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Experimental Characterization of Metallic Dampers for Seismic Retrofit of Highway Bridges

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The seismic effectiveness of metallic dampers as vibration isolators and energy dissipation devices as well as the dynamic performance of high rocker bearings are investigated experimentally. The scope of the study includes optimizing the metallic dampers for maximum dissipation of energy, characterizing full-scale metallic dampers, and understanding the seismic behavior of a small-scale bridge with dampers. Three full-scale dampers, two of straight and one of linearly tapered rods, were fabricated and tested under a progressive cyclic load. Test results consistently show that the tangential stiffness of the metallic dampers does not degrade significantly as the number of loading cycles increases even though slack in the test fixture exists. For practical applications, a 10 percent damping ratio is recommended for the design of metallic dampers composed of straight rods, although a significantly higher ratio can be used for tapered dampers. Finally, a small-scale damper was fabricated and installed in an approximately one-tenth-scale steel-girder bridge model. The model was mounted on a shake table and tested under harmonic and earthquake loads. The test results indicated that the metallic damper is an effective isolator that can prevent energy transmission from the substructure to the superstructure of a bridge. They also show that high rocker bearings are stable even at the table acceleration of 0.54 *g* (*g* = 9.8 m/s²).

Damage to bridge structures can be catastrophic in the event of a strong earthquake. Closure of the damaged bridge, if it is in a critical transportation network, will block emergency services to those in a heavily damaged area immediately after an earthquake. Earthquakes can also cause social and psychological impacts on those living in the area. The fallen bridge often slows not only the reconstruction of structures in the area but also the reconstruction of people's lives. There exists a need to retrofit these bridges in order to upgrade their seismic capacity and prevent loss of life or severe disruption to the everyday functioning of society in the event of a strong earthquake.

High rocker bearings were widely used in the design of highway bridges several years ago. Their seismic performance was generally considered unsatisfactory, and thus several states recently prohibited their use in new construction as well as in the retrofitting of existing bridges. Considering the infrequent but high magnitude of earthquakes in the central and eastern United States, it may be economical to retain the bearing arrangement of existing bridges and improve bridge performance by using supplemental dampers that can be simply fabricated and installed on bridges. The purpose of this study is to investigate the seismic effectiveness of metallic dampers in terms of their isolation and energy dissipation effects. Also addressed by using shake table tests is the dynamic stability of high rocker bearings.

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ALTERNATIVE TO CURRENT ISOLATION SYSTEMS

Metallic dampers can be installed between the bridge deck and capbeam of a pier. They function as a fixed support to carry longitudinal forces induced by all nonseismic loads. Under the design earthquake, the metallic dampers yield before a plastic hinge can potentially develop at the column base of the bridge pier. This localized, fuselike ductile failure can prevent catastrophic damage to the bridge substructures (*1*). As a flexible link between the superstructure and substructure of the bridge, the dampers isolate the superstructure from receiving the vibration energy at the foundation level. The excessive seismic response in the bridge is also suppressed through the metallic dampers.

The combination of metallic dampers and expansion rocker bearings provides an alternative to other isolation systems such as lead-rubber elastomeric bearings. The advantage of using metallic materials to retrofit highway bridges is their strength in performance, simplicity in installation, and familiarity to practitioners. These advantages allow engineers to easily apply this system in their current engineering practice. The bearing arrangement of the system is suitable to accommodate seismic forces and it allows for free thermal expansion.

During the past decade, metallic plate dampers have received great attention from the earthquake engineering community, and their implementations in building design have been cited in several studies (*2, 3*). The state of the art and state of the practice in the development of metallic plate dampers were reported by Hanson et al. (*4*, pp. 449–471). Over the years, many types of dampers made of mild steel were developed to fit in many different applications. Several geometric configurations such as triangular and hourglass shapes have been employed in the design of these dampers so that the yielding spreads almost uniformly throughout the material. The result of these efforts has led to devices that are able to endure repeated inelastic deformations in a stable manner, averting concentrations of yielding and premature failure. Extensive experimental studies have investigated the cyclic behavior of the individual damper and its effectiveness to suppress seismic responses of a building structure (*5, 6*). Dargush and Soong (*7*) also conducted analytical work on the behavior of metallic dampers.

