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Shaking table test on ultimate behavior of seismic isolation system

Part 1: Outline of the test and response of superstructure

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ABSTRACT:To evaluate the seismic margin of a base isolated nuclear building, shaking table tests with small models which had two different height of gravity center were carried out up to the state in which laminated rubber bearings were ruptured. Through the tests totally five rubber bearings were ruptured. When input motion level was smaller than 2.5S1(S1=329gal:tentative design earthquake), rubber bearings didn't show hardening and the behavior of superstructure was qualitatively the same. When input motion level were between 2.5S1 and 3.0S1, rubber bearings showed hardening and vertical acceleration of superstructure rapidly increased, as the level of input motion increased. Even after one bearing ruptured, the performance of the seismic isolation were not degraded for input motion of design level. And we checked up the other response behavior of the seismic isolation systems.

1 OUTLINE OF THE TESTS

Before the tests, shaking table tests had been carried out using the model of 3-story steel frame structure supported by nine rubber bearings, where the level of input seismic motion had been nearly design level and the effect of base isolation system had been confirmed.

This time, two types of concrete model were used for the super structure, and the input seismic motion was increased from the design level up to the vicinity of the ultimate state of rubber bearings.

1.1 Similitude

Table 1 shows the similitude adopted,which were based on the following rules.

1) The stress of the laminated rubber bearings must be equal to that of the prototype.

2) The amplitude of the input acceleration must be equal to that of the prototype.

3) The geometry of the bearings must be similar to that of the prototype and the scale ratio must be 1/15.

1.2 Superstructure

Fig.1 shows the dimension of superstructures. They are reinforced concrete rigid bodies with the weight of 17.8 tons (174 kN) each. Two types of models are adopted in order to investigate the effect of the overturning

Table 1. Similitude.

Scale of		Similitude
Displacement	L	$L_p/L_m=\lambda=15$
Acceleration	α	$\alpha_p/\alpha_m=1$
Frequency	f	$f_p/f_m=\lambda-1/2=0.258$
Stress	σ	$\sigma_p/\sigma_m=1$
Strain	γ	$\gamma_p/\gamma_m=1$
Force	F	$F_p/F_m=\lambda 2=225$

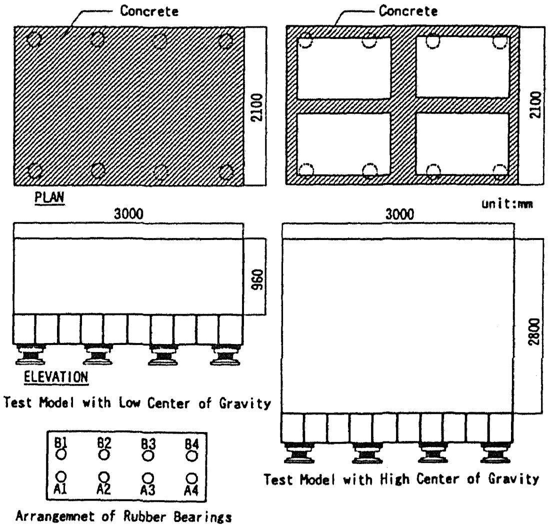


Figure 1. Dimension of superstructure.

moment of the superstructure upon the ultimate response behavior of the rubber bearings. The ratio of the height of the gravity center to the model width are 0.5 and 0.25 for respective models. The high gravity center model was made so that the stress at the edge causing by overtuning moment would be same as that of the prototype.

1.3 Rubber bearings

Lead-rubber bearings (LRB) were used. Table 2 shows the design specification of LRB. The number of bearings used for a superstructure was 2 rows x 4units=8. They were 1/15 reduced scale models of the prototype bearings of which the rated capacity was 500 tons (4900 kN) each.

Table 2. Design specification of LRB.

Loading Weight	2.22tf(22.8kN)
Horizontal Spring Const.	0.336tf/cm(3.29kN/cm)
Natural Frequency	1.94Hz
Diameter	107mm
Rubber Layers	0.60mm×25

1.4 Input seismic motion

The tentative design wave (NE,EW,NS)(Ishida, k. 1989) (El Centro wave(1940), and Hachinohe wave(1968) were used for the input seismic motion. The tentative design wave which is employed as the S1 wave was proposed for this seismic isolation test program and the level of its response spectra (Sv h=5%) in the slightly long period region (2 ~ 10sec) was set to 100 kine. These waves were reduced in time to $1/\sqrt{15}$ according to the similitude. Further, due to the capability of the shaking table, components of the wave longer than 3 second periods were omitted to bring the response displacements of the bearings close to its ultimate level. Fig.2 shows the tentative design wave.

