EXPERIMENTAL STUDY OF FRICTION-PENDULUM ISOLATION SYSTEM

BY Anoop Mokha, M. C. Constantinou, Associate Member, ASCE, A. M. Reinholdt, and Victor A. Zayas, Member, ASCE

ABSTRACT: A shake-table study of the friction-pendulum isolation system, installed in a six-story, quarter-scale, 32-kip model structure, is presented. Two bearing materials are studied, one with a peak friction coefficient of 0.035 and another of 0.005. In both cases, the isolation system has a rigid-body mode period of 1 sec. The isolated structure is found to be capable of withstanding strong earthquake forces of different frequency content, in axis with the El Centro motion, the isolated structure systems, without any damage, a peak ground acceleration six times greater than what it could under fixed-based conditions. It is found that the bearing displacements are low and that the permanent bearing displacements at the end of free vibration are very small, in general, not exceeding 6% of the bearing design displacement. The system is shown to have quantifiable properties, and analytical techniques are presented that provide accurate prediction of the response.

INTRODUCTION

Base isolation is a design technique for reducing the effects of earthquake motions on structures. This technique is becoming widely accepted. Currently, as many as 10 building and bridge structures in the United States and 40 buildings in Japan have been constructed, or are under construction, on some form of isolation system (Buckle 1986; Kelly 1988). Furthermore, several base-isolated structures have been constructed in New Zealand (Buckle 1986). Most of these structures employ elastomeric isolation systems for earthquake protection. A 50,000-gallon emergency fire water tank in California and three buildings in Japan are protected by sliding isolation systems.

Sliding isolation systems employ sliding interfaces (usually Teflon-steel interfaces) to support the weight of the structure. These interfaces provide little resistance to lateral loading by virtue of their low friction. Recentering capability is provided by a separate mechanism. In the three sliding isolation structures in Japan, this mechanism takes the form of cylindrical rubber springs (Mokha et al. 1988, 1990a; Kelly 1988). In the isolated water tank in California, the sliding and recentering mechanisms are integrated in one unit in which the sliding surface takes a spherical shape (Zayas et al. 1987). This isolation system carries the name friction-pendulum system (FPS). It is the subject of the experimental study reported herein.

In the friction-pendulum system, the isolated structure is supported by bearings, each of which consists of an articulated slider on a spherical, conical, or hemispherical interface.
cave chrome surface. The slider is faced with a bearing material, which, when in contact with the polished chrome surface, results in a maximum sliding friction coefficient of the order of 0.1 or less at high velocity of sliding, and a minimum friction coefficient of the order of 0.05 or less at very slow velocity of sliding. This dependency of the coefficient of friction on velocity is a characteristic of Teflon-type materials, as described by Mokha et al. (1988, 1990). The PBS bearing tests like a fuse that is activated only when the earthquake forces overcome the static value of friction. Once set in motion, the bearing develops a lateral force equal to the combination of the mobilized frictional force and the restoring force that develops as a result of the induced rising of the structure along the spherical surface. This restoring force is proportional to the displacement and the weight carried by the bearing, and it is inversely proportional to the radius of curvature of the spherical surface. Accordingly, the system has the following important properties:

1. Rigidity for forces up to the static value of coefficient of friction multiplied by the weight.
2. Lateral force that is proportional to the weight carried by the bearing. As a result of this significant property, the resultant lateral force develops at the center of mass, thus eliminating eccentricities. This property has been confirmed in shake-table tests by Zayas et al. (1987).
3. Period of vibration in the sliding mode that is independent of the mass of the structure and related only to the radius of curvature of the spherical surface.

In addition to these properties, the friction-pendulum system has other properties common to sliding isolation systems, like low sensitivity to the frequency content of excitation and high degree of stability (Mokha et al. 1988, Constantinos et al. 1996, Su et al. 1995, Mortagheil and Khodaverdian 1987).

An experimental study of the friction-pendulum system, reported by Zayas et al. (1987), has been carried out with a two-story model in which the bearings were mounted on top of the first-story columns. The properties of the model structure were varied so that a wide range of structural flexibilities and distribution of mass and stiffness were obtained. The results confirmed the theoretically predicted properties of the system.

