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RESEARCH ON INFLUENCE TO EARTHQUAKE RESPONSES OF BASE ISOLATED STRUCTURES DUE TO THE ADHESION OF THE SLIDING BEARING TO THE SLIDING PLATE

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SUMMARY

The purpose of this paper is to examine by dynamic experiments and simulation analyses how the adhesion of sliding bearings influence the responses of structures. Specimens for experiments consist of a sliding plate and a stainless steel plate coated with PTFE. After constant axial loading sustained during a specified period from one week to 4 months, experiments had been carried out by dynamic lateral sinusoidal loading. From the experiments it was found that the influence of sustained period to adhesion were comparatively small on the hysteresis characteristics of lateral force and displacement, the tendency for reaction force at initial loading to have large coefficient of friction from the stable loop became more clear, as specified sustained period of specimen longer. Based on these results, the rule of hysteresis loop was formulated into a mathematical model, in which the influence of adherence was taken into account. In order to examine the influence of the adherence on earthquake responses of structures, simulation analyses were performed using this hysteresis loop model. The in-house-software used in the analyses can take effects of variable axial force and velocity dependency on the hysteresis loop into consideration. The earthquake input motions were one with longer duration time and pulse-like one. The analyses results in that on the whole the maximum response displacements were affected less by the adherence.

INTRODUCTION

Sliding bearings of base isolated structures is used widely that have advantage to enable the building to have longer natural period [1]. However, it is anticipated that behavior of structures during earthquakes is affected by the loading condition of permanent axial force and the influence of adhesion of sliding bearings derived from the permanent axial force has not been clarified. Therefore when sliding bearings are applied, it might be required to verify the influence of adhesion that it has on the structure response.
From this point of view, experiments on the influence of adhesion were carried out using specimens of sliding bearings keeping permanent axial load during some periods and afterward dynamic tests were

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carried out. Based on the experimental results, the rule of hysteresis loop considering the influence of adhesion was formulated into a in-house-software and simulation analyses were performed.
This paper presents the results of experiments and simulation analyses and discusses on the influence of adhesion for the design view.

EXPERIMENT OF ADHESION OF SLIDING BEARING

Figure 1 shows the test piece and equipment for experiments in which a pair of test pieces of sliding bearings is equipped in the both sides of a sliding plate. Since no influence of rubber bearing on adhesion is presumed, sliding bearings without rubber part are only applied for test specimens in the experiments.. The diameter of sliding bearing specimens is 80mm. Surface pressure is given by axial force to prestressing bar through which is loaded managing a calibration value due to strain gage. In order to avoid stress relaxation, the bowl springs are put into the bar.
The equipment for experiments is shown in Photo 1 and its specification in Table 1. The excitation is carried out by a sinusoidal wave of displacement control following the specification in Table 2. Measurement items are friction force, displacement of sliding plate and axial force of prestressing bar.

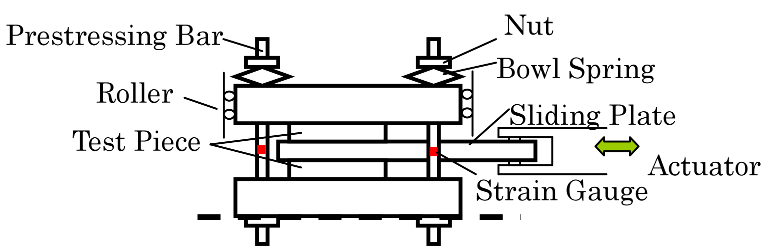


Figure 1. Surface Loading

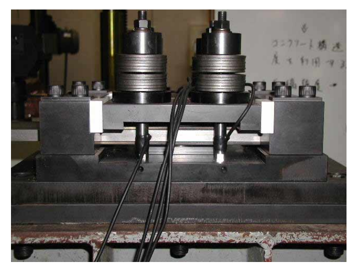


Photo 1. Test Piece

Table 1. Specification of Equipment

Items	Specification
Dynamic Load	30 kN
MAX Velocity	18.8 cm/s
Stroke	±100mm
Control System	Displacement
Excitation Wave	Sine Wave

Table 2. Input Displacement Specification

Frequency	0.3 Hz
MAX Displacement	2.5cm
MAX Velocity	5.65cm/s

Experiment cases

Eight kinds of test cases in which 3 specimens in each case are made are applied in the experiments. Their parameters are shown in Table 3. The produced makers are A and B companies, the specified friction coefficients high and low (case name of L and H) and periods sustained by standard axial force are 3 or 4 months or no sustained period. The experiment results in the following are obtained by averaging results of 3 specimens.

