FUNDAMENTAL EXPERIMENT AND ANALYTICAL STUDY OF SEISMIC RESPONSE REDUCTION EFFECT WITH LOAD SLIDING OF AN ELASTOPLASTIC FRAME (ADDITIVE DAMPING RATIO BY LOAD SLIDING)

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Abstract

The design load for structural design and for calculating the seismic force of building the live load of which is larger than the dead load, such as warehouses, is set depending on the engineering judgment of structural designers because there is no regulation regarding the design load of such buildings in Japan. Although the seismic response reduction effect with load sliding, hereinafter referred to as the load sliding effect (slide effect), is not considered in typical structural design, consideration of this effect may contribute to a rational structural design. In the present study, in order to obtain the basic characteristics of the slide effect for an elastoplastic frame, including the yield shear force of the frame, shaking table tests were carried out on a single-story elastoplastic steel frame while varying the experimental parameters. In order to incorporate the slide effect for various designs of general buildings, an analytical model with load sliding was constructed based on the results of static experiments. In addition, the additive damping ratio due to the slide effect was analytically calculated in order to evaluate the slide effect using design variable. Based on the results of the shaking table tests and seismic response analyses, we found the followings: (1) The slide effect increased with decreasing dynamic friction coefficient of the weight and increasing maximum velocity of the input seismic motion. (2) The slide effect increased with increasing maximum sliding displacement and cumulative sliding displacement of the weight. (3) The response tendencies of the frame and weight of the analytical results for the parameters of interest generally agreed with the experimental results. (4) The additive damping ratio due to weight sliding increased with increasing mass ratio and decreasing coefficient of dynamic friction of the weight.

Keywords: structural design, seismic force, elastoplastic frame, slide effect

Word Count: 4248

1. INTRODUCTION

The seismic response reduction effect of the acceleration of loads and the displacement of structures with load sliding on the structures (hereinafter referred to as the slide effect) at the time of earthquake occurrence has been confirmed in previous studies (Ogawa, 1986; Takanashi et. al., 1987; Gao and Takanashi, 1990; Smith-Pardo et. al., 2014; Smith-Pardo et. al., 2015; Yamagishi, 2015; Sasaki and Yamagishi, 2017a; Sasaki and Yamagishi, 2017b). In the event of a major earthquake, a load will slide when the inertial force of the load exceeds the frictional force, and some seismic energy of the structure is dissipated by friction. Thus, the seismic response displacement of structures could be reduced by load sliding. Although the slide effect is not considered in general structural design, consideration of this effect may reduce the live load for a rational structural design, as compared with a design that assumes fixed loads (Takanashi and Gao, 1989). However, the experimental frame models used in previous studies were elastic, and the characteristics of the slide effect for an elastoplastic frame remain unclear. Therefore, it is important to quantitatively obtain the slide effect for an elastoplastic frame.

In recent years, a structural design method considering energy has been adopted in Japan. Since stress and deformation of structures are the criteria in all structural design methods, it is necessary to quantitatively evaluate the slide effect using design variable in order to incorporate the slide effect in rational structural design. However, there has been no quantitative research on evaluating the slide effect using design variable.

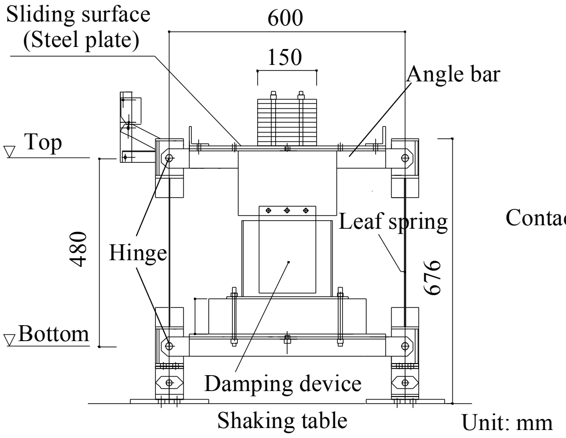


Fig.1 Experimental elastoplastic frame

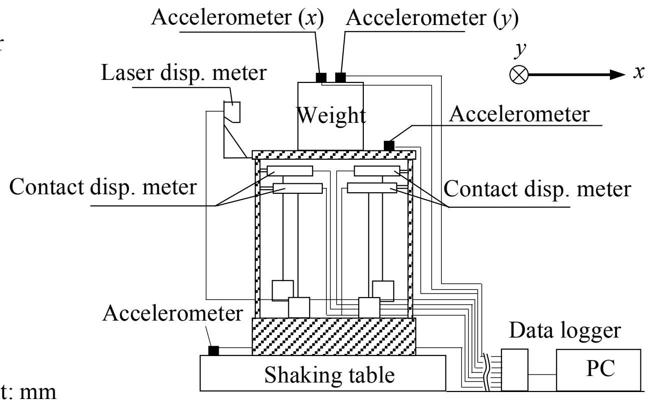
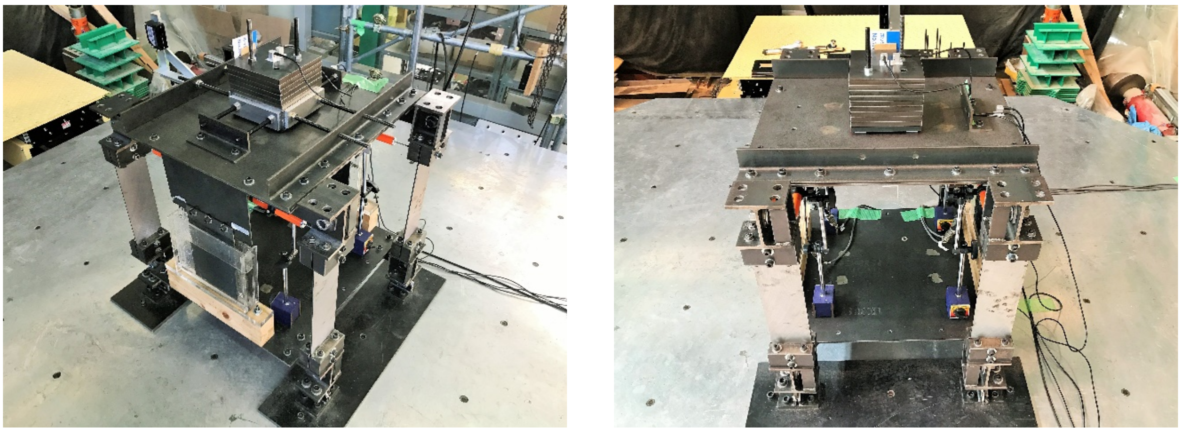