The main purpose of the research reported in this paper is to investigate the feasibility of the friction-pendulum system in isolating taller buildings with large aspect ratio of height to distance between bearings. For this purpose, shake-table tests were performed on a quarter-scale artificial-mass-simulation model of a six-story, steel, moment-resisting frame in which the ratio of height to maximum distance between bearings was 2.25. The model was subjected to several simulated earthquake motions of significantly different frequency content and with peak accelerations of as much as 1 g. In all tests, the model frame remained elastic with peak interstory drift restricted to values less than 0.005 times the story height. The same drift was obtained in fixed-base tests with peak table acceleration of only 0.1 g.

In the conducted tests, two new bearing materials were used, a material called Technet-B and a woven-Teflon-fabric composite. Both materials exhibit a coefficient of friction that depends on the velocity of sliding. This property appears to be important in theoretical predictions of the behavior
of the system. A mathematical model of friction that is appropriate for these materials (Constantinou et al., 1990) is employed in the analysis of the tested system; the obtained results are in excellent agreement with the experimentally obtained results.

Test Structure

The shake-table experiments were carried out with a model that represents a section in the weak direction of a typical steel, moment-resisting frame at approximately quarter scale. The model is six stories tall, with three bays (Fig. 1). Concrete blocks were used to add mass as necessary for similitude requirements, bringing the model weight to 51.4 kips (229.2 kN). The columns were bolted to two heavy W14 × 90 sections and the bearings were placed between these beams and the shake table.

The natural frequencies, damping ratios, and mode shapes of the model structure under fixed-base conditions were determined experimentally; they are listed in Table 1. The identification tests were carried out on the shake table, using as input a bended (0–50 Hz) white noise of 0.04 g peak acceleration. The structural parameters were identified from the absolute acceleration transfer functions of the six floors of the model using modal identification techniques (Reinhorn et al., 1989).

The model structure was analyzed using a commercial finite element program (GTSTRUDL). A three-dimensional frame model was used, which was subsequently condensed to one dimension with only six degrees of freedom, corresponding to the displacement of each of the six floors of the structure. The analytically determined frequencies and mode shapes are listed in Table 1. These quantities compare quite closely with the experimental frequencies and mode shapes. In general, the analytical frequencies are lower than the experimental ones, indicating that the structure is actually stiffer than predicted by the theory.

![Six-Story Test Structure](image)

FIG. 1. Six-Story Steel Test Structure (1 ft = 304.8 mm)
<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Damping ratio</th>
<th>Floor 1 (4)</th>
<th>Floor 2 (5)</th>
<th>Floor 3 (6)</th>
<th>Floor 4 (7)</th>
<th>Floor 5 (8)</th>
<th>Floor 6 (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.34</td>
<td>0.0142</td>
<td>0.214</td>
<td>0.347</td>
<td>0.632</td>
<td>0.979</td>
<td>0.521</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(1.34)</td>
<td>(0.164)</td>
<td>(0.393)</td>
<td>(0.411)</td>
<td>(0.791)</td>
<td>(0.823)</td>
<td>(0.422)</td>
<td>(1)</td>
</tr>
<tr>
<td>1</td>
<td>7.76</td>
<td>0.0290</td>
<td>0.163</td>
<td>0.900</td>
<td>0.326</td>
<td>-0.433</td>
<td>-0.979</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(7.72)</td>
<td>(0.230)</td>
<td>(1)</td>
<td>(0.956)</td>
<td>(0.398)</td>
<td>(-0.401)</td>
<td>(-0.996)</td>
<td>(-0.979)</td>
</tr>
<tr>
<td>1</td>
<td>13.28</td>
<td>0.0255</td>
<td>0.822</td>
<td>0.750</td>
<td>-0.348</td>
<td>-1</td>
<td>-0.435</td>
<td>2.820</td>
</tr>
<tr>
<td></td>
<td>(13.04)</td>
<td>(0.804)</td>
<td>(0.885)</td>
<td>(-0.229)</td>
<td>(-1)</td>
<td>(-0.383)</td>
<td>(0.317)</td>
<td>(-0.820)</td>
</tr>
<tr>
<td>4</td>
<td>19.04</td>
<td>0.0155</td>
<td>1</td>
<td>-0.016</td>
<td>-0.827</td>
<td>0.281</td>
<td>0.619</td>
<td>-0.461</td>
</tr>
<tr>
<td></td>
<td>(17.98)</td>
<td>(1)</td>
<td>(0.194)</td>
<td>(-0.290)</td>
<td>(0.790)</td>
<td>(0.240)</td>
<td>(0.908)</td>
<td>(-0.619)</td>
</tr>
<tr>
<td>5</td>
<td>24.80</td>
<td>0.0095</td>
<td>0.739</td>
<td>-0.651</td>
<td>0.329</td>
<td>0.706</td>
<td>-1</td>
<td>0.425</td>
</tr>
<tr>
<td></td>
<td>(24.02)</td>
<td>(1)</td>
<td>(-0.794)</td>
<td>(+0.027)</td>
<td>(0.905)</td>
<td>(-0.946)</td>
<td>(0.397)</td>
<td>(-0.820)</td>
</tr>
<tr>
<td>6</td>
<td>28.92</td>
<td>0.0086</td>
<td>0.215</td>
<td>-0.850</td>
<td>1</td>
<td>-0.902</td>
<td>0.001</td>
<td>-0.209</td>
</tr>
<tr>
<td></td>
<td>(28.87)</td>
<td>(0.679)</td>
<td>(-0.519)</td>
<td>(-0.879)</td>
<td>(-0.580)</td>
<td>(-0.186)</td>
<td>(1)</td>
<td>(-0.209)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are analytical.

