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EXPRIMENTAL AND ANALYTICAL EVALUATION OF SEISMIC PERFORMANCE OF HIGHWAY BRIDGES WITH BASE ISOLATION BEARINGS

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ABSTRACT

The effect of the implementation of the lead-rubber bearing (LRB) seismic isolator to a highway bridge structure was evaluated under seismic loads using the substructure hybrid loading (pseudodynamic) test method. The seismic response behavior of the isolated bridge structre was successfully obtained. The effectiveness of isolation is examined based on acceleration and displacement amplifications using earthquake response results. The hybrid loading tests asuuming linear and nonlinear characteristics of the pier are carried out to investigate the effect of the bridge piers nonlinear behavior to the seismic response of the superstructure.

KEYWORDS

Seismic base isolation; on-line hybrid loading test; pseudodynamic test; substructure technique

INTRODUCTION

The advantage of the seismic base isolation in protecting highway bridge structures from destructive seismic attack has become of major interest and a growing number of application of such devices has been already in use. The research and development efforts of seismic isolation bearings for bridges have dramatically intensified accordingly. In Japan, there already exist a number of base-isolated buildings designed and constructed. Acceptance of the seismic isolation concept to bridges will be easier since bridges are typically designed to be supported on bearings, whereas building structures are conventionally designed to be fixed at their base.

An intensive test program between the Public Work Research Institute of the Japanese Ministry of Construction and 28 private companies (PWRI 1991; 1992) was conducted with the main objective of developing menshin devices for bridges and formulating design guidelines. A hybrid earthquake loading system had been developed at the Dept. of Civil Engineering, Kyoto University and was used to test a high-damping rubber isolation bearing for its fundamental cyclic behavior and earthquake response behavior (Iemura et al, 1991).

For bridge applications, the plane of isolation is below the girder superstructure so that inertial forces from the heavy superstructure that are transmitted to the critical pier supports can be reduced by the base isolation system (or more appropriately, seismic isolation system). In such cases, single-unit compact isolation devices are desirable since the bridge seats may not provide enough space. In addition, these devices must be made of robust construction due to exposure to harsher environmental conditions. Therefore, necessary mechanisms are contained in a single unit to achieve seismic isolation for such an application: flexibility to lengthen the natural period of the supported structure, damping to limit excessive deformation, vertical stiffness to support heavy superstructure, and sufficient stiffness at low loads for serviceability against ambient vibrations. In the seismic isolation bearings, laminated elastomers made of rubber materials provide the required flexibility and interleaved steel plates give vertical stiffness. The lead-rubber bearing, which was originally developed in New Zealand, has a lead core at the center and utilize plastic yielding of the lead core for hysteretic damping. Many other types of devices and ways of providing damping have been proposed and developed, e.g. high-damping rubber bearings, sliding rubber bearings, etc. As base isolation concept gains more acceptance, new isolation techniques and configurations will continue to be developed. Excellent state-of-the-art reviews of the base isolation concept since its inception up the present time can be found in Kelly (1986), Izumi (1988), Buckle and Mayes (1990) and Skinner et al. (1993).

It is necessary to evaluate and verify the seismic performance of seismic isolation devices under earthquake excitations and for different structural configurations for the practical application. However, the effectiveness of seismic isolators is very much dependent on the characteristics of the input earthquake motion and the supported structures. The requirement of applying high vertical loads due to the high dependance of isolation characteristics on axial bearing pressure would necessitate a large-capacity table to a full-scale specimen; or specimens would have to be drastically scaled down in order to accommodate them in most shaking tables. In this paper, the performance of the bridge structure with seismic isolators is evaluated via a substructured on-line hybrid loading test method, which permits the test for inelastic earthquake response of structures. The description of the tests and the results are presented in the following sections.

SUBSTRUCTURE HYBRID LOADING TEST OF HIGHWAY BRIDGE WITH LRB

The substructure hybrid loading test combines the analytical part numerically solved in the computer, and the experimental part loaded with quasi-static loading equipment, to evaluate the nonlinear seismic response of a structural system. Using the substructured hybrid loading test technique, it is possible to limit the experiment only to a critical portion for which an accurate modelling is difficult, while the rest of the structure numerically in a computer. In this section, the methodology used in the testing of the seismic base isolators and the modelling of the isolators are described.

