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HYSTERETIC BEHAVIOR OF REINFORCED CONCRETE BRIDGE PIERS BY DYNAMIC LOADING TESTS AND SHAKING TABLE TESTS

Kazuhiko KAWASHIMA[1], Kinji HASEGAWA[2],
Tatsuhiko KOYAMA[3] and Takeshi YOSHIDA[3]

[1] Head, Earthquake Engineering Division,
Earthquake Disaster Prevention Department,
Public Works Research Institute, Ministry of Construction,
Tsukuba Science City, Japan
[2] Research Engineer, ditto
[3] Assistant Research Engineer, ditto

SUMMARY

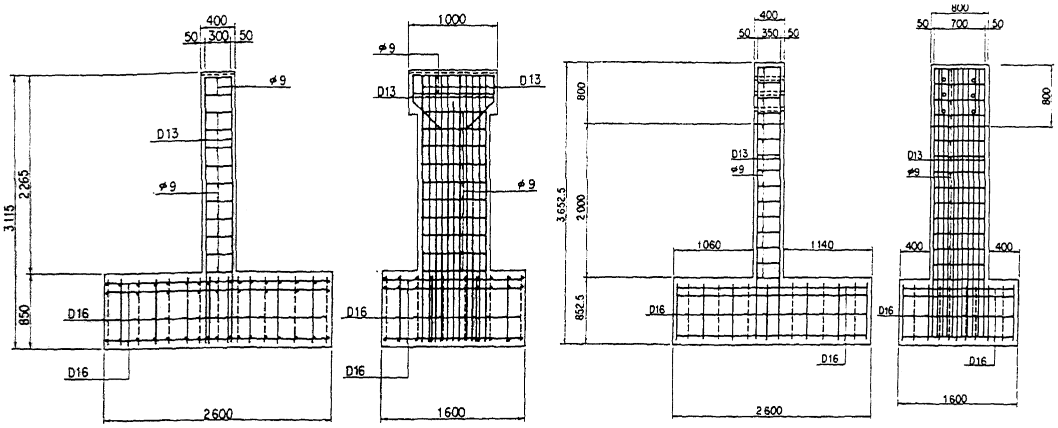
Studied was a difference of loading procedure on hysteretic behavior of reinforced concrete bridge piers between excitation by a shaking table and a dynamic actuator. A shaking table test to realize inelastic behavior and failure mode of reinforced concrete bridge piers subjected to significant earthquake ground motions and a dynamic loading tests with use of an actuator were made. It was found from the study that the difference of loading procedure has less significant effect on hysteretic behavior of reinforced concrete piers.

INTRODUCTION

Various loading tests have been made to study inelastic behavior of reinforced concrete bridge piers subjected to severe ground motions. In many cases of those tests, cantilever specimens of reinforced concrete bridge piers were subjected to either static or dynamic loadings at crest with use of an actuator. Time history of displacement used in these tests was usually sinusoidal motions with step-wise increasing symmetrical loading reversals. However actual response of bridge piers developed during an earthquake is not necessarily idealized by symmetrical load reversals since it vibrates as a response for the earthquake ground motion. This study presents a shaking table test to realize inelastic behavior and failure mode of reinforced concrete bridge piers subjected to earthquake ground motions. Dynamic lateral loading tests with use of an actuator was also carried out and the effect of two different loading procedures was studied.

TEST SPECIMENS AND EXPERIMENTS PROCEDURE

Test Specimen Test specimens of reinforced concrete bridge piers used in the shaking table tests and the dynamic lateral loading tests are shown in Fig. 1. Height of the piers was selected so that effective heights designated as distance from the bottom to the loading points be the same between two types of specimens. The specimens have a cross section of 40 cm x 80 cm and a shear span ratio h/d, which is defined as the effective height h of 240 cm divided by the effective depth d of the cross section of 35 cm, of 6.9. Longitudinal and tie reinforcement ratio is 0.87% and 0.08%, respectively. Yielding stress of the longitudinal and tie reinforcements was 3500 kgf/cm^2 and 3200 kgf/cm^2, respectively. Compression strength of the concrete was 300 kgf/cm^2 and 370 kgf/cm^2 for specimens used for the shaking table tests and the dynamic lateral loading tests, respectively. It should be noted that since weight of the superstructure supported by the cantilever specimen is 40 tf, seismic coefficient of the specimen can be regarded as 0.15. Yield displacement δy corresponding to one displacement ductility factor and yield strength of the piers is 12 mm and 7.3 tf, respectively, in which the yield displacement δy was defined the displacement at loading point at which reinforcing bars at the extreme tension fiber firstly reached yield strain. A number of strain gauges were placed on the longitudinal reinforcements, and the averaged strain, which was detected at the foot of pier, was used to determine the yield displacement δy. The yield strain of reinforcement was assumed as 1800 μ based on a number of tensile test. Fundamental natural frequency of the piers subjected to the weight of superstructure can be estimated as 1.9 Hz by assuming yielding stiffness.



