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Estimation of Live Loads in Warehouses during Earthquakes Considering the Load Sliding Effect

[1] Ryo Sasaki, [2] Kuniaki Yamagishi
[1] Kanazawa Institute of Technology, [2] Kanazawa Institute of Technology.

Abstract:-- **Although the seismic response reduction effect with load sliding (slide effect) is not considered in general structural design, consideration of this effect may contribute to a more rational design. In the present study, seismic response analyses were performed on an analytical model while varying certain parameters to obtain the basic characteristics of the slide effect on a warehouse. Based on the analytical results, the design load used both for the structural design and for calculating the seismic forces acting on a warehouse was estimated**

Indexterms: **Load-sliding effect, RC column - S beam structure, Warehouse, Live load during earthquake.**

I. INTRODUCTION

Current Japanese building codes only specify the live load on slabs for warehouse-type buildings and consideration of the live load on the frame is left to the judgement of the structural engineer. This rationale is coming under increasing scrutiny as the understanding of the impact of live loads on warehouses increases. The response reduction of load acceleration and the displacement of structures with loads on the slabs sliding due to inertial forces (hereinafter referred to as the “slide effect”) have been confirmed in previous studies [1]–[7]. Although the slide effect is not considered in general structural design, its consideration may reduce the live load used in the frame design and aid in the analysis of seismic lateral forces, as compared with current design protocols that assume fixed loads [8]. The response reduction due to the slide effect on steel structure (S) and reinforced concrete structure (RC) was confirmed by quantitative analysis in a previous study [9]. Although the number of warehouse buildings with reinforced concrete columns and steel beams (RC+S) has increased in recent years, the slide effect on RC+S structures has not been investigated. In this study, in order to obtain the basic characteristics of the slide effect on RC+S and S structures, analytical models were constructed and seismic response analyses were performed. The analytical results were then used to estimate seismic lateral forces.

II. SEISMIC RESPONSE ANALYSIS OF WAREHOUSE MODEL

A. Analytical Model of Warehouse Using the Load Sliding

Fig. 1 shows the floor plan and Fig. 2 shows an elevation of the warehouse used in the study. The area of each floor was 10,000 m2, and the height of each floor was 5 m. Based on trial designs, the dead loads of the RC+S structure were set to 6.73 kN/m2 for the standard floor and 6.42 kN/m2 for the roof floor (RF), and dead loads of the S structure were set to 5.22 kN/m2 for the standard floor and 4.91 kN/m2 for the RF. The live load was set to be 15 kN/m2, and the total weight of the load when fully loaded on the floor excluding passages and common areas was 98,185 kN on each floor. Fig. 3 shows the analysis model used in this study. The analysis model was a multi-degree-of-freedom (MDOF) model in which the weight of each floor was concentrated into point loads. The stiffness of each layer was estimated from the period calculated by simple formula and yield resistance distributions based on Japanese building codes; i.e., the stiffness of each layer was assumed to be proportional to

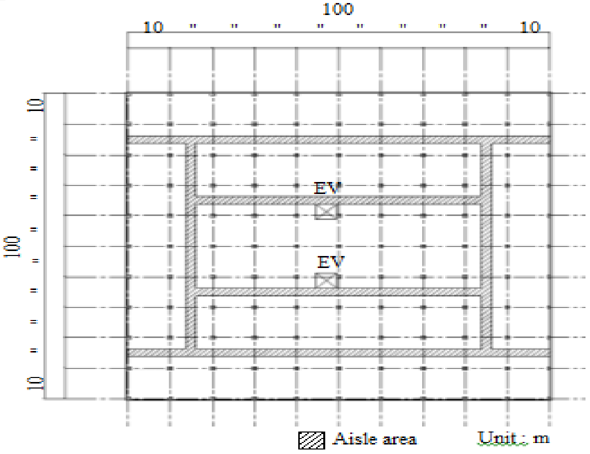

Fig. 1 Model floor plan

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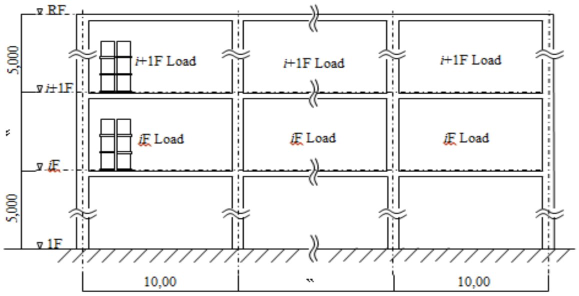