The instrumentation consisted of accelerometers and sonic displacement transducers, which were placed at each floor to measure the horizontal acceleration and displacement of that floor with respect to a stationary reference frame. At the sixth and third floors and at the base of the structure, accelerometers and displacement transducers were placed at both sides of the model to measure any torsional motion of the model. Accelerometers also were placed above the bearings, to measure vertical acceleration and help determine whether the model lifted up from its supports. A total of 39 channels of data were recorded, of which seven channels recorded the shakeable response.

**Isolation System**

The isolation system consisted of four F99 bearings, which were placed under the base of the model at 8 ft (2.44 m) distance, as shown in Fig. 1. In this configuration the aspect ratio of height of model to distance between bearings is 2.25.

The bearing design is shown in Fig. 2. The bearing consists of an articulated slider on a polished-chrome, concave surface of radius of curvature, R, equal to 9.75 in. (247.65 mm). The spherical cavity housing the articulated slider is faced with a low-friction material. The sides of the slider in contact with the polished concave surface is faced with a bearing material. Two different bearing materials were used:

1. A material that carries the trade name Techno-B (product of Otis Industry Co., Japan). Average pressure at the sliding interface was about 7 psi (48.3 MPa). Under these conditions this material exhibited a higher coefficient of friction than the high-load, woven-Teflon fabric.
2. A form of woven Teflon with reinforcing fibers to provide high load-carrying capacity. In this case, the Teflon fabric was backed by a thin steel plate.
of smaller dimensions than the slider (which had a diameter of 1.5 in. or 38.1 mm) so that the average pressure at the interface under the load of the model was about 20 ksi (138 MPa).

An interesting complication developed as a result of the high stiffness of the beams (W14 × 90 section) forming the base of the model. Prior to testing the FPS system, another isolation system consisting of flat sliders, was tested. The flat sliders were placed on top of axial load cells, which were raised with a system of leveling plates and bolts until all four sliders were subjected to the same load. In this position the load cells were bolted to the shake table and grouted. The load cells were flexible in the horizontal direction and plates were welded all around, reducing them to simple pedestal, as shown in Fig. 1. To install the FPS bearings, the model was locally jacked up and the flat sliders were replaced two at a time. The sliding concave surface of the FPS bearings was leveled, then bolted and grouted to the pedestal below. This procedure resulted in uneven distribution of load to the four bearings. This was discovered at the conclusion of the tests, when the bearings were removed and we found that only three experienced wear. The model was essentially riding on three supports. Despite this, the model moved only in the testing direction without any torsional movement.

The properties of the isolation system were determined by the following test. The base of the model was connected to a reaction frame by two stiff rods, which were instrumented with load cells, as shown in Fig. 1. The shake table was driven in displacement controlled mode with specified frequency and displacement amplitude. The force recorded by the load cells represented the force mobilized at the isolation system, provided that the structure above remained motionless. Force-displacement loops recorded for the woven-Teflon bearing material are shown in Fig. 3. Evidently, the mobilized force depends on the velocity of sliding as a result of the velocity dependence of the coefficient of sliding friction (Mokha et al. 1988, 1990b).