(a) Shaking Table Test (b) Dynamic Loading Test

Fig.1 Test Specimen of Reinforced Concrete Bridge Pier

Shaking Table Test Setting up of the specimen in the shaking table test is presented in Fig. 2. The specimen was anchored at the center of a shaking table, and two spans of simply supported girders with total weights of 40 tf and length of 15 m were placed on the specimen. Because two ends of the girder could not be supported by the shaking table, they were supported by two steel frames placed outside the table. The specimen and girders were connected by a fixed bearing support. The steel frames and girder were connected by movable supports so that inertia force developed during excitation at the girder be directly applied to the specimen.

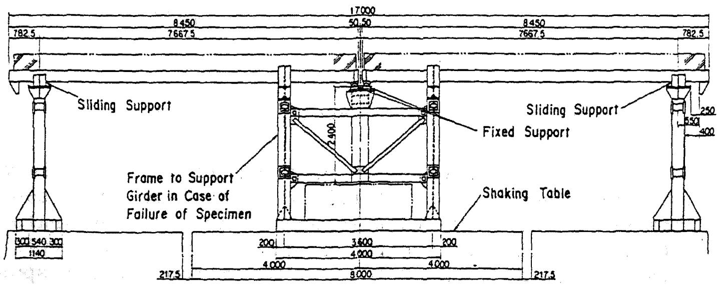


Fig.2 Set-up of Shaking Table Test

The shaking table was excited along bridge axis. An acceleration record triggered at the Hachirogata during the Nihonkai-chubu, Japan, Earthquake of 1983 was used as an input motion by reducing the time axis one half so that the predominant frequency of the record matches with the fundamental natural frequency of the specimen. Intensity of the record was varied as two times, three times and four times of the original as a parameter to be investigated, and they are designated herein as Tests A, B and C, respectively.

Extensive instrumentations were made to measure basic parameters including accelerations at the foot of pier and at the girder as well as relative displacements of the girder with reference to the shaking table. Inertia force of the superstructure was calculated by multiplying the acceleration developed at the girder by the mass of the girder.

Dynamic Loading Test Setting up of the specimen for the dynamic loading test is shown in Fig. 3. The dynamic loading tests were made only for Tests A and B, because relative displacement developed in Test C exceeded the stroke of the actuator. Vertical load associated with dead weight of the superstructure was disregarded here because of limitation of experimental facilities. This is one of major differences between the shaking table test and the dynamic loading test. Relative response displacement of the girder which was developed during the shaking table test was applied in this test through the actuator with use of displacement control. Loading velocity of the dynamic loading test in Tests A and B was taken as the same and 1/5 of the original response velocity developed during the shaking table tests, respectively.

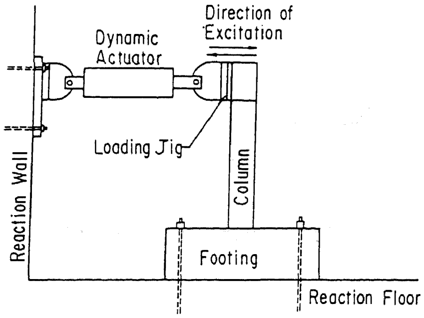
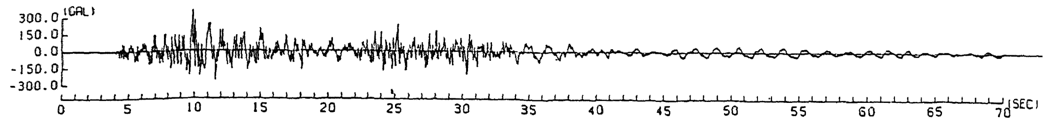


Fig.3 Set-up of Dynamic Loading Test

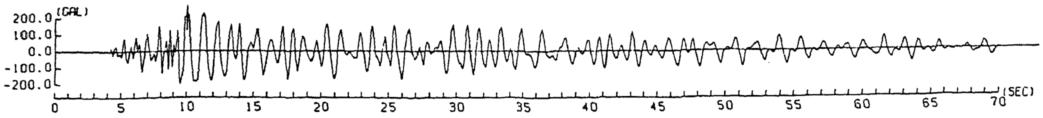
TEST RESULT

In Tests A and B, cracks of concrete were observed at the base of the columns only during the excitations. However residual of such cracks could not be detected after completion of the excitations. In Test C, significant cracks and the spalling-off of cover concrete was developed as well as outward buckling of longitudinal reinforcements between two adjacent tie bars near the foot.