Table 3. Outline of Test Pieces

Case Name	Maker	Friction Coefficient (Specification)	Standard Surface Pressure (N/mm^2)	Standard Axial Force (kN)	Sustained Period
AL-0	A	Low (0.029)	12	60.3	No
AH-0	A	High (0.135)	12	60.3	No
BL-0	B	Low (0.013)	15	75.4	No
BH-0	B	High (0.112)	15	75.4	No
AL-4M	A	Low (0.029)	12	60.3	4 Months
AH-4M	A	High (0.135)	12	60.3	4 Months
BL-3M	B	Low (0.013)	15	75.4	3 Months
BH-3M	B	High (0.112)	15	75.4	3 Months

Experimental results

Results of friction force and friction coefficient

Table 4 shows the maximum friction forces Q_m, which indicates peak force at initial loading, ones Q_s during steady state cycle on an average sense and their friction coefficients, μ_m and μ_s, converted from friction force and axial force.

It is found in Table 4 that in the low friction type of specimens Q_m and μ_m which are affected by adhesion become twice to 4 times than Q_s and μ_s in Cases of A and about twice in Cases of B. The ratio of Q_m / Q_s in the high friction type of specimens becomes 1.1 to 1.2.

Table 4. Friction Force and Friction Coefficient

Case Name	Friction Force			Friction Coefficient		
	MAX (kN) Q_m	State (kN) Q_s	Ratio Q_m / Q_s	MAX μ_m	State μ_s	Ratio μ_m / μ_s
AL-0	14.8	3.77	3.93	0.120	0.035	3.43
AH-0	14.0	11.76	1.19	0.116	0.106	1.09
BL-0	3.6	2.56	1.40	0.024	0.015	1.57
BH-0	16.4	14.37	1.14	0.106	0.095	1.12
AL-4M	9.8	5.65	1.74	0.081	0.046	1.74
AH-4M	21.0	17.84	1.18	0.183	0.172	1.06
BL-3M	6.0	3.34	1.79	0.039	0.017	2.29
BH-3M	20.3	18.90	1.07	0.136	0.114	1.19

Characteristics of friction during cyclic loops and time histories

The cyclic loops of the relationship between friction force and displacement are shown in Figures 2 to 5 for various cases. As shown in Figures 2 and 4, the friction force and friction coefficient in the low friction type specimens increases immediately after excitation by adhesion of sliding bearing . On the other hand the high friction type specimens in Figures 3 and 5 are affected less by adhesion of sliding bearing.

Figure 6 is the time histories of Q_s/N (N: axial force, μ_s: Absolute of Q/N) and displacement in the case of AL-0. In this figure it is found a phenomena that Q_s/N which is calculated from shear force divided by axial force considering the sign of velocity momentarily becomes large at the time maximum

displacement occurs. Since the large friction coefficients generate when the cyclic displacement turns over at the first and second loop (A and B in a Figure) , the phenomena might be influenced by adhesion.
While the influence by adhesion is less in the cases of high friction, in the cases of low friction keeping loading conditions during 3 or 4 months increases more or less the friction coefficient. An examination of the influence of adhesion after sustaining axial load during a few years is important and that is our future task.
The time histories of observed axial force are shown in Figures 7 and 8. Comparing those with standard axial force shown in dashed line in Figures 7 and 8, observed axial forces vary in time within the range of 5 to 10 kN. We expect the fluctuation of axial force is arise by the relaxation of prestressig bar and the low precision of specimens in producing.

