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BEHAVIOR OF A SEISMICALLY ISOLATED HOUSE WITH FRICTION PENDULUM SYSTEM DURING EARTHQUAKE AND STRONG WIND

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Abstract

To reduce the seismic response of superstructures, a seismic isolation is one of effective structural systems. It is confirmed that the seismic isolation has an important role of reducing acceleration responses of buildings during strong earthquake. In case of seismically isolated techniques for light weight houses such as family houses made of timber or steel, rubber bearing isolators are not suitable because of slender width and tall height to elongate a predominant period of isolated system. A buckling failure will probably occur with a large horizontal displacement. A sliding system (a friction type), which is less dependent on weight of superstructures, is applicable for the light structures. In case of sliding system, a coefficient of friction will be relatively small. Even if the sliding system shows good performance against earthquakes, it is needed to confirm that the sliding will occur or not against strong winds.

Seismically isolated detached house model with friction pendulum system was designed and constructed in 1998 in Tsukuba city. Accelerometers and displacement transducers were installed in the full-scale house model. An earthquake observation has been continued from 1998 until today. In case of a little friction force, the sliding will probably occur under high speed wind. To measure the behavior of the house model during strong winds, an anemometer was set at very near site of the house model. The trigger accelaration for earthquake observation was set to be 5 gals in each direction of the foundation accelerations. In case of observation under strong winds, the trigger is 20 m/s in the maximum wind velocity.

Based on the horizontal loading test on the friction pendulum system, the coefficient of friction were about 0.03. The coefficient of friction is almost consistent with the design value of dynamic coefficient of friction. Under earthquake observation, total numbers of earthquake records were 403 until January in 2019. 29 earthquakes among them show any displacement of the isolated layer. When maximum accelerations reach to about 70 gals, the friction pendulum starts sliding and the isolated effect is recognized. Max. acceleration record was observed at Marth 11th in 2011 Tohoku-Pacific Ocean Earthquake. Max. acceleration of foundation, 1st, 2nd and roof truss floors are 213, 129, 124 and 218gals, respectively. Max. acceleration of all floors are less than that on the foundation. The remarkable effect of isolation was confirmed. And in case of strong winds, isolators were sliding during typhoons three times for about 20 years. When max. instantaneous wind velocity exceeded about 27.7 m/s, the isolators started sliding.

Based on various observed results such as; the horizontal loading test, maximum acceleration during earthquakes and behavior of isolators during strong winds, the behavior of the house model can be understood. When the friction coefficient is a little small, the effect of isolation on reduction of the response of the house is remarkable. While the strong wind is large, isolators start sliding. This point is very important to consider the safety of light weight structures with friction type isolators.

Keywords: seismically isolated house; sliding system; earthquake behavior; strong wind behavior; safety of isolation

1. Introduction

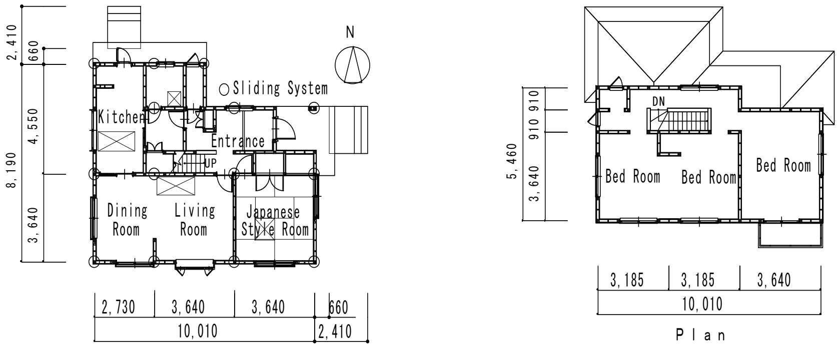
Seismically isolated buildings have been interested and increased to design after the Hyogoken-Nambu earthquake in 1995 in Japan [1]. Because there were two seismically isolated buildings which had observation records during the Hyogoken-Nambu earthquake. The observation records showed an excellent performance for isolation phenomena [2]. There was little family house (small or light houses) with the seismic isolation in 1995. There are some issues to apply the seismic isolation. The most critical issue was that there was no isolator for practical uses to houses. A project was stared related to the development of isolators and the verification of behavior of seismically isolated light houses, under the collaboration with structure engineers, device manufacturers and house constructors. Some kinds of isolators were listed, such as; rubber bearings types without buckling, sliding types and rolling types as candidates. Several shaking table tests were conducted for evaluating characteristics of isolators and applicability to practical use [3] - [6]. Because practical data for the performance against earthquakes were necessary, a model house with a friction pendulum system was designed and constructed to make sure the performance of isolated model house.

