Seismic Responses of Reduced-weight Multi-storied Steel Frames with Base Isolation Systems of Passive Friction Dampers

Jingye LIU[a] , Takuya NISHIMURA[a] and Minoru YAMANARI[b]

[a] Graduate School of Science and Technology, Kumamoto University, 2-39-1
Kurokami, Chuo-ku, 860-8555 Kumamoto, JAPAN
e-mail: 178d9408@st.kumamoto-u.ac.jp
[b] Faculty of Advanced Science and Technology, Kumamoto University, 2-39-1
Kurokami, Chuo-ku, 860-8555 Kumamoto, JAPAN

ABSTRACT

This research addresses vibration control systems using passive friction dampers settled at the base of steel buildings and the effect of reducing the total steel weight of multi-storied frames with sliding bearings. The vibration control system permits the downsizing of members of the steel super-structure, which reduces the total steel weight. The earthquake-resistant performance of the frame equipped with friction dampers has been improved through a series of research by the authors. The size of members in the frame with the dampers can be reduced from that of the frame that fixed on the foundation. However, It is concerned with uplifting of the bottom of the column in the first story because the overturning moment of a high-rise building becomes rather large. Therefore, the height of the frames dealt in this research should be less than 60m. 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 investigated for the research. The first story consists of large-sized columns and beams, whereas the members in other stories are usual and smaller members. The stiffness of the frame with the downsized members will also be reduced. Both steel frames used columns on 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 story shear force, inter-story drift angle, and seismic energy under earthquake excitations. Finally, the effect of the base-isolation on the total weight reduction of the multi-storied steel frame was discussed.

1. INTRODUCTION

This paper describes seismic responses of reduced-weight multi-storied steel frames with base isolation systems of passive friction dampers. The research is conducted based on the experimental study of the mechanical behavior of the column base using graphite as fictional material for lubricant. The frictional material is effective for reducing resistance against seismic force[3]. Friction dampers settled at the bottom of a building frame without connections 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. 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. This permits the reduction of the total steel weight, achieved by downsizing the members of the steel frame equipped with passive friction dampers. 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 responses of the frames and friction dampers are examined by means of analytical simulations.

2. ANALYTICAL FRAME

Models of the two analyzed frames are shown in Fig. 1. The two-bay three-story steel frame, designed based on Japanese building codes, that the maximum inter-story drift angle of each story of the frame does not exceed 0.02rad even under extremely strong earthquake, was prepared for a series of numerical analyses. The original frame is depicted both with and without friction dampers, as is a reduced-weight version of the same frame.

The columns and beams of two frames 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 two frames are shown in Table 1 and Table 2 that were selected out of the catalogue of the structural steel sections provided by Japanese steel producers. The size of cross section of BF1 and BF2 is the same with that of B1 and B3 respectively specified in Fig.1. The total weight and total steel weight of the original and reduced-weight frames are shown in Table 3. The yield strength and Young's modulus are 235 [N/mm^2] and 205 [kN/mm^2], respectively, for all members.

