Hybrid Seismic Response Control System for Nuclear Power Station

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ABSTRACT

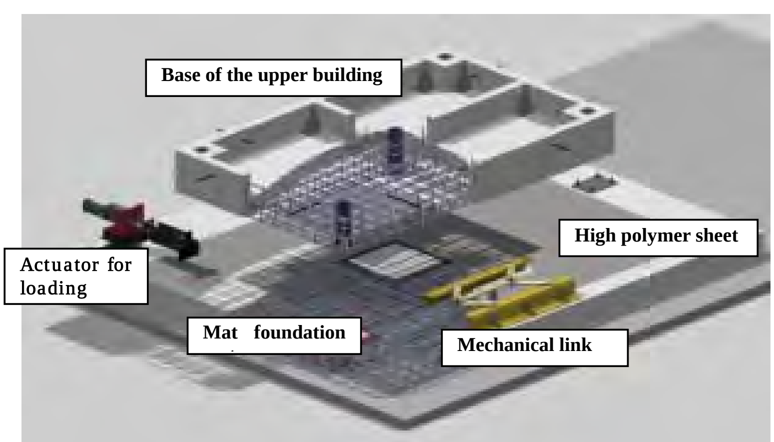
Nuclear Power Stations (NPS) should be so designed as the structural and non-structural members not to be subject to slightest damage even if the seismic ground motion is extremely strong. There are two alternative ways to achieve this design purpose. One is to place the station on very hard rock where very small amplification of ground motion is expected. The other is to use a base isolation system to minimize the transfer of the seismic force from the ground to the upper building. In the case of constructing a next generation reactor building on seismically active site, the latter is regarded inevitable. The problem *is* what sort of base-isolation system to apply.

There are already many sorts of base-isolation systems. Though they have been confirmed to be quite effective to let the buildings survive even very strong earthquake ground motions, the number of the base-isolated building has not increased very much, especially the house. One of the reasons can be attributed to that those conventional industrial isolators are a bit too expensive, especially for houses. Therefore, we proposed[1] the use of a less expensive handmade sliding base system for houses. The system consists of, from the bottom to the top, a concrete mat foundation, a polyvinyl chloride sheet and an upper structure with solid base. General view of the lower part of the test structure is shown in a figure at the bottom. We experimentally confirmed that the system yields quite stable load-deflection relation with the friction coefficient of around 0.2. Since the upper structure is actually not ideally rigid, acceleration on the top will be higher than that on the sliding base. So, such high-damping devices as oil dampers or friction dampers are supposed to be used together. We confirmed analytically that, by installing some oil dampers into the upper building, the maximum acceleration of the top of a two or three story house would be no greater than 400 cm/s^2.

We propose here to apply this hybrid seismic response control system with a sliding base and additional damping devices to seismic design of a next generation reactor building. The target maximum acceleration is no greater than 500 cm/s^2. There are lots of things that are quite different from the case of the house. For example, the NPS is so heavy that we use tougher polyethylene terephthalate or ultra high molecular weight polyethylene. In order to let the sliding behavior quite stable, concrete surface is subject to finishing. There might be some rotational vibration around the vertical axis caused by such non-uniform distribution of the friction and the mass. In relation to this, it was confirmed in the previous study that excessive rotation could be avoided by installing some mechanical links between the foundation and the base of the upper building as shown in the figure below. In the new system, mechanical link is replaced by hydraulic links, which are expected to be used as oil jacks to remove the residual displacement after very strong ground motion.

This study aims at showing the prospect of making use of the proposed sliding base-isolation system in the seismic design of NPS. The study consists of three parts as follows.

1) Feasibility study on availability of a proposed hybrid seismic response control system.
2) Experimental study on the mechanical properties of the sliding base made up of grinded concrete surface and high polymer sheet.
3) Analytical study on the seismic behavior of a structural model of NPS with base-isolation system consisting of sliding base and extra oil and friction dampers in the upper building.



General view of the test structure of the sliding base for houses1)

INTRODUCTION

In Japan, a demonstration plant and a commercial plant of an FBR are planed to be in operation in 2025 and in 2050 respectively. In order that those plants be free from any slightest damages even when subject to intense seismic ground motion, use of a base-isolation system is taken for granted. Since we have had some strong ground motions recently, Japanese regulatory guide for seismic design of NPS is now extensively reviewed and the intensity of seismic design ground motion is very likely to become much higher than that prescribed in the current guide. Therefore, most structural engineers understand that for economy's sake the whole NPS has to be base-isolated in the horizontal direction. They think that the primary heavy component can be vertically base-isolated by means of specially installed devices or systems.

