influences seismic response of steel frame. Indexes for grasp of seismic responses of the frame and friction elements are inter-story drift angle, inter-story shear force, sliding displacement of friction elements and the amount of dissipated energy in the frame. Seismic responses of the frame and friction elements are examined by comparing with respect to the indexes by means of analytical parameters.

2. ANARYTICAL MODEL

In this chapter, the outline of analysis frame shown in Fig. 2.1 is explained. The one-bay two-story steel frame that was designed based on the building code of Japan, was prepared for a series of numerical analyses.

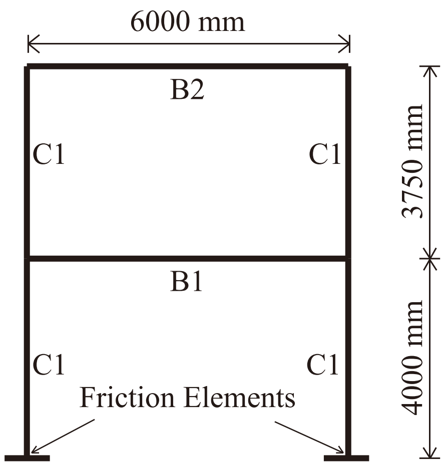


Figure 2.1. Mathematical models

The columns and beams are steel hollow sections and steel wide-flange sections respectively, while the friction devices are represented by special mechanical elements. Hysteretic behavior of the columns takes isotropic hardening, and that of the beams takes kinematic hardening. The size of cross section and the material property of each member are summarized in Table 2.1 and 2.2. The lumped mass, which is used in dynamic analysis, is given at joint of framework. The weight of each story is shown in Table 2.3.

Table 2.1. Cross section of numbers

Designation of frame	C1	B1	B2
Section (mm)	RHS-318.5x318.5x9	H-396x199x7x11	H-346x174x6x9

Table 2.2. Material property

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

Table 2.3. Weight of stories

Story number	1	2
Weight (tf)	23.4	23.4

2.1. Friction Element

In this paper, friction dampers are called friction elements in the analysis. Hysteretic behavior of friction elements, which is based on Coulomb friction, is shown in Eqn. 2.1.

$$F_S = \mu \cdot W \tag{2.1}$$

F_S is the slip load, μ is the sliding coefficient, W is the contact pressure of the friction element. When the load of the friction element reaches at the slip load the friction element starts to slide. Depend on sliding of the friction elements, the incremental dynamic force of the frame decreases. It is assumed that the pressure on the friction elements keep constant and no deterioration of surface of friction devises through the analyses.

3. ANARYTICAL PARAMETER

In this chapter, the analytical parameter and input ground motions are showed.

3.1 Sliding Coefficient

The pressure of the friction elements, which is considered 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 parameter. The sliding coefficient varied from 0.1 to 1.0 covering over wide range.

3.2 Input Ground Motions

The direction of ground motion is applied to the frame in the X-direction for all analyses. Four ground motions shown in Table 3.1 are used for the analyses. While the friction elements do not slide under dynamic acceleration, the damping of the frame cannot be obtained. Therefore, the maximum velocity of ground motion is set to 0.5 m/s, which represents medium intensity of earthquake, in order that the friction elements should slide. The step time of numerical integration of seismic response analyses is 0.001 s. The duration of the analyses is 20.0 s.