Through the various results from the horizontal loading test of isolators, behaviors of the model house during earthquakes and strong winds, the comprehensive safety of light weight structure with isolation is evaluated.

2. Seismically isolated house model

The seismically isolated house model (house model) was constructed at site of Building Research Institute in Tsukuba city of Japan in 1998. An external appearance of the house model is shown in Photo. 1. 1st and 2nd floor plans are shown in Fig. 1. A superstructure is two-story house using the conventional post and beam structure system in Japan. Total floor area of the house model is 120.9m^2 (1st floor; 69.56m^2 and 2nd floor; 51.34m^2) that is a standard one in Japan. Heights of 1st and 2nd stories are 2.93m and 2.78m, respectively. Maximum height of the house model from ground level is 8.33m. The mat foundation on improvement grounds was constructed for the prevention from any settlement.

Photo. 1 – Overview of house model (Taken from the north)



a) 1st floor b) 2nd floor

Fig.1 – Floor plans of house model

A construction period of the house model was from June to September in 1998. Because the purpose of the construction of the house model is to make sure the structural performance during earthquakes and strong winds. The air conditioning equipment and plumbing system were omitted. As the live load of the house, plastic containers filled with water were set on the floors.

3. Isolators

The section of isolator layer is shown in Fig 2. The mat foundation, isolators, the sill and stairs are included in the figure. As structural member which support weights of 1st floor, sills made of laminated lumbers of a large section (dimension; 210mm x 360mm) were used. The plywood of 35mm in thickness is used to keep a stiffness of floor in plane. The height of isolator was 600m. The reason why the height is a little large is to consider the exchange to different kinds of isolators in future. The thickness of isolators with 300mm to the maximum will be possible to set in the isolated layer.

The friction pendulum system (FPS) was adopted as isolators of the house model. 14 FPSs were set in the isolated layer. A cross section of the FPS is shown in Fig. 3. The FPS is a kind of sliding isolators with curved surface in a sliding plate. The FPS consists of two spherical plates and a sliding body. To preventing from invasion of dusts and insects, dust covers were set on outer peripheral face. The horizontal load and displacement characteristics of the FPS shows a bilinear curve with about 0.02 in friction coefficient and a second stiffness related to curvature of the plate. The maximum displacement of the FPS is 250mm.

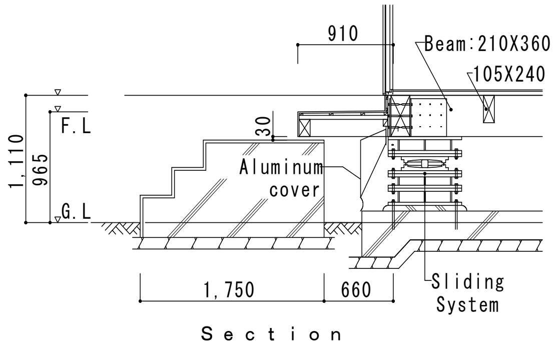


Fig.2 – Section of isolated layer

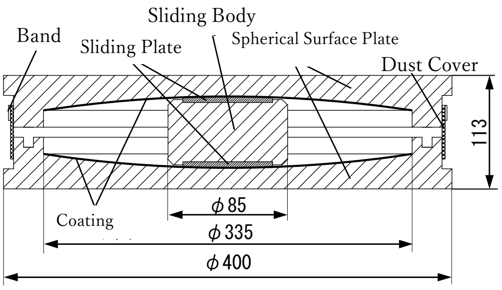


Fig.3 – Section of isolator (FPS)

4. Dynamic characteristics of superstructure

To investigate dynamic characteristics of superstructure, a forced vibration test was carried out. Under the horizontal vibration force being small, the isolators were kept at rest (no movement). The natural frequency under base-fixed condition was obtained. Resonant frequencies of the superstructure in NS and EW directions are about 6.0 and 6.5 Hz, respectively. The natural frequency in the structural design was about 2.8 Hz. The predominant frequencies of the house model were about two times, because non-structural members were not considered in the design. The damping factors of the house model were about 6.4 and 8.4% in NS and EW directions, respectively. The damping factors were larger than a general design value of 5%. The Mass distribution is 8.68, 16.3 and 13.55 t at roof, 2nd and 1st floors, respectively.