Fig. 2 Model elevation

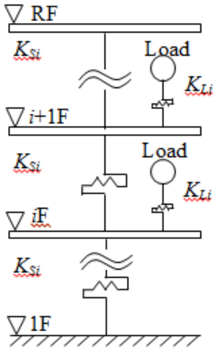

Fig. 3 Analysis model

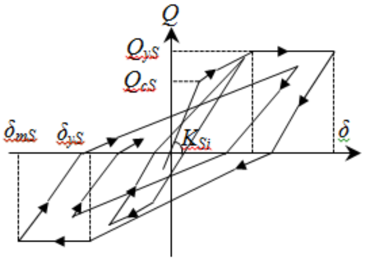

Fig. 4 Takeda model for RC+S structure

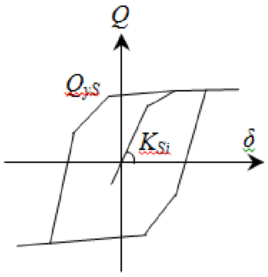

Fig. 5 Takeda model for S structure

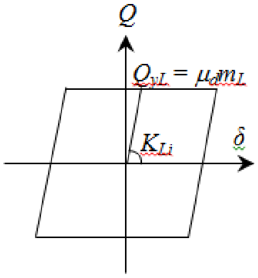

Fig. 6 Bi-linear model for load

The seismic shear force based on the Ai distribution, which is the Japanese original seismic force distribution. The natural period of the RC+S structure was calculated by 0.026h (h: warehouse height) as in [10] and the natural period of the S structure was calculated as 0.03h. The initial stiffness of each structure was calculated using each natural period The restoring force characteristics of each layer spring for the RC+S structure were based on the Takeda model, as shown in Fig. 4, which was developed for RC structures. The Tri-linear model shown in Fig. 5 was used for the S structure. The yield strength of each structure was calculated using the required ultimate lateral strength and assuming the yield shear strength coefficient to be 0.4. The restoring force characteristics of loads acting on each floor was a Bi-linear model with frictional forces corresponding to the friction coefficient of a pallet and the floor, as shown in Fig. 6. DAP Ver. 2.0 (KOZO SYSTEM) was used in the analyses.

B. *Analytical Parameters*

The analytical parameters used in the analysis are shown in Table I. The five analytical parameters of interest are as follows: (1) structural classification, (2) dynamic friction coefficient of the load and floor surface μ_d, (3) number of floors n_f, (4) damping ratio of building h_1, and (5) loading ratio R_L. The dynamic friction coefficient of the load and floor surface μ_d is an important parameter related to the sliding behavior of the load. Generally, the dynamic friction coefficient of a pallet is approximately 0.3, and a smaller dynamic friction coefficient corresponds to a higher sliding effect. Therefore, μ_d = 0.15 was used as a reference value. In addition, an upper limit $\mu_d = \infty$ (completely fixed to the floor) and a lower limit value μ_d = 0.0001 were used to determine the effects of μ_d. The damping ratio of the experimental frames used in previous studies to quantify the slide effect was approximately 0.2% [1]. The damping ratio of general buildings h1 is approximately 3% for RC structures and 2% for S structures. Therefore, to obtain the slide effect

Table 1 Analysis parameters

Parameter	Value
Structural classification	Hybrid(RC+S), Steel(S)
Coefficient of friction μ_d	0.0001, 0.1, $\boxed{0.15}$, 0.2, 0.3, 0.5, ∞
Number of floors n_f	2, $\boxed{3}$, 5
Damping ratio h_1 (%)	1, $\boxed{3}$, 5, 10
Loading ratio R_L (%)	25, 50, $\boxed{75}$, 100