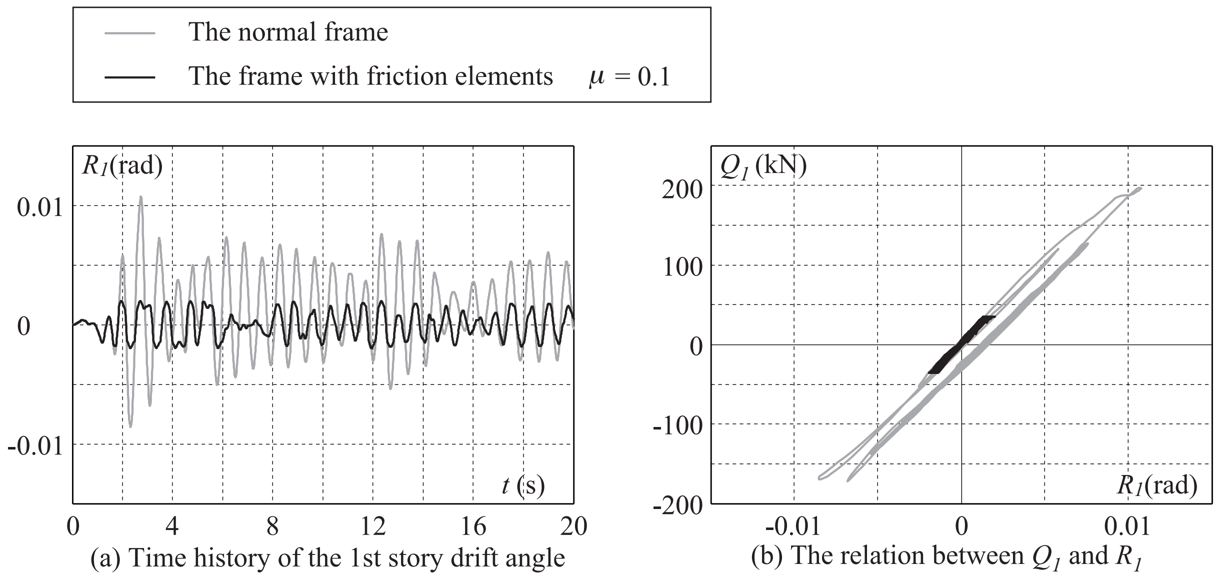
Table 3.1. Input ground motions

Ground motion name	Acceleration (m/s^2)	Velocity (m/s)	Duration time (s)
El Centro NS	5.11	0.5	20
NTT Kobe NS	1.90	0.5	20
JMA Kobe NS	4.92	0.5	20
Taft EW	4.97	0.5	20

4. RESULT OF ANALYSES

In this chapter, dynamic behavior of the frame is showed.

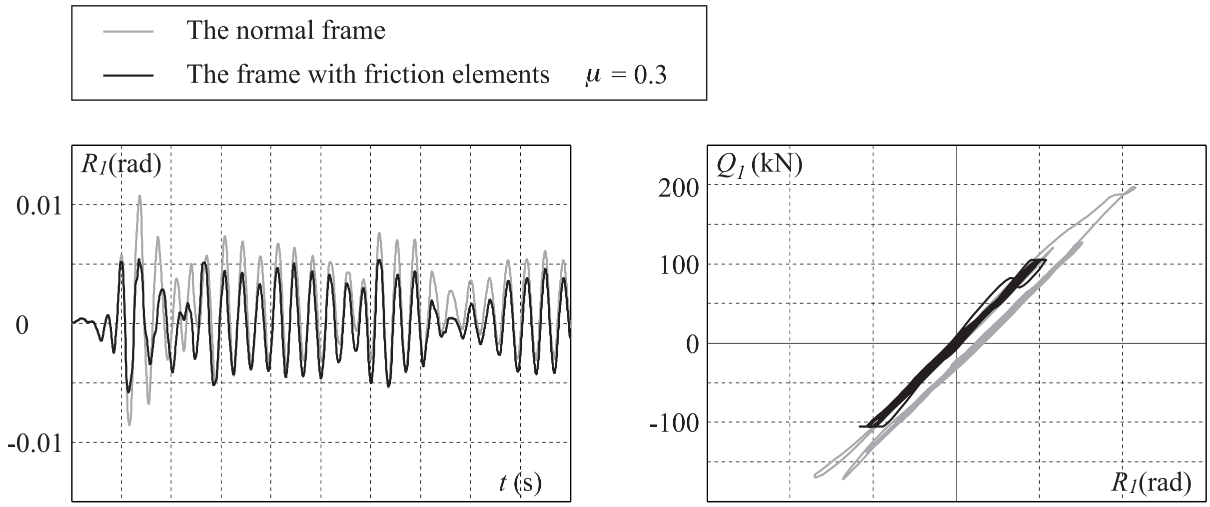
Time history of the inter-drift angle of the 1st story in the frame (R_1) and the relationship between the shear force (Q_1) and inter-drift angle (R_1) at the 1st story are shown in Fig. 4.1 to 4.3 in case that El Centro NS ground motion is applied to the frame. Three results in case that the sliding coefficient takes 0.1, 0.3 and 0.5 are shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3 respectively.