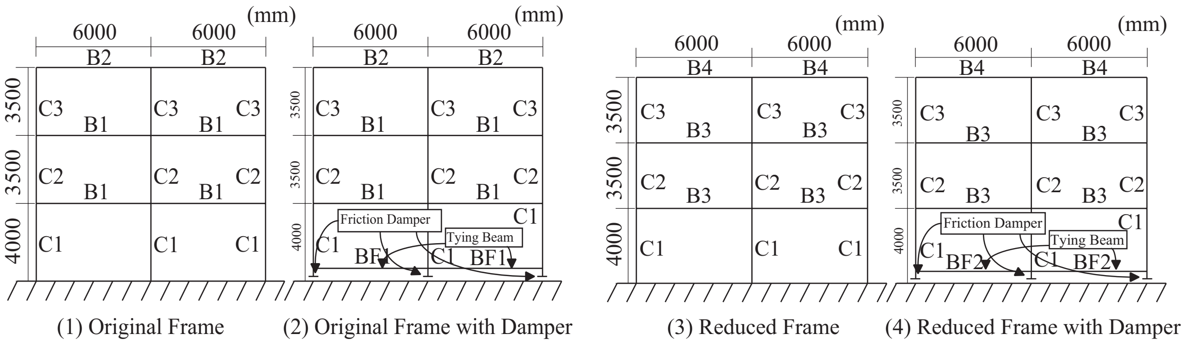

Figure 1. Analytical frame models

When the frame is equipped with friction dampers, the maximum inter-story drift angle is reduced. Reducing the cross-sections of the members of the original frame may reduce damage under the same earthquake. However, the amount of weight that can be removed from the structure is unknown. In this study, only the reduction of the cross-sections of the beams is considered. The maximum inter-story drift angle would exceed 0.02rad with the coefficient of friction is range from 0.1 to 0.6 in the case that the reduced-weight frame with friction dampers were designed.

A reduced-weight frame with 93.30% of the total steel weight of the original frame was prepared by simulation methods. The total weight of the reduced frame was reduced by 1.39% relative to that of the original frame. The maximum inter-story drift angle, coefficient of friction, maximum slide deviation, and energy were compared for the original and reduced-weight frames. This comparison characterizes the effect of the reduction of the total steel weight of multi-storied frames with sliding bearings on the buildings' behavioral responses to seismic shocks.

Table 1. Cross-section of members of original frame

Story	Column		Beam	
3F	C2	RHS - 250 × 250 × 12	B2	H - 354 × 176 × 8 × 13
2F	C1	RHS - 300 × 300 × 16	B1	H - 404 × 201 × 9 × 15
1F	C1	RHS - 300 × 300 × 16	B1	H - 404 × 201 × 9 × 15

Table 2. Cross-section of members of reduced-weight frame

Story	Column		Beam	
3F	C2	RHS - 250 × 250 × 12	B2	H - 350 × 175 × 7 × 11
2F	C1	RHS - 300 × 300 × 16	B1	H - 400 × 200 × 8 × 13
1F	C1	RHS - 300 × 300 × 16	B1	H - 400 × 200 × 8 × 13

Table 3. Total weights of two frames

	Total weight (t)	Total steel weight (t)
Original Frame	70.60	15.56
Reduced Frame	69.62	14.52
Weight reducing rate	1.39%	6.7%

3. FRICTION DAMPER

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

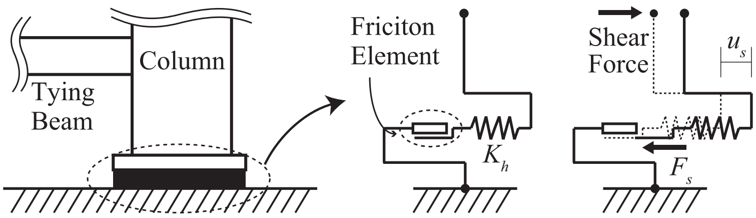

Figure 2. Analytical and mechanical models of friction damper

K_h is the stiffness of the friction damper. 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 Eq. (1).

$$F_{\mathrm{s}} = \mu \cdot W \tag{1}$$

F_{s} is the slip load, μ is the coefficient of friction, and W is the contact force on the friction dampers. 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 damper and its deterioration under dynamic loading must be closely related. However, it is assumed that the surface of the friction damper experiences no deterioration throughout the analyses in this research.

4. 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. A static response analysis was conducted in order to investigate the capacity of the damper to control vibrations under earthquake conditions. Static forces were applied to the frame in the horizontal direction for all analyses. The numerical work was performed with push-over analysis using displacement control. Dynamic analyses were also conducted. The vibration equation of a frame with the base of dynamic analyses is expressed as Eq. (2).

$$\boldsymbol{M\ddot{x}}+\boldsymbol{C\dot{x}}+\boldsymbol{Kx}=-\boldsymbol{M\ddot{y}} \tag{2}$$

where, $\boldsymbol{x}$ and $\boldsymbol{y}$ are the displacement vectors, $\boldsymbol{M}$**,** $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass matrix, the damping matrix and the stiffness matrix of the system. The dots above the notes as the displacements mean the derivative with respect to time. In the dynamic analyses, ground motion was applied to the frames in the lateral direction. The ground motion followed the *El Centro* (1940) NS vibration data. 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 where β equals 1/4. The Rayleigh damping model was used with both first and second damping constants equal to 0.02.