The first part of the study consists of two preliminary analyses. The analysis using a single degree of freedom (SDOF) rigid body model with a rigido-plastic element to represent the sliding base indicates that the sliding base really works to isolate the upper building structure from the ground motion. Important thing to note is that the system may accompany quite a lot of shifted and hence the residual displacement during a strong ground motion. It also includes the analysis by multi-degrees of freedom (MDOF) model to investigate the effect of acceleration amplification from the base to the top of the structure. Based on these analytical results, proper value for the friction coefficient for the sliding base is identified to be among 0.1 to 0.2. It is also suggested that some additional damping devices have to be installed if we want the maximum acceleration at the top of the structure be less than 500 cm/s^2. The second part deals with the experimental study to find out the combination of materials to yield the identified proper friction coefficient. We noticed that good quality concrete could easily be grinded as smooth as the polished marble stone and we found out that the sliding between the grinded concrete surface and such high polymer materials as polyethylene terephthalate or ultra high molecular weight polyethylene (UHMWPE) yield friction coefficient that we wanted. The last part describes another analytical study to show that the proposed hybrid structural system is useful to reduce maximum acceleration at the top without excessive displacement at the bottom.

FEASIBILITY ANALYSIS OF THE PROPOSED STRUCTURAL SYSTEM

Seismic Response of a SDOF Model

A simple SDOF model shown in Fig. 1 is used in the analysis to show how the sliding base works. Load-deflection relation of the sliding base is assumed to be an ideal rigid-plastic one as shown in Fig. 2. Sliding force changes depending on the friction coefficient μ of the sliding base. Original ground motion record of the NS component of 1995 Hyogo-ken Nanbu Earthquake (Kobe_NS) is used in the analysis. Four different values of friction coefficient are tested, ranging from 0.1 to 0.4. Displacement time histories in Fig.3a show that they accompany unstable drift and corresponding residual displacement. The maximum displacement seems not so sensitive to the friction coefficient and is as great as nearly 30 cm, as is usually expected in the normal base-isolated building with rubber bearings and dampers. Although the displacement seems quite unstable, maximum acceleration is almost precisely in proportion to the friction coefficient as seen in Fig. 3b. This result suggests that the sliding base is useful to cut off the transmission of seismic force from the base to the upper buildings. However, some proper measure has to be taken into consideration to deal with the possible residual displacement after intense ground motion.

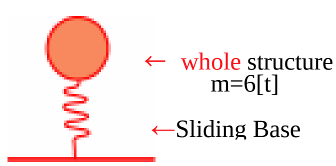


Fig. 1 Parameters for Model

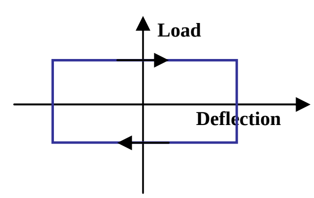
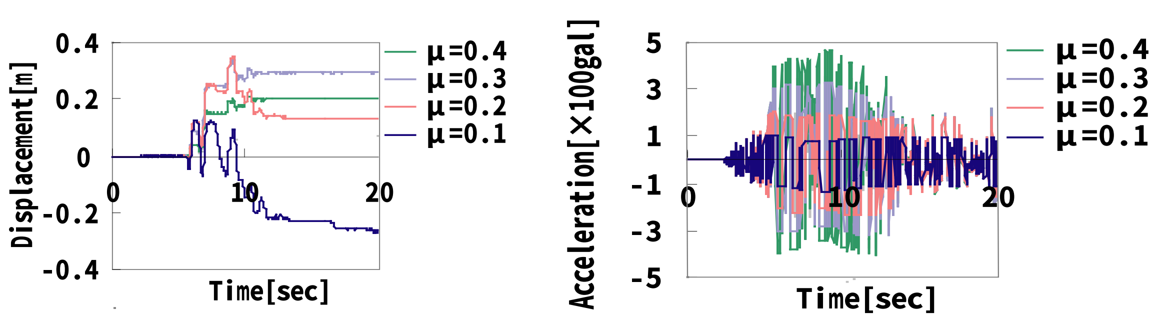