(a) Time history of the 1st story drift angle

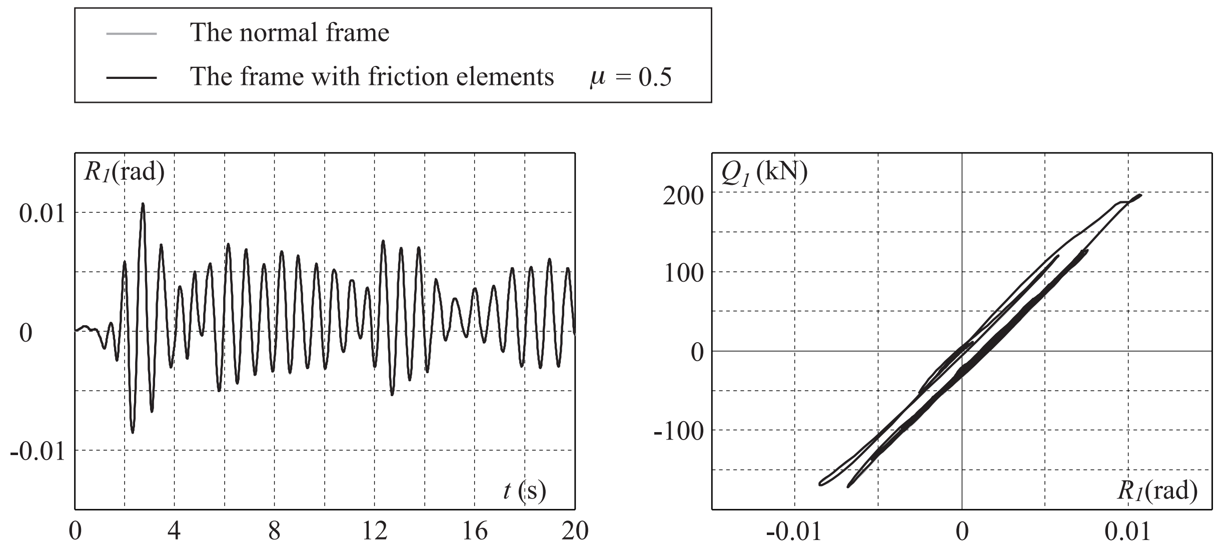
(b) The relation between Q_1 and R_1

Figure 4.1. Dynamic behavior (Sliding coefficient = 0.1)



(a) Time history of the 1st story drift angle (b) The relation between Q_1 and R_1

Figure 4.2. Dynamic behavior (Sliding coefficient = 0.3)



(a) Time history of the 1st story drift angle (b) The relation between Q_1 and R_1

Figure 4.3. Dynamic behavior (Sliding coefficient = 0.5)

The comparison between the result of the normal frame and that of the frame with friction elements is conducted in order to examine an effect of the friction elements. When the normal frame deforms up to the maximum amplitude, inter-story drift angle reaches approximate 1/100. On the other hand, the inter-story drift angle of the frame with the friction dampers, whose sliding coefficient is 0.3, reaches no more than about 1/200. In case that the friction elements take the values of smaller sliding coefficient, the maximum deformation of the frames deformed with smaller amplitude. The reason why this tendency appeared in the numerical results is that the friction dampers cut the shear force at the base of the frame or dissipated the energy from the ground. However, the maximum of inter-story drift angle in case that the sliding coefficient is 0.5 is as large as the one of the normal frame because inter-story shear force, which loads to the bottom of each column, does not reach sliding load. Therefore, friction elements cannot work for external force unless sliding load is suitably established.

5. INDEXES FOR EVALUATION

In this chapter, the indexes, which are provided in order to examine a tendency of dynamic behavior of the friction elements and the frame, are showed.

5.1 The Maximum Inter-story Drift and Inter-drift Shear

The maximum inter-story drift angle and inter-drift shear force are defined as what become the maximum momentary. R_{imax} and Q_{imax} denote the maximum inter-story drift angle and the maximum inter-drift shear force. Those obtained through a suite of numerical analyses with variation of the value of the friction coefficient are shown in Fig. 5.1 and 5.2.