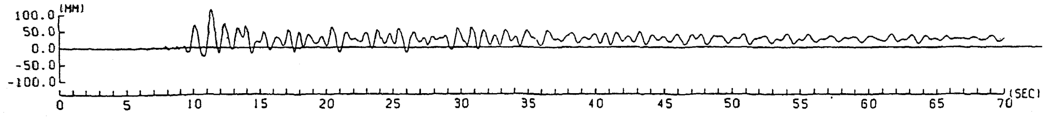
Figs. 4 and 5 show response accelerations and displacement for Tests B and C, respectively. The specimen developed residual lateral deformation with an amount of 2 cm and 4 cm at the pier crest after Tests B and C, respectively. Such a permanent displacement is clearly observed in Figs. 5 from biased inelastic response displacement. It is interesting to note that such a drift of response displacement seems to be developed at the first large excursion which exceeded the yield displacement, i.e., accumulation of drifting of response displacement after the first large excursion seems less significant.



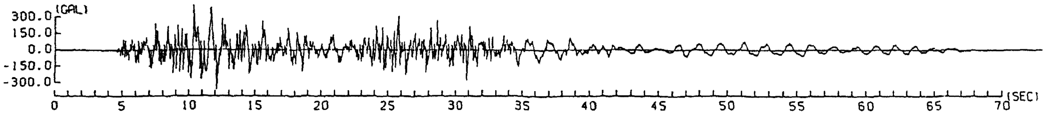
(a) Acceleration at Footing



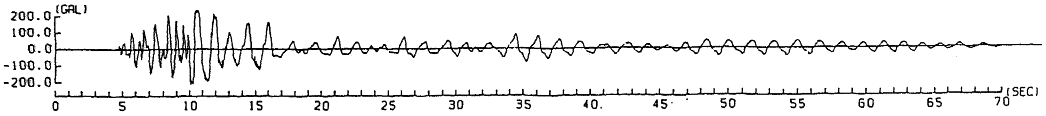
(b) Acceleration at Girder



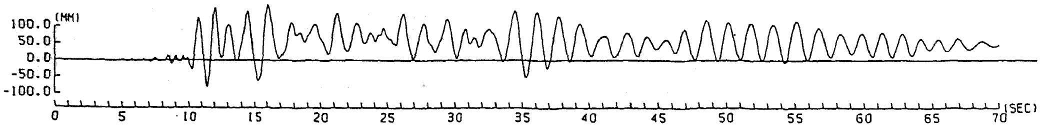
(c) Relative Displacement at Girder
Fig.4 Response Acceleration and Displacement in Test B



(a) Acceleration at Footing

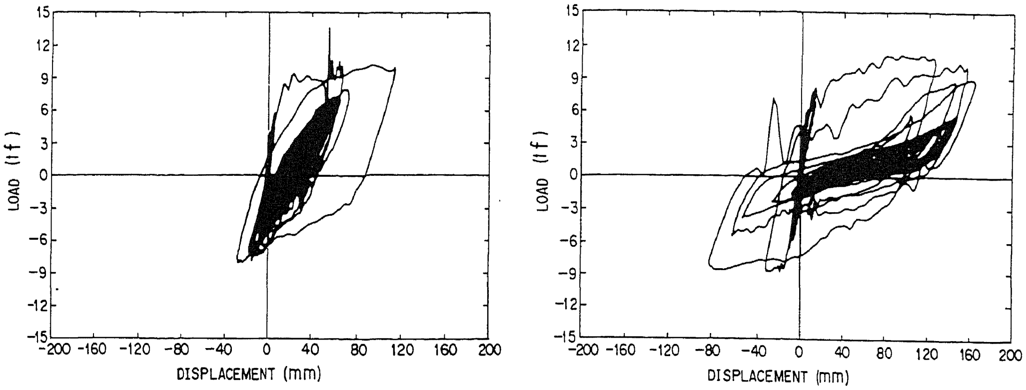


(b) Acceleration at Girder



(c) Relative Displacement at Girder
Fig.5 Response Acceleration and Displacement in Test C

The hysteresis loop of the load and displacement relation in Tests B and C are shown in Figs. 6. It can be seen from these figures that the biased vibration was developed after the first significant movement with larger displacement exceeding the yield displacement. The degradation of the stiffness in accordance with nonlinear response can be clearly observed.



