Protective Systems for Bridges: Sliding Seismic Isolation Systems

by Michael Constantinou

Abstract

A significant number of bridges are seismically isolated throughout the world. Applications of bridge seismic isolation systems in the U.S. have been primarily with lead-rubber bearings, and a few with sliding bearings. Currently in the U.S., about 60 isolated bridges with a total deck length exceeding 12 km, have either been completed or are in the construction or design stage. Japan recently moved towards a cautious implementation of modern isolation systems in bridges, having previously used an early form of a sliding bearing-viscous damper isolation system in over 100 bridges of the Shinkansen. So far, the application is restricted to primarily longitudinal isolation using elastomeric systems.

Despite the wide implementation of sliding isolation systems in bridges, their evaluation has been largely based on component testing and analysis, without large scale shake table testing having been conducted. Furthermore, a number of sliding isolation systems have been implemented in buildings but not evaluated for bridge applications, while other systems have been proposed but not experimentally evaluated.

In 1991, NCEER and Taisei Corporation began a collaborative research program on the experimental study of advanced sliding seismic isolation systems for bridges. The project had the objectives of producing and experimentally verifying a class of sliding isolation systems by modifying and/or adapting existing technology. Particular emphasis was given to the adaptation and use of aerospace and military hardware. Furthermore, the project included the study of established sliding isolation systems which have been used in a number of other applications.

A 160 kN, quarter length scale bridge model with flexible piers was used for the test program. The model could be configured to resemble either a non-isolated multiple-span bridge, or singly-, two- and multiple-span isolated bridges. Three isolation systems were tested. (a) systems consisting of flat sliding bearings and restoring force devices in the form of rubber springs with fluid dampers or fluid restoring force/damping devices, (b) spherically shaped (friction pendulum system) sliding bearings; and (c) lubricated sliding bearings with yielding steel dampers.

All systems were configured for areas of strong seismic loading such as California and Japan, and all were characterized by significant energy absorption capability. However, the design criteria were different in the three basic types. In systems type (a), the design criteria were to reduce the transmission of force to the bridge substructure while restricting bearing displacements to less than 200 mm (8 in) in prototype scale In systems type (b) and (c), the design criteria were to minimize the transmission of force to the bridge substructure without restricting the bearing displacements

Collaboration

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Objectives and Approach

The primary objective of this project was to produce and experimentally verify a class of bridge sliding seismic isolation systems by modifying and/or adapting existing technology. The second objective was to experimentally study established isolation systems which have not been previously tested on shake tables within a bridge structure. The third objective was to develop mathematical models for these isolation systems, compare experimental and analytical results and develop design aids for these systems.

This research task is part of NCEER's Bridge Project (now the Highway Project). Task numbers are 90-2101 and 91-5411B.