1.5 Test cases

Table 3 shows test cases. At first, excitations were carried out using random waves of white noise in order to investigate the basic characteristics of the test models. Then, seismic wave excitations were applied, where the amplitude of the wave for each test was gradually increased from the level of 1.0S1 up to the vicinity of the ultimate state of bearings.

Table 3. Test cases.

Test Model	Center of gravity /Test model width	input wave	input level	input direction
A	0.25	random wave	50gal	X,Y,Z
		tentative wave	1.0S1~	X
B	0.5	random wave	50gal	X,Y,Z
		tentative wave	1.0S1~	X
C	0.25	random wave	50gal	X,Y,Z
		tentative wave El Centro wave Hachinohe wave	1.0S1~	X,XY,XZ

1.6 Method of measurement

Measured items were as follows.

1. the axial and shearing forces acting on each bearing
2. relative displacement between the shaking table and the superstructure
3. absolute acceleration of the shaking table and the superstructure

The axial and shearing forces were measured by component force transducers which are a kind of load-cells and can measure both forces simultaneously. FIg.3 shows the arrangement of instruments. Leveling devices were installed under component force transducers to equalize the initial load of

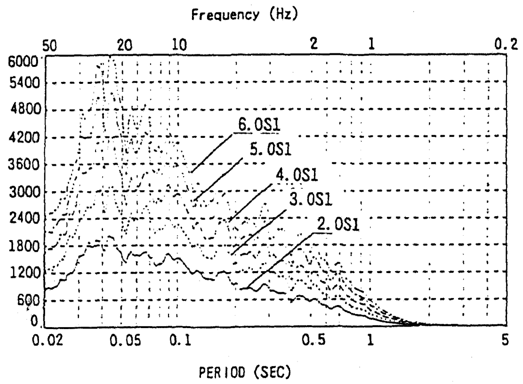


Figure 2. Tentative design response spectra for tests (h=5%).

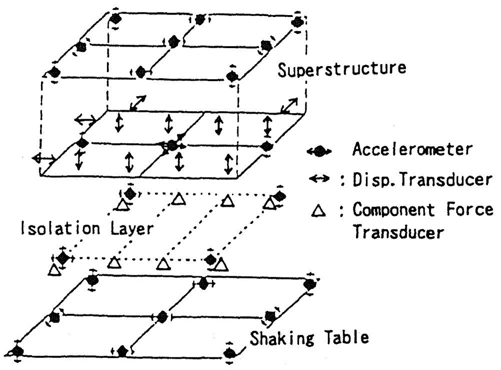


Figure 3. Arrangement of measuring instruments.

each bearing. Fig.4 shows a set of isolation devices.

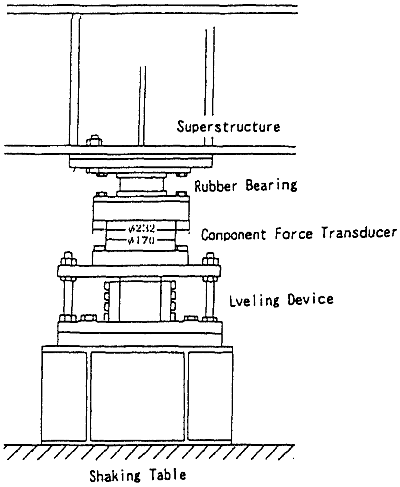


Figure 4. A set of isolation devices.

2. THE RESPONSE BEHAVIOR OF SUPERSTRUCTURE IN A STATE BEFORE RUPTURE OF RUBBER BEARINGS

Through the test low gravity center model could be excited up to the rupture of bearings, where maximum input seismic motion level was 6.75S1(2221gal). However in the case of high gravity center model, the shaking table was stopped when the level of input seismic motion reached 4.6S1 because the vertical acceleration of the table exceeded the allowable level, and no bearings were ruptured.

2.1 Time histories of response values

Fig.5 shows the comparison of time histories of the models with different height of gravity center at the input motion level of 4.0S1.

Due to the violent rocking motion of the super structure, the high frequency components of compressive force, and vertical acceleration of high gravity center model were rather large. The maximum values of the compressive force and vertical acceleration of high gravity center model were much larger than those of the low gravity center model. But horizontal acceleration of both models were nearly the same. The shearing force of low gravity center model was larger than that of high gravity center model.