The lateral force at the isolation level follows with excellent accuracy the following relationship

1205
FIG. 3. Force-Displacement Loops of Isolation System (Woven-Teflon Material) Determined in Sinusoidal Motion Tests (1 in. = 25.4 mm, 1 kip = 4.45 kN)

\[
F_b = \left( \frac{W}{R} \right) U_b + \mu(U_b) W \, \text{sgn}(\dot{U}_b) \tag{1}
\]

in which \( W \) = the weight of the model; \( R \) = the radius of curvature of the bearings; \( \mu \) = the coefficient of friction mobilized during sliding; and \( U_b \) = the bearing displacement. The first term in Eq. 1 corresponds to the stabilizing tendency of pendulum action of the FPS bearings, with the quantity \( W/R \) representing the slope of the force-displacement relationship (see Fig. 3). Accordingly, the period of vibration of the structure in its rigid body condition is

\[
T = 2\pi \left( \frac{R}{g} \right)^{1/2} \tag{2}
\]

where \( g \) = the gravitational acceleration. This, of course, is the natural period of a pendulum of length \( R \), which shows that the fundamental concept of the system is based on principles of pendulum motion (Zayas et al. 1987). The radius of curvature of the bearings was 9.75 in. (247.65 mm) resulting in a period of 1 sec (2 sec in the prototype scale).

From force-displacement loops, like those depicted in Fig. 3, the coefficient of friction was determined from the recorded force at zero displacement and found to follow the following relation, which was proposed by Constantinou et al. (1990)

\[
\mu(U_b) = f_{\text{max}} - Df \exp(-\alpha|\dot{U}_b|) \tag{3}
\]

in which \( f_{\text{max}} \) and \( (f_{\text{max}} - Df) \) are the maximum and minimum mobilized coefficients of friction, respectively; and \( \alpha = a \) parameter that controls the variation of the coefficient with the velocity of sliding. For the bearings with woven Teflon, these parameters were \( f_{\text{max}} = 0.075 \), \( Df = 0.035 \), and \( \alpha = 1.1 \) sec/in. (43.3 s/m), whereas for the bearings with Techmeter-B, these parameters were \( f_{\text{max}} = 0.095 \), \( Df = 0.045 \), and \( \alpha = 0.9 \) sec/in. (35.4 s/m).
The isolated model was tested with six different earthquake motions and one sinusoidal motion of 2.44 Hz frequency. This frequency coincides with the fundamental frequency of the six-story model superstructure. The characteristics of the earthquake motions are listed in Table 2. The records have significantly different frequency contents, with the Hachinohe and Mexico City being long-period motions. The records were time scaled by a factor of two to satisfy similitude requirements of the quarter-scale model. The time-scaled Mexico City motion has a frequency content almost entirely at 1 Hz, which coincides with the rigid-body mode frequency of the isolated model.

The earthquake tests were performed at varying peak acceleration levels for each of the signals. Table 3 lists the input signals in the test program, the isolation system condition, the peak table acceleration, and the maximum response of the model in terms of base shear over weight (51.4 kips) ratio, bearing displacement, floor acceleration, interstory drift, and permanent displacement at the end of free vibration response. The base shear was computed from the floor and base acceleration records, assuming that the mass of the model was concentrated at the level of the base and floors. The weight distribution used in the computation is: 7.65 kips (34.1 kN) at sixth floor, 7.84 kips (34.9 kN) at fifth to first floors and 4.56 kips (20.3 kN) at the base. Each earthquake signal was run at increasing levels of peak table acceleration (e.g., the case in Table 3 of El Centro 200%) corresponds to an increase of the actual peak acceleration by approximately a factor of two) until the peak interstory drift reached approximately the value of 0.18 in. (4.57 mm) or 0.005 times the story height. This value has been analytically determined to be the limit of elastic behavior of the model structure.