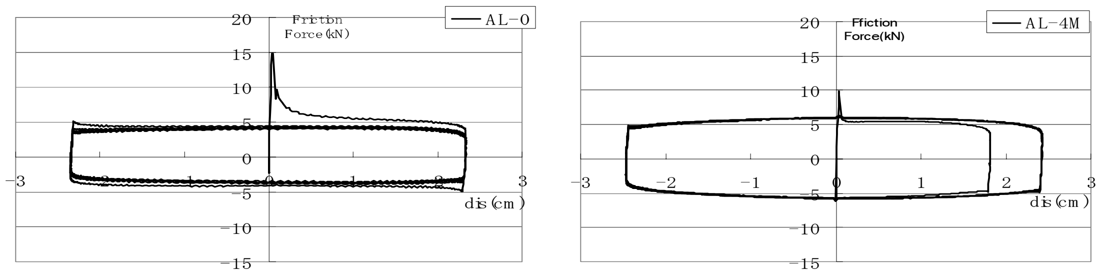


Figure 2 (a). Relationship between Friction Force and Displacement（Case AL）

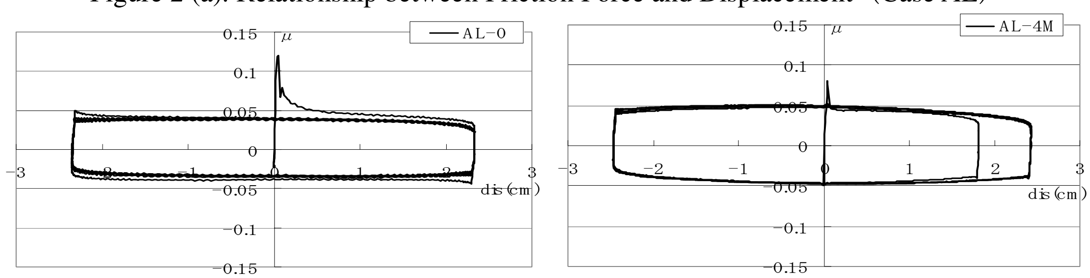


Figure 2(b). Relationship between Friction Coefficient and Displacement（Case AL）

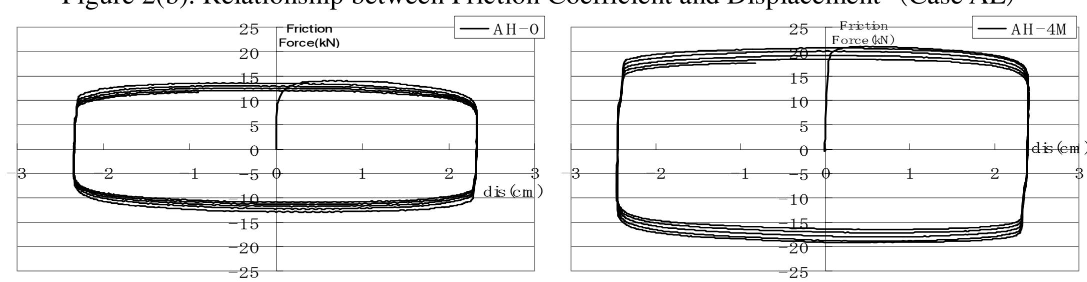


Figure 3(a). Relationship between Friction Force and Displacement（Case AH）

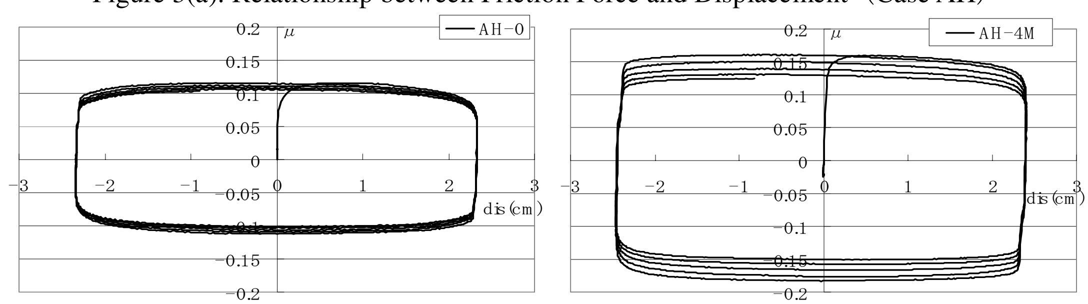


Figure 3(b). Relationship between Friction Coefficient and Displacement（Case AH）

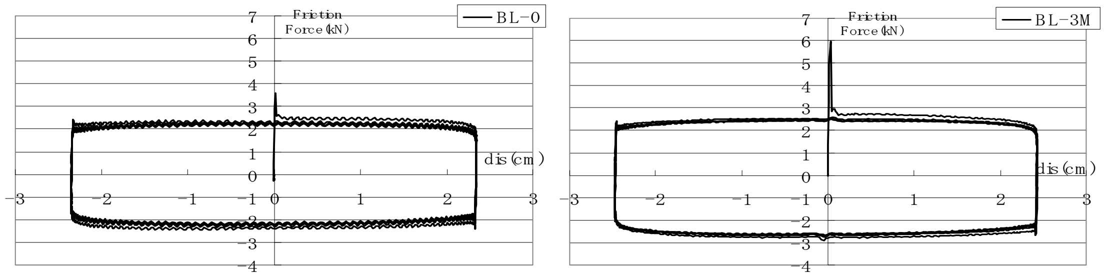


Figure 4(a). Relationship between Friction Force and Displacement（Case BL）

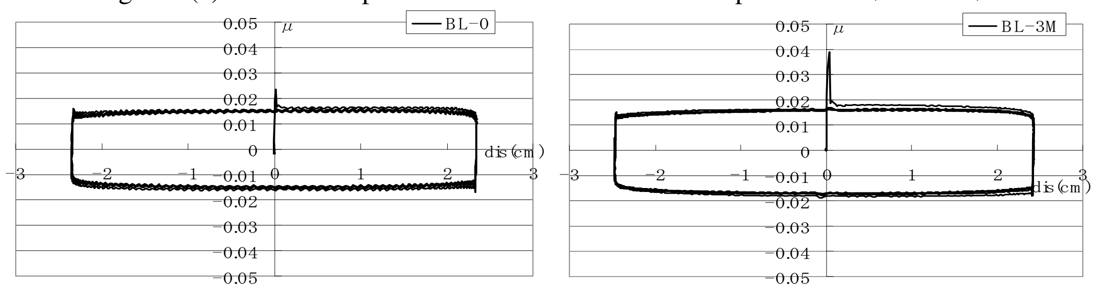