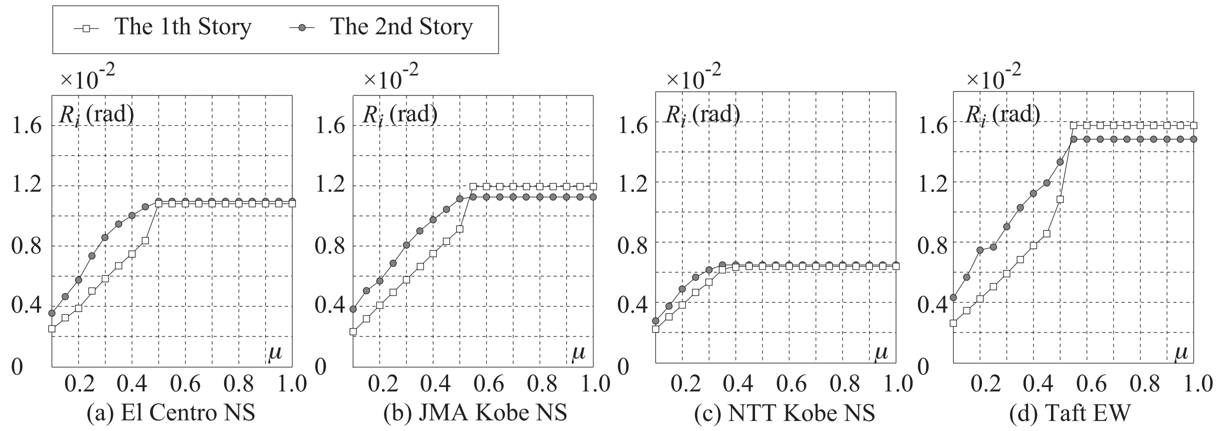


Figure 5.1. Maximum inter-story drift angle

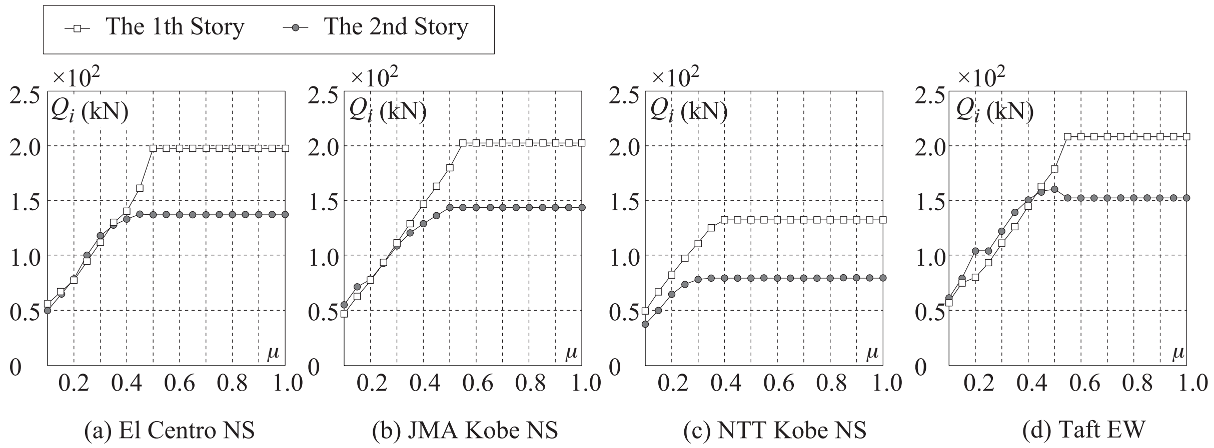


Figure 5.2. Maximum inter-drift shear force

R_{imax} and Q_{imax} increase almost proportionally with the sliding coefficient and then they become the constant value after the sliding coefficient changes larger than some value. This is reason why the friction elements do not slide. The smaller sliding coefficient is, the higher damping effect is. The friction elements do not suffer external force, which is larger than sliding load. The high level of the control capability of a friction element is shown in this phenomenon. During the friction elements slide, the reduction of the 1st story shear force is much larger than the one of the 2nd story shear force.

5.2 The Maximum Sliding Displacement of Friction Elements

The maximum sliding displacement of the friction elements ($u_{s\,max}$) is shown in Eqn. 5.1.

$$u_{s\,max} = \left| u_{s\,pmax} \right| + \left| u_{s\,nmax} \right| \tag{5.1}$$

$u_{s\ pmax}$ is positive maximum sliding displacement of friction elements, $u_{s\ nmax}$ is negative side. In dynamic analyses, perhaps friction elements slide both positive and negative directions. Here, right direction takes positive. Depending on the kind of seismic wave and coefficient of friction, the drift of the frame occurs. In order to investigate of improvement the drift, the maximum sliding displacement was defined by Eqn. 5.1. In this case of the actual design, which restrains the horizontal displacement of the base, it is necessary to evaluate the maximum sliding displacement.