5. STATIC ANALYSIS

The static analysis was performed to predict the value of μ_s at which sliding would occur simultaneously with the yielding of the frame. Horizontal forces were applied at the floor levels of the frame, based on an A_i distribution proportional to the distribution of shear forces along the frame height. The A_i distribution faction with respect to the story number i is expressed as Eqs. (3) and (4).

$$A_i = 1+\left(\frac{1}{\sqrt{\alpha_i}}-\alpha_i\right)\times\frac{2T}{1+3T} \tag{3}$$

$$\alpha_i=\frac{\Sigma W_i}{W} \tag{4}$$

where, the T is the basic natural period of the frame for the structural design, W_i is the sum of the weight upper than ith story, and W is the whole weight of the super frame that means the frame above the ground level. The incremental loading analysis continued until the top horizontal displacement of the frame reached 1/20 of the total frame height. The relationships between shear force and inter-story drift angle of the two frames at each story are shown in

Fig. 3. The reduced frame denotes the frame with members having smaller cross sections; the loading capacity of the reduced frame is smaller than that of the original frame.

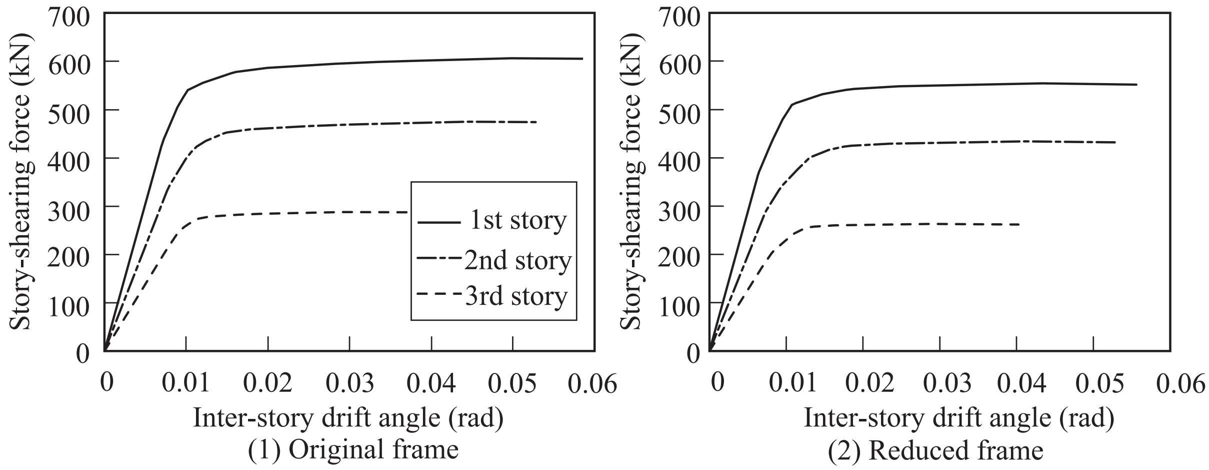

Figure 3. Relationship between shear force and inter-story drift angle

6. DYNAMIC ANALYSIS

Details of dynamic analysis

The contact force on the friction dampers, 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 0.6. Equal horizontal ground motion was applied to the frame for all analyses, using data from the *EI Centro* (1940) NS wave. Because the various possible magnitudes of earthquakes can cause very different results, the maximum velocity of the 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].

Maximum inter-story drift angle

The maximum inter-story drift angle $R_{i\,\max}$ for each story in the original un-damped, original friction-damped, and reduced-weight friction-damped building models is shown in Fig. 4. The values of $R_{i\,\max}$ for the two friction-damped frames are smaller than that of the original frame for all stories. When the coefficient of friction is equal to 0.10, the value of $R_{i\,\max}$ in the first story is decreased by approximately 82.17% relative to that of the un-damped original frame. 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 coefficients of friction.