Fig.2 Measurement diagram



Picture 1 Experimental elastoplastic frame with measurement equipment

In the present study, in order to obtain the basic characteristics of the slide effect for an elastoplastic frame, shaking table tests were carried out on a single-story elastoplastic steel frame while varying the experimental parameters such as the dynamic friction coefficient of the weight and the maximum velocity of the seismic motion. An analytical model considering the nonlinear behavior of the frame and weight sliding was constructed for the purpose of comparing the response results of the experiment and the analysis. In addition, the additive damping ratio due to the slide effect was analytically calculated in order to evaluate the slide effect using design variable.

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Table 1 Experimental parameters

Parameters	Values
Yield shear force coefficient C_y	0.248 , 0.314 , 0.413 , 0.612 , ∞
Coefficient of dynamic friction μ_d	0.100 , 0.188 , 0.435 , ∞
Maximum velocity V_{max} (m/s)	0.2 , 0.3 , 0.4 , 0.5
Mass ratio R_m	0.219 , 0.438 , 0.657

* Boxes indicate reference values

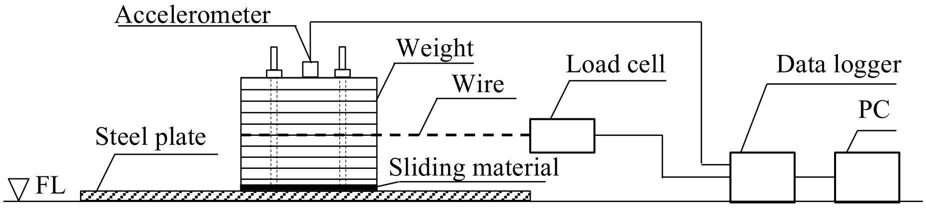


Fig. 3 Sliding experiment for measuring dynamic friction coefficient of sliding materials

2. SHAKING TABLE TESTS OF A SINGLE-STORY ELASTOPLASTIC FRAME

2.1. Outline of the single-story elastoplastic steel frame

The experimental frame is a single-story elastoplastic steel frame with a weight (representing a live load) placed atop of the frame (Fig. 1 and Pic. 1). The frame consists of a steel plate supported by leaf springs and angle bars, both of which are fixed with bolts through hinges. The yield strength of the frame Q_{yf} was changed by adjusting the tightening torque T_h of the bolts at the hinges. The damping devices using a viscous fluid were installed in the story of the frame, and the damping ratio h_1 became 4.04 % as a result of adjusting the viscosity, assuming the damping of general buildings. The frame mass m_f above the center of the columns, including the measurement equipment, is 47.5 kg, and the primary natural period of the frame without the damping devices and weight is 0.153 s (6.54 Hz).

Figure 2 shows the measurement diagram of the experiment. In order to measure the response acceleration of the frame and weight, accelerometers were installed at four positions: on the shaking table, on the steel plate of the frame, and on top of the weight for the *x* and *y* directions. Contact-type displacement meters were installed on each leaf spring to measure the story drift of the frame, and a laser displacement meter was installed on a bracket attached to the steel plate in order to measure the relative displacement (sliding displacement) between the frame and the weight. The maximum story drift of the frame in the following graphs was defined as the mean value of the maximum drifts obtained from the four leaf springs.

2.2 Experimental parameters

The four experimental parameters of interest are as follows: (1) the yield shear force coefficient of the frame C_y, (2) the dynamic friction coefficient of the weight m_d, (3) the maximum velocity of the input seismic motion V_{max}, and (4) the weight-to-frame mass ratio R_m (Table 1).

The yield shear force coefficient C_y in the present study is the ratio of the yield strength of the frame Q_{yf} to the frame mass, including the mass of the weight. Then, by adjusting the tightening torque T_h, C_y became 0.248, 0.314, 0.413, and 0.612. However, the results for C_y = 0.248 are presented in the following. In addition, T_h was adjusted to be sufficiently large (C_y = ∞) for the purpose of comparison with the elastic response of the frame.

The dynamic friction coefficients m_d at the interface of the weight and the steel plate of the frame were calculated based on the horizontal forces obtained through a static sliding experiment involving the weight for various sliding materials adhered to the bottom of the weight. Based on the sliding experiment, three types of sliding materials were selected: polytetrafluoroethylene (m_d = 0.100), ultra-high-molecular-weight polyethylene (m_d = 0.188), and natural rubber (m_d = 0.435).

The maximum velocity of the input seismic motion V_{max} was set based on the assumption of a range of from moderate earthquake motion (V_{max} = 0.2 m/s) to extremely rarely occurring earthquake motion (V_{max} = 0.5 m/s) in 0.1-m/s increments.

By adjusting the number of weights (1-ply = 2.08 kg) to 5-, 10-, and 15-ply, the weight-to-frame mass ratio R_m varied as 0.219, 0.438, and 0.657, respectively. The primary natural periods of the frame with fixed weights are 0.173 s (5.77 Hz), 0.184 s (5.44 Hz), and 0.200 s (5.00 Hz).

2.3. Selected input seismic motions

The three seismic motions used in the present study, which have relatively larger maximum acceleration and different predominant periods, observed in Japan, were standardized according to maximum velocity (Figs. 4 and 5). These three seismic motions: (a) HYG024_2013_EW ((a) HYG), (b) KMM008_2016_ EW ((b) KMM), and (c) ISK005_2007_EW ((c) ISK), were observed in Higasiura, Hyogo (2013), Uto, Kumamoto (2016), and Anamizu, Ishikawa (2007), respectively.