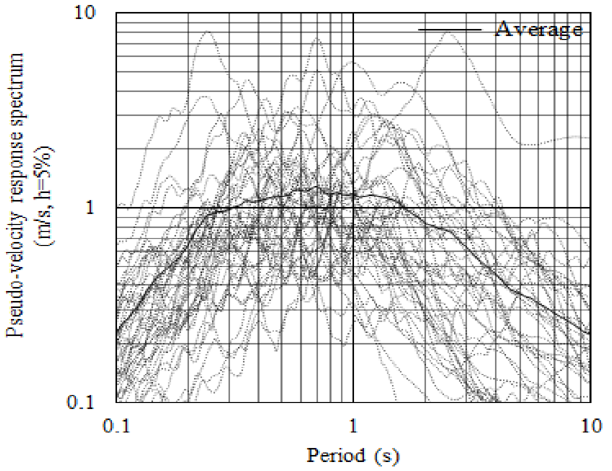

Fig. 7 Pseudo-velocity response spectrum of all input motions

considering the actual value of h1, it was set to 1, 3, 5, and 10%. The reference value was assumed to be 3% for the RC+S structure, because 10% is an extremely high damping ratio.

The loading ratio RL represents the ratio of actual to full load. The live load for each RL is the product of the live load per unit area (15 kN/m2) and the loading ratio. The reference value was set to be RL = 75% because it is unlikely that full loading occurs in the warehouse at time of the earthquake.

C. Input Seismic Motions

The input seismic motions for high-rise buildings used in current structural design in Japan are based upon the El Centro 1940 NS, Taft 1952 EW, and Hachinohe 1968 EW earthquakes. Generally, seismic motions are produced by unique source characteristics, wave propagation, and amplification at the surface. However, it may not be sufficient to verify building safety using just such seismic motions, and many and various seismic motions are necessary to incorporate the response characteristics with the slide effect into the structural design. In this study, seismic response analyses were conducted by using 42 seismic motions observed in Japan, and the magnitudes of these events were all greater than 6.0. Fig. 7 shows the pseudo-velocity response spectra of the input motions, in which the black solid line indicates the average of the spectra. The maximum velocity of the input seismic motions used in the analyses was standardized to 0.5 m/s. The analytical results in the following graphs are the average response results to the 42 input seismic motions.

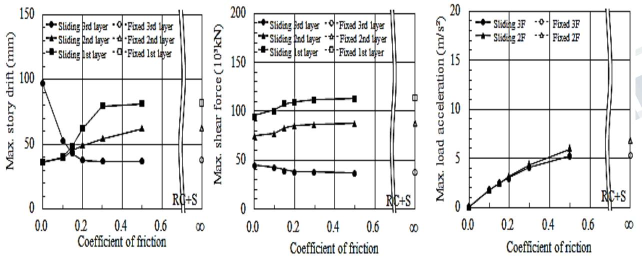

Fig. 8 Response of RC+S structure and load for coefficient of friction [nf = 3, h1 = 3%, RL = 75%]

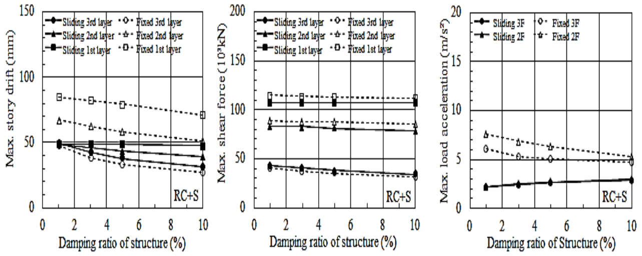

Fig. 10 Response of RC+S structure and load for damping ratio [□d = 0.15, nf = 3, RL = 75%]

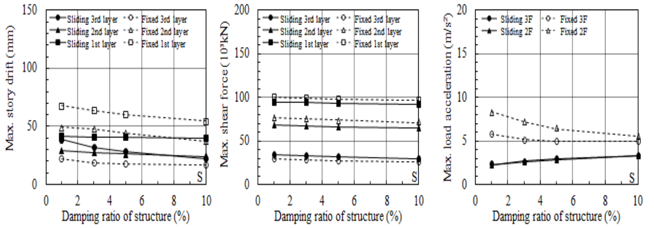

Fig. 11 Response of steel structure and load for damping ratio [□d = 0.15, nf = 3, RL = 75%]

results in the following graphs are the average response results to the 42 input seismic motions.