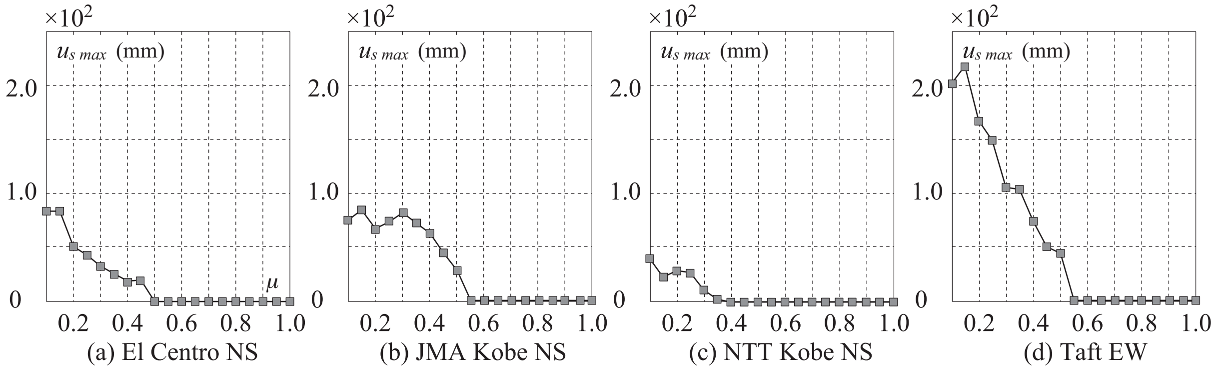


Figure 5.3. Maximum sliding displacement of friction elements

The maximum sliding displacement of the friction elements by the parameters is shown in Fig. 5.3. When the value of sliding coefficient increases, $u_{s\ max}$ decrease almost linearly. The smaller the sliding coefficient is, the larger $u_{s\ max}$ is. The value of $u_{s\ max}$, which is the largest of four earthquakes, is about 200 mm. This value is available for an actuality design in the simulation that the clearance of sliding displacement in order to prevent base crash of the frame is considered. However, there is a disadvantage that a tiny sliding coefficient is awkward to adopt.

5.3 The Amount of Energy Dissipation

Energy dissipation is dynamic energy absorbed by sliding of the friction elements. The variation of the amount of energy dissipation influences the hysteric behavior of the frame. While the frame suffers lateral force, the frame and friction elements absorb dynamic energy. As evaluation of energy, the comparison of the amount of energy dissipation by friction elements (E_P) and the amount of strain energy by the frame (E_C) conducts. The amount of accumulable strain energy, which is obtained by inter-story drift and inter-story shear, is shown in Eqn. 5.2.

$$E_C = \int Q_i \left(R_i\right) dR_i \tag{5.2}$$

On the other hand, the amount of the energy dissipation, which is obtained by friction force and the displacement concerning with sliding, is shown in Eqn. 5.3.

$$E_P = \int F \left(u_s\right) du_s \tag{5.3}$$

The amount of the energy dissipation by parameters is shown in Fig. 5.4. As a general tendency, when the sliding coefficient increases, E_P increases and then E_P decrease because of the relation between sliding displacements and friction force. The larger displacement response is, the larger energy dissipation of the friction elements is. Because the range of the maximum energy dissipation is uneven at each earthquake, it is necessary to conduct a lot of numerical experiments.

