Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Substructured hybrid loading tests of high-damping rubber seismic isolators for inelastic earthquake response of bridge structures

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ABSTRACT: Substructured on-line hybrid loading tests of high-damping rubber isolators are conducted for bridge pier models. Thus, effectiveness of the seismic isolation system can be evaluated directly in terms of earthquake response characteristics of the total structure. In addition, on-line hybrid loading tests (pseudo-dynamic tests) have been used to determine earthquake response and resonant response of seismic isolation devices as well as the usual cyclic loading tests. All of these tests were conducted under a single physical set-up. High-damping rubber (HDR) bearings were tested and have been verified to have energy-absorbing capacity equivalent to about 11–15% damping ratio of the linear elastic models. In addition, the response of the HDR isolators for extreme load conditions has been experimentally verified.

1 INTRODUCTION

In recent years, there has been a tremendous amount of interests in using seismic isolation as an effective and practical approach to earthquake-resistant design. New isolator techniques and configurations continue to be developed. For these to be widely accepted for use by the structural engineering profession, their fundamental engineering properties and their expected behavior during earthquakes should be well established. Extensive experimental tests are very much needed to study their behavior and provide data for analytical modeling and design.

Extensive experimental tests on high-damping rubber (HDR) seismic isolators were conducted using an on-line hybrid computer-actuactor experimental system for earthquake response analysis. Seismic performance of HDR-supported systems can be evaluated under different earthquake ground motions. Resonant response under frequency-sweeping sine input excitations can also be determined. In addition, the normal procedure of repeated cyclic loading test can be conducted using the same testing facility. Thus, the integrated testing system can test for: (a) fundamental mechanical properties, (b) resonant response, and (c) earthquake response. Effectiveness of the isolators is discussed in terms of structural acceleration and displacement response which is directly connected to design requirements.

With these ranges of obtained results, the developed loading system offers a versatile testing system in the early development stage, as well as for final verification and proof tests.

2 HIGH-DAMPING RUBBER SEISMIC ISOLATORS

A total of four tested HDR isolator specimens are presented in this report. Geometrically, the specimens are of 25-cm×25-cm square in plan (Fig. 1). The specimens were loaded vertically with 40 tonf giving an axial bearing pressure of 64 kg/cm^2.

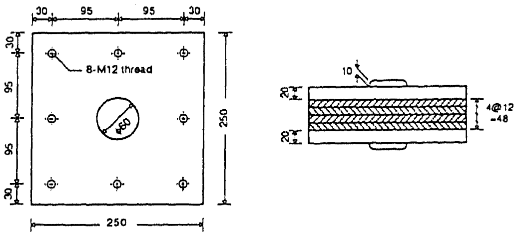

Figure 1. Plan and dimensions of HDR isolators.

3 TEST SET-UP

The test rig shown in Fig. 2 is used in this experiment. The specimen is bolted to the underside of the load-transfer beam and to a rigid platform that is attached to the rails of the strong reaction floor.

A computer that can be highly programmed to control instrumentations is used to: (1) control the load actuators; (2) receive feedback forces; (3) do dynamic structural analysis in on-line hybrid tests; and (4) do other data acquisition and recording functions. Digital displacement control values are sent to a digital-to-analog converters (DAC), while analog feedback sig-

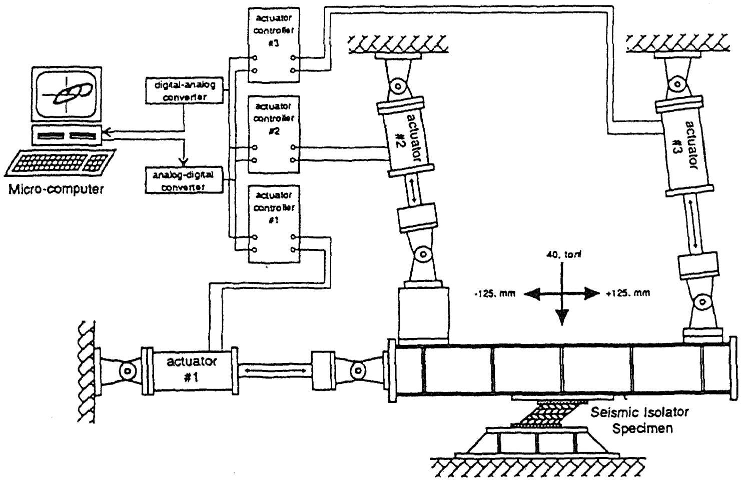

Figure 2. Specimen is laterally displaced, while sustaining an axial load.

nals are received through an analog-to-digital converter (ADC). Timing parameters are set within the control program to operate the loading system at the desired loading rate.