DESIGN AND TEST OF FULL-SCALE METALLIC DAMPERS

Optimization of Metallic Dampers

In building applications, metallic plate dampers are installed and restrained to deform in the plane of a frame between the floor beam and brace. Hourglass plates and triangular plates thus provide maximum energy dissipation when subjected to double-curvature and single-curvature bending, respectively. However, in bridge applications dampers may be installed between deck and capbeam. They are subjected to lateral seismic forces from virtually any direction. It is therefore appropriate to design dampers with structural components of a symmetric cross section. Circular rods are used in this study.

Under a concentrated load at its tip, a cantilever circular rod with a diameter decreasing with height to the one-third power is subjected to a uniform curvature along the entire length. To evenly distribute the load on a damper unit from any direction, a symmetric configuration of steel rods is preferred. The best scheme is to place steel rods in a circular pattern. Although this is the optimal bar shape and configuration, at this time it is not economical to fabricate. Therefore, two differently shaped rods arranged in a square and triangular pattern will be tested—straight rods and linearly tapered rods.

Design of Full-Scale Dampers

The full-scale dampers to be tested were designed on the basis of a typical bridge in the vicinity of the New Madrid faults in Missouri. Consider a 67-m (220-ft) four-span continuous steel-girder bridge in Cape Girardeau County, Missouri, with seven girders supporting two-lane traffic. The steel girders are fixed in the traffic direction at the center pier and are free to move at the others. Each girder carries a dead load of 14 590 kN/m (1,000 lbf/ft). According to the 1996 AASHTO specifications for highway bridges, the bridge site is classified as Soil Profile Type II with a peak acceleration of 0.15 *g*. With a response modification factor of 10 to 12 because of the presence of the metallic damper, seven dampers are required with steel rods 38 mm (1½ in.) in diameter. When low-carbon mild steel with a yielding stress of $\sigma_y = 248$ MPa (36 ksi) is used, five steel rods are adequate for the design earthquake load (*8*). The expected yielding displacement at the cantilever end of such a steel rod is 1.4 mm (0.055 in.). With $\sigma_y = 400$ MPa (58 ksi), three rods are sufficient.

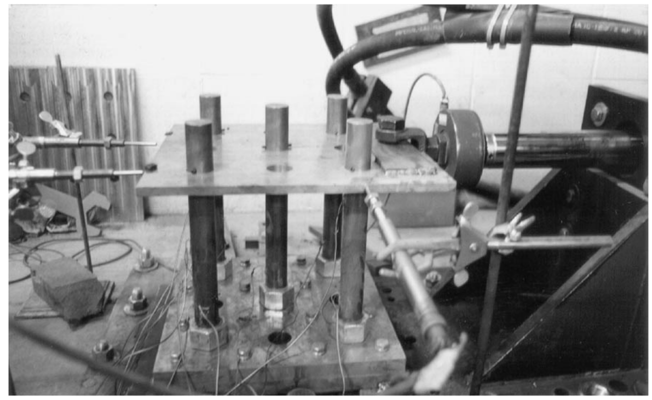

FIGURE 1 Test setup of full-scale dampers.

Test Setup and Results of Full-Scale Dampers

Three dampers were fabricated in a local machine shop and assembled at the test site. Each damper was bolted to the floor and load was applied using the available 98-kN (22-kip) MTS hydraulic actuator as shown in Figure 1. Two linear variable differential transformers (LVDTs) were connected to the top plate of the damper to measure the displacement in the direction of the applied load, and several strain gauges were attached to the steel rods in the front row. The applied load is measured with a donut-type load cell. The damper tests were conducted under a progressive cyclic displacement load.

To investigate the behavior of a damper unit, tensile tests on several specimens of the material were conducted. The resulting stress-strain relation of one specimen is presented in Figure 2. As can be seen, the yielding strength of the material is over 400 MPa (58 ksi) even though significant effort was made to secure low-strength steel in the market. For this reason, two dampers with straight rods were tested as summarized in Table 1. Damper 1 has five straight rods and Damper 2 has three straight rods. In addition, Damper 3 with three linearly tapered rods was also tested to verify its superior energy dissipation effect. Figure 3 shows the load-displacement hysteresis loops for the three dampers. It can be observed that all the load-displacement loops are almost symmetrical about the origin. The area enclosed by the loops represents the energy dissipation of the tested dampers. The hysteresis curves appear sucked in at the middle. This