(a) Test B (b) Test C

Fig.6 Hysteretic Loop of Load vs. Displacement Relation

Table 1 shows the peak values of response acceleration and relative displacement. Nonlinear response of reinforced concrete pier can be clearly seen by comparing peak response acceleration with peak relative response displacement at the girder, i.e., relative response displacement of the girder increases with increasing input acceleration while peak response acceleration of the girder takes almost the same value independently of the intensity of input motion.

Table 1 Peak Response Accelerations and Displacements

Test No.	Peak Acceleration		Peak Displacement of Girder
	Footing	Girder	
Test A	275 gal	216 gal	45 mm
Test B	360 gal	220 gal	114 mm
Test C	402 gal	238 gal	163 mm

Skeleton curves of the load vs. displacement hysteresis loop obtained from Tests A, B and C are compared in Fig. 7. Although the displacements developed during Tests A and B are much smaller than that developed during Test C, it seems that the skeleton curves between the three tests show essentially identical results.

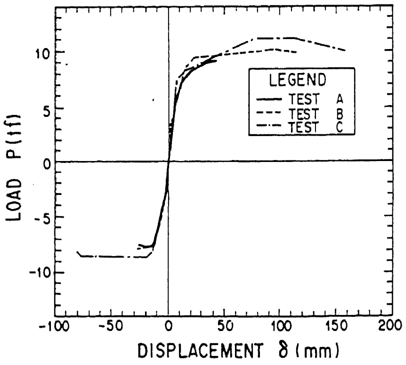
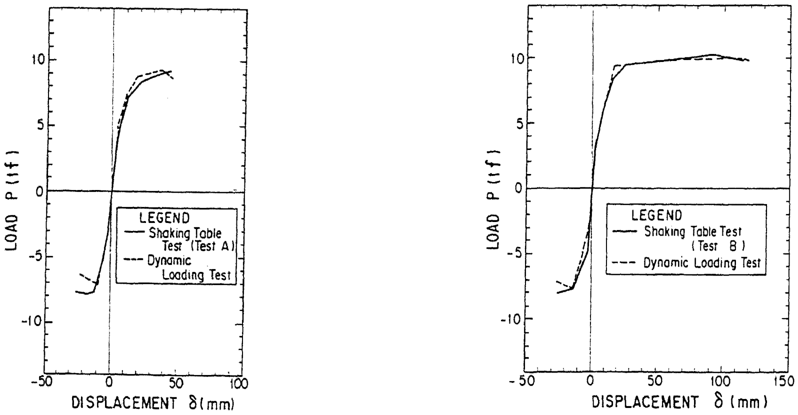


Fig.7 Skeleton Curves of Load and Displacement Hysteresis Loop



(a) Test A (b) Test B

Fig.8 Comparison of Skeleton Curve between Shaking Table Test and Dynamic Loading Test

Comparison of the dynamic loading test results with those of the shaking table test was made in terms of skeleton curves of the load vs. displacement hysteresis loop as shown in Fig. 8. Few differences are observed between two loading procedures, which implies that the inelastic behavior of reinforced concrete bridge pier induced by the shaking table test can be simulated by the dynamic loading test, provided that the response displacement at the cantilever top be correctly obtained.

CONCLUDING REMARKS

For aiming to study inelastic behavior of reinforced concrete bridge piers, shaking table tests were conducted by varying intensity of earthquake ground motion as well as dynamic loading tests with use of response displacement of the specimen as an input motion. The following conclusions may be deduced from these tests:

1) Acceleration responses developed at the girder in the shaking table test do not increase with increasing intensity of input ground acceleration while the relative response displacements of the girder increase in accordance with increase of intensity of input ground motion.
2) In the shaking table tests, specimen showed biased response to one side at the principal motion, which is never developed by dynamic loading tests with symmetrical step-wise increasing load reversals under displacement control.
3) Difference of two loading procedures between the shaking table test and the dynamic loading has less significant effect on nonlinear hysteretic characteristic of reinforced concrete cantilever piers.

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