2.2 Acceleration response spectra

Fig.6 shows acceleration response spectra. When input motion levels were 1.0S1 and 2.0S1, response spectra of high gravity center model were larger than those of low gravity center model at and higher than the first resonant frequency. But when input motion levels were 3.0S1 and 4.0S1, response spectra of low gravity center model were larger than those of high gravity center model at first resonant frequency. In the case of 4.0S1, both models had new peaks at the period of about 0.1 and 0.15 second. Besides, high gravity center model had a peak at the period of 0.05 second.
Those peaks were thought to be caused by rocking of superstructures and sharpened waves of the time histories.

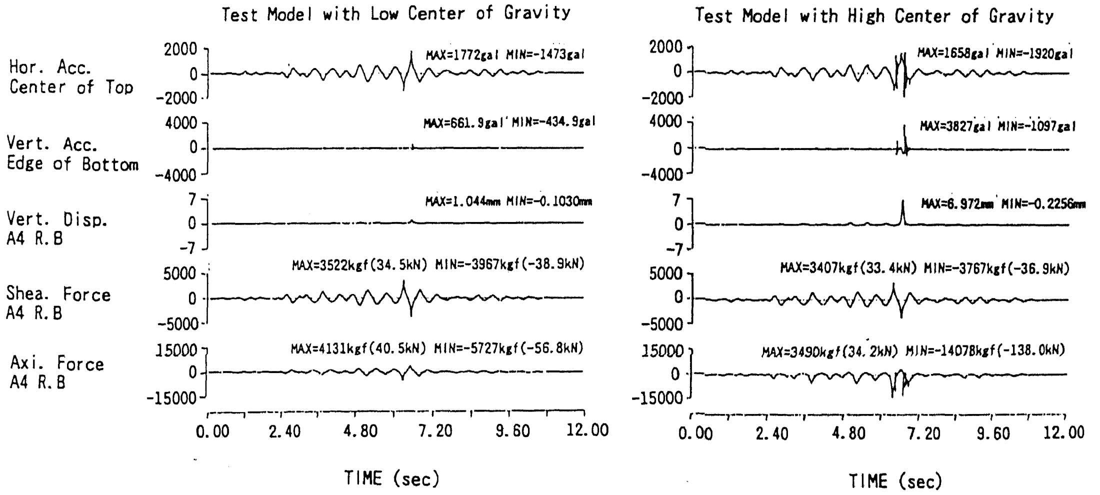


Figure 5. Comparison of time histories at the center of gravities of the two models at the input level of 4.0S1.

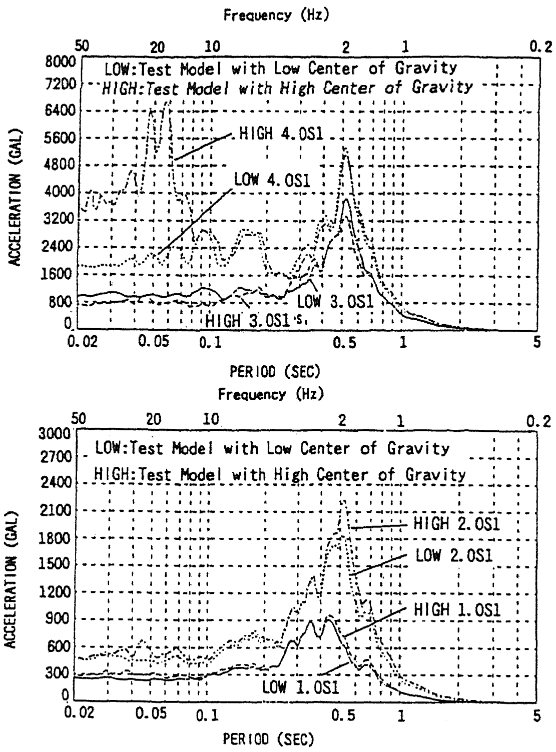


Figure 6. Comparison of Acceleration response spectra at the center of gravities of the two models.

2.3 Maximum acceleration of gravity center

Fig.7 shows the maximum horizontal acceleration of the gravity center of the superstructures at each excitation level. When input motion level was under 2.5S1, there was no effect of the difference of gravity center height on the horizontal acceleretion. When input motion level were between 2.5S1 and 3.0S1, horizontal acceleration of the high gravity center model was a little larger than that of the low gravity center model. And at the cases when *input level was over 3.0S1, horizontal* acceleration of the low gravity center model became larger than that of high gravity center model. The reason of this difference was thought that the stiffness of rubber bearings of the high gravity center model became smaller than that of low gravity model because of larger axial force givened to the rubber bearings of the high gravity center model.