3. EXPERIMENTAL RESULTS

3.1 Maximum story drift of the frame for the yield shear force coefficient

Figure 6 (i) shows the relationship between the yield shear force coefficient C_y and the maximum story drift of the frame d_{fmax} for each input seismic motion (experimental parameters: m_d = 0.188, V_{max} = 0.4 m/s, and R_m = 0.438). The symbols in the figure indicate the results for the input seismic motions: (a) HYG (circle), (b) KMM (square), and (c) ISK (triangle). The symbol ∞ on the horizontal axis indicates the results for the elastic response of the frame. The solid and dashed lines indicate the response results for the sliding weight (Sliding) and the fixed weight (Fixed), respectively.

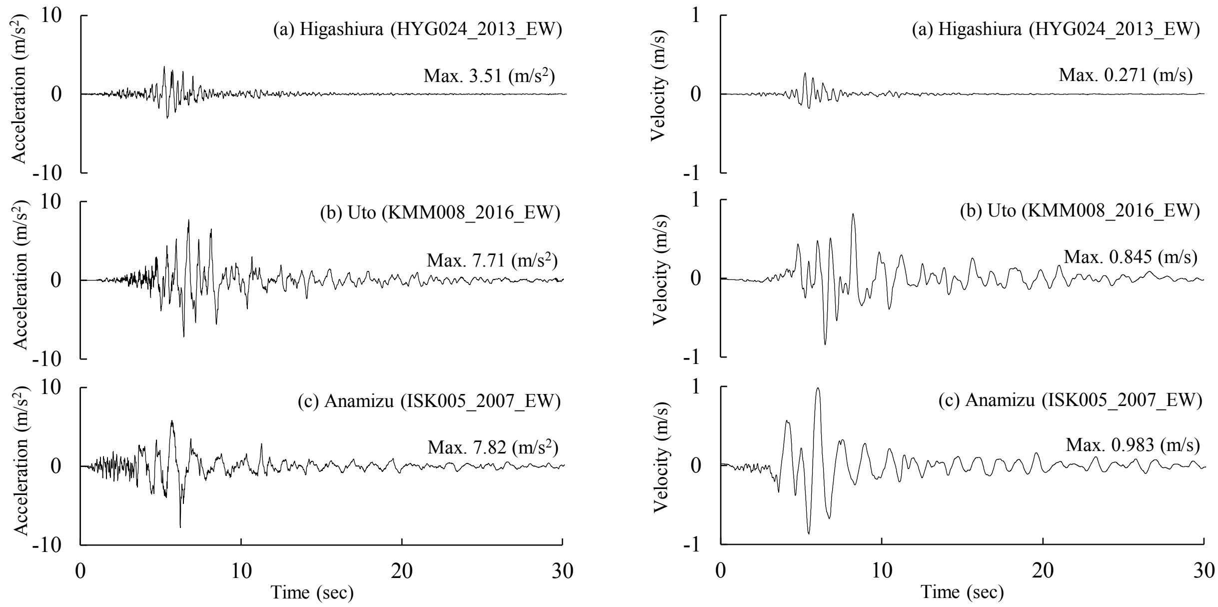


Fig. 4 Acceleration and velocity time histories of input seismic motions

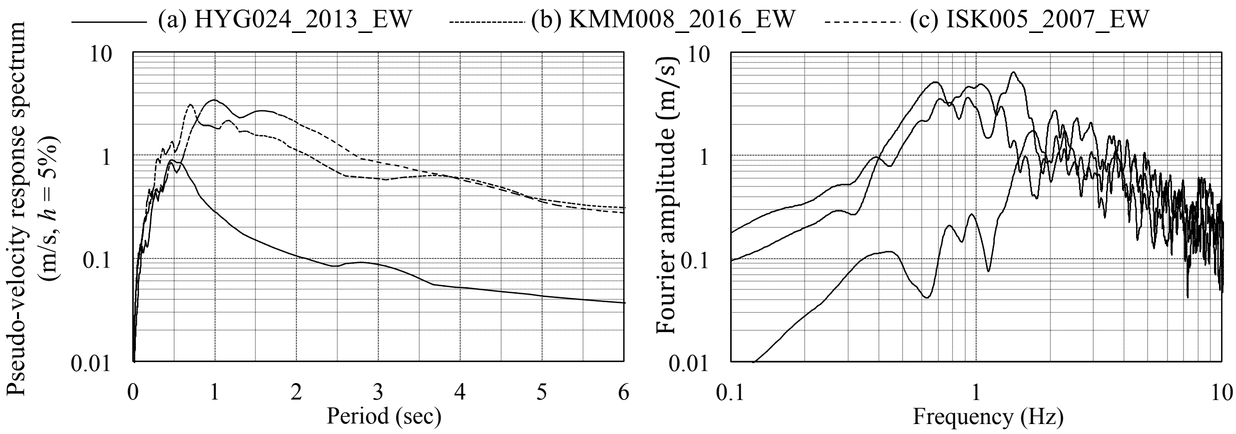
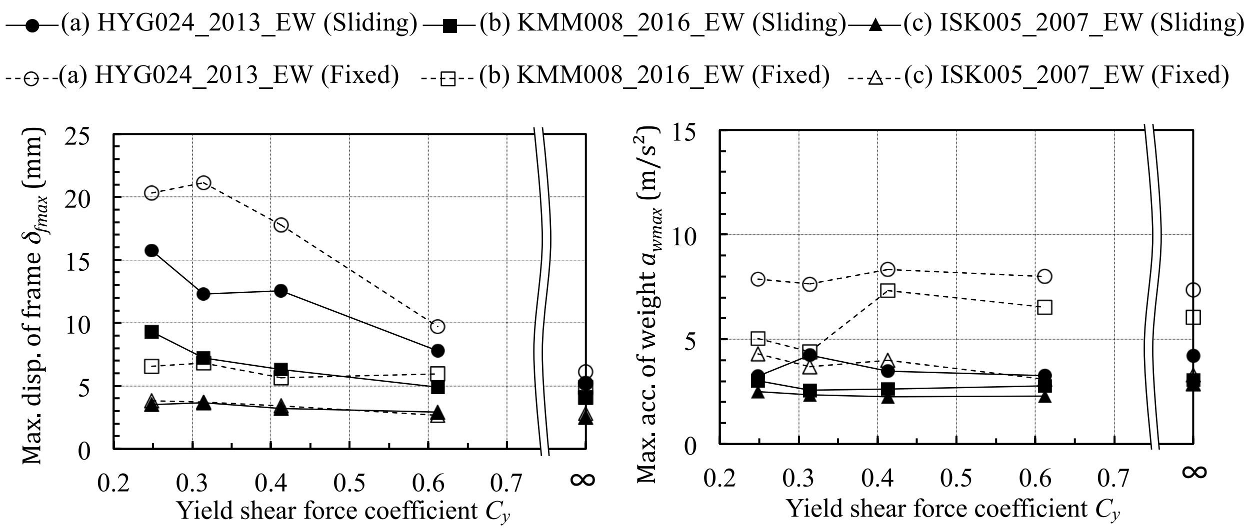