5. Horizontal loading test of isolated layer

To make sure the relationship between horizontal load and displacement at isolated layer, the loading test was conducted in 1998 and 2002. As shown in Fig.4, static jacks were installed between 1st floors and reaction columns extended form the mat foundation. Two jacks were set in each direction of NS and EW. The result of loading test of NS direction conducted in 2002 are shown in Fig. 5. There are two figures; one is with the dust cover and the other is without that, as shown Fig.6. As mentioned before, the dust covers made of rubber were set on outer peripheral face of isolators to preventing from invasion of dusts, etc. The condition without dust cover means to remove it for checking effects of dust cover on horizontal characteristics. In case with dust cover, in the beginning of loading a little large frictional force occurs. With increasing displacement (about 20 to 30mm) the force is gradually reduced and the relationship between force and displacement goes along bilinear characteristics with the frictional coefficients of 0.02. At beginning of displacement, the friction between rubbers and peripheral plates occurs. The reaction forces are the frictional forces of isolators and dust covers. Figure 5b) shows the result in case of only frictional force of isolator. At the time of sliding occurrence, it can be seen that the static frictional force is larger than the dynamic one.

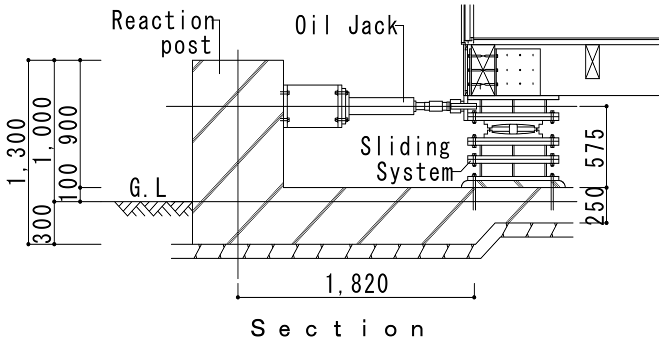
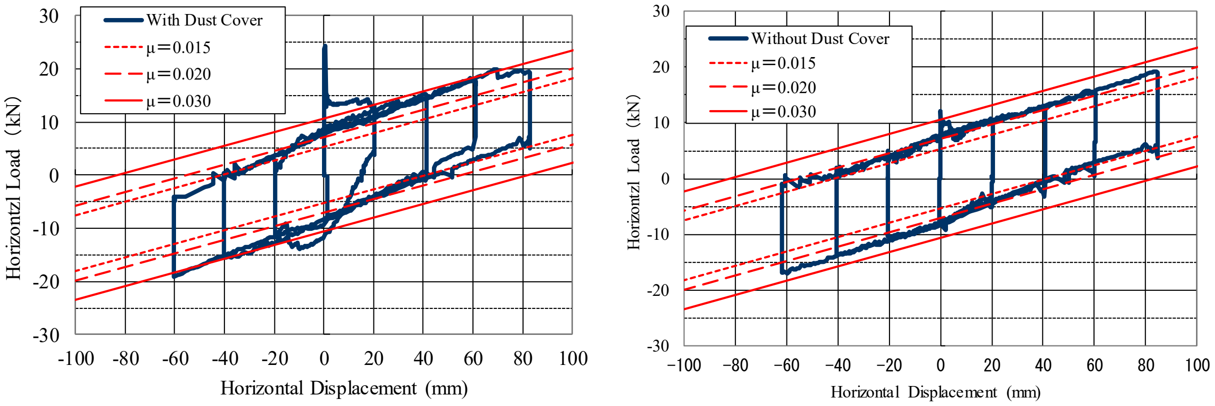


Fig.4 – Horizontal loading test at isolated layer



a) With dust covers

b) Without dust covers

Fig.5 – Horizontal force vs. horizontal displacement at isolated layer

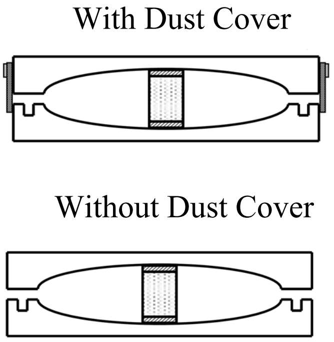


Fig.6 – Conditions of dust cover

Photo. 2 – Displacement of isolator(no dust cover)

The comparison between test results in 1999 and that in 2002 is presented in Fig.7. At first sliding stage, characteristics of both results are similar. At repeated process, the result in 1999 is keeping the effect of dust covers and being larger in the friction force.