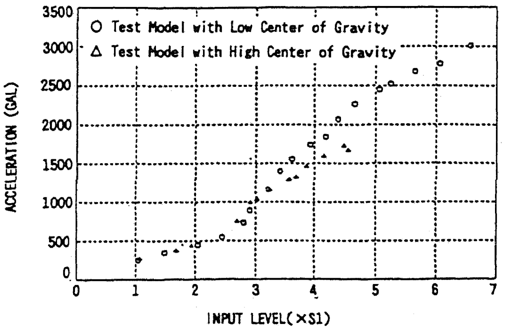


Figure 7. Comparison of Maximum horizontal acceleration at the center of gravities of the two models.

Fig.8 shows maximum vertical acceleration of the gravity center of the superstructures at each excitation level. When input motion level was larger than 3.0S1, vertical acceleration sharply increased as the input motion increased, and the maximum amplitude of high gravity center model was remarkably larger than that of low gravity center model.

It is regarded that the sharp increase of the amplitude of both horizontal and vertical acceleration was caused by occurrence of tensile stress and hardening of rubber bearings.

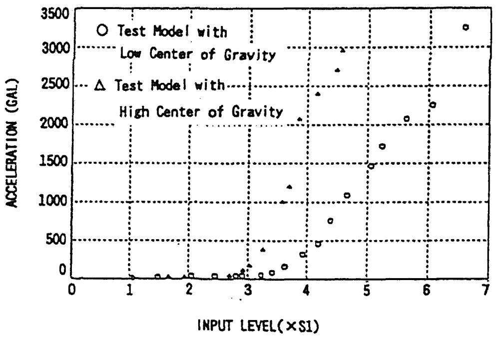


Figure 8. Comparison of Maximum vertical acceleration at the center of gravities of the two models.

2.4 Response acceleration ratio

Fig.9 shows response acceleration ratio (the ratio of response acceleration to input acceleration). When input motion level was smaller than 3.0S1, response acceleration ratio of both models were nearly the same and the values were less than 1.0. When input motion level was larger than 3.0S1, response acceleration ratio of both models exceeded 1.0. The ratio of low gravity center model was larger than that of high center model.

2.5 Predominant frequency

Fig.10 shows predominant frequency at each input motion level. There was no difference between the two models with different height of gravity center.

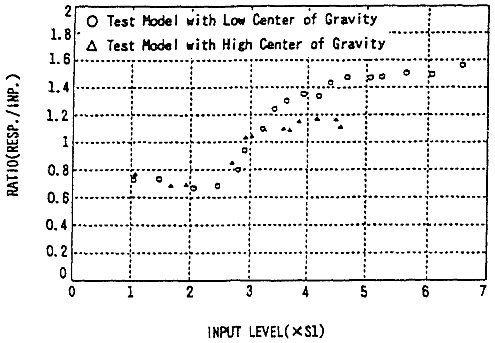


Figure 9. Response acceleration ratio (the ratio of response acceleration to input acceleration).

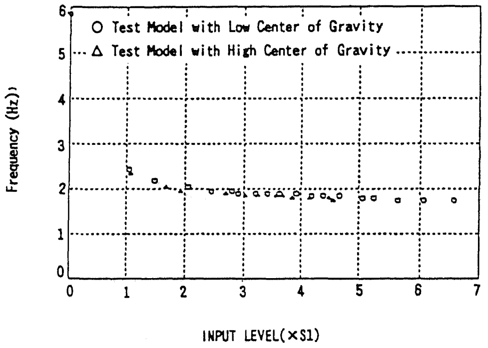


Figure 10. Predominant frequency at each input motion level.

3 THE BEHAVIOR OF SUPERSTRUCTURE IN A RUPTURE STATE OF RUBBER BEARINGS.

3.1 Process of rupture of rubber bearings

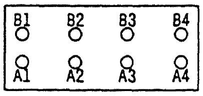
Table 4 shows the process of rupture of rubber bearings for case C (low center model).

The tests were carried out increasing the input level by 0.25S1 for each case until rubber bearings were ruptured. Even though Input motion level was increased up to 6.75S1, no bearing ruptured. That input level was nearly the limit of the capability of the shaking table. As the next excitation was carried out with the level of 6.0S1, then A4 bearing firstly ruptured. After that, excitations were repeated at almost the same input motion level. Finally four rubber bearings were fractured by excitations in case C.