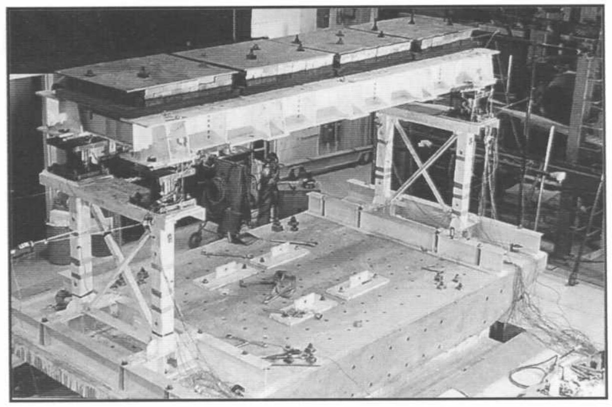


Figure 1
View of Bridge Model on Shake Table

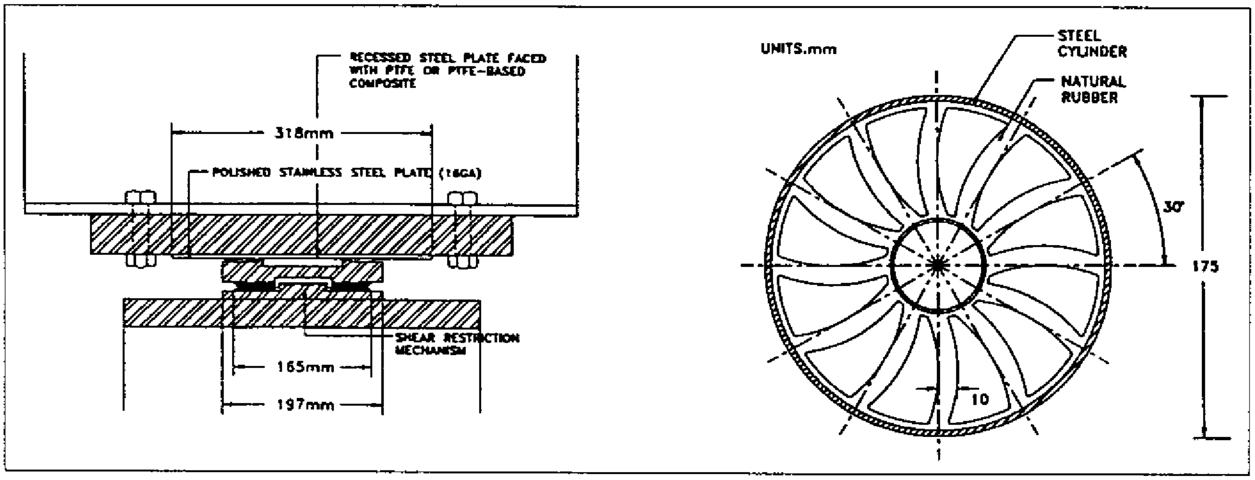
Bridge Model and Isolation Systems

The bridge model is shown in Figure 1. At quarter length scale, it had a clear span of 4.8 m (15.7 feet), height of 2.53 m (8.3 feet) and total weight of 160.8 kN (36 kips). The deck itself weighed 143 kN (32 kips). Each pier consisted of two steel square tube columns with the top made of a channel section. The columns transferred the gravity load to the overhangs of the concrete extension of the shake table at a point located 0.57 m (1.87 feet) beyond the edge of the table. This resulted in significant vertical motion of the two overhangs, which increased the severity of testing.

In its non-isolated configuration, with the deck pinned to the flexible piers, the bridge had a fundamental period of 0.26 seconds (or 0.52 seconds in prototype scale) and damping ratio in the range of 0.04 to 0.08 of critical. The damping was the result of hysteretic action, not in the columns of the model, but in the overhangs of the concrete extension. Thus, while the columns remained elastic, the pier system displayed realistic hysteretic action.

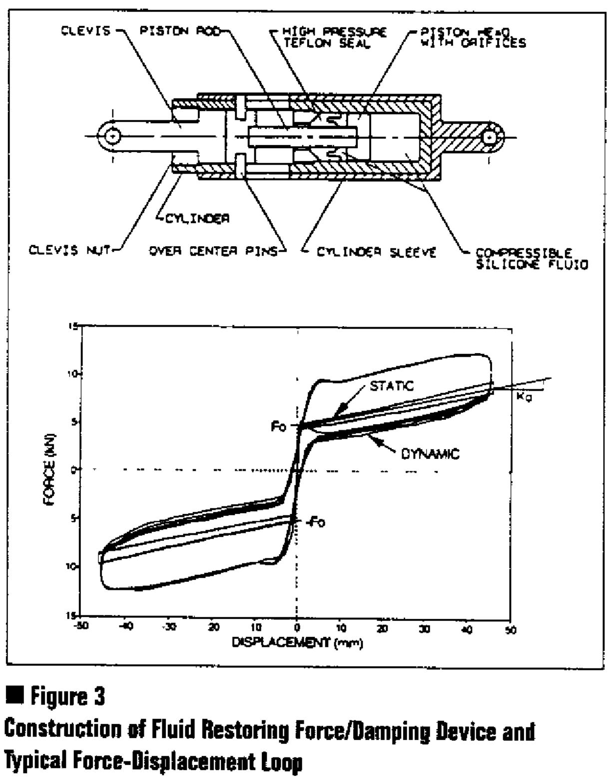
A total of 25 isolation system and bridge configurations were tested. Representative results for three of these configurations are presented in this paper. All three systems had both piers flexible as shown in figure 1. The isolation systems were:

(a) A system consisting of four flat sliding bearings (unfilled PTFE-stainless steel interface) with coefficient of friction at high velocity of sliding f_{max} = 0.150. Restoring force was developed by two rubber springs, each of which provided an effective stiffness 112.3 kN/m (0.64 kip/inches) at displacement of 35 mm (1.38 inches). Beyond this displacement, the devices exhibited increased stiffness and acted as displacement restrainers. They had a maximum displacement capacity of 50 mm (2 inches). The effective period of the isolation system at displacements below the limit of 35 mm (1.38 inches) was 1.60 seconds (or 3.20 seconds in prototype scale). Figure 2 shows the construction of the sliding bearings and rubber springs.



■ **Figure 2**
Construction of Sliding Bearing and Rubber Spring

(b)In a number of tests, isolation system (a) was enhanced by four linear viscous fluid dampers with displacement capacity of 50 mm (2 inches) and combined constant equal to 61.7 kN-s/m (0.352 kip-s/inch). The dampers provided a damping ratio to the isolation system of nearly 54% of critical at the temperature of 25°C.



■ **Figure 3**
Construction of Fluid Restoring Force/Damping Device and Typical Force-Displacement Loop

(c)A system consisting of the same four sliding bearings and two fluid restoring force/damping devices.The construction and typical force-displacement characteristics of one of these devices are shown in figure 3. It may be observed that the device exhibits preload (Fo), that is a constant restoring force. This preload was selected to be equal to 9.5 kN (for two devices) that is slightly more than the friction force at zero velocity, which was conservatively estimated to be 0 06 x 143 kN = 8.58 kN. This would completely eliminate permanent displacements, and indeed the experiments confirmed the design. Moreover, the mild stiffness and biased damping force (more on loading than on unloading) of the device resulted in a nearly constant force output with increasing displacement.

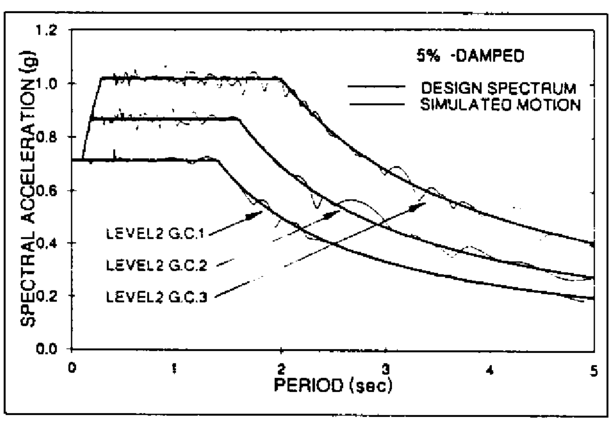
The fluid devices used in the tests originated in applications of the U.S military. The fluid viscous dampers were based on a design originally developed for a classified application on the U.S. Air Force B-2 Stealth Bomber. Other applications include the Tomahawk missile, the Space Shuttle, U.S. Navy launch gantries and more recently the seismic isolation system of the San Bernardino County Medical Center in California. Devices with output force of over 2000 kN and stroke of ±610 mm have been produced.

The fluid restoring force/damping devices have been developed for use on the arresting hook of carrier based aircraft and for weapons grade shock isolation systems for the MX missile and the Seawolf submarine. Output force ranges for these applications are between 1 and 1500 kN.