Fig.5 Pseudo-velocity response spectrum and acceleration Fourier spectrum of input seismic motions

Although there is a slight variation in d_{fmax}, d_{fmax} decreases as C_y increases for all seismic motions. However, d_{fmax} increases in the order of the input seismic motion, i.e., (c) ISK, (b) KMM, and (a) HYG, because d_{fmax} may increase by the seismic motion for which the predominant period is close to the primary natural period of the frame. d_{fmax} of the Sliding case is lower than the Fixed case for the case of (a) HYG, and the slide effect was confirmed. In addition, it is considered that the frame was in the elastic response in the case of (c) ISK since d_{fmax} for all C_y is generally equal including the case of $C_y = \infty$.

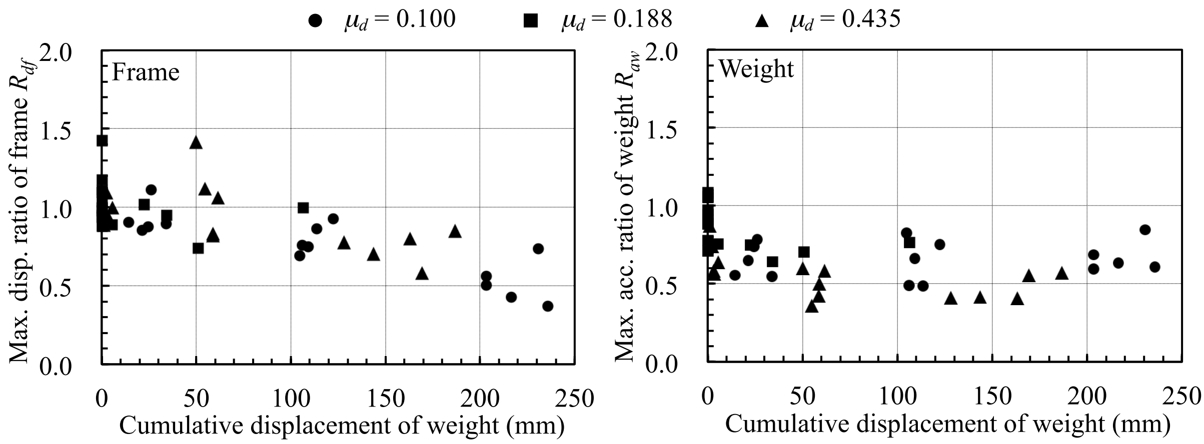
3.2. Maximum acceleration of the weight for the yield shear force coefficient

Figure 6 (ii) shows the relationship between the yield shear force coefficient C_y and the maximum acceleration of the weight a_{wmax} for each input seismic motion (experimental parameters: m_d = 0.188, V_{max} = 0.4 m/s, and R_m = 0.438). a_{wmax} of the Sliding case is lower than that of the Fixed case for all C_y and seismic motions. In addition, except for the Fixed case of (b) KMM, a_{wmax} is approximately constant regardless of C_y in both the Sliding and Fixed cases. The slide effect has been confirmed only in the elastic frame. However, the maximum story drift of the frame and the maximum acceleration of the weight were reduced by the weight sliding in the elastoplastic frame.



(i) Maximum story drift of the frame (ii) Maximum acceleration of the weight

Fig.6 Relationship between C_y and maximum response of the frame and weight
[μ_d = 0.188, V_{max} = 0.4m/s, R_m = 0.438]



(i) Maximum story drift ratio of the frame (ii) Maximum acceleration ratio of the weight

Fig.7 Relationship between cumulative displacement of weight and maximum response ratio of sliding to fixed

3.3. Response reduction ratio of the frame and weight for cumulative sliding displacement

In the previous section, the slide effect was discussed based on the maximum response displacement of the frame d_{fmax} and the maximum response acceleration of the weight a_{wmax} for the yield shear force coefficient C_y. According to the experimental results, the slide effect tended to increase when the maximum sliding displacement of the weight d_{wmax} was large. In other words, it is considered that the slide effect increases when the sliding amount of the weight is large. Therefore, the cumulative sliding displacement of the weight d_{wcum} was calculated based on the time history waveform of the sliding displacement in order to obtain the relationship between the Sliding-to-Fixed displacement ratio of the frame R_{df} and d_{wcum} (Fig. 7(i)) and the relationship between the Sliding-to-Fixed acceleration ratio of the weight R_{aw} and d_{wcum} (Fig. 7(ii)). The symbols in the figure indicate the results for the dynamic friction coefficients: m_d = 0.100 (closed circles), m_d = 0.188 (closed squares), and m_d = 0.435 (closed triangles). The slide effect can be confirmed if R_{df} and R_{aw} are less than 1.0. Although there are some R_{df} which is more than 1.0 (Fig. 7(i)), R_{df} and R_{aw} are generally less than 1.0. Based on Figures 7(i) and (ii), d_{wcum} increases with decreasing m_d, and both R_{df} and R_{aw} decrease with increasing d_{wcum}. Therefore, the slide effect increases with increasing d_{wcum}.