Figure 4(b).　Relationship between Friction Coefficient and Displacement（Case BL）

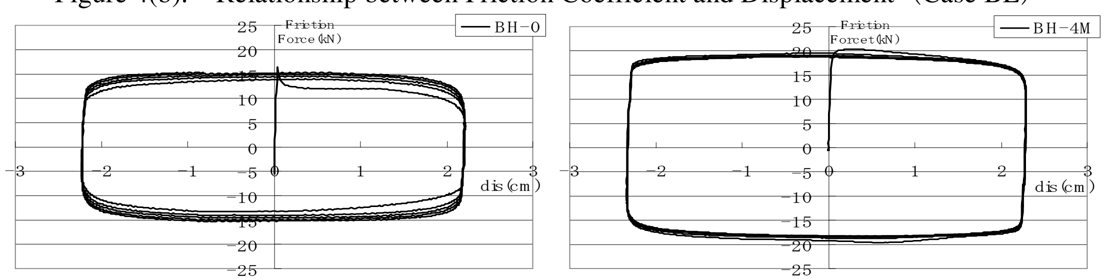


Figure 5(a). Relationship between Friction Force and Displacement（Case BH）

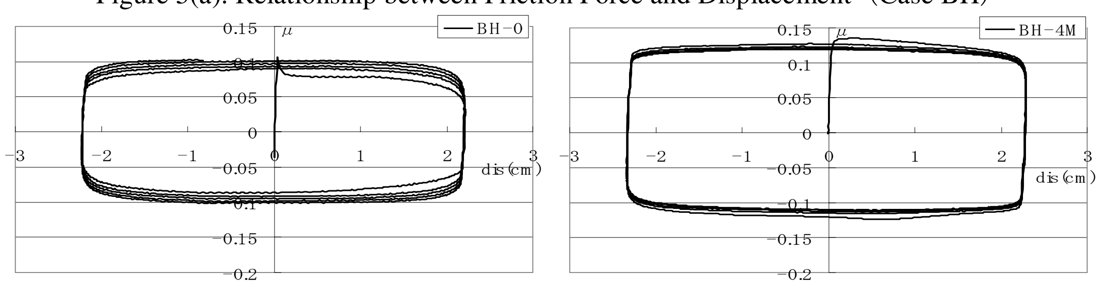


Figure 5(b).　Relationship between Friction Coefficient and Displacement（Case BH）

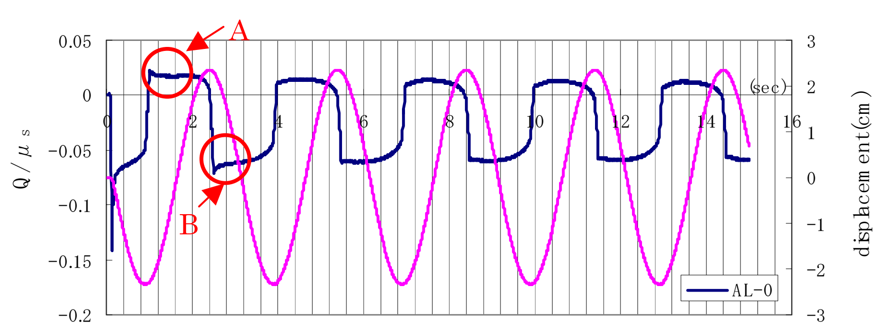


Figure 6.　Time History of Q_s/N and Displacement

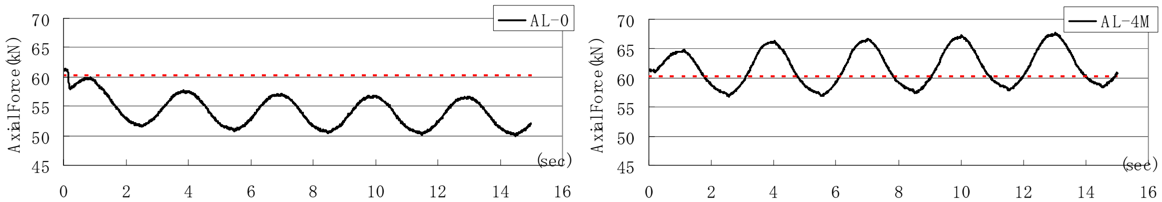


Figure 7(a). Time History of Axial Force (Case AL)

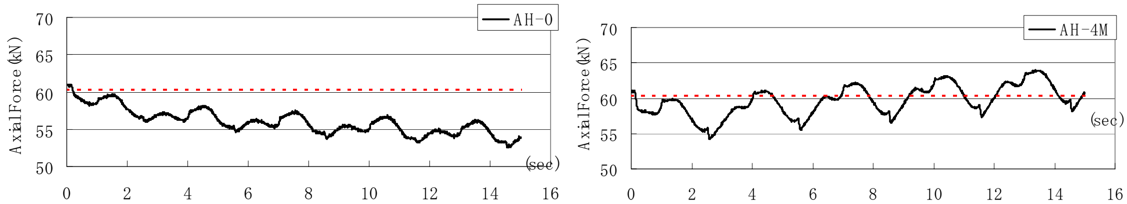


Figure 7(b). Time History of Axial Force (Case AH)