Modelling of the seismically isolated structure

The model considered in the test is a reinforced concrete pier with the seismic isolator, shown in Fig. 1. Only the movement in the logitudinal direction of the structure is taken into account. This structure is modelled as a 2-DOF model, shown in Fig. 2; the superstructure and the top of the pier correspond to the two DOFs. The pier and column are treated in the numerical modelling, while the isolator is subjected to experimental loading.

It is assumed that 7 LRB-type isolators are installed to between the pier and the superstructure in this model. Since the weight of the superstructure is 280ton, the axial load per isolator is 40tonf. Two types of pier i.e. a linear-elastic model and a nonlinear model are assumed. The load-deformation behavior of the pier for the nonlinear case is represented by a tri-linear model (Fig. 3), which is widely used in the analysis of RC structures. The stiffness of the linear model was assumed to be equal to the initial stiffness of the nonlinear model. The parameters for the tri-linear model is shown in Fig. 4. The damping ratio for the two modes is 5%.

Test method

On-line hybrid test method is a computer-controlled experimental technique in which direct step-by-step time integration is used to solve the equations of motion. The computed displacement at each step is statically imposed on a specimen through computer-controlled load actuators in order to measure its restoring forces at the current deformation state. The measured restoring forces are then fed into the equations of motion to compute the next set of displacements. The numerical time integration process and the on-line loading process are carried out for

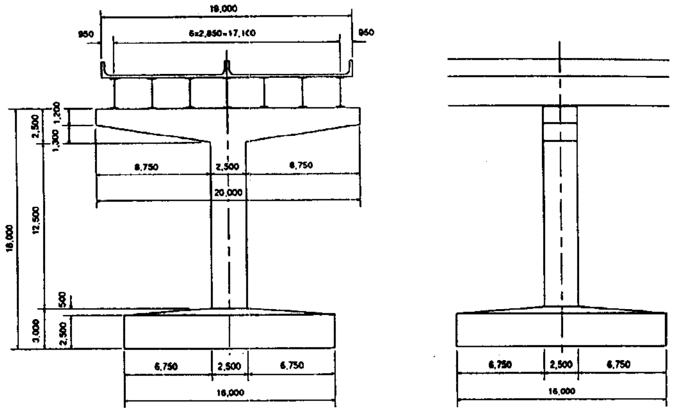
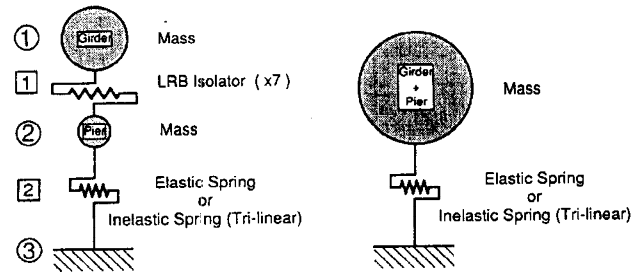


Fig. 1 Highway Bridge Structure



(a) Isolated Structure (b) Unisolated Structure

Fig. 2 Modelling of the Structural System

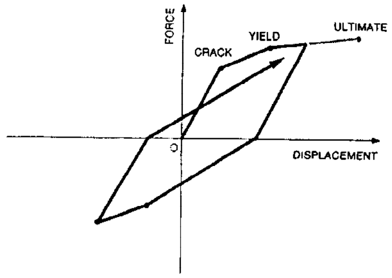


Fig. 3 Tri-linear Hysteresis Model

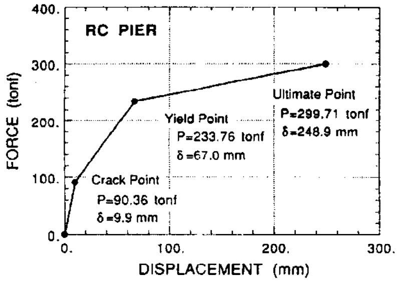


Fig. 4 Assumed Characteristics of Nonlinear RC Pier Model

A highway bridge structure with seismic isolators is modelled as a 2-DOF system, and the substructure hybrid loading technique was applied to this structural system. The equation of motion, including the seismic isolator specimen regarded as a substructure, is expressed as follows:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{r}(t) = \mathbf{f}(t)$$

where **M** is the mass matrix, **C** is the damping matrix, $\mathbf{x}(t)$ is the displacement vector, $\mathbf{r}(t)$ is the restoring force vector, and $\mathbf{f}(t)$ is the external force vector. In the case of seismic excitation, the external force vector can be expressed as $\mathbf{f}(t) = -\mathbf{M}\mathbf{1}\ddot{z}(t)$, where $\ddot{z}(t)$ denotes the ground acceleration. The restoring force vector $\mathbf{r}(t)$ is expressed as the sum of the restoring force from the analytical model $\mathbf{r}_{comp}(t)$ and that from the experiment $\mathbf{r}_{exp}(t)$, i.e.