Fig. 2 Load-deflection relation of sliding base

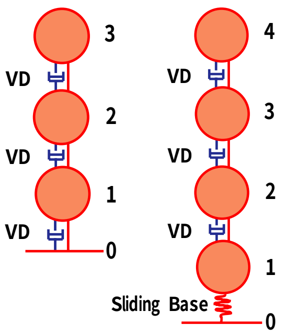


a. displacement b. acceleration

Fig. 3 Displacement and acceleration time histories

Seismic Response of a MDOF Model

In this section, three and four degrees of freedom models are used. The former is to represent normal structural system fixed to the ground and the latter, the one rested on a sliding base. The four degrees of freedom model consists of one mass for sliding base and the three masses for the upper building to take into consideration the acceleration amplification from the bottom to the top. Yield strength of the sliding base is the friction coefficient times the total weight of the model including sliding base. The mass are listed in Table. 1. The load-deflection relations of the upper structure stories are assumed to be bi-linear ones as listed in Table 2. Natural period and mode vectors are shown in Fig. 5. Inherent damping property of the upper structure is assumed to be 2% for the first mode when the super structure alone is subject to vibration. In this analysis, four different structural systems are compared. First one corresponds to the normal one that has neither sliding base nor any extra damping devices. Next one has no sliding base either but additional viscous dampers are installed. The third one has a sliding base without damping devices. The last one corresponds to a proposed hybrid seismic response control system with a sliding base and damping devices in the upper building. Amount of the extra viscous dampers is changed according to the damping factor from 0.1 to 0.3 for the first natural mode. Fig. 6a compares the maximum story deflection when subject to the original Kobe_NS ground motion. Fig. 6b compares the maximum acceleration. Broken lines correspond to the case of no extra viscous damping devices and the solid lines the case with the dampers. We can see that by placing the upper building on a sliding base, both the maximum deflection and the maximum acceleration can be significantly reduced. But, in order to let the maximum response be no greater than 400-500 cm/s^2, we install some extra damping devices into the upper structure.



Model A model B

Fig. 4 Normal structural system model A (left) and proposed hybrid system model B (right)

Table 1 Mass data

	m1 Sliding Base	m2 2nd Floor	m3 3rd Floor	m4 Top Floor
mass[t]	0.05816	0.01432	0.01432	0.01068

Table 2 Mechanical properties of model A

story	1st Stiffness [kN/m]	2nd Stiffness [kN/m]	Yield Point [kN]
3	86.75	0.694	0.39
2	88.34	0.70672	0.39
1	92.31	0.73848	0.39

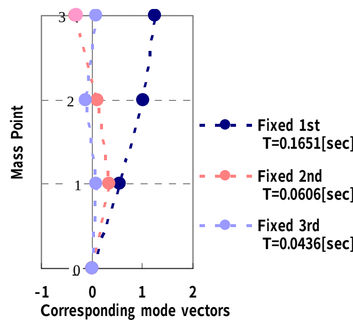
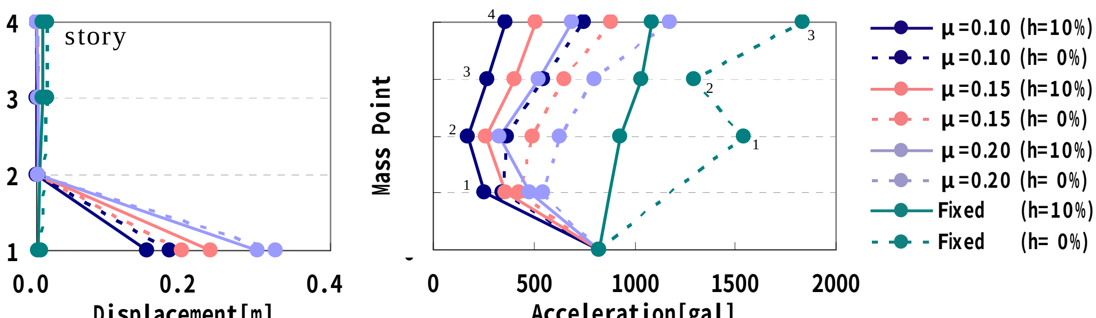


Fig. 5 Natural period and corresponding mode vectors of model A



a. maximum story deflection of model B b. maximum floor acceleration of models A and B

Fig. 6 Comparison of maximum response

Fig. 7 is prepared to see how the coefficient of friction of the sliding base and the damping property of the upper structure work together to decrease the maximum acceleration of the top of the building. As is mentioned in the introduction, our primary concern is to let the maximum acceleration in the upper building be no greater than 400-500 cm/s^2. So, it is concluded that the proposed hybrid seismic response control structural system could be realized by the use of both the sliding base with the friction coefficient of 0.1–0.2 and the extra damping devices corresponding to the equivalent first mode damping factor of 20-30%.