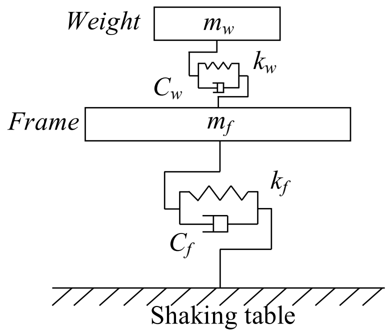


Fig.8 Analytical model

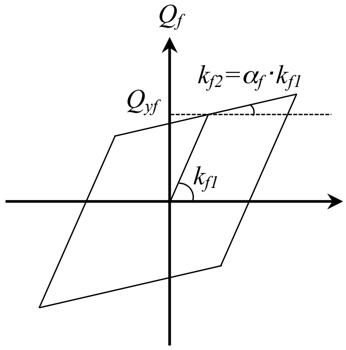


Fig.9 Bi-linear model of the

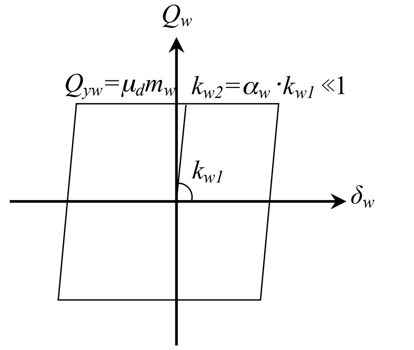


Fig.10 Bi-linear model of the weight

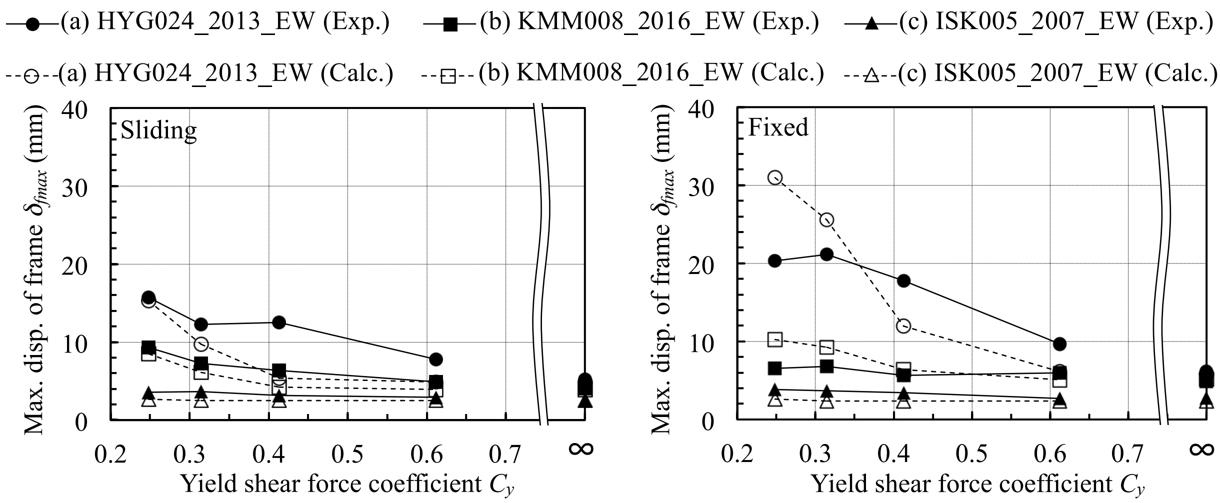


Fig.11 Comparison of the experimental and analytical response of the frame
[μ_d = 0.188, V_{max}=0.4m/s, R_m=0.438]

4. SEISMIC RESPONSE ANALYSIS CONSIDERING THE SLIDE EFFECT

4.1 Analytical model

The slide effect was quantitatively obtained based on the results of the shaking table test for the single-story elastoplastic steel frame described in Section 3. It is necessary to simulate the dynamic behavior of the elastoplastic frame with load siding in order to incorporate the slide effect for various designs of general buildings. Therefore, an analytical model considering the nonlinearity behavior of the frame and weight sliding was constructed for the purpose of discussing the predictability of the seismic response analysis by comparing the response results of the experiment and the analysis. In addition, we attempted to obtain the relationship between the decrease in the story drift and the additive damping ratio.

The analytical model consists of an elastoplastic two-degree-of-freedom system with the mass of the frame m_f and the mass of the weight m_w (Fig. 8). The restoring force characteristics for the frame and the weight sliding are bilinear models, as shown in Figs. 9 and 10, respectively. The initial stiffness k_{f1}, the second stiffness k_{w2}, and the yield shear force Q_{yf} of the frame were obtained from static cyclic loading tests, which were conducted separately. The initial stiffness k_{w1}, the second stiffness k_{w2}, and the dynamic frictional force Q_{yw} of the weight were estimated by free vibration tests and sliding tests of the weight. The second stiffness of the weight k_{w2} during sliding is assumed to be extremely low, and the stiffness lowering rate a_w was set to be 1.0×10^{-6} (a sufficiently small value). The damping was assumed as a tangent stiffness proportional damping for each part: h_f = 4.04% for the frame by the free vibration tests, and h_w = 6.53% for the weight by free vibration tests and