$$\mathbf{r}(t) = \mathbf{r}_{comp}(t) + \mathbf{r}_{exp}(t)$$

for the above equation. Therefore, the displacement vector at the time $t+\Delta t$ can be computed by using the central difference integration scheme:

$$\mathbf{x}(t+\Delta t) = \left[\frac{1}{\Delta t^2}\mathbf{M} + \frac{1}{2\Delta t}\mathbf{C}\right]^{-1}\left\{\mathbf{f}(t) - \mathbf{r}(t) + \frac{2}{\Delta t^2}\mathbf{M}\mathbf{x}(t) - \left(\frac{1}{\Delta t^2}\mathbf{M} - \frac{1}{2\Delta t}\mathbf{C}\right)\mathbf{x}(t-\Delta t)\right\}$$

in which the restoring force $\mathbf{r}(t)$ is obained from the restoring force from the experimental part at time t, $\mathbf{r}_{exp}(t)$ and the computational part, $\mathbf{r}_{comp}(t)$. The computed displacements are then separated into the experimental and the computational components. The former is provided to the loading system via the digital/analog converter, as the new displacement to be imposed to the test specimen. This process is repeated for the duration of the response time. The outline of the substructur hybrid loading test is shown in Fig. 5.

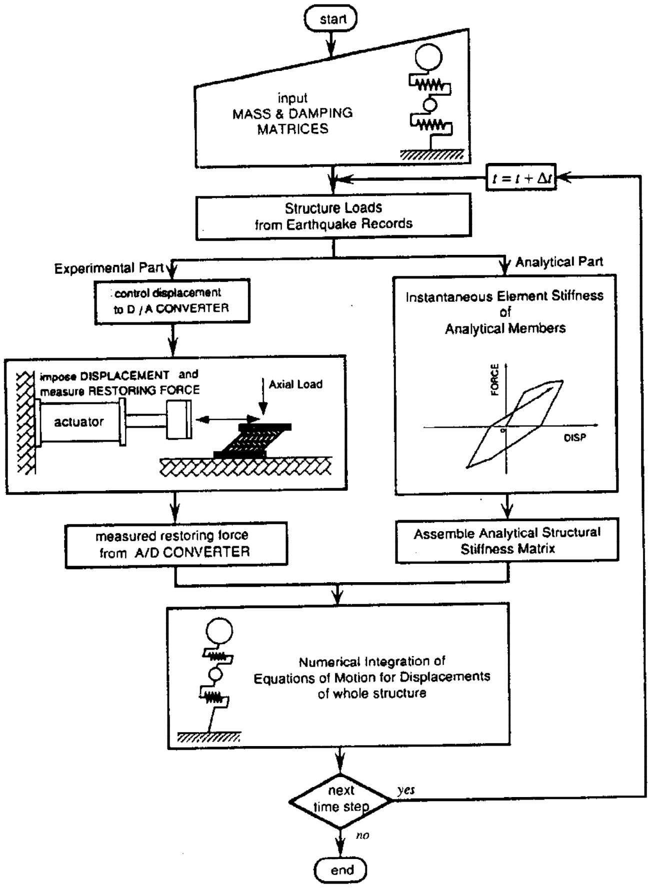


Fig. 5 Outline of Substructure Hybrid Loading Test

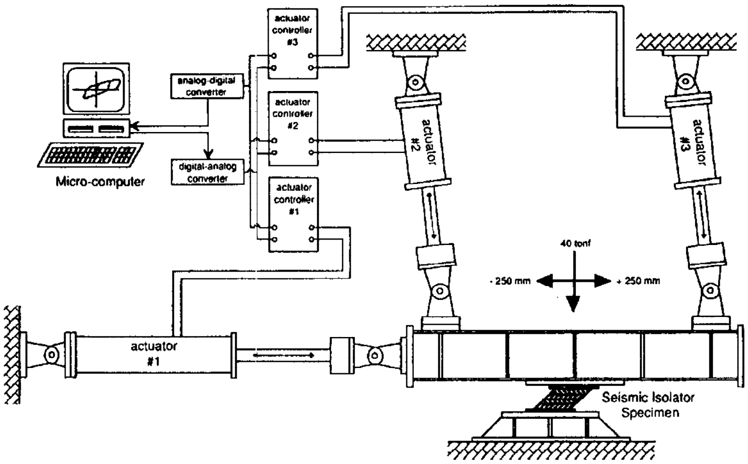


Fig. 6 Loading System Overview

TEST SETUP

The test set-up used in this experiment is shown in Fig.6. The specimen is bolted to the underside of the rigid load-transfer beam and to a rigid platform that is fixed to the rails of the strong reaction floor. Different heights of isolator specimens could be accommodated by inserting filler plates between the specimen and the test platform.

The actuator for horizontal motion (labeled No.1) has a maximum stroke of ±250mm. Each of the vertical actuators (No.2 and No.3) has load capacity of 40 tonf; hence, a vertical load as high as 80 tonf can be applied on a specimen.