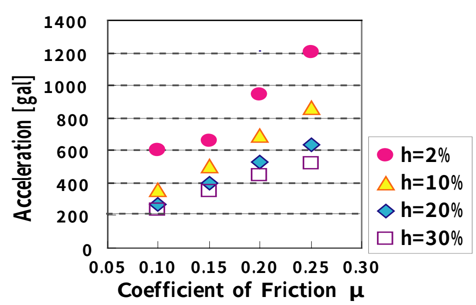


Fig. 7 Max acceleration of the top floor

EXPERIMENTAL STUDY TO IDENTIFY IDEAL SLIDING SYTEM

Outline of Experiment

This section describes the experimental study to find out proper sliding system with the friction coefficient ranging from 0.1 to 0.2. One important thing we want to achieve is to get far less expensive sliding system than those conventional industrial sliding isolators. Our preliminary test showed that good quality concrete could easily be finished very smooth. So, finely grinded concrete is chosen as one side of the friction surface. As the other side of the friction surface, we use ultra high molecular weight polyethylene (UHMWPE) and barium ferrite coated polyethylene terephthalate (BaFe). Effect of the degrees of roughness of the concrete surface is investigated. Other important parameters considered in the experiment are the loading velocity and the pressure on the sliding surface.

Figure 8 shows the loading system. Concrete plate is fixed to the base beam. Four pieces of UHMWPE block or BaFe sheet are bonded to the steel plate as the slider. Zero to five pieces of 5 kg weights are used to let the friction surface be subject to six different compressive stress. In the case that sliding sheet is spread all over between the mat foundation and the concrete base of a full scale normal NPS, the pressure is supposed to range from 0.2 to 0.4 MPa. In order to investigate the effect of the loading velocity, various combinations of different amplitude and frequency are used in the test as listed in Table 3.

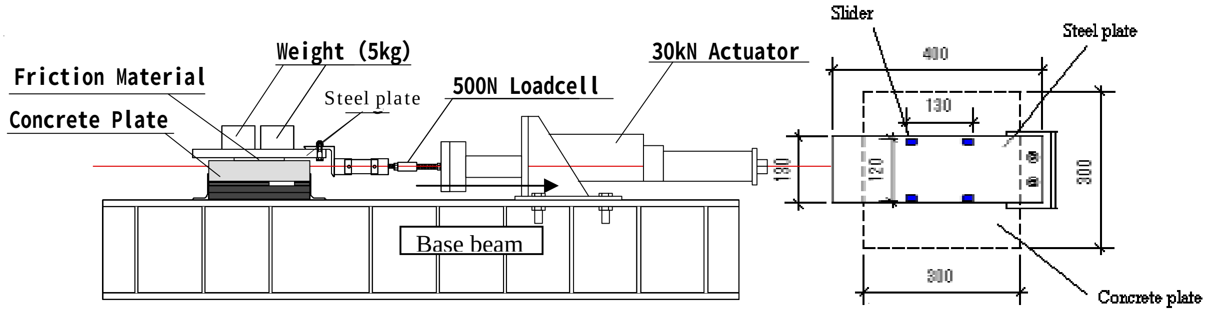


Fig. 8 Loading system (left) and arrangement of piece of sliding sheet or block on the friction surface (unit: mm)

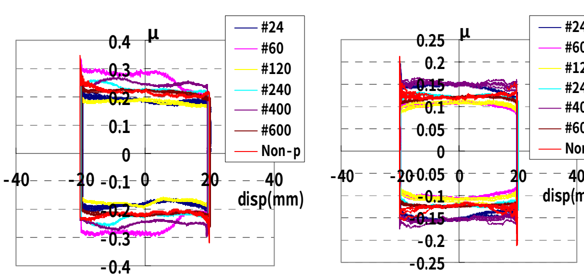
Test Results

Effect of the roughness of concrete surface

Figure 9 shows the effect of the roughness of the concrete surface. In this test, 0.1 Hz sine wave displacement is applied. In the case of using UHMWPE, if there is no grinding, friction is unstable, but some grinding finish seems to make friction property quite stable.