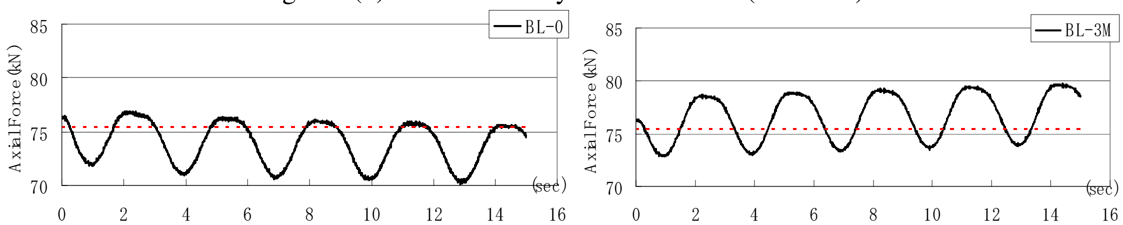


Figure 8(a). Time History of Axial Force (Case BL)

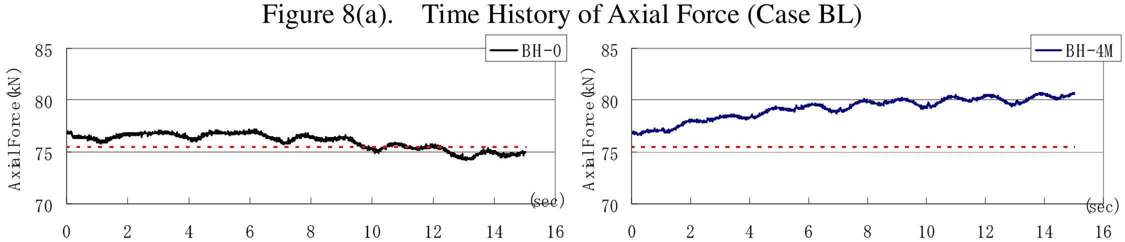
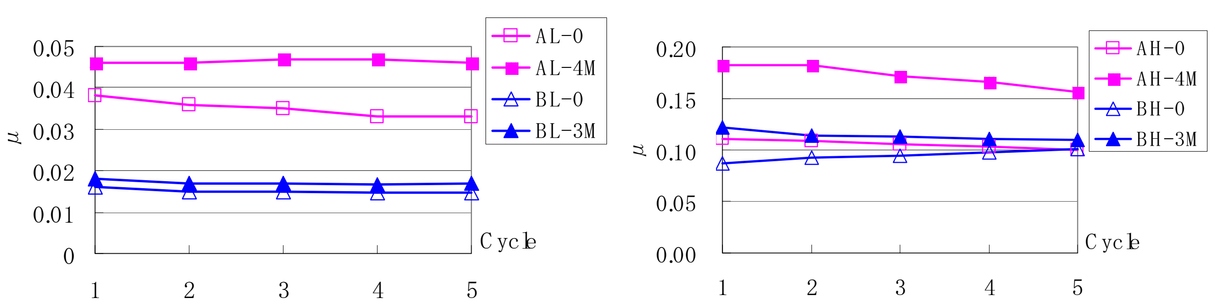


Figure 8(b). Time History of Axial Force (Case BH)

Variations of friction coefficients associated with cyclic loadings

Figure 9 shows the relationship between friction coefficients and cyclic numbers of loading. The friction coefficients are the mean value of a positive side and negative side. From Figure 9 it can be seen that the coefficients of the A-type specimens at the first and second cycle are larger than the specification coefficient shown in Table 3 and those after the third cycle come to the specified value. In the case of AH-0, the coefficient dose not come to the specified value because the axial force of prestressing bar decreases than the standard force as shown in Figure 7(b).



Low Friction Type High Friction Type

Figure 9. Change of Friction Coefficient by Repetition Loading

RESPONSE ANALYSES WITH CONSIDERATION OF THE INFLUENSE OF ADHESION

Earthquake response analyses in which the influence of adhesion is taken into account are performed here applying the 3-dimensional earthquake response analysis program called as DAISY to be the in-house-software . The DAISY used in the analysis can take a restoring force characteristics with hysteresis loop dependent on variable axial force and velocity into consideration. Using these functions of DAISY, simulation analyses on the influence of adhesion in sliding bearings are performed in the following .

Analysis model

A structure for analysis model is a concrete-filled-tube frame super-structure with isolated bearings at basement shown in Figure10. The super-structure is 11-story with 45 meters total hight of typical floor of 4 meters and has the fundamental natural period 2.9 seconds under the fixed base condition and the critical damping ratio of 0.02. In the analysis, super-structure elements of beams and columns are a linear beam model.
Figure 11 shows the plan of basement floor and the arrangement of isolated bearings. Two types of sliding bearings are chosen in the analysis case, which have a low and high friction coefficient of 0.035 and 0.11 (named as AL and AH), respectively. The isolation system of the high friction type is composed of 16 rubber bearings, 3 sliding bearing and 2 oil dampers. In the low friction type, two oil dumpers added in high friction type are settled. The rubber bearing and the sliding bearing are modeled into a linear and bi-linear spring element, respectively.
Analytical conditions in 8 cases including input earthquake motions of El-Centro-NS and Kobe-NS are summarized in Table 5. On the influence of adhesion in sliding bearings, one analysis model takes that into account and the other is without consideration, which are named as Y and N, respectively. The fundamental hysteresis loop of restoring force characteristics in the non-adhesion model and the model considering the influence of adhesion are shown in Figure 12. Base on the experimental results, the characteristics of the adhesion model are changed so that the friction force of adhesion might be 3 times the usual friction force. Though the high friction type in experiments has been less influence of adhesion, the hysteresis characteristics are assumed to be the same as that in the low friction type because of consideration of effects of longer loading.