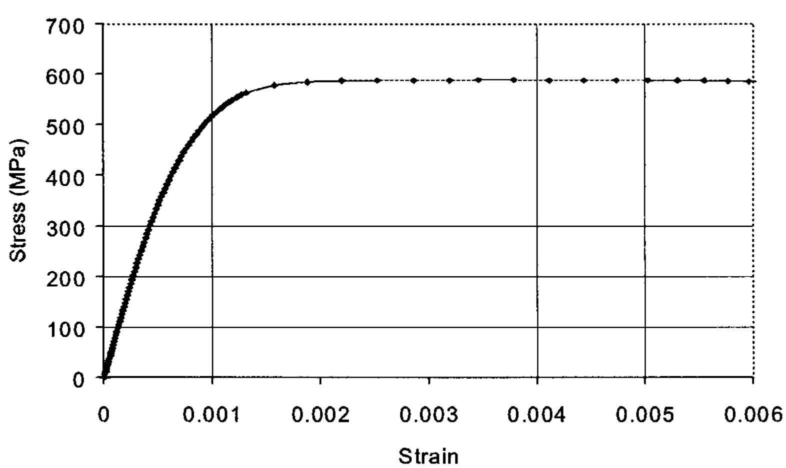

FIGURE 2 Stress-strain relation of steel material.

TABLE 1 Test Results of Full-Scale Dampers

Test	Number of Bars	Load at Initial Yielding (kN)	Displ. at 0.003 Strain (mm)
1[a]	5	89	10
2[a]	3	53	10
3[b]	3	49	11

[a]Straight Rods
[b]Tapered Rods

shape is mainly because the slack in the connections of the test fixture (between the hydraulic actuator arm and the damper or between the rods and the base plate) absorbs about 8.9 mm (0.35 in.) without the application of any load on the steel rods. All the factors contributing to the slack of the test setup can be removed in real applications by casting the steel rods and the bottom plates at one time and tightly bolting the top plate to a bridge member. Nevertheless, the test results show the steady development of the hysteresis loop as the input displacement increases.

For a better understanding of the range in which yielding has occurred, the maximum strain of the cross sections is presented in Figure 4 as a function of rod height for Dampers 1 and 3. The yielding strain (approximately equal to 0.003) observed from the test data is also shown for reference. For Damper 1, it can be seen that only the bottom 6.0 cm (2.36 in.) of rod experiences yielding at the loading level, whereas the bottom 12.7 cm (5 in.) of the rod in Damper 3 has yielded at the same level of applied displacement, indicating an improved energy dissipation capacity. It is noted that for the tapered rods, the strain level increases first and then decreases along the height. This effect occurs because the linearly tapered rod tested has a smaller diameter at the location of the middle strain gauge than the optimum diameter. It is also worth noting that the strain gauges at the top of the steel rods indicate a negligible strain at this location. This result confirms the pin condition in the test setup.

To quantify the energy dissipation capability of the dampers, the equivalent viscous damping ratio is determined according to Clough and Penzien (*9*). It is plotted as a function of displacement in Figure 5. It can be seen that the damping ratio of Dampers 1 and 2 decreases under small displacement and then increases slowly with increasingly larger displacements. The initial decrease in damping ratio is mainly due to the small elastic energy stored in the steel rods at small displacement. However, the overall variation of the damping ratio is insignificant, especially for large displacement. Therefore, for practical applications, it can be considered as a constant. As a conservative estimation, 10 percent damping is recommended for straight-bar dampers in bridge applications. It can also be seen that the damping ratio of Damper 3 increases significantly at large displacement. This finding agrees with the initial assumption that tapered rods are capable of dissipating more energy than are straight rods.

To see the consistency in performance of the three dampers, the load and displacement at the top of the dampers corresponding to 0.003 strain at the bottom of the rods are compared in Table 1. It can be observed that the first damper of five straight rods and the second damper of three straight rods experienced similar displacement and their loads are proportional to the number of bars. Compared with Damper 2, the third damper of three tapered rods experienced a larger displacement from the additional flexibility due to tapering of the rods.