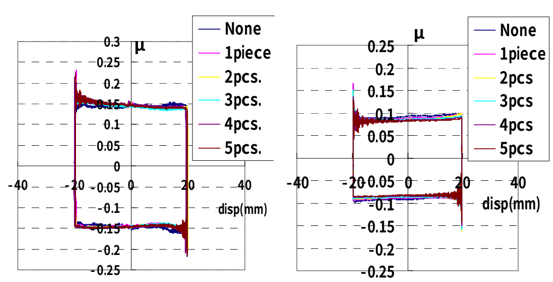
Table 3 Loading parameters

Frequency[Hz]	Amplitude[mm]	Roughness	Surface pressure(kN/m²)	Weight
0.1	10	not grinded	153.56	none
0.5	20	#24	216.06	1piece
1.0	30	#60	278.56	2pcs.
		#120	341.06	3pcs.
		#240	403.56	4pcs.
		#400	466.06	5pcs.
		#600		



UHMWPE BaFe

Fig. 9 Effect of roughness of concrete surface on coefficient of friction (sine wave 0.1Hz, 0.28MPa)



UHMWPE BaFe

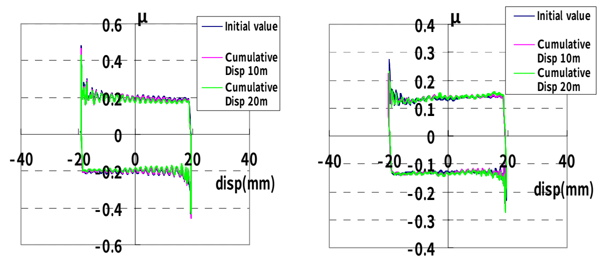
Fig. 10 Hysteresis of coefficient of friction (triangular wave, 0.1Hz, #24, 0.28MPa)

Effect of the pressure

Figure 10 compares the effect of compressive stress on the load-deflection relation of the sliding surface. In this test, roughness of the concrete surface corresponds to a #24 grinder. We can see that the all load-deflection relations are quite stable and almost the same regardless of the magnitude of the stress.

Effect of the long term loading

This test is performed to see if the load-deflection relation of the sliding base deteriorates when subject to large amount of cumulative displacement. Analytically expected cumulative displacement for single intense ground motion is around 10m. Fig. 11 compares the coefficient of friction at the beginning of the loading and at the end of every 10m cumulative displacement. Test results show that we do not have to worry about the deterioration of the sliding surface. Since the existing pressure on the sliding base would be less than 1/100-1/50 of the yielding stress of UHMWPE and BaFe, there would be no need to take creep deflection into consideration.



UHMWPE BaFe

Fig. 11 Hysteresis of coefficient of friction (triangular wave, 0.1Hz, 0.28MPa, not grinded)

ANALYTICAL STUDY ON HYBRID SEISMIC RESPONSE CONTROL OF NPS

Structural Model

In this analysis, four and five degrees of freedom shear models are used to represent a sample structural model[2]. The former is used for normal building structure and the latter a hybrid one with sliding base and extra damping devices In Table 4, the node 1 corresponds to the sliding base. Friction coefficient is assumed to be 0.1. Mechanical properties of the analytical model are also listed in Table 4. In the table, the term BL stands for the bilinear element to represent load-deflection relation of the fifth steel frame story. It is also used to represent the frictional property of the sliding base. MTK is the abbreviation for the modified Takeda model to represent reinforced concrete element of the first through the forth story. First and second yield points of the MTK element correspond to concrete cracking strength and yielding of steel reinforcement respectively. Natural damping property of the main structure is assumed to be 2% for the first mode. In the case that the sliding base is applied, viscous and friction damping device is installed in the top steel frame story to get less maximum acceleration. The same original Kobe_NS ground motion as in the previous analyses is used.