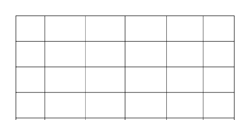
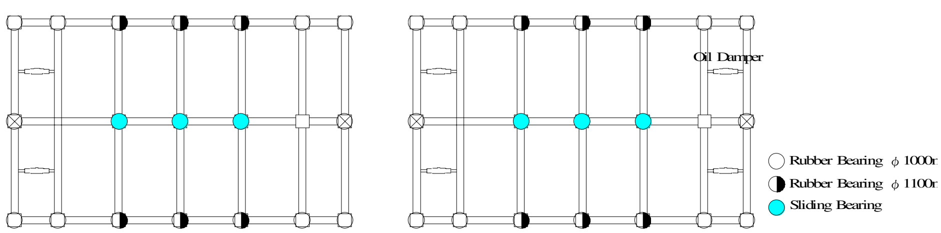


Figure 10. Section

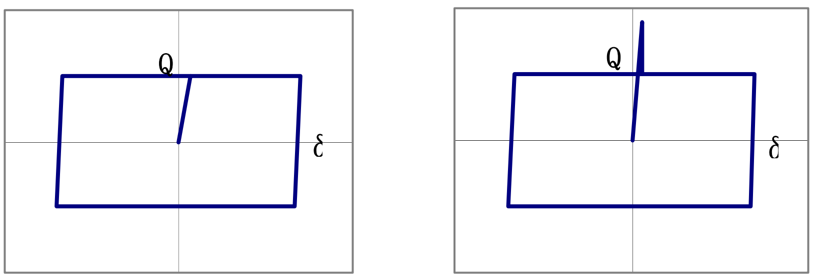


＜High Friction Type＞ ＜Low Friction Type＞

Figure 11. Location of Sliding Bearing and Rubber Bearing Isolators

Table 5. Analysis Case

Analysis Case	Input Earthquake Motion	Friction Coefficient	Adhesion of Sliding Bearing
AL-E-N	El-Centro-NS	Low	No
AH-E-N	El-Centro-NS	High	No
AL-E-Y	El-Centro-NS	Low	Yes
AH-E-Y	El-Centro-NS	High	Yes
AL-K-N	Kobe-NS	Low	No
AH-K-N	Kobe-NS	High	No
AL-K-Y	Kobe-NS	Low	Yes
AH-K-Y	Kobe-NS	High	Yes



(a) Non-Adhesion Model (b) Adhesion Model

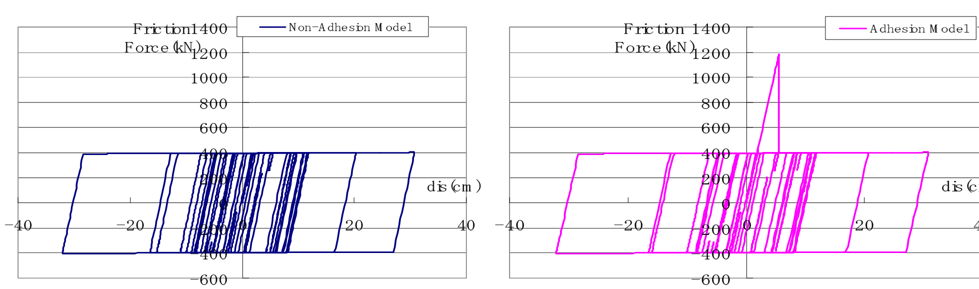
Figure 12. Hysteresis Characteristics of Sliding Bearing

Results of earthquake response analyses

Relationship between force and displacement of isolated bearings

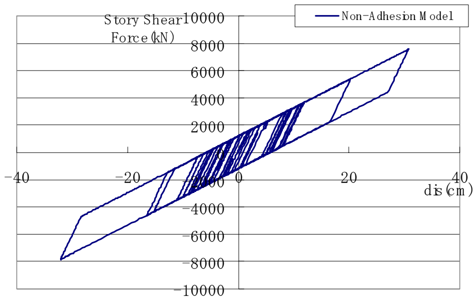
The relationships between friction force and displacement of sliding bearings are shown in Figure 13. Figure 14 is the relationship between total shear force and displacement at the basement arranged isolation system. It is recognized from the results of adhesion cases in Figures13 and 14 that the effects of adhesion at early stages of excitation is evaluated well.