III. SEISMIC RESPONSE ANALYSIS RESULTS

Response Result for Coefficient of Friction

Fig. 8 shows the response results of the RC+S (n_f=3) structure and load for the coefficient of friction μ_d, and Fig. 9 shows the response results of the S structure and load for μ_d. The symbols in the figures indicate the results of 3rd layer (circle), 2nd layer (triangle), and 1st layer (square). The left-hand graph shows the maximum story drift of the building, the middle graph shows the maximum shear force in the building, and the right-hand graph shows the maximum acceleration response of the load.

The story drift and the shear force of the 1st and 2nd layers decreases with decreasing μ_d. The story drift of the 1st layer is reduced by approximately 41% in the RC+S structure and by approximately 36% in the S structure at μ_d = 0.15 compared with the fixed load case ($\mu_d = \infty$). However, the

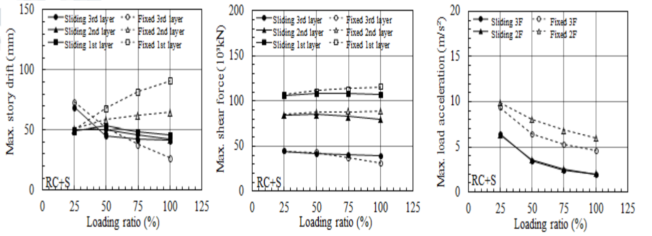

Fig. 12 Response of RC+S structure and load for loading ratio [μ_d = 0.15, n_f = 3, h_1 = 3%]

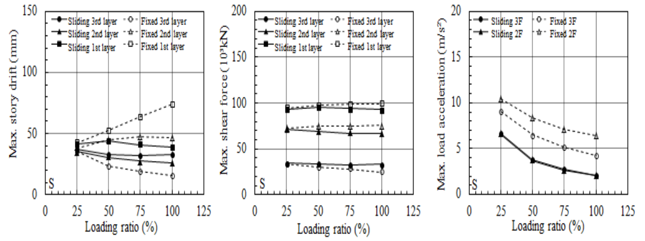

Fig. 13 Response of steel structure and load for loading ratio [μ_d = 0.15, n_f = 3, h_1 = 3%]

story drift and shear force of the 3rd layer increases with decreasing μ_d for both the RC+S and S structures. Conversely, the acceleration response of the load decreases with decreasing μ_d for both the 2nd and 3rd floors. For both the RC+S and S structures, the response acceleration of the load on each floor is reduced by approximately 60% at $\mu_d = 0.15$ compared with $\mu_d = \infty$. A significant slide effect can be seen when the friction coefficient of the load is lower.

B. Response Result for Damping Ratio

Fig. 10 shows the response results for the RC+S structure and load for the damping ratio of building h_1, and Fig. 11 shows the response results for the S structure and load for h_1. The solid and dashed lines indicate the response results for the sliding and fixed load cases, respectively. The story drift and the shear force decrease with increasing damping ratio for both the RC+S and S structures. The story drift and the shear force of the sliding case are lower than that of the fixed case for the 1st and 2nd layers. The story drift of the 1st layer is reduced by 33% at $h_1 = 10\%$ and 43% at $h_1 = 1\%$ in the RC+S structure, and by 26% at $h_1 = 10\%$ and 39% at $h_1 = 1\%$ in the S structure. The response acceleration of the load increases with increasing h_1 in the sliding case and decreases with increasing h_1 in the fixed case for both the RC+S and S structures. Therefore, the slide effect is significant when h_1 is lower.

C. Response Result for Loading Ratio

Fig. 12 shows the response results of the RC+S structure and load for loading ratio R_L, and Fig. 13 shows the response results of the S structure and load for R_L. For both the RC+S and S structures, the story drift decreases with increasing R_L in the sliding case and increases with increasing R_L in the fixed case except for the 3rd layer. In accordance with increasing R_L, the difference in the story drift of each layer story drift and shear force of the 3rd layer increases with decreasing μ_d for both the RC+S and S structures. Conversely, the acceleration response of the load decreases with decreasing μ_d for both the 2nd and 3rd floors. For both the RC+S and S structures, the response acceleration of the load on each floor is reduced by approximately 60% at $\mu_d = 0.15$ compared with $\mu_d = \infty$. A significant slide effect can be seen when the friction coefficient of the load is lower.