Table 4 Mechanical properties of structural model

Floor and Story	Structure	mass [t]	Hysteresis Characteristic	1st Stiffness [kN/m]	2nd Stiffness [kN/m]	3rd Stiffness [kN/m]	1st Yield Point [kN]	2nd Yield Point [kN]	Stiffness Chanfe [%]
5	Steel	5.12E+03	BL	4.52E+06	4.52E+03		9.00E+04		
4	RC	8.48E+03	MTK	4.52E+07	1.13E+07	4.52E+05	6.13E+04	1.84E+05	-20
3		9.98E+03		6.92E+07	1.73E+07	6.92E+05	9.38E+04	2.81E+05	-20
2		9.79E+03		8.91E+07	2.23E+07	8.91E+05	1.21E+05	3.62E+05	-20
1		9.42E+03		1.05E+08	2.63E+07	1.05E+06	1.25E+05	4.28E+05	-20
Isolation		2.34E+04	BL	1.00E+09	1.00E-02		*		

Results and Discussions

Figure 12 shows the displacement time history of the sliding base. Drifted and residual displacement is quite significant. It looks unstable, but the load-deflection relation is quite stable as seen in Fig. 13. Fig. 14 compares the load-deflection relations of the first story of the building model when it is fixed to the ground and when it is placed on the sliding base. Although the strength of the first story is more than half of the total structural weight, the fixed building may be subject to quite amount of structural damage. However, when the building is placed on the sliding base, the first story remains almost elastic. From figures 12-14, it can be said that the upper building is free from damage in compensation for the large displacement of the sliding base including the residual displacement.

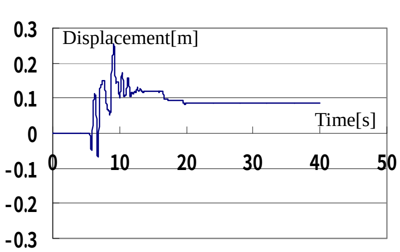


Fig.12 Displacement time history of sliding base

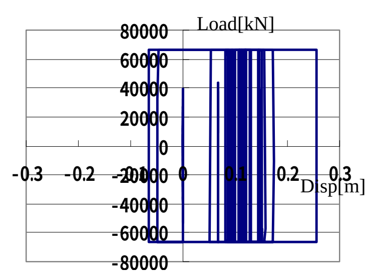


Fig.13 Load-deflection relation of sliding base

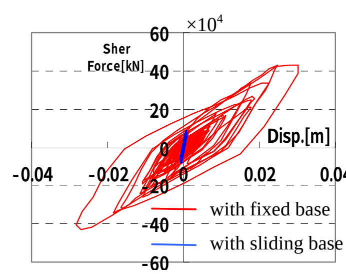


Fig.14 Load-deflection relation of first story

Even when the sliding base is installed, acceleration increases from the sliding base to the top. Broken line in Fig.15 shows that the acceleration of the top floor can not be reduced much if there is sliding base alone and no damper is installed in the top steel frame story. Whereas, when some extra oil dampers are installed in the fifth steel frame story, the acceleration at the top would be no greater than 500 cm/s^2 as shown by solid line. Fig.16 compares acceleration time histories of the top floor of the building with and with out hybrid seismic response control system. Broken line corresponds to the fixed building structure and solid line the hybrid building structure. It can be concluded that proposed hybrid structural system is quite effective to reduce the maximum acceleration of the upper building.

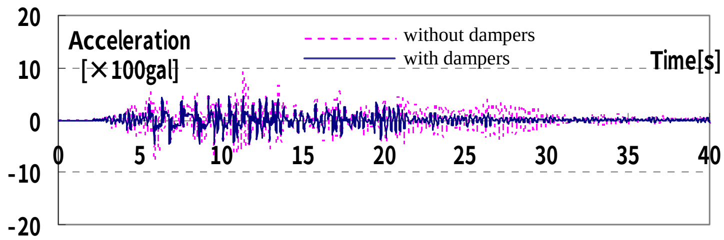


Fig.15 Acceleration time history at the top of hybrid structure with/without oil dampers