FUNDAMENTAL PROPERTIES OF LEAD-RUBBER BEARING

The details and dimensions of the tested isolator specimens (lead-rubber bearing) are shown in Fig.7. The most fundamental test being done on seismic isolators is the repeated cyclic loading test (or quasi-static test). This is a test procedure to establish some mechanical properties of the isolators, such as hysteretic load-deformation behavior, cyclic energy absorption capacity, performance deterioration under repeated loads, etc.

An example of the fundamental load-deformation characteristics of the bearing is shown in Fig. 8. As can be seen in this figure, the load-deformation behavior is approximately a bilinear-type hysteresis loop, with reasonably small hardening effects which typically appear in the large deformaion range of the isolator. In Fig.8b, the equivalent damping ratios h_{eq}, derived from the elastic potential amd the hysteretic energy dissipation per cycle, are plotted against the shear strain ratio (total deformation divided by total height of rubber layers). Two loading test, denoted by BCL-1 and BCL-2, were carried out for the same specimen, and the slight difference in the damping ratios can be seen in the figure.

TEST CASES AND INPUT EARTHQUAKE RECORDS

The effect of the seismic isolation is investigated with the comparison of the test results and the numerical simulations. Also, results from the linear and nonlinear pier models are compared. The three earthquake records prescribed in the Specifications for Highway Bridges (S.H.B.) of Japan (Japan Road Association, 1990), shown in Fig. 10, were used in the test. The corresponding response spectra are also shown in the figure. The records were then scaled to 50gal, 100gal, 200gal and 300gal, and applied to the linear pier model, and the nonlinear