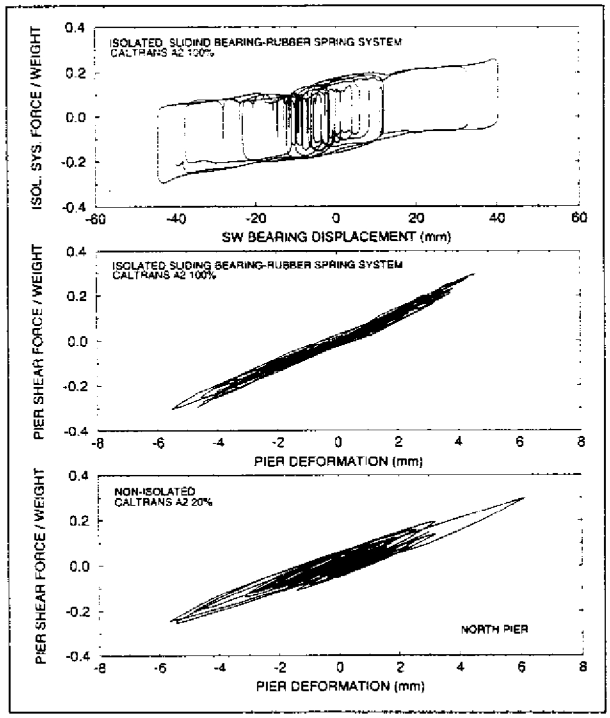
Experimental Results

A total of 643 earthquake simulation tests were performed using 24 recorded and artificial earthquakes. Only a small portion of the obtained results is presented herein. The presentation is restricted to results obtained with the 1940 El Centro Earthquake, component S00E and artificial motions compatible with Japanese Level 2 bridge design spectra and the California Department ofTransportation 0.6g deep alluvium bridge design spectra (designated as CalTrans A2 motion). Tests were conducted within and without the vertical ground component. The effect of vertical component was found to be small and it is not further discussed herein. The interested reader is referred to the reports and papers in the list of publications for a detailed presentation.

The response spectra of the Japanese Level 2 bridge design motions are shown in figure 4. The



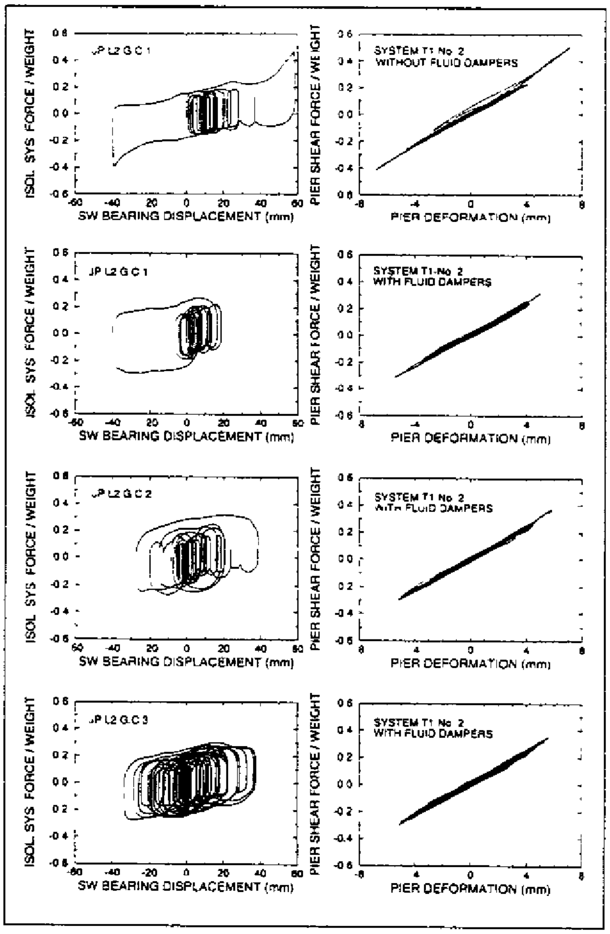
■ **Figure 4**
Japanese Level 2 Bridge Design Spectra



■ **Figure 5**
Comparison of Response of Isolated Bridge with Sliding Bearing and Rubber Spring System to Response of Non-Isolated Bridge

difficulties in achieving effective seismic isolation for these motions are apparent. For example, the spectrum for Ground Condition 3 (deep cohesionless soil) extends to a period of two seconds with a spectral value of 1g. To obtain effective isolation, it is required that the period is shifted to a value beyond three seconds, which for typical light weight bridges is only possible with sliding systems.

The effectiveness of the system with sliding bearings and rubber springs in the strong CalTrans 0.6g deep alluvium motion is demonstrated in the results of figure 5. The isolated bridge sustains the full motion with bearing displacements below 50 mm (or 200 mm in prototype scale), while transmitting a force to the substructure about equal to 30 percent of the deck's weight. The same level force and deformation has been measured in the piers of the non-isolated bridge when subjected to only 1/5 of the full motion.



