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MULTI DIRECTIONAL EARTHQUAKE INPUT TEST AND SIMULATION ANALYSIS OF BASE ISOLATED STRUCTURE

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1. INTRODUCTION

In applying base-isolation system to nuclear facilities such as the fast breeder reactor (abbreviated as FBR), it is very important to evaluate the seismic safety margin of the base isolation layer.

From this point of view, dynamic breaking tests on base isolation layer consisting of a group of scaled laminated rubber bearings are conducted on shaking tables.

In the series of the tests, horizontal one-way, horizontal two-way and horizontal-and-vertical simultaneous earthquake input tests are carried out.

The present paper shows the results of horizontal two-way and horizontal-and-vertical earthquake input tests and simulation analysis of horizontal two-way earthquake input tests.

2. HORIZONTAL TWO-WAY EARTHQUAKE INPUT TEST

In horizontal two-way earthquake input tests, NS and EW waves are inputted for X and Y direction respectively. The waves are artificial seismic waves that have the same degrees of power and spectral characteristics. Both waves are made using the phases of horizontal two-way component of actual seismic waves. The input level of NS wave is raised up to three levels as follows. (Same as in the one-way input tests described in Reference 1.)

- Design level : 100 Gal input : laminated rubber bearing stay in linear condition
- Hardening level : 350 Gal input : non-linear behavior
- Target breaking level : 700 Gal input : ultimate state

The acceleration ratio between both waves is kept constant during the test.

The specimen consists of four laminated rubber bearings, two rows of two each, and the super-structure made of reinforced concrete rigid body. Figure 1 shows the outline of specimen.

In excitation at the design level, the two-way responses coincided roughly with the results of superposing on the time-history responses under the individual excitation.

In excitations at above hardening level, the two-way responses showed a trend differing from the one-way input responses due to the effects of orthogonal direction input.

However, it was found that the two-way responses are roughly the same as the one-way responses based on the following results, when the test results were arranged taking the primary axis in the maximum deformation direction that varied with time, as shown in Fig. 2.

First, the shear strain at breaking is shown in Fig. 3 in terms of relationship with the axial force ratio obtained by the horizontal one-way and two-way input tests. In the two-way input tests, the shear strain is evaluated by primary-axis direction deformation $\boldsymbol{D}$. The two-way test results are equal to those from the one-way tests.

Next, the horizontal-direction hystereses in the X and Y directions at the hardening level obtained in the horizontal two-way input tests are shown in Fig. 4. Disturbance of the hysteresis properties is seen due to the effects of orthogonal direction input. However, these hystereses are converted into more simple style as shown in Fig. 5(1) when organized with primary-axis direction deformation $\boldsymbol{D}$, primary-axis direction force $\boldsymbol{F_{PR}}$ and orthogonal-axis direction force $\boldsymbol{F_{TR}}$. According to the figure, the orthogonal-direction force $\boldsymbol{F_{TR}}$ is sufficiently small compared with the primary-axis direction force $\boldsymbol{F_{PR}}$. It can be seen that the restoring force characteristics in horizontal two directions may be represented by the primary-axis direction only. Similarly, the result of excitation at the target breaking level is shown in Fig. 5(2). The horizontal-direction hysteresis of the one-way input test in terms of the absolute value is shown in Fig. 6. From a comparison of Figs. 5 and 6, it can be seen that the horizontal two-way restoring force characteristics converted into the primary-axis direction indicate almost the same trend as for the one-way restoring force characteristics including hardening and slipping phenomena.

3. HORIZONTAL-AND-VERTICAL EARTHQUAKE INPUT TEST

The input waves used in horizontal-and-vertical earthquake input test was the NS wave and UD wave. The UD wave is artificial seismic wave made using the phase of the vertical component of the actual wave that is utilized in making the corresponding NS wave.

In Fig. 7, the relationship between shear strain and axial force ratio of the laminated rubber bearings in excitation at the design level is shown in the form of comparison of the result of horizontal-and-vertical simultaneous input test and the superposed result on the respective one-way input test in time histories. It can be seen from this figure that superposition of horizontal and vertical responses, each one-way, at the design level is effective.