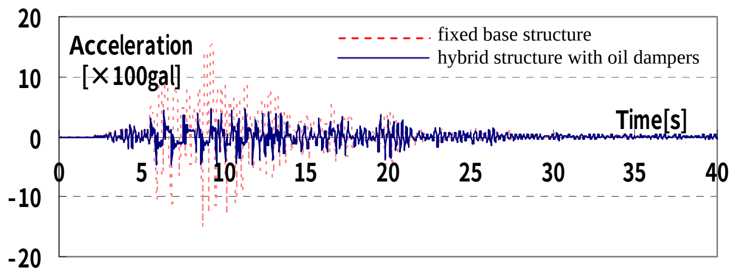


Fig.16 Acceleration time history at the top of fixed base structure and hybrid structure

Fig.17 compares load-deflection relations of the top steel frame of the hybrid structure with and without oil dampers. Fig.18 corresponds to the case that friction dampers[3] are used instead of oil dampers. In this case, strength of the friction damper is set to 30% of the steel frame’s weight. Both dampers seem to work almost the same. Fig. 19 compares the acceleration when oil dampers are used with when friction dampers are used instead. Time histories do show some difference, but the maximum accelerations are almost the same.

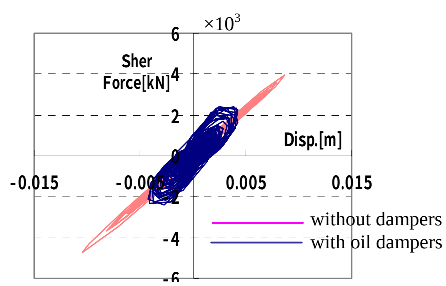


Fig.17 Load-deflection relation of top story with and without oil dampers

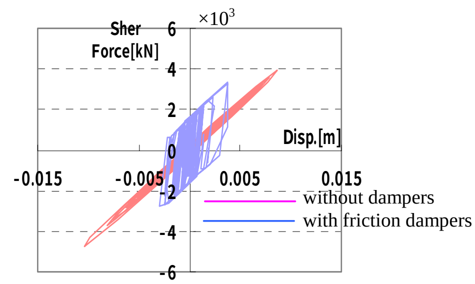


Fig.18 Load-deflection relation of top story with and without friction dampers

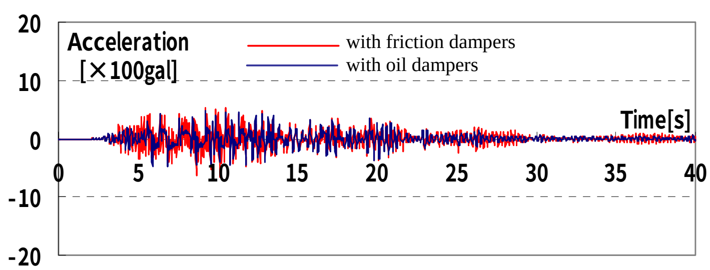


Fig.19 Acceleration time history of the top of the hybrid structure with oil dampers and friction dampers

Hydraulic Link[4]

Since the mechanical properties of the building including the sliding base is not always uniform, there would be some rotation about the vertical axis and even some residual displacement after strong ground motion. We do not think that rotation or residual displacement cause undesirable seismic effects on the building. But they should be removed before the next strong ground motion. We are thinking of installing hydraulic link systems[4)] between the foundation and the base of the upper building instead of the mechanical link shown in the figure on the first page. The links not only work to prevent the rotation of the sliding base but also be used as the jacks to remove the residual displacement.

CONCLUSIONS

Important findings in the study are as follows:
1) Sliding base works to cut off the transmission of seismic force from the mat foundation to the base of the upper building. It often accompanies residual displacement which should be removed after intense ground motion.
2) Sliding base alone does not work to let the maximum acceleration in the upper building be no greater than 400-500 cm/s^2. Proposed hybrid seismic response control structural system could be realized by the use of both the sliding base with the friction coefficient of 0.1–0.2 and the extra damping devices corresponding to the equivalent first mode damping factor of 20-30%.
3) Grinded surface of good quality mat concrete could be used as one side of the friction surface. Such high polymers as ultra high molecular weight polyethylene and barium ferrite coated polyethylene terephthalate are identified to be the other side of the friction surface, exhibiting coefficient of friction around 0.1-0.2. There is no need to worry about the deterioration of the sliding surface and the creep deflection of the polymers.
4) Even when the sliding base is installed, acceleration increases from the base to the top of the building. But, the top acceleration would be no greater than 500 cm/s^2 when some extra oil dampers or friction dampers are installed in the top steel frame of an NPS building.

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