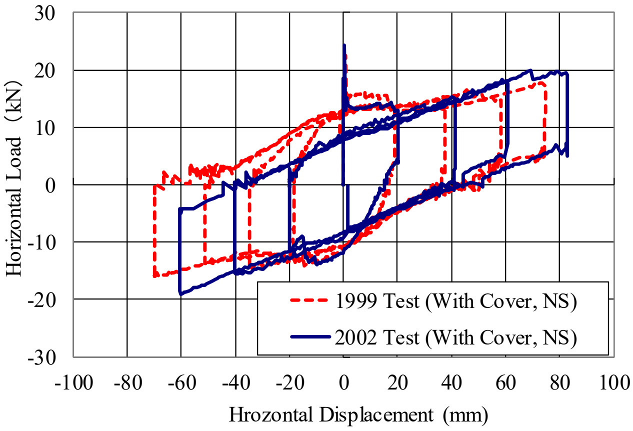


Fig.7 – Horizontal force vs. horizontal displacement at isolated layer(Tests in 1999 and 2002)

6. Observation system for earthquakes and strong winds

To make sure the characteristics of the house model during earthquakes and strong winds, the observation system was set in the house model. Sensors installed in the house model is listed in Table 1. The sensors from 1ch to 16ch are accelerograms or velocity transducers, and those from 17ch to 20ch are displacement transducers. Accelerometers (servo accelerometer) were installed on each floor and the roof truss, in three components of NS, EW and UD directions. Velocity transducers (Servo velocity-meter) were installed on the foundation in three components. The four displacement transducers were set at the isolated layer, and two of them were set in NS and EW directions, respectively. Sensors from 21ch to 24ch were prepared to measure the data during strong winds. There are the wind direction and wind velocity (maximum wind velocity), whose data are measured by an anemometer installed at 10m far from the house model. And two air pressure transducers on the north wall at medium heights (1.5m height from the floor) of each story were installed.

Sampling frequencies for earthquakes and strong winds are 100Hz and 12.5Hz, respectively. In the

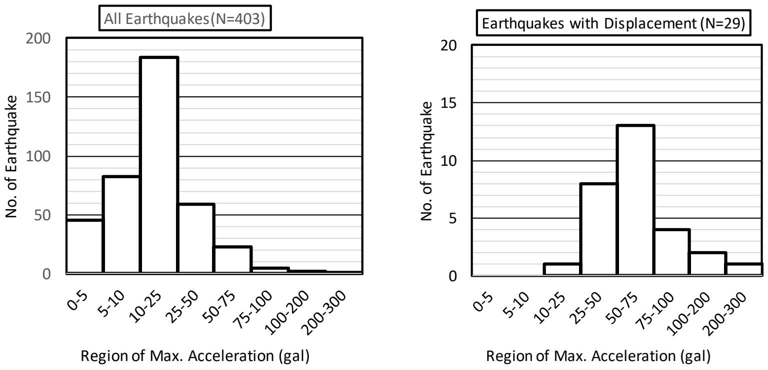
Table 1 – Sensor lists for measuring data of house model during earthquakes and strong winds

CH	Location	Measured value	Direction		CH	Location	Measured value	Direction
1	1st Floor	Acceleration (cm/s^2)	NS(X)		13	Foundation	Velocity	EW(Y)
2			EW(Y)		14			
3			UD(Z)		15		Acceleration	UD(Z)
4	2nd Floor		NS(X)		16		Velocity	
5			EW(Y)		17	Isolated Layer	Displacement (mm)	NS(X)-1
6			UD(Z)		18			EW(Y)-1
7	Roof Truss		NS(X)		19			NS(X)-2
8			EW(Y)		20			EW(Y)-2
9	Foundation		NS(X)		21	Wind Direction	Degree*	-
10		Velocity (cm/s)			22	Wind Velocity	Velocity(m/s)	-
11					23	1st story (wall)	Air Pressure	NS(X)-1F
12		Acceleration	EW(Y)		24	2nd story (wall)		NS(X)-2F

*Wind Direction; the degree of 0 or 360 is just direction from the North observation during strong winds, 100Hz sampling were sometimes used. The trigger acceleration for earthquake observation was set to be 5 gals in each direction of the foundation accelerograms. In case of wind observation, the trigger was set to be 20 m/s in maximum wind velocity.