It should be noted that the peak table acceleration in Table 3 for the same earthquake and level of input varies in the two sets of tests with Techmet-B and woven Teflon. This is because the table-drive signals were not cor-
<table>
<thead>
<tr>
<th>Excitation (1)</th>
<th>Stimulation condition (2)</th>
<th>Peak table acceleration (g) (3)</th>
<th>Swinging displacement (in) (4)</th>
<th>Base shear/weight (k) (5)</th>
<th>Peak model base acceleration (g) (6)</th>
<th>Peak model flooring acceleration (g) (7)</th>
<th>Peak model4 flooring displacement (in) (8)</th>
<th>Permanent displacement (in) (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Centro 30E 30%</td>
<td>Float</td>
<td>0.10</td>
<td>0.235</td>
<td>—</td>
<td>0.47 (6)</td>
<td>0.171 (2)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>El Centro 30E 150%</td>
<td>FF5-LP</td>
<td>0.32</td>
<td>0.395</td>
<td>0.136</td>
<td>0.15 (2)</td>
<td>0.21 (2)</td>
<td>—</td>
<td>0.011</td>
</tr>
<tr>
<td>El Centro 30E 150%</td>
<td>FF5-HF</td>
<td>0.31</td>
<td>0.764</td>
<td>0.137</td>
<td>0.16 (2)</td>
<td>0.16 (2)</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>El Centro 30E 200%</td>
<td>FF5-HF</td>
<td>0.78</td>
<td>1.279</td>
<td>0.231</td>
<td>0.56</td>
<td>0.65 (6)</td>
<td>0.17 (2)</td>
<td>0.044</td>
</tr>
<tr>
<td>Tab N75E 30%</td>
<td>FF5-HF</td>
<td>0.17</td>
<td>0.112</td>
<td>0.199</td>
<td>0.23</td>
<td>0.27 (e)</td>
<td>0.12 (7)</td>
<td>0.022</td>
</tr>
<tr>
<td>Miyahara-Oki EW 100%</td>
<td>FF5-HF</td>
<td>0.35</td>
<td>0.892</td>
<td>0.173</td>
<td>0.51</td>
<td>0.66 (5)</td>
<td>0.12 (7)</td>
<td>0.058</td>
</tr>
<tr>
<td>Miyahara-Oki EW 200%</td>
<td>FF5-HF</td>
<td>0.19</td>
<td>0.076</td>
<td>0.098</td>
<td>0.18</td>
<td>0.31 (0.6)</td>
<td>0.07 (2)</td>
<td>0.005</td>
</tr>
<tr>
<td>Hachinohe NS 10%</td>
<td>FF5-HF</td>
<td>0.57</td>
<td>0.323</td>
<td>0.138</td>
<td>0.68</td>
<td>0.65 (5)</td>
<td>0.11 (3)</td>
<td>0.023</td>
</tr>
<tr>
<td>Hachinohe NS 15%</td>
<td>FF5-HF</td>
<td>0.22</td>
<td>0.568</td>
<td>0.133</td>
<td>0.40</td>
<td>0.50 (6)</td>
<td>0.09 (2)</td>
<td>0.017</td>
</tr>
<tr>
<td>Sendai 2.4 Hz</td>
<td>FF5-HF</td>
<td>0.26</td>
<td>1.12</td>
<td>0.199</td>
<td>0.43</td>
<td>0.50 (6)</td>
<td>0.12 (2)</td>
<td>0</td>
</tr>
<tr>
<td>Pescara 374W 10%</td>
<td>FF5-HF</td>
<td>0.17</td>
<td>0.120</td>
<td>0.106</td>
<td>0.22</td>
<td>0.39 (g)</td>
<td>0.07 (2)</td>
<td>0.03</td>
</tr>
<tr>
<td>Pescara 374W 20%</td>
<td>FF5-HF</td>
<td>0.92</td>
<td>1.46</td>
<td>0.203</td>
<td>0.64</td>
<td>0.63 (6)</td>
<td>0.17 (2)</td>
<td>0.028</td>
</tr>
<tr>
<td>Pescara 515E 50%</td>
<td>FF5-HF</td>
<td>0.57</td>
<td>1.11</td>
<td>0.198</td>
<td>0.47</td>
<td>0.63 (6)</td>
<td>0.16 (2)</td>
<td>0.034</td>
</tr>
<tr>
<td>El Centro 50E 150%</td>
<td>FF5-LF</td>
<td>0.31</td>
<td>0.432</td>
<td>0.156</td>
<td>0.33</td>
<td>0.46 (6)</td>
<td>0.19 (2)</td>
<td>0.003</td>
</tr>
<tr>
<td>El Centro 50E 200%</td>
<td>FF5-LF</td>
<td>0.40</td>
<td>1.76</td>
<td>0.247</td>
<td>0.34</td>
<td>0.79 (6)</td>
<td>0.17 (2)</td>
<td>0.013</td>
</tr>
<tr>
<td>Tab N75E 10%</td>
<td>FF5-LF</td>
<td>0.17</td>
<td>0.136</td>
<td>0.060</td>
<td>0.22</td>
<td>0.35 (6)</td>
<td>0.07 (2)</td>
<td>0.003</td>
</tr>
<tr>
<td>Tab N75E 30%</td>
<td>FF5-LF</td>
<td>0.53</td>
<td>1.04</td>
<td>0.173</td>
<td>0.48</td>
<td>0.35 (6)</td>
<td>0.13 (2)</td>
<td>0.007</td>
</tr>
<tr>
<td>Miyahara-Oki EW 100%</td>
<td>FF5-LF</td>
<td>0.19</td>
<td>0.050</td>
<td>0.085</td>
<td>0.19</td>
<td>0.32 (3)</td>
<td>0.06 (2)</td>
<td>0.007</td>
</tr>
<tr>
<td>Miyahara-Oki EW 200%</td>
<td>FF5-LF</td>
<td>0.56</td>
<td>0.560</td>
<td>0.125</td>
<td>0.64</td>
<td>0.51 (6)</td>
<td>0.12 (2)</td>
<td>0.012</td>
</tr>
<tr>
<td>Hachinohe NV 10%</td>
<td>FF5-LF</td>
<td>0.22</td>
<td>0.588</td>
<td>0.136</td>
<td>0.35</td>
<td>0.36 (6)</td>
<td>0.09 (2)</td>
<td>0.051</td>
</tr>
<tr>
<td>Hachinohe NV 15%</td>
<td>FF5-LF</td>
<td>0.22</td>
<td>1.36</td>
<td>0.261</td>
<td>0.41</td>
<td>0.80 (6)</td>
<td>0.16 (7)</td>
<td>0.061</td>
</tr>
<tr>
<td>Sendai 2.4 Hz</td>
<td>FF5-LF</td>
<td>0.92</td>
<td>1.32</td>
<td>0.198</td>
<td>0.83</td>
<td>0.48 (5)</td>
<td>0.07 (2)</td>
<td>0</td>
</tr>
<tr>
<td>Mexico N92W 40%</td>
<td>FF5-LF</td>
<td>0.56</td>
<td>0.530</td>
<td>0.114</td>
<td>0.34</td>
<td>0.12 (5.6)</td>
<td>0.06 (2.3)</td>
<td>0.032</td>
</tr>
<tr>
<td>Mexico N92W 70%</td>
<td>FF5-LF</td>
<td>0.11</td>
<td>0.363</td>
<td>0.18 (e)</td>
<td>0.18</td>
<td>0.85 (7)</td>
<td>0.07 (2)</td>
<td>0.079</td>
</tr>
<tr>
<td>Mexico N92W 70%</td>
<td>FF5-LF</td>
<td>0.12</td>
<td>0.930</td>
<td>0.176</td>
<td>0.31</td>
<td>0.33 (6)</td>
<td>0.13 (2)</td>
<td>0.114</td>
</tr>
</tbody>
</table>