The specimens were tested for: (a) fundamental mechanical properties, (b) resonant response, and (c) earthquake response.

4 CYCLIC LOADING TESTS

Cyclic loading tests are the most common standard tests for determining mechanical properties of the isolators. These are usually done to evaluate lateral stiffness and equivalent damping ratios of the isolators. In this experiment, cyclic loading tests were done up to 200% shear strain (Fig. 3).

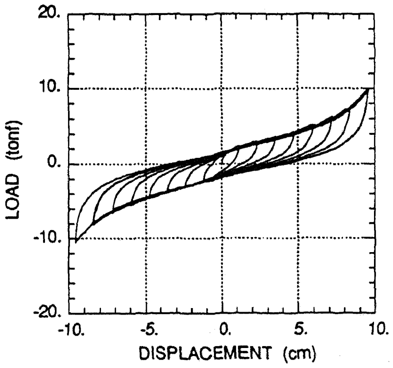

Figure 3. Cyclic hysteresis behavior of HDR isolator.

5 ON-LINE HYBRID TESTS FOR EARTHQUAKE RESPONSE

On-line hybrid (pseudo-dynamic) test is a computer-controlled experimental technique in which direct numerical time integration is used to solve the equations of motion. The computed displacement at each step is statically imposed on a specimen through a 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 development, current activities and future prospects of on-line hybrid test methods have been reported by Takanashi and Nakashima [1987], and Mahin et al [1989].

It can be assumed in this very preliminary stage that the isolated superstructure would move as a rigid body. More refined analytical modeling of the superstructure can be implemented in a substructured on-line hybrid test. The structure is modeled as a single-degree-of-freedom (SDOF) system with a natural period of 2 seconds. For this relatively flexible SDOF system, numerical stability of explicit form of direct integration schemes poses no special problem. The central difference scheme is found sufficient for this experiment.

Effectiveness of seismic isolators are very much dependent on the characteristics of the input earthquake motion and the supported structures. Two representative types of earthquake records are used. These are: (a) the NS-component of the El Centro record during the 1940 Imperial Valley Earthquake; and (b) the NS-component of the Hachinohe record during the 1968 Tokachi-oki Earthquake. These records are scaled to evaluate isolator performance at different range; i.e., 150% strain for ideal bilinear behavior and 200% strain for assumed overload range. Results have been presented in Iemura et al [1991].

6 ON-LINE HYBRID SWEEP TEST

In order to check for resonance, a model is usually subjected to sweeping-frequency sine input in a shakingtable test. This can also be implemented in an on-line hybrid test. A typical sweeping-frequency sine input is shown in Fig. 4. The first sine wave has a frequency of 0.2 cps or period of $T = 5$s. The period is then reduced by an decrement of 0.2s until $T = 3$s. Between $T = 3$s and $T = 1$s, the period of the sine wave is decrement by a smaller interval of 0.1s to give better detail to the resonant range. Finally, period is decremented again by 0.2s after $T = 1$s. In this experiment, the final period used was 0.6s. The input sine waves are discretized at 0.02s, the same integration time step used in the tests. The constant amplitude level is scaled to give response within some desired ranges, e.g., at 150% strain and 200% strain. Results have been presented in Iemura et al [1991].

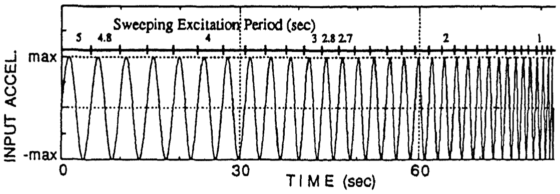

Figure 4. Input frequency-sweeping sine ground excitation.