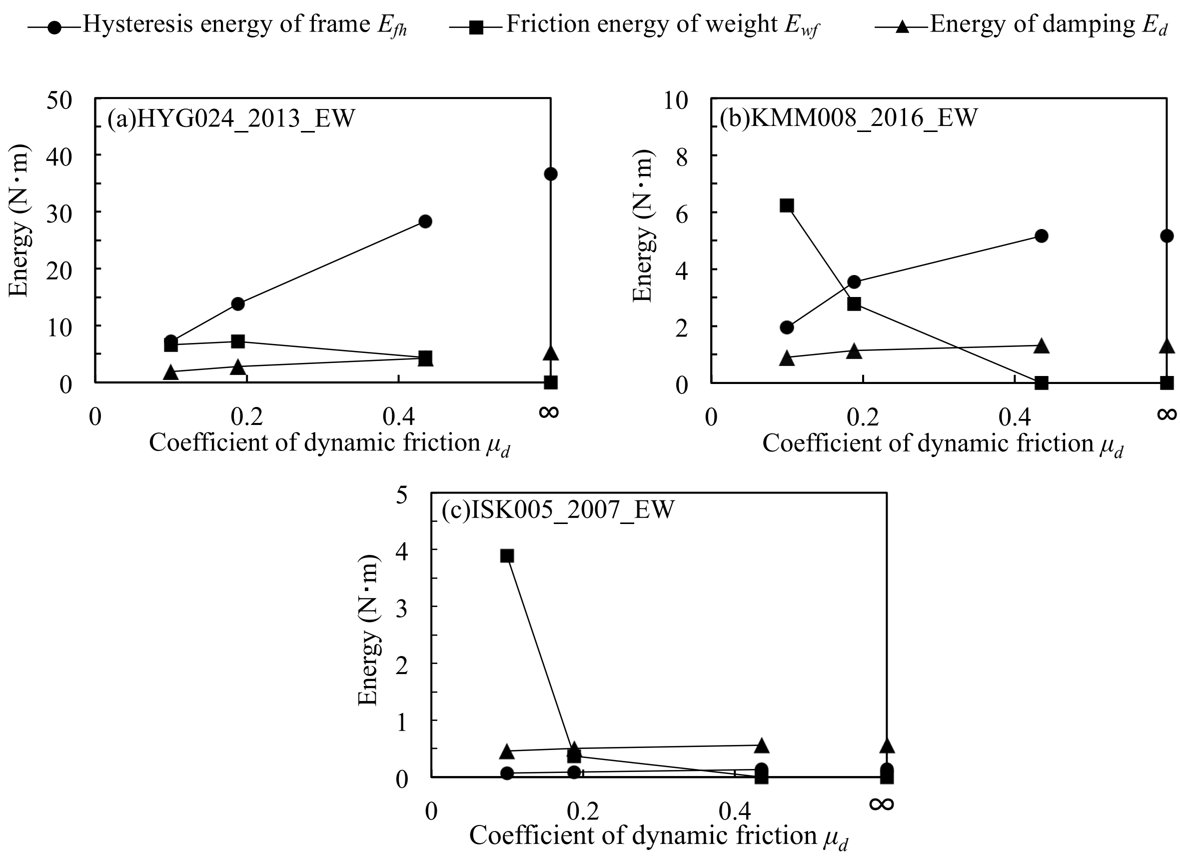


Fig.12 Analytical energy of the frame, weight, and damping [C_y = 0.248, V_{max} = 0.4 m/s, R_m = 0.438]

sliding tests. The Newmark β method (β = 0.25) was used to obtain the numerical solution, and SNAP Ver. 7 (KOZO SYSTEM) was used in the analyses.

4.2. Comparison of the experimental and analytical results for the single-story elastoplastic steel frame

Figure 11 shows the relationship between the yield shear force coefficient C_y and the maximum story drift of the experimental and analytical results (parameters: m_d = 0.188, V_{max} = 0.4 m/s, R_m = 0.438). The symbols in the figure indicate the results for the input seismic motions: (a) HYG (circles), (b) KMM (squares), and (c) ISK (triangles). The solid and dashed lines indicate the response results of the experiment and the analysis, respectively. In both the experimental and analytical results, d_{fmax} decreases with increasing C_y for both the fixed weight (left-hand graph) and the sliding weight (right-hand graph). When the sliding displacement of the weight is relatively small, the analytical results are roughly in agreement with the experimental results for (b) KMM and (c) ISK. However, the difference between the experimental and analytical results is large for (a) HYG, when the sliding displacement of the weight is large. Although the analytical and experimental results for d_{fmax} were not in perfect agreement, the tendencies of the response results for the parameters of interest were simulated.

4.3. Energy ratios of the structural system for the dynamic friction coefficient

The slide effect is related to the friction energy due to the sliding weight. In this section, the hysteresis energy of the frame E_{fh}, the friction energy of the weight E_{wf}, and the damping energy E_d were calculated analytically.

Figure 12 shows the each energies at 30 s to the dynamic friction coefficient m_d for each seismic motion (analytical parameters: C_y = 0.248, V_{max} = 0.4, and R_m = 0.438). The symbol ∞ on the horizontal axis indicates the results for the case in which the weight is fixed. The total sum of the energies increases in the order of the input seismic motion, i.e., (c) ISK, (b) KMM, and (a) HYG. Therefore, the energies are influenced by the phase characteristics of the seismic motions. The hysteresis energy of the frame E_{fh} decreases with decreasing m_d, and the damping energy E_d is constant regardless of m_d. On the other hand, the friction energy of the weight E_{wf} is approximately 0 in the case of $m_d = \infty$, and E_{wf} increases with decreasing m_d. E_{wf} is larger than E_d for all input seismic motions in the case of m_d = 0.100. In other words, it is considered that the damping ratio corresponding to the damping ratio h_1 = 4.04% of the frame was added by the weight sliding. Therefore, the friction energy generated by the sliding weight is not small when compared to the input energy and the damping energy, and a certain damping effect of load sliding can be expected for the structural design.

4.4 Additive damping ratio by load sliding

It is necessary to quantitatively evaluate the slide effect using design variable in order to incorporate the slide effect in rational structural design. In recent years, a structural design method considering energy has been adopted in Japan. Stress and deformation of structures are criteria in all structural design methods. Therefore, the additive damping ratio of the frame with the slide effect was evaluated by converting the decrease in the story drift due to the slide effect into the increase in the damping ratio of a dashpot that was newly installed between the layers of the analytical model. In other words, a rational design can be realized by using the response displacement obtained from an appropriately evaluated additive damping ratio.