In excitation at the target breaking level, UD wave was inputted at almost 1,200 Gal (excitation limit of the shaking table) corresponding to approximately double the extreme design earthquake, but the test result was that there was not much difference from that of horizontal one-way input. Fig. 8 shows the comparison of the horizontal-direction hystereses between horizontal one-way input tests and horizontal-and-vertical input tests. The hysteresis configurations hardly differ and the displacements at which breaking occurred were equal.

4. SIMULATION ANALYSIS OF HORIZONTAL TWO-WAY INPUT TESTS

4.1 Analytical model

To examine analytical techniques for evaluating the ultimate behaviors of base isolation layer, simulation analyses of horizontal two-way earthquake input tests were performed.

The technique of horizontal two-way input response analysis with the nonlinear range has been actively studied in recent years, and Multi-Shear-Spring (MSS) models and fiber models have been proposed. However, there are few horizontal two-way response analysis models that have been proposed for a system of complex stress condition with large influence of repetitions such as hardening phenomena of laminated rubber bearings.

As described in the results of horizontal two-way input tests, findings from tests were that

- Two-way restoring force characteristics can be organized roughly with only the primary-axis directions of deformations at each moment.
- Restoring force characteristics arranged according to primary-axis directions of deformation correspond well with restoring force characteristics at time of one-way input including hardening and slipping phenomena.

Here, the model modifying the MSS model as the restoring force model reflecting these findings will be developed and examined.

In attempting to apply the conventional type of MSS model to the present test results, we found it difficult to reflect the slipping phenomena of restoring force characteristics. This is because each spring independently behaves in a conventional-type MSS model.

Therefore, a restoring force model in which the restoring force characteristics of the individual springs comprising the spring group act interlocked was developed modifying the conventional-type MSS model.

The basic rules are as follows:

- The individual springs comprising the spring group possess common information such as concerning the kink points of the restoring force characteristics at all times.
- With regard to slipping of the restoring force characteristics, the rule for one-way spring is expanded and it is defined that when one spring slips the other springs will also slip as shown in Fig. 9.

The modified MSS model is referred to as "isotropic-hardening-linked MSS" (abbreviated as "IHL-MSS").
The response analysis model, as shown in Fig. 10, is a one-mass-spring model having freedom in horizontal two directions. The base isolation layer is assumed to follow an IHL-MSS model expressed by a group of eight shear springs. The restoring force characteristic of each shear spring shown in Fig. 11 is similar to that of the one-way spring developed in discussion of one-way input tests (Ref. 1). It is set up that the restoring force characteristics as a whole of MSS coincides with the one-way spring as shown in Fig. 12, at the initial rigidity and the skeleton of the restoring force characteristics at infinitely large displacement.

4.2 Analytical results

The analytical results by the IHL-MSS model are shown compared with test results.

The orbit of two-way response displacement in hardening-level excitation is shown in Fig. 13. According to this figure, the response maximum values and response properties in the X and Y directions are reproduced well.

The shear hysteresis in the X direction in hardening level excitation is shown in Fig. 14. As stated in test results, the shear hysteresis of test results is considerably disturbed by the orthogonal input, but this is also reproduced well by the IHL-MSS model.

The orbit of two-way response displacements at target breaking level is shown in Fig. 15. As stated in horizontal two-way test results, breaking of the laminated rubber bearing occurs at primary-axis direction deformation of approximately 5.6 cm (700% for shear strain γ). It can be seen in this figure that the displacement response orbit until $\gamma = 700\%$ is reproduced well in the analytical results.

5. CONCLUSIVE REMARKS

The following results were obtained from the horizontal two-way input tests and horizontal-and-vertical input tests conducted with the purpose of examining the response characteristics of the base isolation layer under multi-directional inputs.

- With regard to input of design level, the response under two-way input can be evaluated by superposition on the time histories of the responses under the respective individual inputs.
- In case of horizontal two-way input, shear strain at breaking evaluated by the primary-axis direction of deformation is equal to that of one-way input.
  Further, the horizontal-direction restoring force characteristics of the primary-axis direction indicate the same trend as that of one-way input.
- In case of horizontal-and-vertical simultaneous input, the horizontal-direction restoring force characteristics and shear strain at breaking are affected very little by vertical motion with the low center-of-gravity building of this case and input of around 1.2 G.