7 SUBSTRUCTURED HYBRID TESTS OF MDOF BRIDGE PIER MODELS

Most recently, a substructured hybrid loading system for MDOF structures with seismic isolators has been developed. In the substructured loading test, the isolator elements are taken as experimental substructures. Bridge pier is modeled as shown in Fig. 5, first as a fixed-base model. Soil-structure interaction is considered in the second model. The superstructure girder is modeled as a lumped mass, while the column elements are modeled by inelastic spring elements characterized by linear, bilinear, and three-parameter hysteretic models. The total structure is subjected to different earthquake motions such as the 1940 El Centro record and the three input earthquake records of the Specifications for Highway Bridges in Japan. The maximum ground acceleration of each record is scaled to 60 gal, 90 gal, and 120 gal to obtain earthquake response characteristics giving different displacement response levels (up to 200% shear strain) of the high-damping rubber seismic isolation bearing.

Earthquake response of the fixed-base model under the El Centro record and No. 3 earthquake of the Specification (hereafter, S.H.B. earthquake 3) is presented. For the case presented here, the fixed base bridge pier model (A in Fig. 5) is subjected to the El Centro record (fig. 6) with the maximum acceleration scaled to 300 gal. The main objective of the seismic isolation here is to enhance seismic safety of the bridge pier. Behavior of the isolator is given by the hysteretic response in Fig. 7 and the time history of displaceement reponse (relative to the top of pier) in Fig. 8. Seismic isolation is very effective for structures subjected to this type of earthquake. Forces due to the inertial effect of the heavy superstructure are reduced and the pier response is reduced (Fig. 9).

Bridges are often constructed on sites with soft ground conditions. The earthquake specified in the Specifications for Highway Bridges were modified from actual records obtained from bridge sites. It is very important to check for possible resonance due to the lengthened natural period of structures with seismic isolation.

Earthquake response of the bridge pier model subjected to the S.H.B. earthquake 3 (Fig. 10) with maximum acceleration scaled to 120 gal is presented in the following. Fig. 11 shows the load-deformation response of the isolator, while Fig. 12 shows the deformation time history response. Displacement of pier top is given in Fig. 13. Even when subjected to earthquake of this type with long period waves, excessive displacement is suppressed due to the high amount of inherent damping present in the HDR isolators.

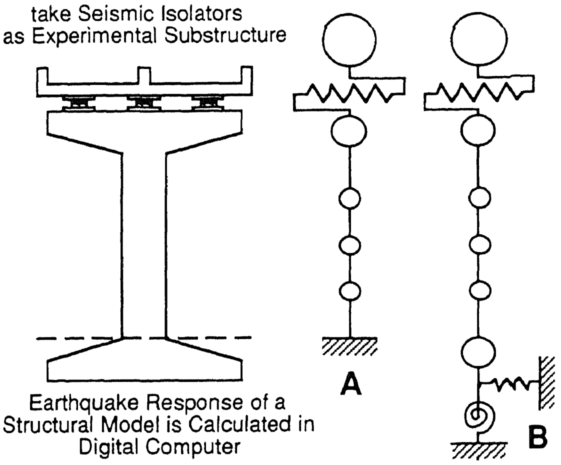

Figure 5. Substructured on-line hybrid test of bridge pier with seismic isolators.

8 CONCLUSIONS

Extensive tests have been conducted on the developed high-damping rubber seismic isolator bearings to establish the mechanical properties, as well as on response characteristics during earthquakes and resonant conditions. With the addition of the newly developed substructured hybrid loading system, accurate earthquake response of total structure can be obtained while experimentally testing only the isolator elements.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and cooperation of the following persons and organization: Dr. Hirokazu Iemura, Mr. Kazuyuki Izuno, Mr. Shinji Nakanishi, Mr. Norio Watanabe of Kyoto University, Katayama Ironworks Co., and Toyo Tire & Rubber Co.

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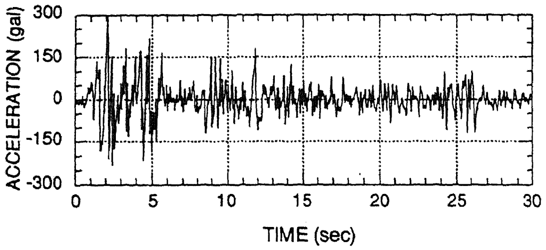

Figure 6. 1940 El Centro record scaled to 300 gal.