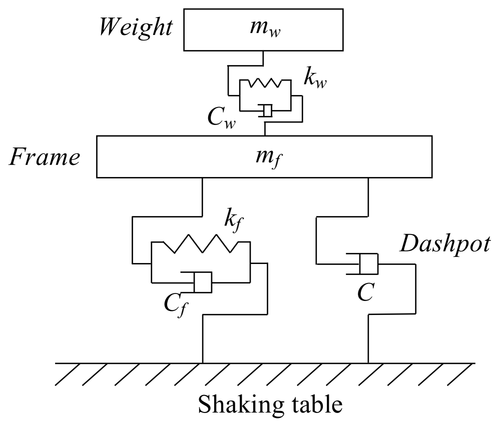


Fig. 13 Analytical model with a dashpot

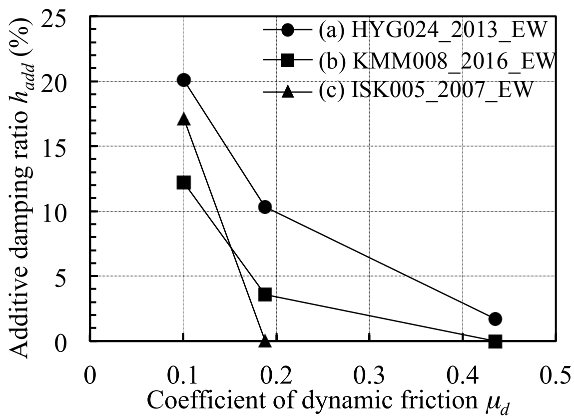


Fig. 14 Relationship between μ_d and h_{add} [C_y = 0.248, V_{max} = 0.4 m/s, R_m = 0.438]

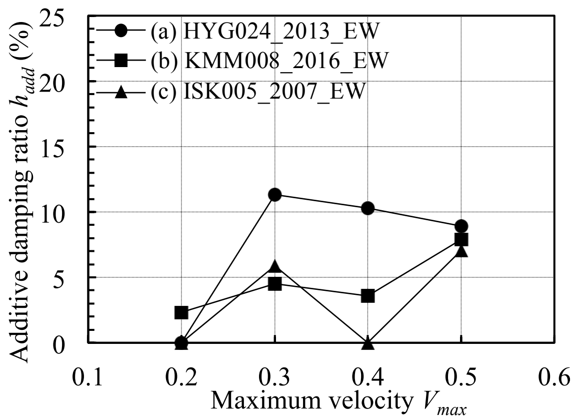


Fig. 15 Relationship between V_{max} and h_{add} [C_y = 0.248, μ_d = 0.188, R_m = 0.438]

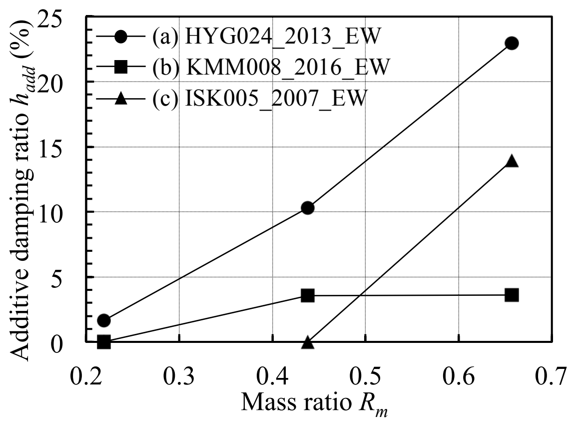


Fig. 16 Relationship between R_m and h_{add} [C_y = 0.248, μ_d = 0.188, V_{max} = 0.4 m/s]

It is possible to estimate the equivalent damping ratio using response spectrum if the frame is elastic. However, this is not possible in the case of an elastoplastic frame because of the nonlinearity characteristics of the frame. Therefore, a dashpot was installed between the layers of the frame for the case of the fixed weight (Fixed), as shown in Figure 13. Seismic response analyses were conducted repeatedly while adjusting the damping coefficient of the dashpot *C* until the displacement error between the Fixed case and the case of the sliding weight (Sliding) was within ±1.0%, and the equivalent damping coefficient C_{eq} was obtained. The damping coefficient C_{eq} was converted to the equivalent damping ratio h_{add} (additive damping ratio) added by the slide effect, which was calculated as follows:

$$h_{add} = \frac{C_{eq}}{2(m_w + m_f)\omega_f} \quad (1)$$

where m_w and m_f are the masses of the weight and the frame, respectively, and ω_f is the natural angular frequency of the frame for the Fixed case.

The additive damping ratio h_{add} is the added damping ratio excluding the frame damping ratio. Therefore, the slide effect is considered to be equal to the effect of reducing the response displacement of the damped building with the damper of h_{add} based on this calculation.

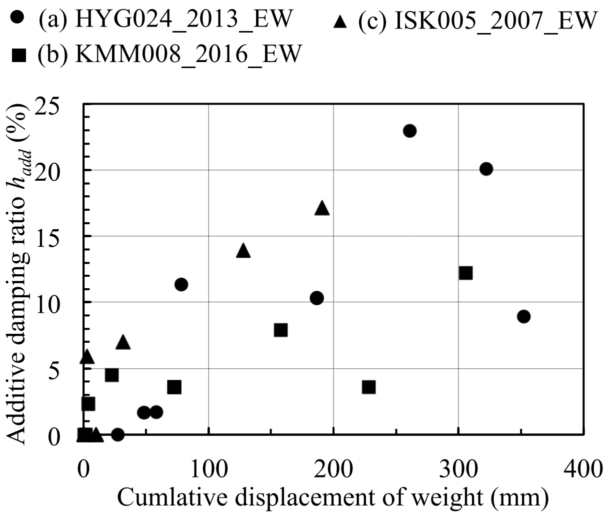


Fig.17 Relationship between cumulative sliding displacement of weight and h_{add} [C_y = 0.248]