Maximum slide deviation

The relationship between the absolute value of the maximum slide deviation and the coefficient of friction for the friction-damped building models are shown in Fig. 5. The maximum slide deviations are similar when the coefficient of friction is set between 0.1 and 0.4. However, the slide deviation is almost zero when the coefficient of friction is set to 0.5 or 0.6, because the friction damper does not slide when the coefficient of friction is large.

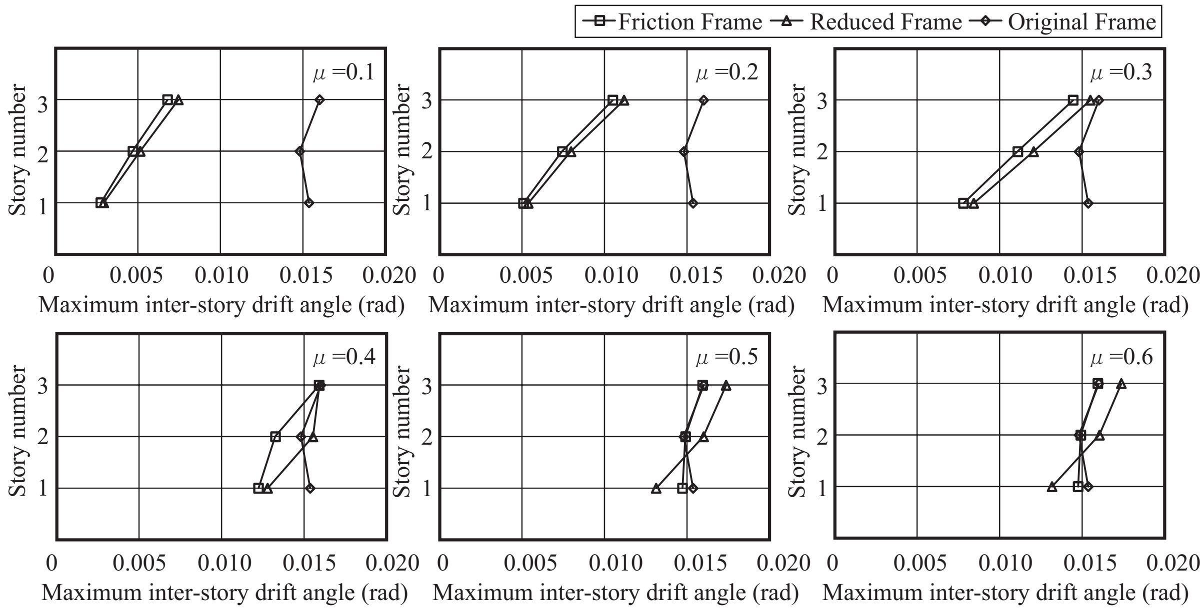

Figure 4. Maximum drift response

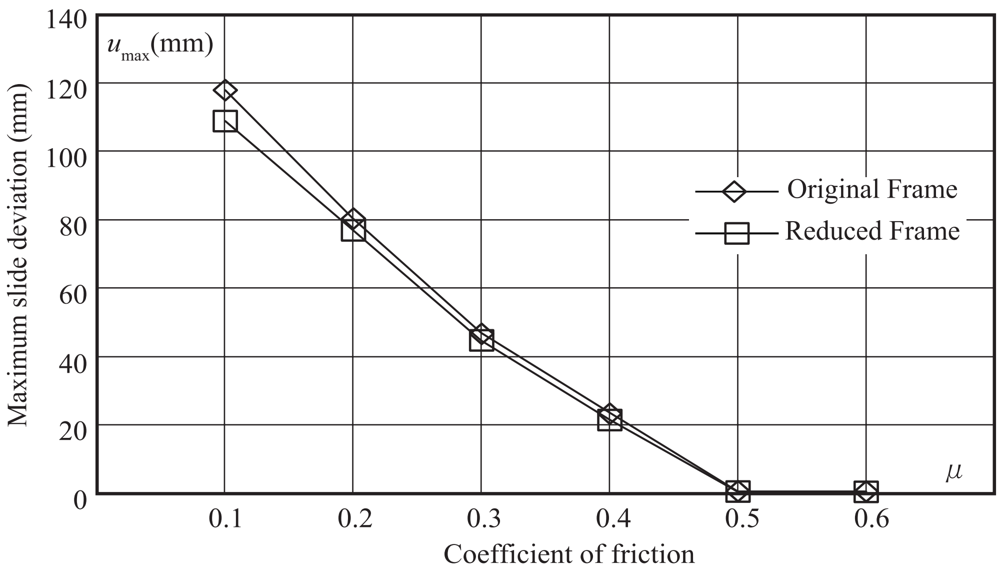

Figure 5. Relationship between coefficient of friction and maximum slide deviation

Energy dissipation

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 behavior 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 accumulated strain energy, obtained by the inter-story drift angle and shear force, is shown in Eq. (5).

$$E_C = \int Q_i(R_i)dR_i \tag{5}$$

The amount of energy dissipation, obtained using the frictional force and sliding displacement, is shown in Eq. (6).

$$E_P = \int F(u_s)du_s \tag{6}$$

The relationship between the energies of the two friction-damped frames and the coefficient of friction is shown in Fig. 6.

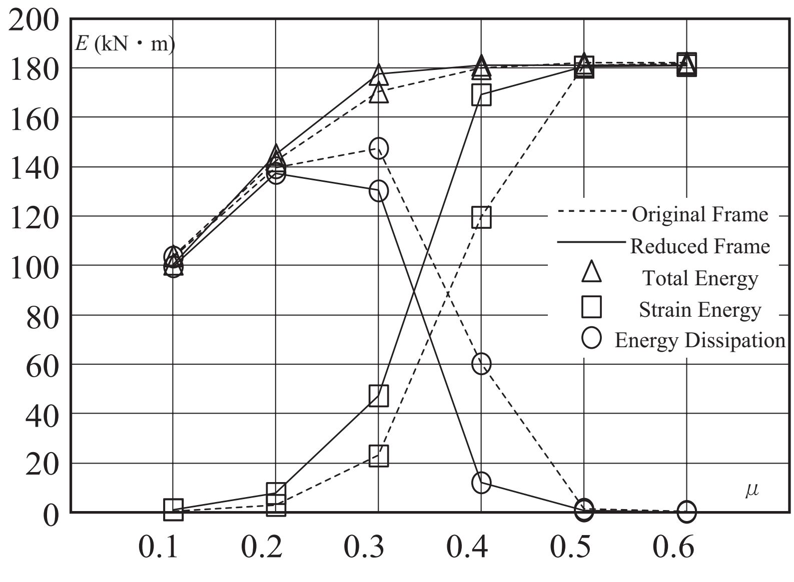

Figure 6. Relationship between coefficient of friction and energy

Because the ground motion data and maximum velocity are equal in the dynamic analyses, the total energy values of the two frames equipped with sliding bearings are approximately equal. 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 is changed from 0.1 to 0.3. In 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 is between 0.3 and 0.4, the effect of energy dissipation is the most efficient.

7. CONCLUSIONS

The maximum inter-story drift angle and the maximum 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 structural members. Two trends were observed by the numerical analyses:

(1) The maximum inter-story drift angle and the maximum slide deviation of the two sliding bearing-equipped frames were similar for small coefficients of friction.

(2) The effect of energy dissipation of the two friction-damped frames is the best when the coefficient of friction is between 0.3 and 0.4.

(3) The maximum inter-story drift angle of the reduced-weight frame with friction dampers almost ensures no more than 0.02rad in case that the coefficient of friction covers over the range from 0.1 to 0.6.

(4) The total steel weight and total weight of the frame could be reduced 93.30% and 1.39% relative to that of the original frame.

8. REFERENCES

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