7. Observation results during earthquakes

The earthquake motion observation was started in September, 1998. Total number of earthquake records was 403 until January in 2019. The numbers of earthquake motions with maximum acceleration (max. of three components) on the foundation are shown in Fig. 8. In the figure, all records and the records with movement of isolators are plotted. In the range of amplitude of maximum acceleration, data of 10 to 25 gals are the largest. The range of maximum acceleration with movement of isolators is more than 50 to 75 gals. The relationship between maximum acceleration on foundation and maximum displacement of isolators is shown in Fig. 9. The seismic isolation performs when maximum accelerations exceed 50 gals.



a)All earthquake b)Earthquake with any displacement of isolator

Fig.8 – Number of observed earthquakes with max. acceleration at foundation

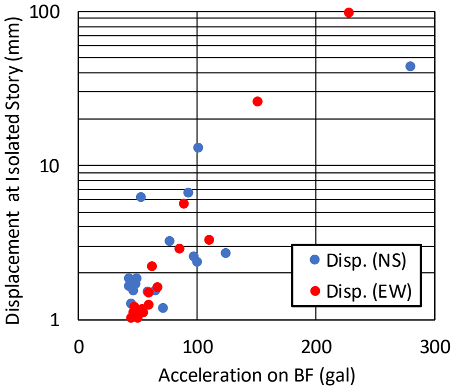
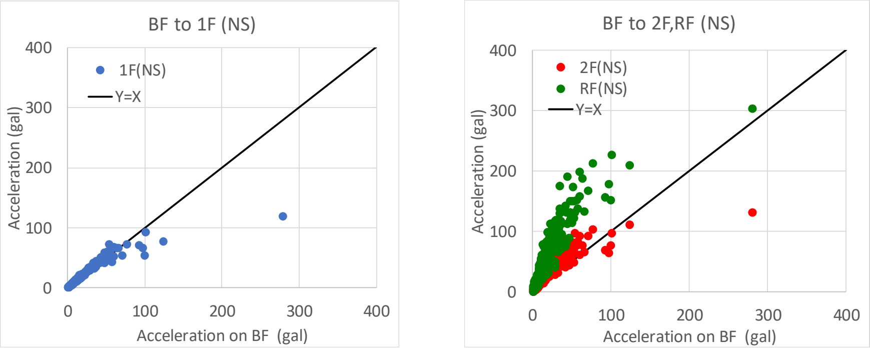


Fig.9 – Relationship between max. acceleration on foundation and max. displacement of isolators

The relationships between maximum acceleration on foundation and maximum acceleration on 1st, and 2nd and roof truss floors in the NS direction are shown in Fig. 10. As to the accelerations of foundation and 1st floor, maximum accelerations are similar in the range that those less than around 70 gals. The acceleration on 1st floor is less than that on foundation, under the acceleration larger than 70 gals. The isolation effect is confirmed through the comparison of acceleration. As to 2nd floor, maximum accelerations are less than those on foundation under those more than around 100 gal. As to the roof truss floor, maximum accelerations are more than those on foundation. The relationships between maximum acceleration on foundation and maximum acceleration on 1st, and 2nd floors in the UD direction are shown in Fig. 11. The accelerations on 1st and 2nd floors are similar and equal to or more than that on foundation.



a) 1st floor

b) 2nd and roof truss floors

Fig.10 – Relationship between max. acceleration on foundation and that on other floors in NS direction

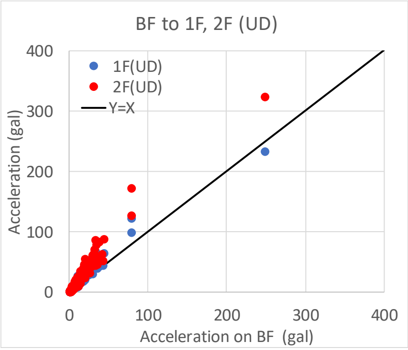
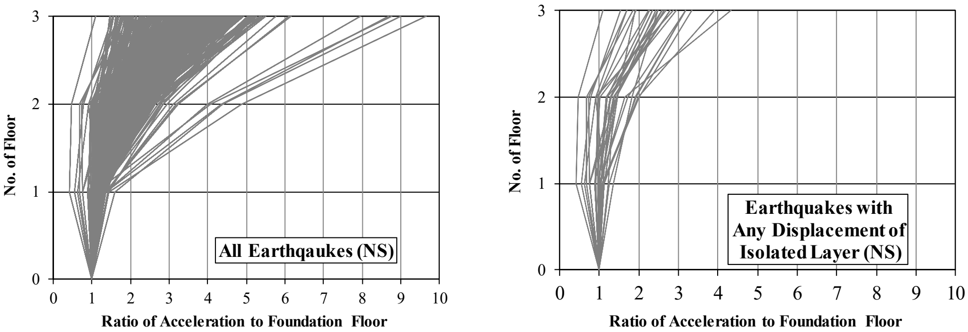