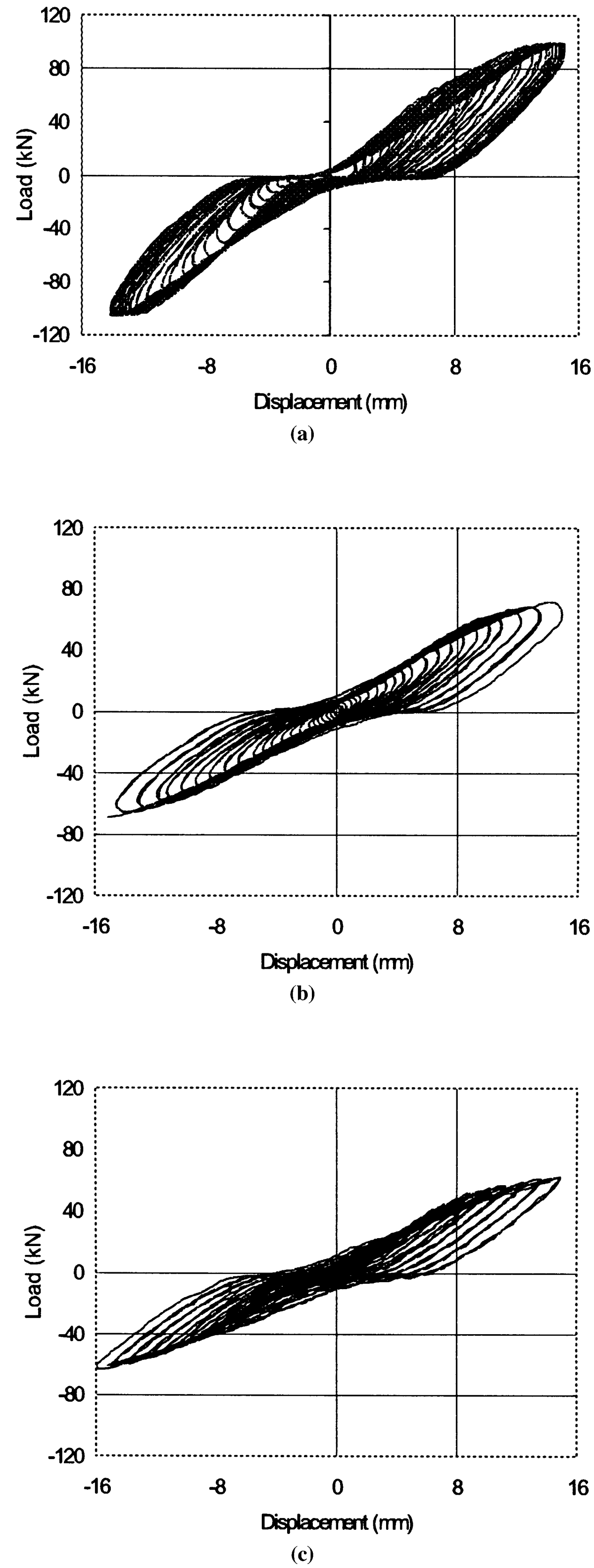

FIGURE 3 Load-displacement hysteresis loops: (*a*) Damper 1; (*b*) Damper 2; (*c*) Damper 3.

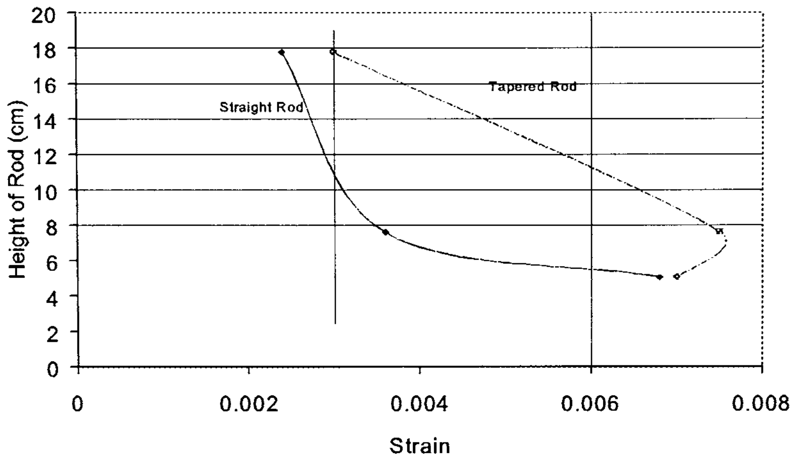

FIGURE 4 Yielding region of steel rods.