For the simulation analysis of horizontal two-way earthquake input tests, an isotropic-hardening-linked MSS (IHL-MSS) model in which the restoring forces of the individual springs act interlocked was developed modifying the conventional type MSS model.

With this horizontal two-way restoring force characteristics' model, conformity with one-way response was amply taken into consideration, and further, the test results were reproduced well.

Therefore we believe that proposed IHL-MSS model is the powerful tool for the simulation of horizontal two-way ultimate state response such as the base-isolation system.

ACKNOWLEDGEMENT

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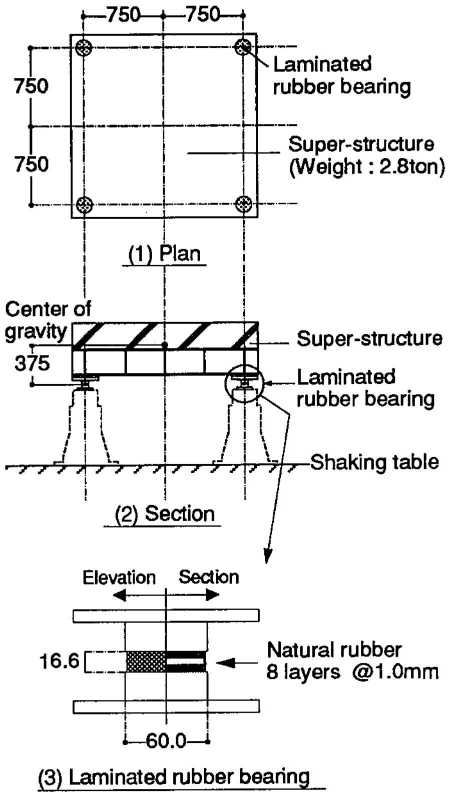


Fig.1 Outline of specimen

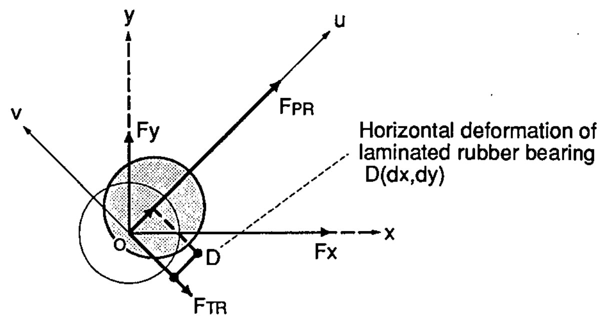


Fig. 2 Transformation of horizontal two-way stress & deformation

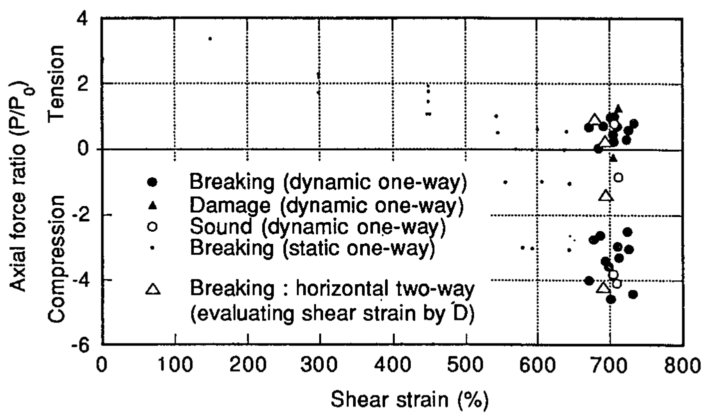


Fig. 3 Comparison of horizontal two-way and one-way test result (Relationship of shear strain and axial force ratio at breaking)