Fig.11 – Relationship between max. acceleration on foundation and that on other floors in UD direction

Max. acceleration distribution with height normalized by that on foundation in NS direction is shown in Fig. 12. There are two figures, one is for all records and another is for records with movement of isolators. Amplification factors of max. acceleration for all records are about 0.5 to 1.5, 0.5 to 5.0 and 1.0-9.0 at 1st, 2nd and roof truss floors, respectively. In case of records with isolation, the amplification factors are remarkably decreased, it can be seen that the responses at 1st and 2nd floors are less than around 2.0.



a)All earthquake

b)Earthquake with movement of isolator

Fig.12 – Max. acceleration distribution normalized by that of foundation (NS direction)

Time histories (EW direction) of the record which was observed on 11th of Marth in the 2011 Tohoku-Pacific Ocean Earthquake are shown in Fig. 13. The record has responses of maximum acceleration ever observed. Maximum accelerations of foundation, 1st, 2nd and roof truss floors are 227gals, 129gals, 124gals and 218 gals, respectively. Maximum acceleration of all floors are less than that on the foundation. After 80 seconds passed in the recorded data, the isolators slide and maximum displacements of two transducers reach 103mm and 93mm. The horizontal force of isolated layer and the relationship between horizontal force and displacement of isolated layer are shown in fig.14. The horizontal force of isolated layer is calculated to sum up the inertia force of each floor and the displacement is the average of two transducers. The horizontal force of isolated layer reaches about 30kN. The horizontal force is similar to the static friction force of about 25kN obtained in the static loading test, as shown in Figs. 5 and 7.

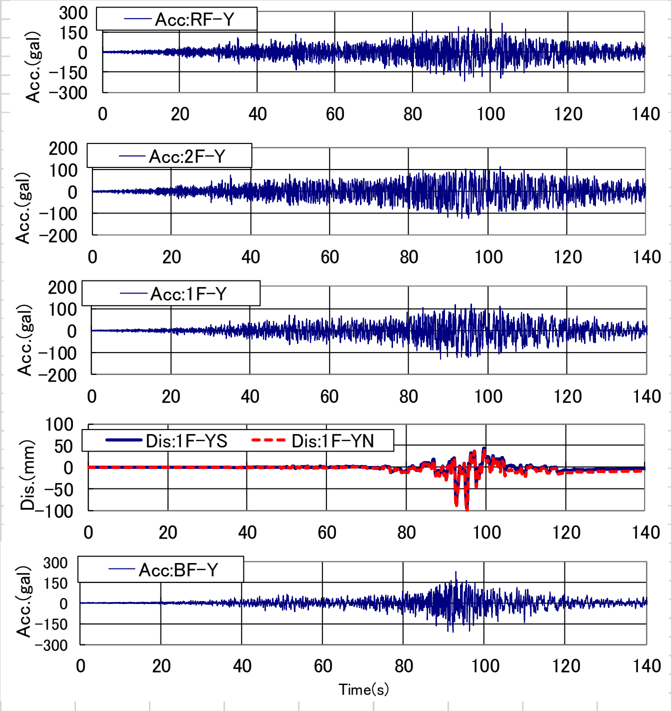


Fig.13 – Time histories of record observed at Marth 11th in the 2011 Earthquake (EW direction)

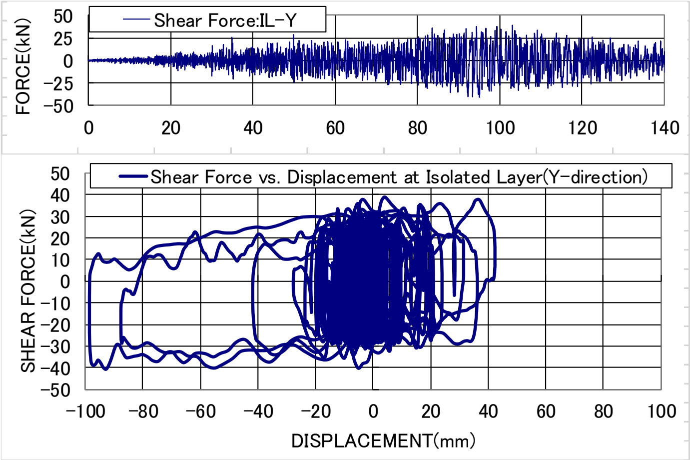


Fig.14 – Time history of horizontal force and relationship between force vs. displacement (EW direction)