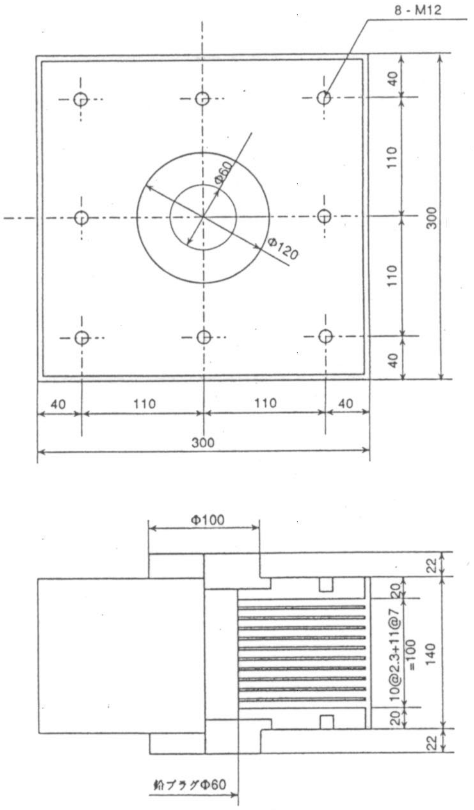


Fig. 7 Detail of LRB Isolator Specimen

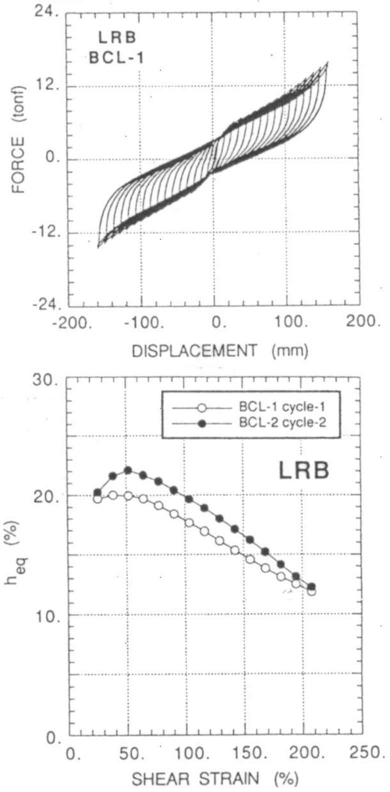


Fig. 8 Representative Restoring Force Characteristics of Isolator

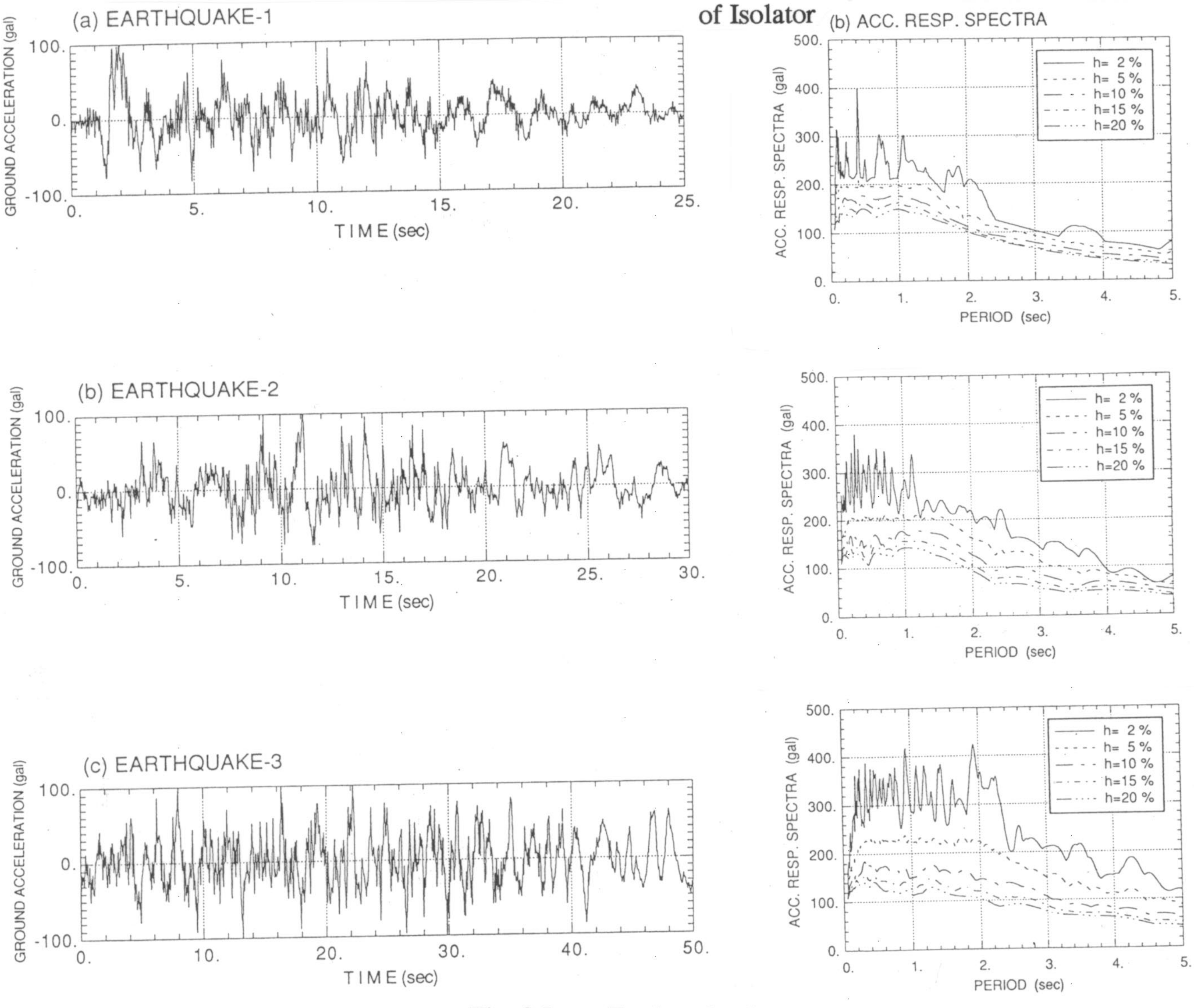


Fig. 9 Input Earthquake Acceleration

model. The time interation step size Δt was set to 0.01 sec, which can be considered to be sufficiently small for the use of central difference time integration scheme.