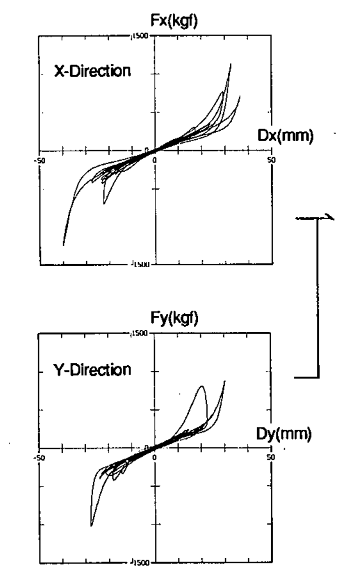


Fig.4 Horizontal hysteresis in X and Y directions under horizontal two-way test (Hardening level excitation)

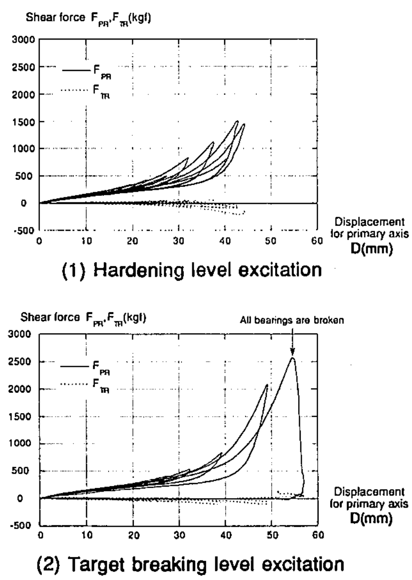


Fig.5 Hysteresis for primary-axis direction and orthogonal direction under horizontal two-way test
(Primary-axis direction deformation : D
Primary-axis direction force : FPR
Orthogonal direction force : FTR)

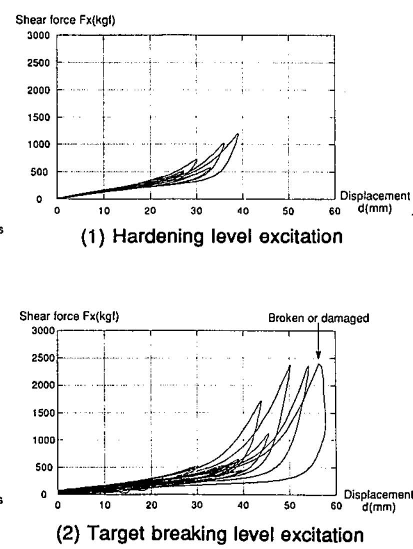
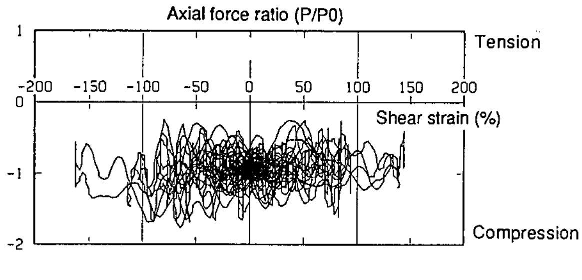
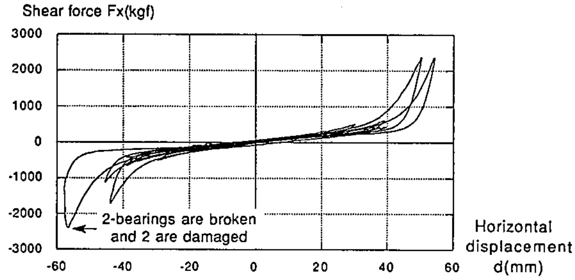


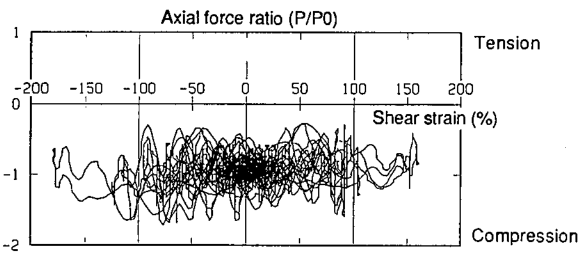
Fig.6 Horizontal hysteresis under one-way excitation (Arranged based on absolute value)