8. Observation results during strong winds

There are three times when isolators started sliding during strong winds. Time histories (NS direction) of the record which was observed at 9th of October in 2004 (Typhoon No. 0422, Ma-on) are shown in Fig. 15. In the moment when the isolators sliding or stopping, the accelerations occur, which are around 20 – 30 gals. The wind direction, wind velocity and shear force at isolated layer are shown in Fig.16. At the time when isolators start sliding, the maximum wind velocity is 27.7 m/s. The average wind direction is 51.4 degrees east from the north. The relationship between the wind direction and the direction of isolator's displacement is shown in Fig. 17. Both directions are similar and isolators move along the wind direction. The point of sliding under winds is very important to keep the safety of light structures with frictional isolator.

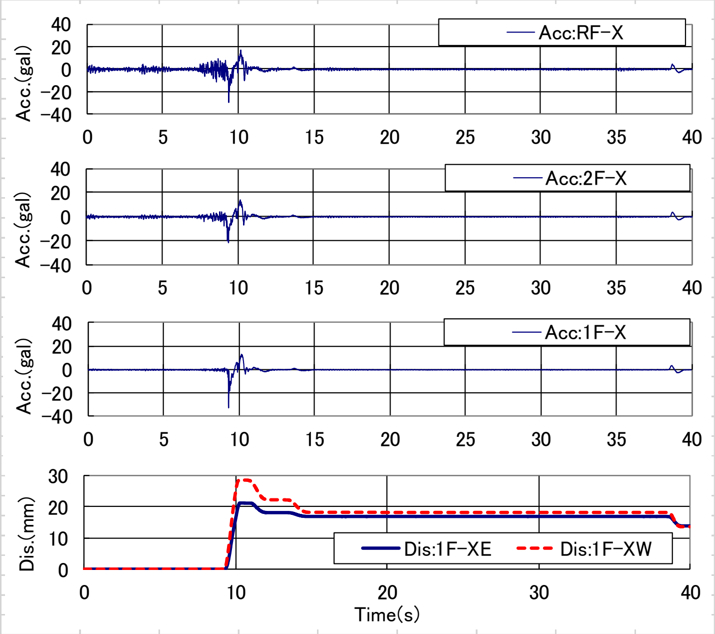


Fig.15 – Time histories of record observed during a typhoon on 9th of October in 2004 (NS direction)

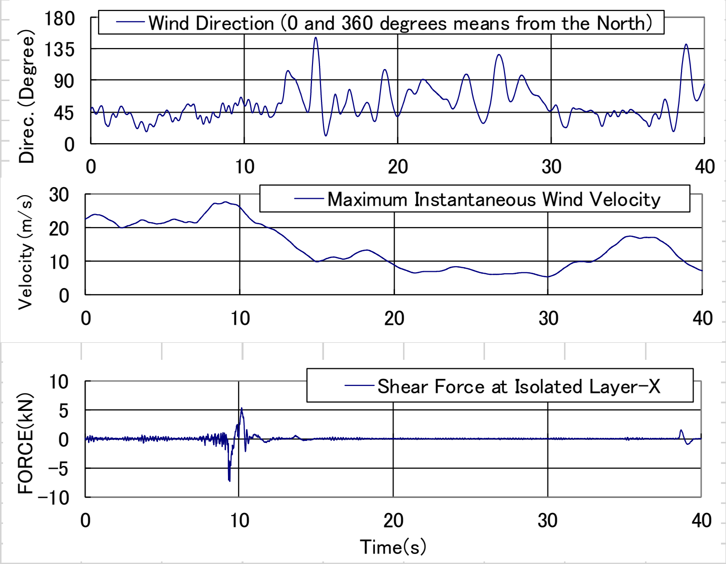


Fig.16 – Time histories of horizontal force of isolated layer and wind condition (NS direction)