For each level and kind of input earthquake, the linear and nonlinear pier models as well as unisolated structural models were utilized to perform the substructure hybrid loading test. To test for virgin earthquake response, the second specimen of each type was subjected to Type-3 Earthquake of S.H.B. This is especially important in that some rubber bearings exhibit exceptionally high stiffness during first displacement excursions. Due to this high initial stiffnesses, isolation effect might be diminished and consequently transmitting large forces to the pier supports.

TEST RESULTS AND DISCUSSIONS

Only a few representative results of the tests is briefly described in this section. A complete report on the test results is given in DPRC (1992).

The peak response values for all test cases are summarized in Table 1. In Figs.10-13, representative test results are shown. It can be seen from Table 1 that the peak acceleration of the superstructure is decreased from the

Table 1 Peak Acceleration and Displacement from Substructure Hybrid Loading Test

(a) Linear Pier Model

Earthquake		Acceleration Response			Displacement Response		
		Isolated		Non-Isolated	Isolated		Non-Isolated
		Girder	Pier Top	Pier-Girder	Girder	Pier Top	Pier-Girder
Type	Input Acc. (gal)	Max. Resp. (gal)	Max. Resp. (gal)	Max. Resp. (gal)	Max. Resp. (mm)	Max. Resp. (mm)	Max. Resp. (mm)
I	50	70.1	147.8	96.2	17.3	2.9	4.4
	100	125.8	170.2	192.6	53.8	5.6	8.8
	200	265.8	335.3	385.3	152.0	10.9	17.6
	300	544.3	442.8	577.9	232.0	18.0	26.4
II	50	63.3	175.8	102.7	13.8	2.8	4.7
	100	108.2	184.2	205.7	36.1	4.7	9.4
	200	218.7	360.9	411.3	119.0	10.6	18.8
	300	467.1	603.8	616.1	210.0	19.0	28.2
III	50	59.8	140.4	107.9	15.2	2.9	4.9
	100	104.2	179.0	216.2	36.2	5.1	9.9
	200	214.9	378.9	431.5	118.0	9.0	19.8
	300	448.1	541.2	647.7	219.0	17.2	29.7

(b) Nonlinear Pier Model

Earthquake		Acceleration Response			Displacement Response		
		Isolated		Non-Isolated	Isolated		Non-Isolated
		Girder	Pier Top	Pier-Girder	Girder	Pier Top	Pier-Girder
Type	Input Acc. (gal)	Max. Resp. (gal)	Max. Resp. (gal)	Max. Resp. (gal)	Max. Resp. (mm)	Max. Resp. (mm)	Max. Resp. (mm)
I	50	70.1	147.8	96.2	17.3	2.9	4.4
	100	125.8	170.2	192.6	53.8	5.6	8.8
	200	259.3	326.3	302.1	143.0	11.4	24.5
	300	439.3	420.8	419.6	229.0	38.1	44.1
II	50	63.3	175.8	102.7	13.8	2.8	4.7
	100	108.2	184.2	205.7	36.1	4.7	9.4
	200	213.8	339.2	315.4	117.0	10.5	26.7
	300	403.6	483.7	457.0	203.0	26.4	50.5
III	50	59.8	140.4	107.9	15.2	2.9	4.9
	100	104.2	179.0	216.2	36.2	5.1	9.9
	200	214.9	378.9	329.6	118.0	9.0	29.1
	300	400.3	485.9	457.0	213.0	24.7	50.4