Through the test, only one bearing was ruptured at each excitation. No evidence was observed that the rupture of one bearing would cause by the rupture of other bearing.

Table 4. Process of rupture of rubber bearings.

Excitation Order	Location of Ruptured Bearings
6.00S1	
6.25S1	
6.50S1	
6.75S1	
6.60S1	A4
1.00S1	
6.60S1	B4
6.60S1	
6.00S1	A1
6.00S1	A3



3.2 The change of floor response acceleration spectra

Fig.11 shows the change of floor response acceleration spectra when the number of ruptured bearing increased. With the increase of the number of ruptured bearings, the maximum response acceleration decreased. The change of the predominant frequency was not so clear.

Fig.12 shows the comparison of the floor response acceleration spectrum when all bearings were functioning properly with the spectrum when one bearing (A4) was ruptured. For each case, the level of input motions was S1(design level). As the result of rupturing of A4 bearing, components of spectrum became a little longer, but it's peak level was hardly changed. The function of seismic isolation effect to reduce response acceleration were maintained after the rupture of A4 bearing.

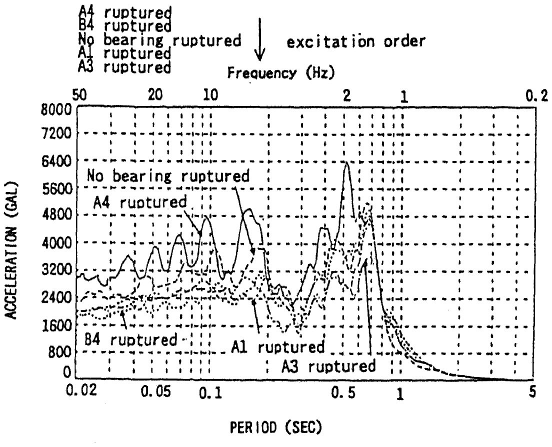


Figure 11. Change of floor response acceleration spectra due to rupturing of rubber bearings.

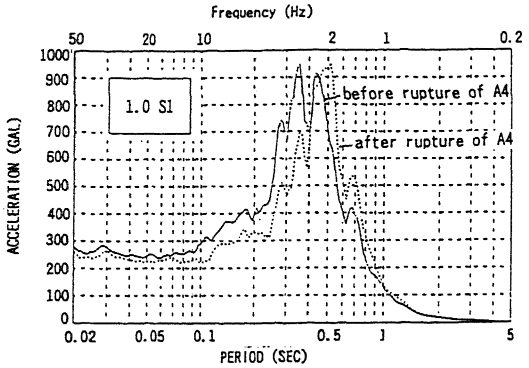


Figure 12. Comparison of floor response acceleration spectra between before and after of rupture of A4.

3.3 The change of predominant frequency

Fig.13 shows the change of predominant frequency when the number of ruptured bearings increased. It is observed that with the result of progress of rubber bearing's rupture, stiffness of seismic isolation layer became softer and it's natural period became longer.

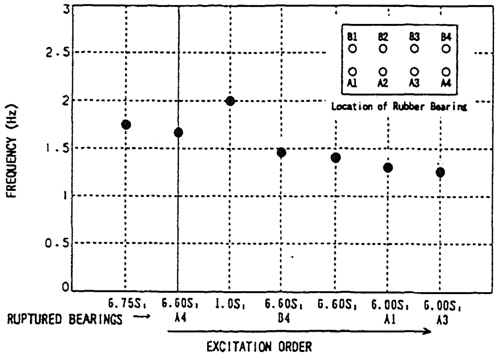


Figure 13. Change of predominant frequency

4 CONCLUSIONS

Through this study, several data were obtained when base isolation elements reached the vicinity of the ultimate state. The results concerning the behavior of superstructure are summarized as follows.

1) When input motion level was smaller than 2.5S1, rubber bearings didn't show hardening. The behavior of superstructure was qualitatively the same and the effect of seismic isolation system was maintained.

2) At the input motion level mentioned above there was no difference between the responses of the superstructure with the different gravity center height.

3) When input motion level were between 2.5S1 and 3.0S1, rubber bearings showed hardening. The horizontal and vertical acceleration of superstructure rapidly increased, as the level of input motion increased, and several new peaks appeared at the high frequency zone of horizontal response spectrum. New peaks were more distinct for the high gravity model.

4) Even after one bearing ruptured, the performance of the seismic isolation were not degraded for input motion of design level.

5) With the increase of the number of ruptured bearings, natural period of the system became longer and the maximum response acceleration became smaller.

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