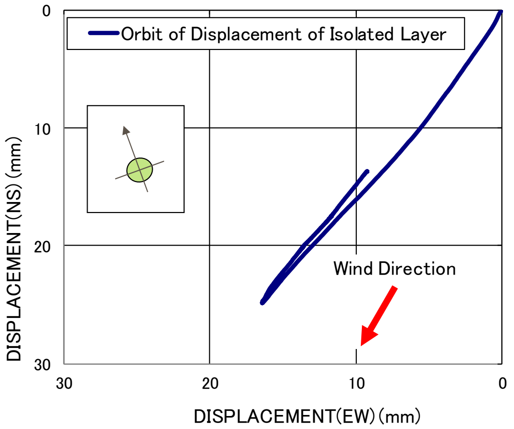


Fig.17 – Relationship between wind direction and direction of isolator's displacement

The horizontal force to the model house is estimated by the wind velocity. The shear force at isolated layer due to wind velocity is persented in Table 2. The maximum wind velocity is 27.7 m/s and average wind direction is 51.4 degrees east from the north. The direction normal to north face of the model house is 20 degrees east from the north. The difference between directions of wind and normal face of wall is 31.4 dgrees. The conponent of wind velocity to the normal face of wall is 23.4 m/s. Considering the wind pressures, wind force coefficients, and aspect areas based on data shown in Fig. 18, the shear force of 26.57kN is calculated at the isolated layer. Compared with the results due to the static loading test as shown in Figs. 5 and 7, the friction force to start sliding is compatible, and the force obtained by the wind velocity is similar to that by the static loading test.

The air pressures have been measured on walls normal to north face. The maximum air pressures were 320 and 228 N/m^2 at 2nd and 1st stories, respectively. The maximum air pressure calculated by measured wind velocity is 337N/m^2, as presented in Table 2. The calculated pressure is similar to measured air pressures to walls.

Table 2 – Shear force at isolated layer due to wind pressure to model house

Direc-tion	Layer	Wind Pressure (N/m^2)^{*1}	Wind Force Coefficient	Aspect Area(m^2)		Shear Force (kN)	Sum of Shear Force(kN)
				Depth(m)	Height(m)		
NS	Roof	337	0.7	10.0	1.50	3.49	3.49
	2nd		1.2		1.39	5.51	9.00
	1st		1.09		2.86	10.30	19.30
	Isolated		1.09		2.02	7.27	26.57

*1) Wind pressure $q=0.6*V^2$, where V: Wind velocity(m/s).
The difference between angles of wind direction and normal direction to wall is 31.4 degrees.
Then the wind velocity normal to wall; $V_n=V*\cos(31.4\ \text{degree})=0.854*V$
Observation results; $V_{max}=27.7$ m/s, then $q_{max}=0.6*V_{n\ max}=337$ N/m^2

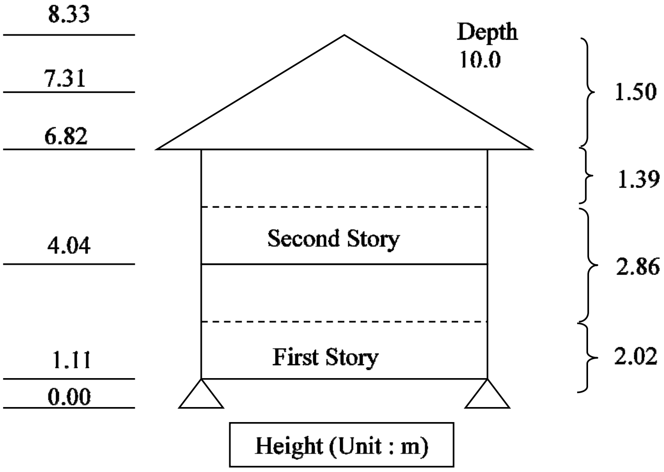


Fig.18 – Geometric dimensions of house model

9. Conclusions

The behavior of seismically isolated house model with sliding isolators is investigated, based on observed records during earthquakes and strong winds. The results are summarized as follows;

1) The coefficient of friction of isolators is similar to the design value under the static loading test.

2) The effect of isolation on reduction of the response during earthquakes is confirmed. With increase of input acceleration, the effect is remarkable.

3) Under strong winds, isolators start sliding. The point of sliding under winds is very important to keep the safety of light weight structures with friction-type isolators.

10. Acknowledgment

The authors express our sincere thanks for members of the collaboration project to participate in earnest discussion and offer important information and precious materials.

11.References

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