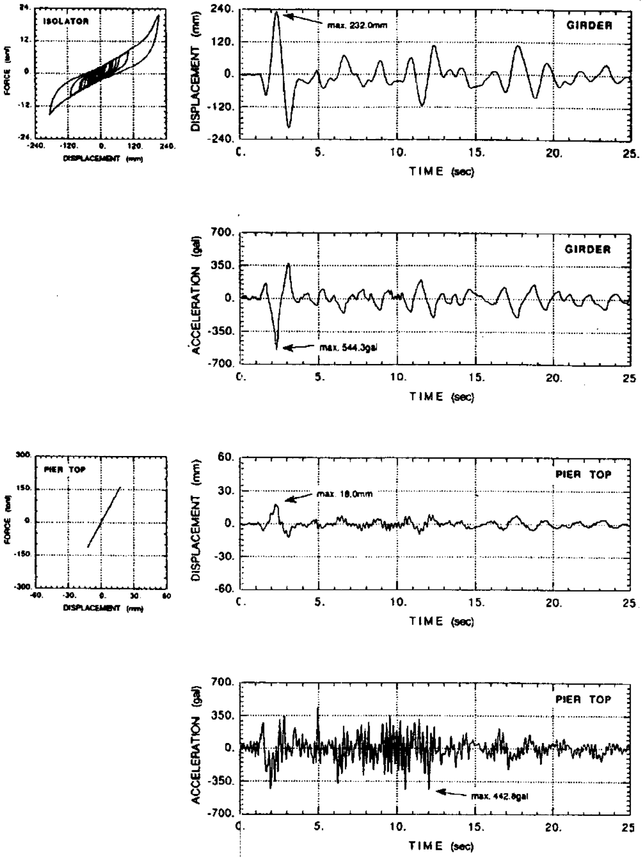


Fig. 10 Result of Substructure Hybrid Loading Test (Linear Pier Model, Earthquake-1,300gal)

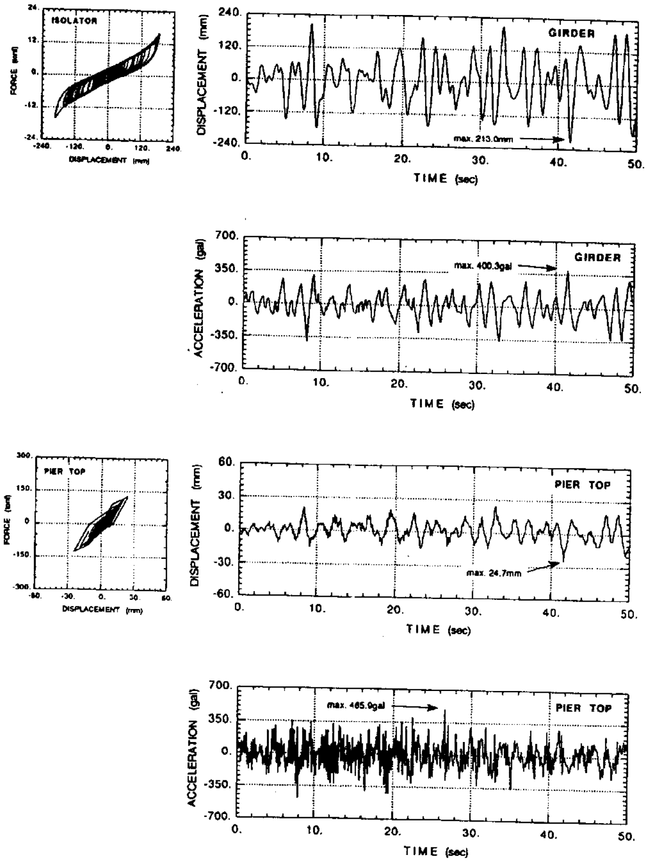


Fig. 11 Result of Substructure Hybrid Loading Test (Nonlinear Pier Model, Earthquake-1, 300gal)