DESIGN, FABRICATION, AND TEST OF SMALL-SCALE BRIDGE

Small-Scale Bridge and Metallic Damper

A small-scale bridge was designed to simulate the three-span continuous bridge A-237 in New Madrid County, Missouri. Since bridge decks are designed for gravity load and are substantially stiffer than a bridge column, the bridge model is simplified into a single span with cantilevers at both ends to fit into the test facility. The concrete bridge deck is 213.4 cm (7 ft) long, 91.4 cm (3 ft) wide, and 8.89 cm (3½ in.) thick. It is supported with shear keys on two W8 × 15 steel girders, which further rest on four expansion rocker bearings. The high rocker bearings are supported on two piers. They were retrieved from a demolished bridge in the state of Missouri. The bridge model is about one-tenth scale of the prototype in terms of bridge width and height.

A small-scale damper is installed between the capbeam of the pier and a crossbeam connected to the girders along the centerline of the capbeam. It has four straight rods 1.27 cm (½ in.) in diameter. The steel rods are welded to a top plate and tightly fit into a slightly oversized hole on the bottom plate to simulate the fixed-pinned condition as considered in the test of the full-scale dampers (set upside down). The bridge model and the small-scale damper were assembled on the MTS shake table as illustrated in Figure 6.

Test Setup and Procedure

The shake table at the University of Missouri–Rolla is 121.9 cm by 213.4 cm (4 ft by 7 ft) and can support a maximum payload of 18 Mg (20 tons). It is effective in the frequency range of 0.01 to 10 Hz with a maximum stroke of ±2.54 cm (1 in.). The MTS 406 controller for the shake table can generate sine waves for harmonic tests. A VXI control machine with an HP1451 card was used to generate the 1940 El Centro and 1952 Taft earthquakes for the small-scale bridge tests and to gather the test data.

Two strain gauges are attached on each of the two front rods as seen from the side view of Figure 6. They are 12.7 cm (5 in.) apart and are attached to the rods near the upper plate of the damper unit. Two LVDTs are used to measure the deformation of the damper on

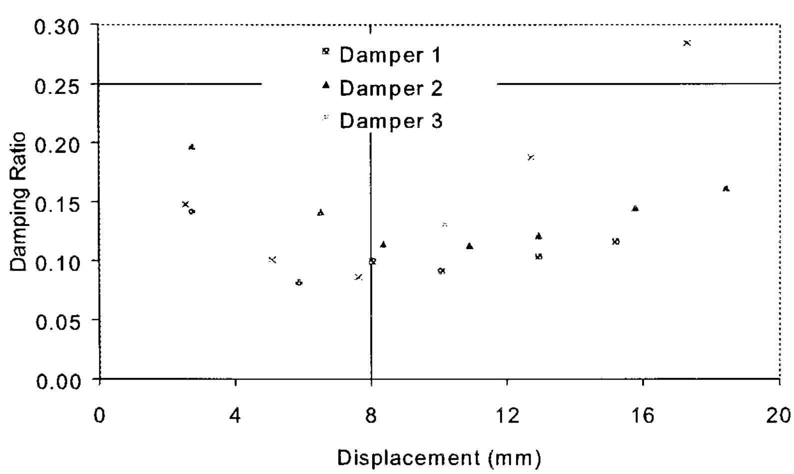

FIGURE 5 Equivalent viscous damping ratio of full-scale dampers.

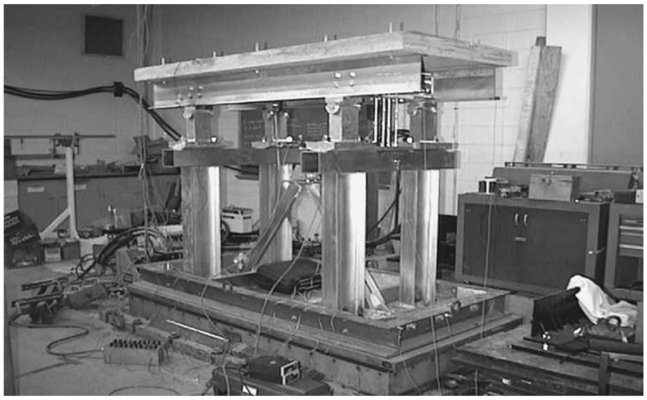

FIGURE 6 Small-scale bridge and damper.

both sides to monitor any torsional motion to which the bridge model may be subjected. Three accelerometers were respectively attached on the shake table, capbeam, and girder to monitor the acceleration amplification at different elevations of the bridge structure.