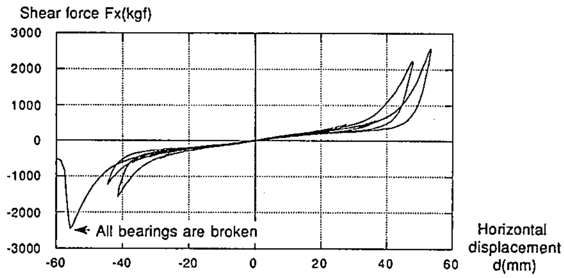
(1) Horizontal-and-vertical simultaneous excitation



(1) Horizontal one-way excitation



(2) Superposition on the respective one-way excitation



(2) Horizontal-and-vertical simultaneous excitation

Fig. 7 Comparison of test results by horizontal-and-vertical simultaneous excitation and superposition on the respective one-way excitation. (Relationship between shear-strain and axial-force ratio in design level excitation)

Fig. 8 Comparison of test results by horizontal one-way excitation and horizontal-and-vertical simultaneous excitation. (Horizontal-direction hystereses in target breaking level excitation)

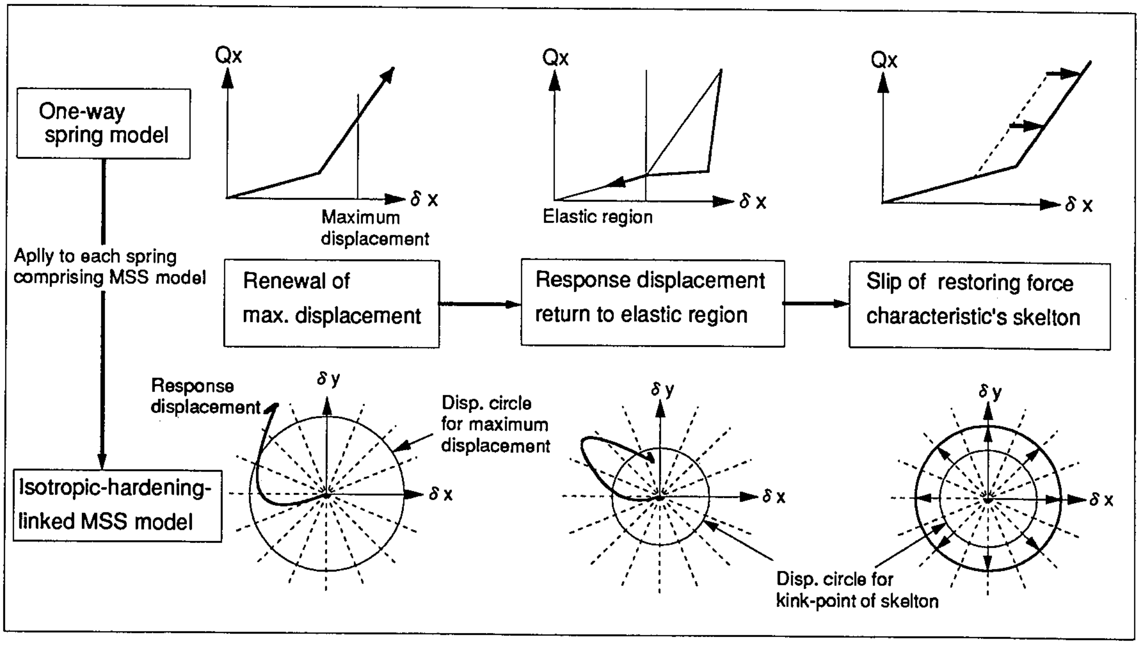


Fig. 9 Expansion of hysteresis rule for one-way spring into Isotropic-hardening-linked MSS model

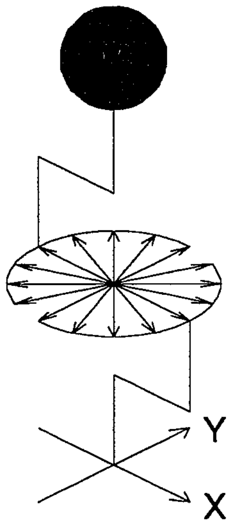


Fig.10 Analytical model by MSS model
(Consist of 8 shear spring)