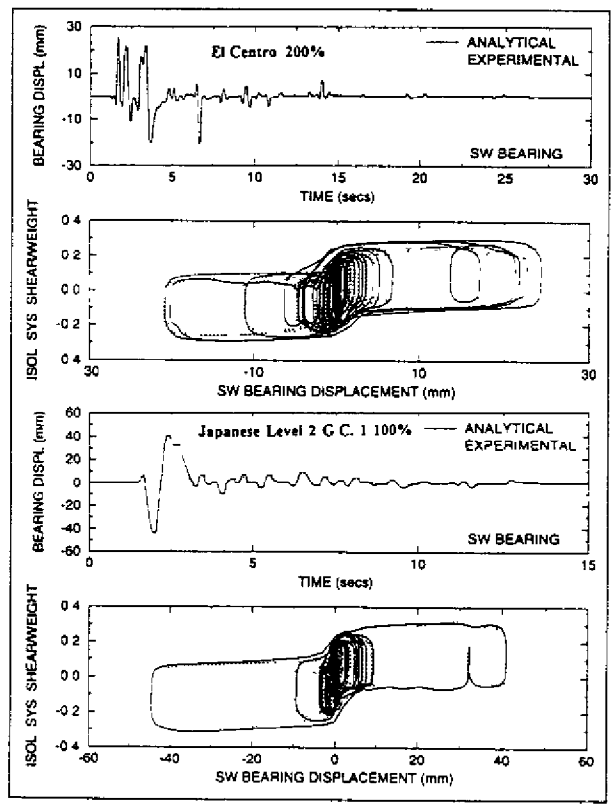
■ Figure 6

Response of Isolated Bridge (Sliding Bearing-Rubber Spring System) Without Fluid Dampers in Japanese Level 2, G.C. 1 Motion (top figures) and With Fluid Dampers in All Ground Conditions of Japanese Level 2 Motions

The same isolation system did not behave in a satisfactory manner in the Japanese Level 2 motions The top two figures of figure 6 show the recorded response of the system in the Ground Condition 1 (that is, stiff soil or rock) motion. Bearing displacement demand exceeded the capacity of 50 mm and large forces, of about 50 percent of the deck's weight, were transmitted to the substructure.

However, when fluid viscous dampers were added to the isolation system, the bearing displacement was restricted to 40 mm (or 160 mm in prototype scale). Moreover, these enhanced systems sustained all Japanese Level 2 motions (for soil conditions ranging from rock to deep cohesionless soil) while showing a remarkable insensitivity to the details of the input motions. Bearing displacements were at about 40 mm and forces transmitted to the substructure were at 30 percent of the deck's weight (see figure 6). This system fulfilled the design requirements by maintaining displacements within the limit of 200 mm in prototype scale and substructure forces at the minimum design level specified for bridges in Japan (30% of weight).

The two tested systems utilized high friction bearings and were, thus, susceptible to the development of permanent bearing displacements. These permanent displacements were measured in each test and found to be noncumulative and not exceeding 35 mm in prototype scale. Complete elimination of permanent displacements



■ Figure 7

Response of Isolated Bridge with Fluid Restoring Force/ Damping Devices in Selected Earthquakes

was accomplished with the third system, in which fluid restoring force/damping devices were utilized. Figure 7 shows the response of the isolated bridge in terms of bearing displacement history and isolation system force-bearing displacement loop in two tests. Evidently, permanent displacements are completely suppressed. The figure also shows analytical results which are in good agreement with the experimental results.

Conclusion

NCEER and Taisei Corporation co-sponsored research that resulted in the development of bridge seismic isolation systems capable of restricting bearing displacements to within 200 mm and substructure forces at or less than 30 percent of carried weight in areas of strong seismic activity, such as Japan and California, and all soil conditions. Key elements in these systems have been devices adopted from military applications. Moreover, isolation systems have been studied which can produce greater isolation effects at the expense of much larger bearing displacements. Finally, the research exposed problems in some systems, such as large permanent displacement.