The 1940 El Centro earthquake and 1952 Taft earthquake records are scaled to a peak acceleration of 0.194 g and 0.218 g, respectively. These factors are determined by the maximum stroke of the shake table since the table is displacement controlled. Their time scale has also been compressed to approximately one-half and two-fifths, respectively, to match their dominant frequency with the natural frequency (4.4 Hz) of the bridge model with the small-scale damper in effect.

The natural frequency of the bridge model varies with and without the presence of the damper. To generate a sizable motion of the bridge, the fundamental frequency of the bridge model is identified first by swept-sine tests. The bridge model is then tested under the excitation of the modified El Centro and Taft earthquakes. Finally, a series of resonant tests is conducted at different amplitudes of harmonic input. Because of space limitations, only the test results under the modified El Centro earthquake are presented in this paper. The actual input to the bridge model (El Centro earthquake) measured at the shake table is shown in Figure 7.

Test Results and Discussion of Results

The bridge model was tested first without and second with the small-scale damper. The first case is implemented by tightly anchoring two expansion bearings on the damper side to the supporting capbeam. Figures 8 and 9 show the variation of acceleration at different locations for the two test cases when the bridge model is subjected to various percentages of the El Centro earthquake. It can be clearly observed that the acceleration at various locations increases with the level of excitation when the damper is not engaged. Compared with the capbeam acceleration, that at the girders is considerably amplified without the presence of the damper and significantly suppressed with the damper engaged. The acceleration at the girders is close to or even smaller than that of the shake table as the level of excitation increases. These results clearly indicate the isolation effect of the metallic damper. It was observed during the tests that the damper is subjected to a small strain under the earthquake loads and therefore it has not yielded yet.

To investigate the damping effect of the metallic dampers, a series of resonant tests were carried out with harmonic excitations up to 0.54 g in peak acceleration at the shake table. Figure 10 shows the load-displacement relationship of the damper. The load shown is defined as the shear force at the end of each steel rod. It is determined from the strains measured at two locations of the front rod using the principle of strength of materials. Figure 10 shows the linear relation between the load on the damper and the damper deformation, indicating that the steel rods are still elastic. Indeed, the maximum displacement of the damper is only 4.3 mm (0.17 in.), considerably smaller than the theoretical 14.1-mm (0.556-in.) yielding displacement of the pinned-fixed steel rod (*8*).

To better understand the behavior of the small-scale damper, the accelerations and displacements at various locations are plotted in Figures 11 and 12, respectively, as the level of input, defined as span length from the MTS 406 controller, increases. It appears that the maximum acceleration at the girder starts decreasing and the displacement is gradually saturated when the excitation level continues to increase from a span length of 0.35. Although this result indicates that the damper is an effective isolator, it makes it impossible to make the damper yield. The saturation of the bridge responses is likely caused by the increase of friction damping from the contact surface between the pin and web as well as between the rocker and masonry

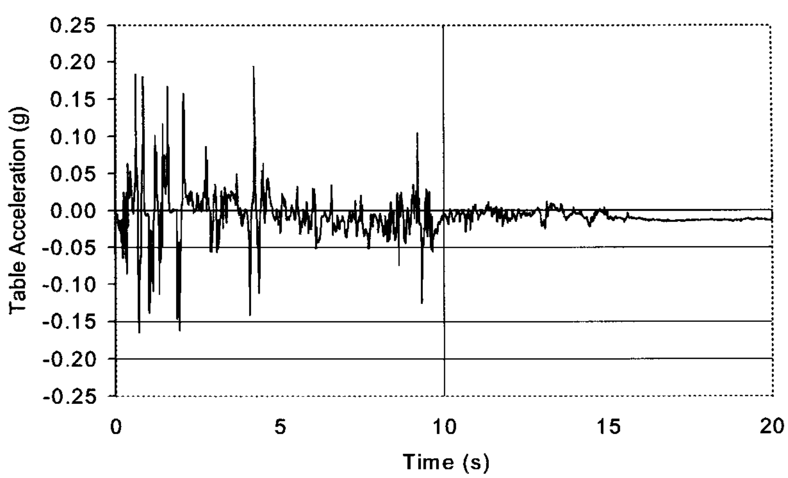

FIGURE 7 Simulated El Centro earthquake input measured at shake table.