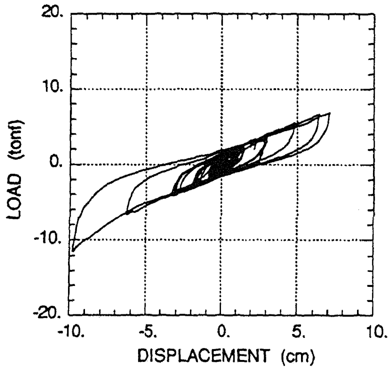

Figure 7. Load-deformation response under 120 gal El Centro.

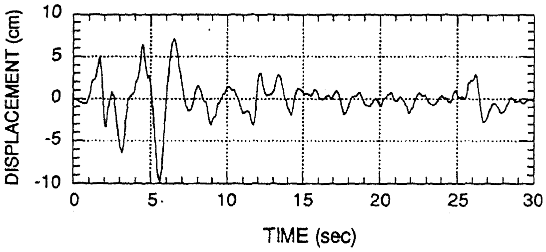

Figure 8. Deformation time history of the isolator under 300 gal El Centro.

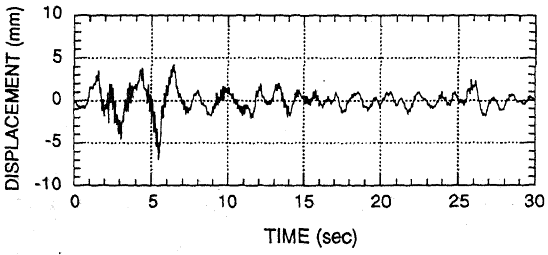

Figure 9. Displacement of pier top under 300 gal El Centro.

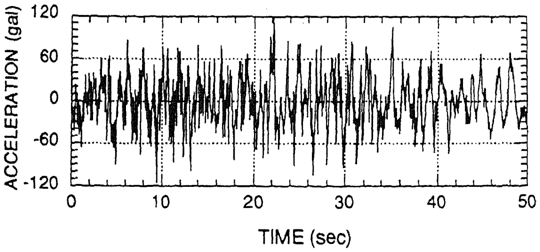

Figure 10. S.H.B. earthquake No. 3 scaled to 120 gal.

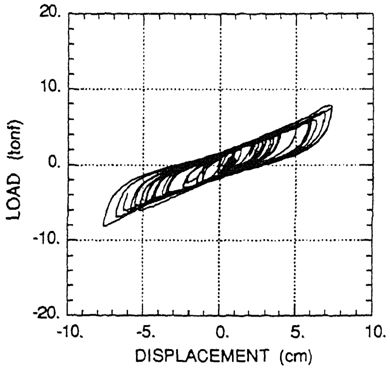

Figure 11. Load-deformation response under 120 gal S.H.B. earthquake 3.

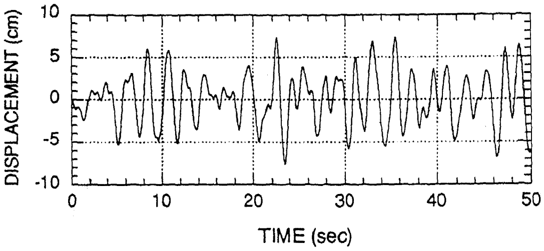

Figure 12. Deformation time history of the isolator under 120 gal S.H.B. earthquake 3.

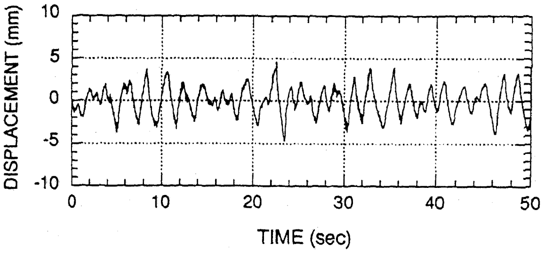

Figure 13. Displacement of pier top under 120 gal S.H.B. earthquake 3.