Personnel and Institutions

Professor Michael Constantinou of the University at Buffalo was the primary collaborator for NCEER. Dr. Shunji Fujii, Susumu Okamoto and Daisuku Ozaki were the primary collaborators for Taisei Corporation, who participated in the research effort over a two year stay at the University of Buffalo.

Other collaborators from NCEER were graduate students P. Tsopelas and Y-S. Kim. Moreover, Douglas P. Taylor of Taylor Devices, North Tonawanda, New York; Dr. Victor Zayas of Earthquake Protection Systems, San Francisco, California; and Agostino Marioni of Alga, S.p.A. Italy collaborated on the design and manufacture of isolation hardware.

Publications

Constantinou, M.C. Fujii, S., Tsopelas, P. and Okamoto, S., "University at Buffalo - Taisei Corporation Research Project on Bridge Seismic Isolation Systems," Proceedings, Third NSF Workshop on Bridge Engineering Research in Progress, La Jolla, CA, p. 235, 1992.

Okamoto, S., Ozaki, D., Constantinou, M.C. and Tsopelas, P. "Fundamental Characteristics of Base Isolation systems for Bridges Using Sliding Bearing and Rubber Device," Proceedings, 47th J.S.C.E. Annual Conference, Japan, 1992 (in Japanese).

Constantinou, M.C., Symans, M.d. Tsopelas, P. and Taylor, D.P., "Fluid Viscous Dampers in Applications of Seismic Energy Dissipation and Seismic Isolation," Proceedings, ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, March 1993, San Francisco, CA.

Okamoto, S., Ozaki, D., Fujii, S., Constantinou, M.C. and Tsopelas, P. "Shake Table Test of a Model Bridge with Sliding Isolation System," Proceedings, 48th J.S.C.E. Annual Conference, Japan, 1993, (in Japanese).

Constantinou, M.C., Tsopelas, P., Kim, Y-S. and Okamoto, S., "NCEER-Taisei Corporation Research Program on Sliding Seismic Isolation Systems for Bridges-Experimental and Analytical Study of Friction Pendulum System (FPS)," Technical Report NCEER-93-0020, National Center for Earthquake Engineering Research, Buffalo, N.Y., 1993.

"Report on the Joint Research Project between Taisei Corp. and NCEER Concerning the Development of Isolation Systems for Bridges-Shake Table Testing of Passive Sliding Type Isolation Systems," Technology Research Center, Taisei Corporation, Japan, 1993, (in Japanese).

Constantinou, M.C., Tsopelas, P. and Okamoto, S., "Experimental Study of a Class of Bridge Sliding Seismic Isolation Systems," Proceedings, Third U.S.-Japan Workshop on Earthquake Protective Systems for Bridges, Berkeley, CA, Jan. 1994.

Tsopelas, P., Okamoto, S., Constantinou, M.C., Ozaki, D. and Fujii, S., "NCEER-Taisei Corporation Research Program on Sliding Isolation Systems for Bridges: Experimental and Analytical Study of Systems Consisting of Sliding Bearings, Rubber Restoring Force Devices and Fluid Dampers," Technical Report NCEER-94-0002, National Center for Earthquake Engineering Research, Buffalo, NY 1994.

Tsopelas, P.C and Constantinou, M.C., "NCEER-Taisei Corporation Research Program on Sliding Isolation Systems for Bridges: Experimental and Analytical Study of System Consisting of Sliding Bearings and Fluid Restoring Force/Damping Devices," Technical Report NCEER-94-0014, National Center for Earthquake Engineering Research, Buffalo, NY, 1994

Tsopelas, P.C. and Constantinou, M.C., "NCEER-Taisei Corporation Research Program on Sliding Isolation Systems for Bridges: Experimental and Analytical Study of System Consisting of Lubricated PTFE Sliding Bearings and Mild Steel Dampers," Technical Report NCEER-94-0022, National Center for Earthquake Engineering, Buffalo, N.Y., 1994

Constantinou, M.C., Tsopelas P and Okamoto, S., "Experimental Study of a Class of Bridge Seismic Isolation Systems," Proceedings, Fifth U S National Conference on Earthquake Engineering, Chicago, July 1994