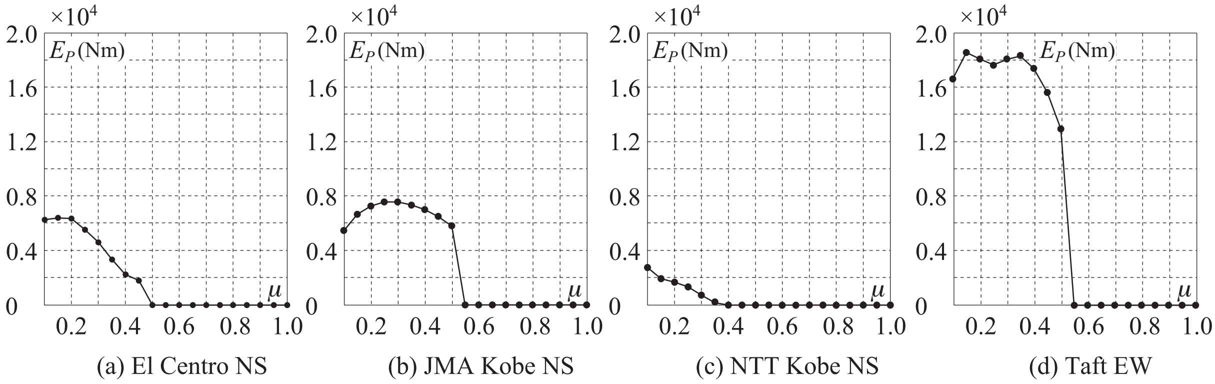


Figure 5.4. The amount of energy dissipation

The sum of the amount of accumulated strain energy in the frame and the amount of the energy dissipation is defined as the total energy (E_T). When the total energy takes 100 %, the energy apportionable values to the total energy with respect to the energy dissipation (R_P) and the strain energy (R_C) are plotted in Eqn. 5.4 and 5.5 respectively.

$$R_P = \frac{E_P}{E_T} \tag{5.4}$$

$$R_C = \frac{E_C}{E_T} \tag{5.5}$$

The contribution of the friction elements and the frame by the parameters is shown in Fig. 5.5. When the value of sliding coefficient increases, R_P decreases. However, the energy dissipation occupies the total distortion energy during sliding of friction elements.

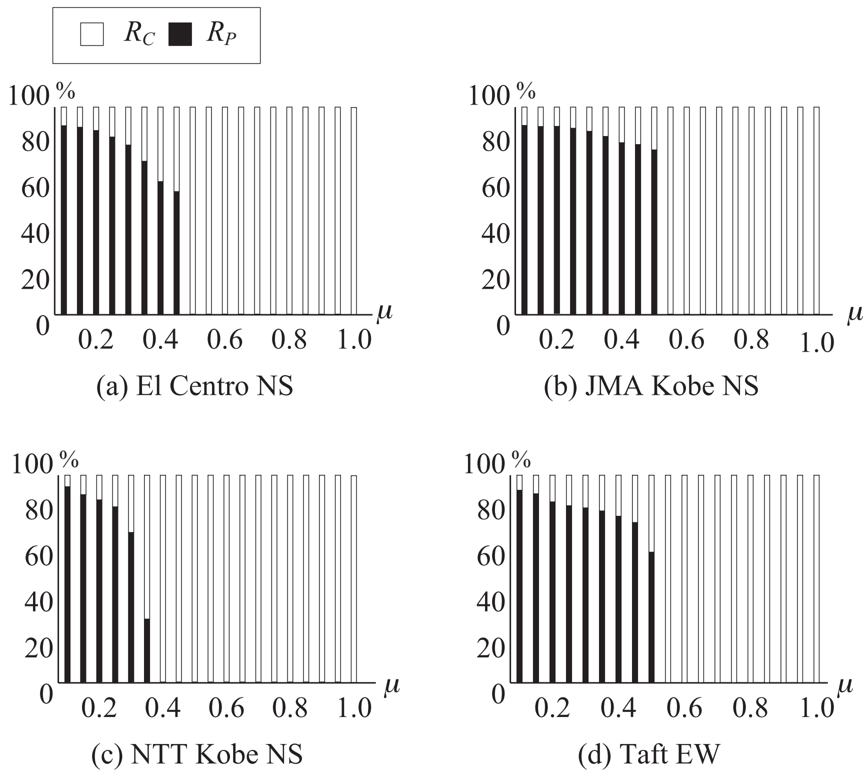


Figure 5.5. The energy rate of friction elements and the frame

6.CONCLUSIONS

It is effective for the measure of reducing dynamic response to incorporate friction dampers in the bottom of the frame through numerical analyses. The tendency, which is obtained by numerical analyses, is that the maximum inter-story drift angle and the maximum inter-drift shear force increases almost proportionally with the value of the sliding coefficient. On the other hand, the maximum sliding displacement of friction elements decrease almost linearly. Therefore, the character of simple behavior of friction elements is clarified. However, the maximum energy dissipation is uneven at each earthquake.

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