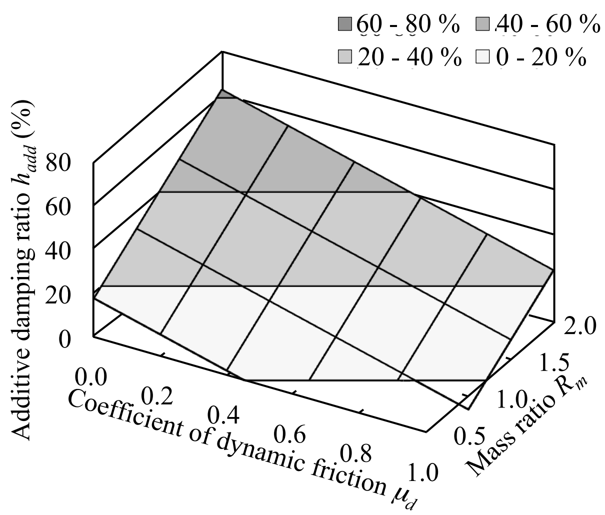


Fig.18 Relationship between μ_d and R_m for h_{add} [C_y = 0.248, V_{max} = 0.4 m/s]

Table 2 Result of multiple regression analysis

	Coefficient	p-value
Segment	2.634	0.657
μ_d	-38.37	0.014
R_m	29.57	0.018

Figure 14 shows the relationship between the coefficient of dynamic friction m_d and the additive damping ratio h_{add} for each input seismic motion (analytical parameters: C_y = 0.248, V_{max} = 0.4 m/s, R_m = 0.438). In the case of m_d = 0.100, h_{add} is approximately 12 to 20%. However, in the case of m_d = 0.438, h_{add} is approximately 2% for (a) HYG and 0% for (b) KMM, (c) ISK. Therefore, the slide effect increases with decreasing m_d, and h_{add} increases with decreasing m_d. Figure 15 shows the relationship between the maximum velocity V_{max} and h_{add} (analytical parameters: C_y = 0.248, m_d = 0.188, R_m = 0.438). The relationship between h_{add} to V_{max} is not as clear as that between h_{add} and m_d. However, in the case of $V_{max} \geq 0.3$ m/s, h_{add} is more than 4%, except for the case of V_{max} = 0.4 m/s for (c) ISK. Since the probability of damage to a building for the case in which V_{max} = 0.2 m/s is low, it is not necessary to consider the slide effect for this level of input seismic motion. Figure 16 shows the relationship between the mass ratio R_m and h_{add} (analytical parameters: C_y = 0.248, m_d = 0.188, V_{max} = 0.4 m/s). Although there are slight variations in the evaluation of h_{add} depending on the phase characteristics of the input seismic motions, h_{add} increases with increasing R_m. In other words, the dynamic frictional force and the friction energy of the weight increase with increasing R_m. Since the friction energy by weight sliding was increased, the additive damping ratio increased and the story drift decreased.

These figures reveal that the increase in the weight sliding is related to the increase in the frictional energy, and the increase in the frictional energy is related to the reduction in the response displacement and the increase in the additive damping ratio. In other words, the sliding displacement of the weight is related to the increase in the additive damping ratio h_{add}. Figure 17 shows the relationship between the cumulative sliding displacement of the weight and h_{add} for the case of C_y = 0.248. Although there are some variations in the data shown in Figure 17, h_{add} tends to increase with increasing cumulative sliding displacement of the weight. In addition, h_{add} is strongly influenced by m_d and R_m, as shown in Figures 14 through 16. Therefore, the cause of the variation in Figure 17 is considered to be related to m_d and R_m. Thus, multiple regression analysis for h_{add} was performed in order to obtain the influence of m_d and R_m based on these analytical results.

Table 2 shows the regression coefficients and p-values calculated by multiple regression analysis, and Figure 18 shows estimated values of h_{add} obtained from the regression equation. Although the analytical results have variations, the multiple coefficient of determination is 0.568, and the p-value of each explanatory variable is less than 0.05. Therefore, it is possible to roughly predict h_{add} based on m_d and R_m. As shown Figure 18, h_{add} is considered to increase with decreasing m_d and increasing R_m. As mentioned in the Introduction, buildings such as warehouses, the live load of which is significantly larger than the dead load, have a larger R_m compared to general building. Therefore, the slide effect is expected to be significant in the case of warehouses, and consideration of this effect may contribute to a rational structural design.

These seismic response analyses results were obtained based on the seismic motions for M6.3 to 7.3 events that occurred in Japan in recent years, and the duration of the principal motions for these events was approximately 10 seconds. As such, the applicability of the analyses to M8 seismic motions with long principal motion duration should be investigated.

5. CONCLUSION

Shaking table tests on a single-story elastoplastic steel frame while varying the experimental parameters, including the yield shear force coefficient, the dynamic friction coefficient of the weight, the maximum velocity of the seismic motion, and the weight-to-frame mass ratio, were carried out in order to obtain the basic characteristics of the slide effect for the elastoplastic frame. The story drift of the frame and the acceleration of the weights were reduced by the sliding of the weights. An analytical model considering the nonlinearity behavior of the frame and weight sliding was constructed for the purpose of comparing the response results of the experiment and the analysis. In addition, the additive damping ratio due to the slide effect was analytically calculated in order to evaluate the slide effect using design variable. Based on the results of the shaking table tests and seismic response analyses, we found the followings:

The slide effect increased with decreasing dynamic friction coefficient of the weight and increasing maximum velocity of the input seismic motion.

The slide effect increased with increasing maximum sliding displacement and cumulative sliding displacement of the weight.

The response tendencies of the frame and weight of the analytical results for the parameters of interest generally agreed with the experimental results.

The additive damping ratio due to weight sliding increased with increasing mass ratio and decreasing coefficient of dynamic friction of the weight.

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