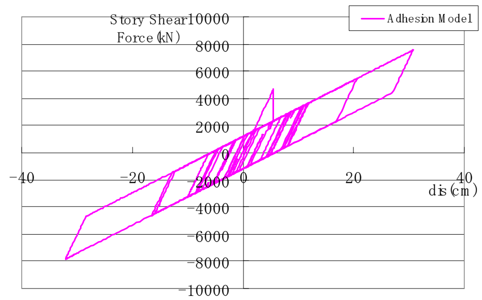
Figures 15 and 16 show the time histories of deformation and friction force in each case, respectively. The deformation in the case of AH becomes large immediately after excitation because of the influence of adherence. However, in any cases there was no large difference on the maximum response displacement.



Non-Adhesion Model (AL-E-N) Adhesion Model (AL-E-Y)

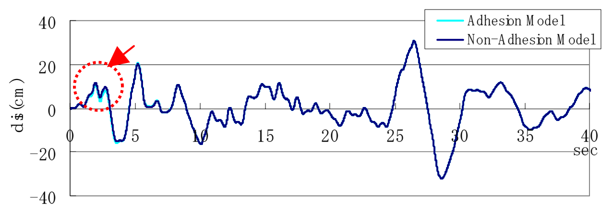
Figure 13. Relationship between Response Friction Force and Displacement

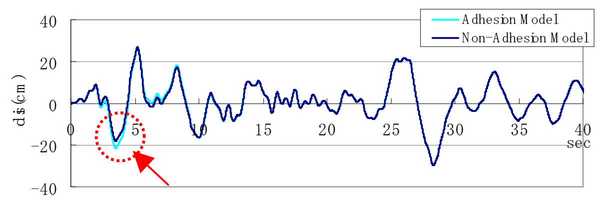




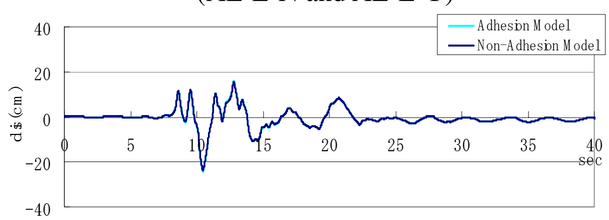
Non-Adhesion Model (AL-E-N) Adhesion Model (AL-E-Y)

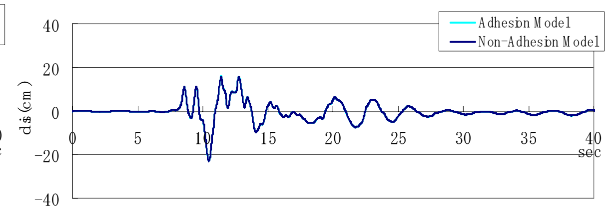
Figure 14. Relationship between Story Shear Force and Displacement





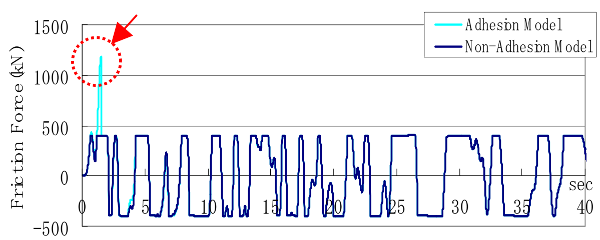
(AL-E-N and AL-E-Y) (AH-E-N and AH-E-Y)

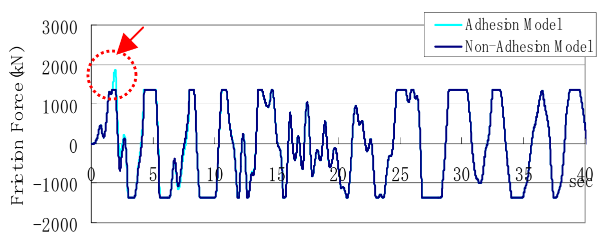




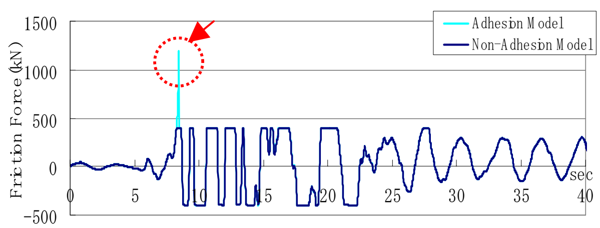
(AL-K-N and AL-K-Y) (AH-K-N and AH-K-Y)

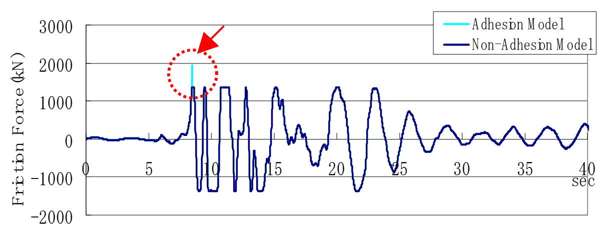
Figure 15. Displacement Time History





(AL-E-N and AL-E-Y) (AH-E-N and AH-E-Y)