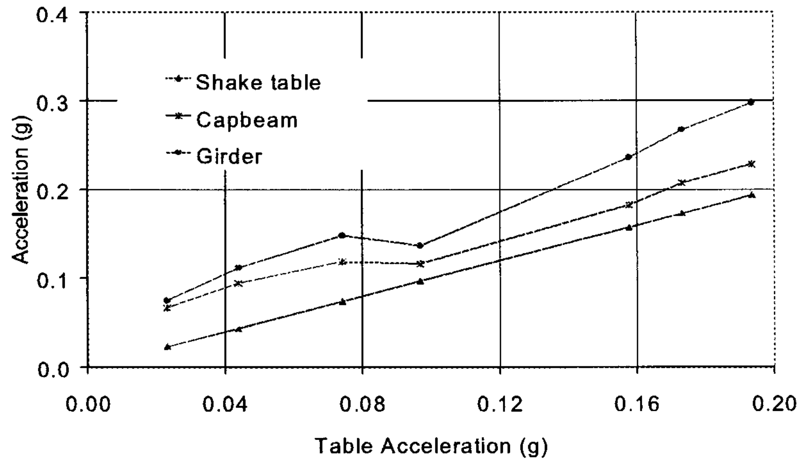

FIGURE 8 Maximum acceleration of bridge model without damper.

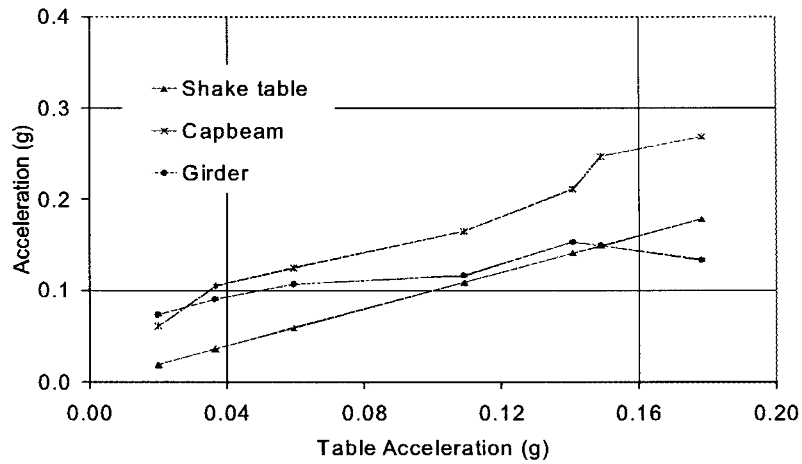

FIGURE 9 Maximum acceleration of bridge model with damper.

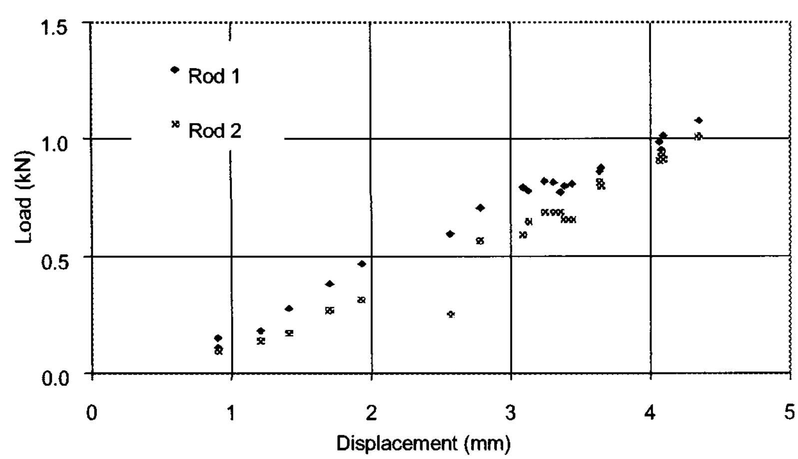

FIGURE 10 Load-displacement relation of small-scale damper.