IV. ESTIMATION OF LIVE LOADS IN WAREHOUSES DURING EARTHQUAKES CONSIDERING THE SLIDE EFFECT

It has been shown that the story drift and the shear force of the building, and the response acceleration of the load are reduced by load sliding during an earthquake. In this section, the ratio of the live load to the design live load during an earthquake is estimated based on the reduction of the shear force between the sliding ($\mu_d = 0.15$) and fixed cases ($\mu_d = \infty$). Fig. 14 shows the maximum shear force in the RC+S and S structures for loading ratio R_L due to the difference in the number of floors n_f. The shear force in the fixed case tends to be the maximum at $R_L = 100\%$. However, the shear force in the sliding case is not the maximum at $R_L = 100\%$; i.e., the shear force is decreased because the slide effect is larger in accordance with the increase in R_L. Therefore, the shear force of the building with load sliding has a maximum value for R_L, and there is no need to consider $R_L = 100\%$ during an earthquake. The live load for seismic forces is assumed to be reduced because the probability that R_L is 100% during an earthquake is low. However, because the shear force is not proportional to RL when all the layers yield, the difference for RL is small. Thus it is thought to be possible to reduce live loads during an earthquake up to RL where the maximum shear force in a load sliding structure for all values

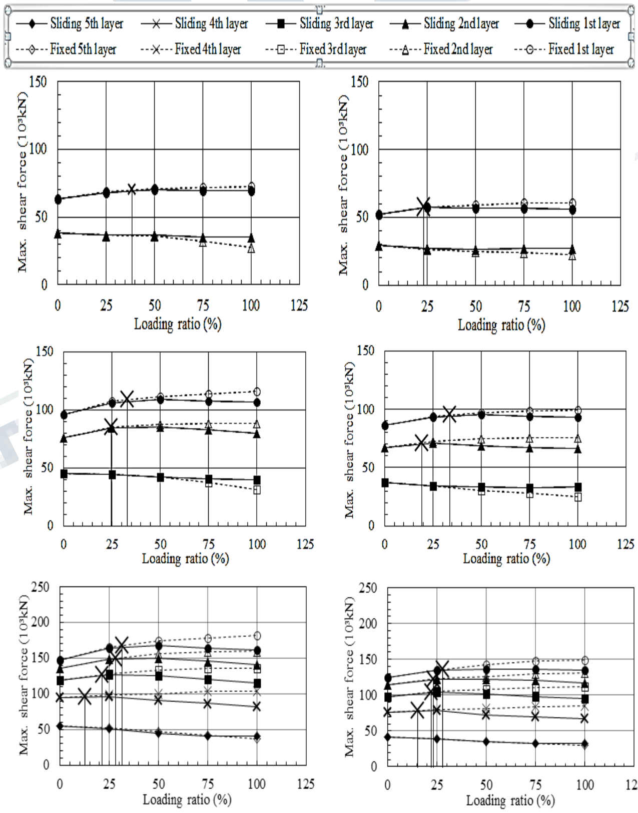

Fig.14 Relationship between loading ratio and maximum shear force of structure [$\mu_d = 0.15$, $n_f = 3$, $h_1 = 3\%$]

of RL is equal to the shear force of a load fixed structure. The X-marks in Fig. 14 are the cross points of maximum shear force for sliding and fixed load structures. Based on these ratios, the live load during the earthquake was calculated by multiplying the design live load by the loading ratio. In the case of the 3-story structure, the loading ratio is 33.0% for the 1st layer and 24.8% for the 2nd layer in the RC+S structure. In the S structure, the loading ratio is 33.6% for the 1st layer and 19.4% for the 2nd layer. Although there are slight variations depending on the layers, the loading ratio is approximately 20 - 30% overall. However, an intersection was not found in the top layer of each story. The live load during an earthquake after taking the slide effect into consideration is considered to be 20 - 30 % of the design live load.

V. CONCLUSION

Seismic response analyses for various parameters were conducted to obtain the basic characteristics of the slide effect and to estimate its impact on live loads in warehouses during an earthquake. Based on the results, we make the following conclusions:

1) The slide effect increases with increasing load friction coefficient and loading ratio.

2) The slide effect decreases with increasing damping ratio.

3) The live load during the earthquake with the slide effect is approximately 20 - 30 % of the design live load when the maximum velocity of the input seismic motions is 0.5 m/s.

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