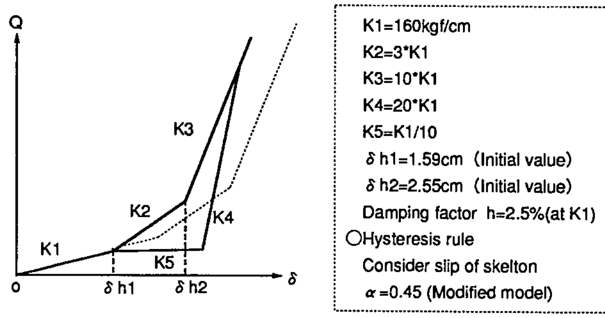


Fig. 11 Restoring force characteristics of each spring comprising MSS model

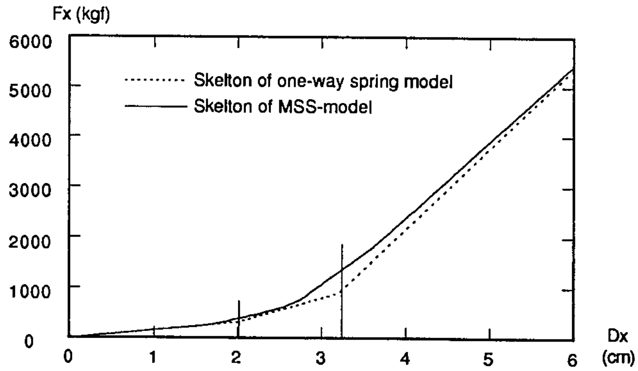


Fig. 12 Comparison of hysteresis skelton between MSS model and one-way shear spring

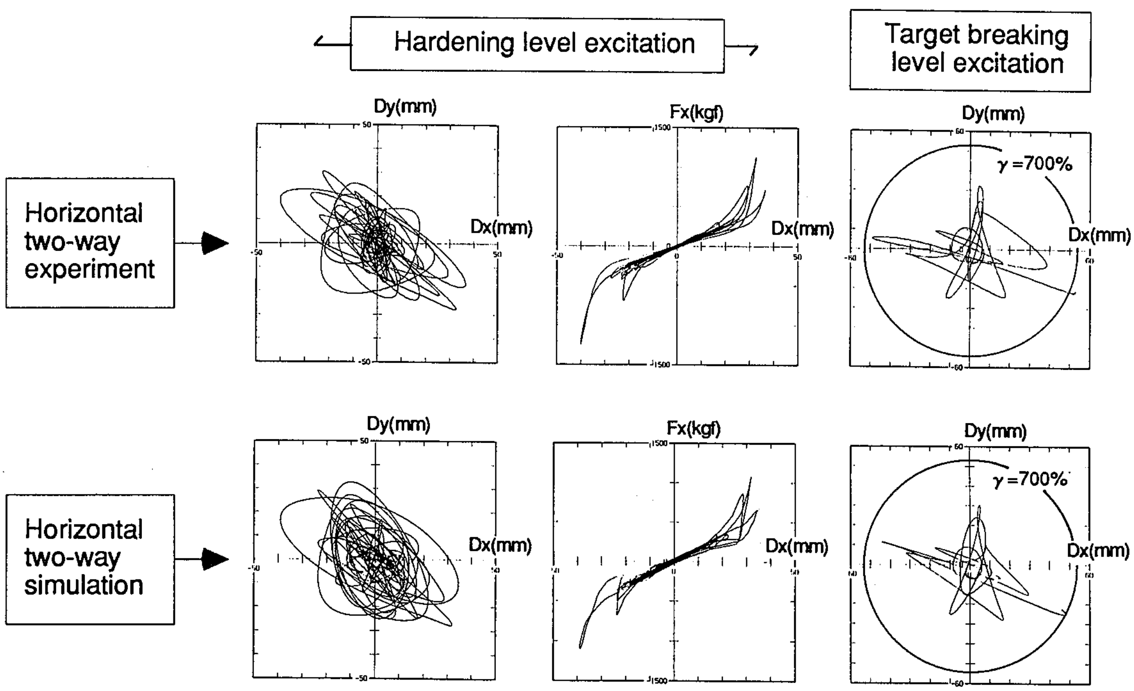


Fig.13 Orbit of two-way response displacement

Fig.14 Horizontal hysteresis (X-direction)

Fig.15 Orbit of two-way response displacement