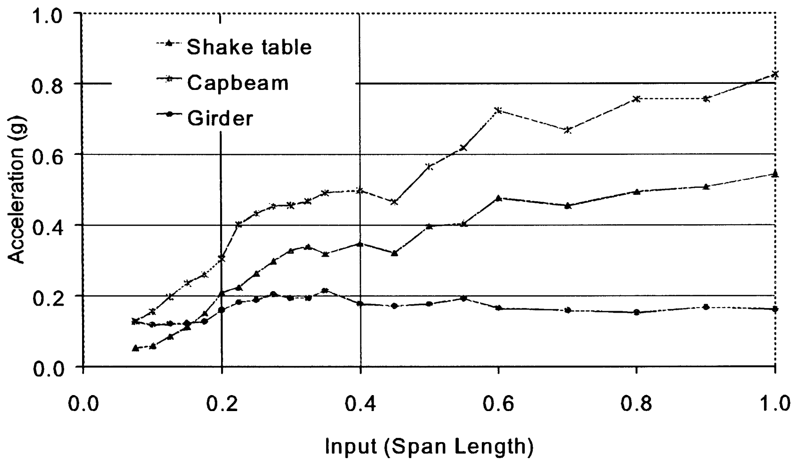

FIGURE 11 Maximum acceleration of bridge model with damper under harmonic loads.

plate of the rocker bearings. It was observed during the tests that an increasingly louder sound was associated with the bridge vibrations as the bridge excitation increased. It is this increasing damping effect that makes the high rocker bearings remain stable even though the bridge is resonant at the peak table acceleration of 0.54 *g*. Figure 12 also indicates that the displacements of the damper measured at two locations 7.62 cm (3 in.) away from the centerline of the bridge are almost identical. This comparison suggests that torsion in the plane of the bridge deck is negligible.

CONCLUSION

The key components of the proposed bearing arrangement are metallic dampers that function as fixed supports for nonseismic loads and as isolators and energy dissipation devices for earthquake loads. On the basis of the experimental study, the following conclusions can be drawn:

1. No significant stiffness degradation of metallic dampers is observed during the full-scale tests. The hysteresis loop of the dampers can be steadily developed. Although the metallic dampers dissipate energy by yielding of the steel material, their equivalent viscous damping ratio slowly changes with the applied load for dampers composed of straight rods. For practical applications, 10 percent damping ratio is recommended for pinned-fixed straight rods in bridge design. A significantly larger damping ratio can be used for tapered rods.

2. Performance of the dampers tested is consistent. The load each damper carries at the same lateral displacement is proportional to the number of rods. At the same applied load, the damper with tapered rods experiences larger displacement. The tapered rods thus dissipate more energy than the straight rods. The difference in energy dissipation increases as the displacement increases.

3. Metallic dampers are effective isolation units. When engaged, they can substantially suppress the acceleration at the superstructure. The acceleration response at girders can be even smaller than the ground motion. The result is that in the event of a destructive earthquake, damage will be localized to the damper and the column retains its structural integrity.

4. Rocker bearings are stable even when the bridge is subjected to a peak acceleration of 0.54 *g* at resonance.

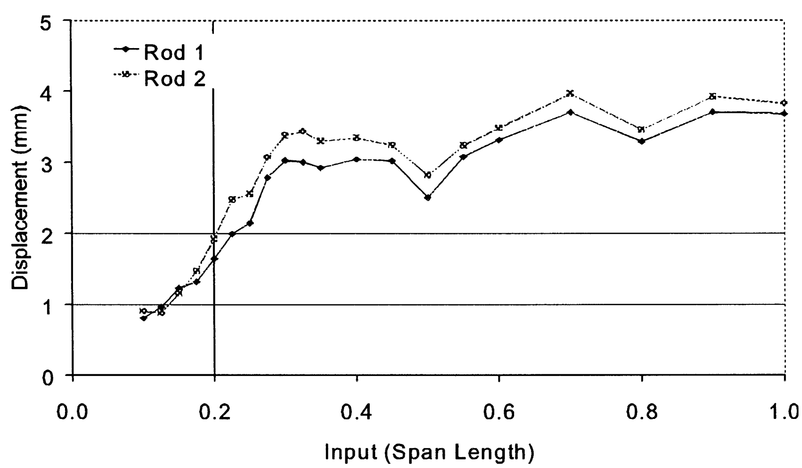

FIGURE 12 Maximum displacement of small-scale damper under harmonic loads.

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