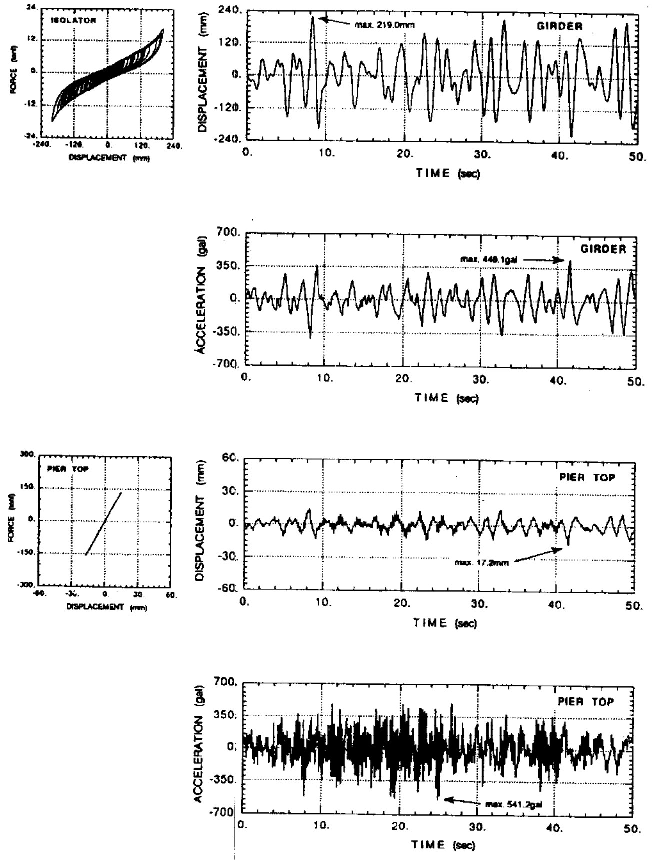


Fig. 12 Result of Substructure Hybrid Loading Test (Linear Pier Model, Earthquake-3, 300gal)

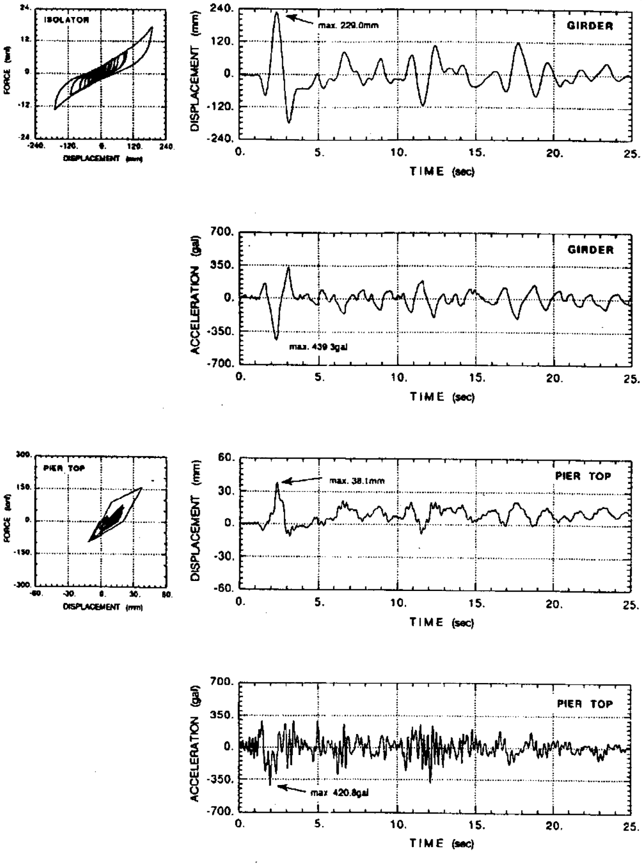


Fig. 13 Result of Substructure Hybrid Loading Test (Nonlinear Pier Model, Earthquake-3, 300gal)

unisolated case. It should be noted, however, that the reduction factor of the peak acceleration decreases as the amplitude of the seismic input becomes greater.It seems that this increase in the acceleration of isolated structures is due to the hardening behavior of the seismic isolators in the larger deformation range. The increase in the dispalcement of the isolated superstructure is also of great concern when subjected to a large amplitude of earthquake input, as can be seen in Table 1. Another point of great interest in Table 1b is that in some cases, ex. Earthquake type 1 of 300gal amplitude case, the acceleration response can be larger than the unisolated structure. Naturally, the piers displacement reached the nonlinear region in those cases, as can be seen in Figs.10-13. However, the peak displacement of the superstructure can be lowerd in the isolated structures, even in those cases.

CONCLUDING REMARKS

A sequence of substructure hybrid loading tests for LRB seismic isolators was carried out. Combined with the quasi-static cyclic loading test , it is possible to investigate the fundamental mechanical properties, earthquake response behavior and resonant response behavior of the isolator. The effectiveness of isolation can be evaluated directly in terms of earthquake response values. In addition, the seismic safety of the total structure will be investigated by substructured hybrid earthquake loading tests to obtain the earthquake response of a MDOF system. Using this technique, it will be possible to examine the effect of the isolation system on the response behavior of the other components of a bridge structure, especially the critical bridge piers.

Moreover, the developed testing system is further extended to permit the test of seismic isolator devices with varying axial loads and varying rotation angle of the upper surface, in addition to the horizontal deformation. After the Kobe (Hyogo-Nanbu) earthquake, an unconventional type of base isolator implementation which would allow the varying axial loads and angle to the base isolators is currently under consideration in Japan, and the experimental validation of the performance of the seismic isolators for such condition is crucial for ensueing the seismic safety of the new bridge structures. This testing program will be reported in future papers.

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