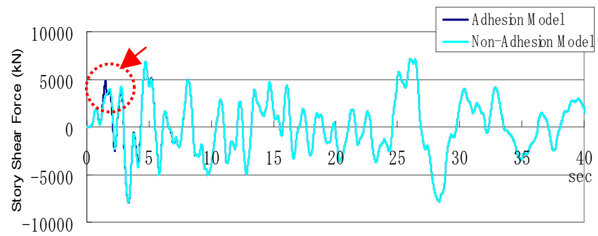


(AL-K-N and AL-K-Y) (AH-K-N and AH-K-Y)

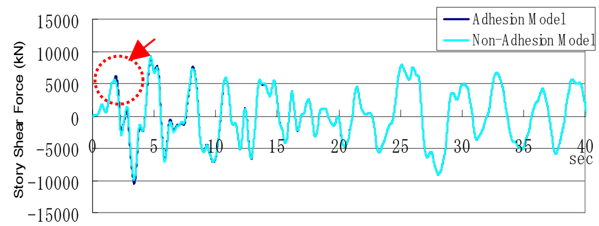
Figure 16. Friction Force Time History

Results of super-structure responses

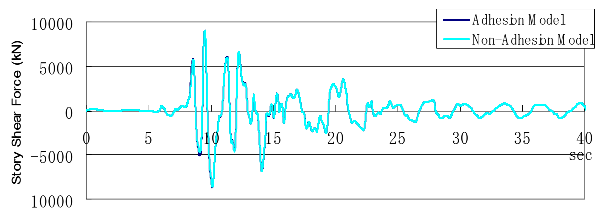
The time histories of story shear forces and accelerations of responses in the super-structure are shown in Figures 17 and 18, respectively. In each case of adhesion model, the responses become slightly large at the time immediately after excitation. However, after that time the influence of adhesion is found little and the responses are almost same as non-adhesion case and the influence in the case of input motion of Kobe having the large amplitude of acceleration on a sudden is not found even at early time.



(AL-E-N and AL-E-Y)



(AH-E-N and AH-E-Y)



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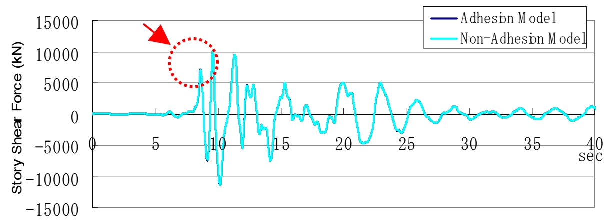
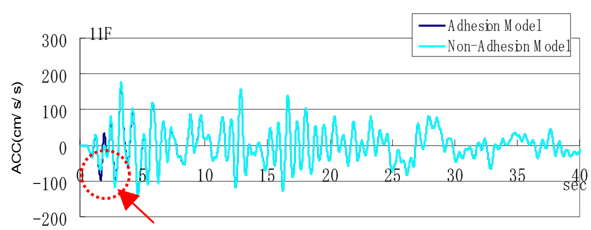
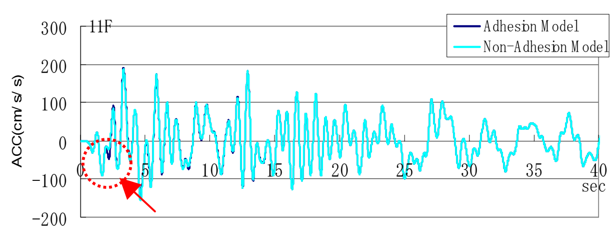


(AH-K-N and AH-K-Y)

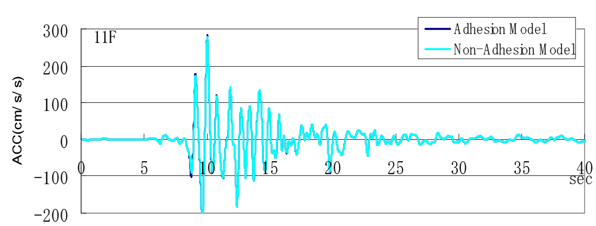
Figure 17. Story Shear Force Time History



(AL-E-N and AL-E-Y)



(AH-E-N and AH-E-Y)



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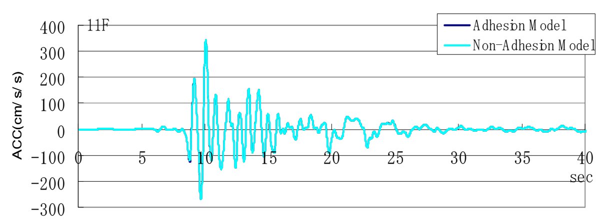

(AH-K-N and AH-K-Y)

Figure 18. Acceleration Time History

CONCLUSIONS

1.It has verified that friction force of sliding bearing increased by adhesion.
2.By high friction type, the influence of adhesion has not been verified in the sustained period of 3 to 4 months.
3.The simulation analysis in consideration of the influence of adhesion was possible.
4.In the sustained period of 3 to 4 months, that adhesion does not affect the structure response has verified in analysis.

ACKNOWLEDGEMENTS

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