*Shear at 0.3g based on IDT 2022 specification for x-axis and y-axis.*

*Question: What is the maximum displacement recorded? 0.114 in.*

*Note: The table contains data from various excitations and stimulations, showing peak accelerations, base shear, and model-based predictions for different earthquake scenarios.*
rected to precisely reproduce the desired motions and because some struc-
ture-table interaction occurred.

The results presented in this paper focus primarily on the results for the
1-sec period FPS model bearings, using the higher-friction Technet-B. Isol-
ator displacements tend to be larger for the lower-friction woven Teflon.
However, the lower-friction value also achieves lower acceleration and drift
within the upper stories of the model.

The first important observation to be made from the results of Table 3 is
the effectiveness of the FPS bearings in reducing the interstory drift. Under
fixed-base conditions, the limit on drift was reached for a peak table accel-
eration of 0.1 g in the El Centro signal. In the isolated condition and for
Technet-B, the same limit was reached for a peak table acceleration of 0.78
g, indicating an eightfold increase in the capacity of the superstructure to
withstand this motion without damage. A more careful investigation of the
table-acceleration records in the two cases revealed that the 0.78 g peak
value was merely a spike and that the record was effectively the original El
Centro record increased by a factor of approximately two. Accordingly, the
increase in capacity is about sixfold, rather than eightfold. The relative bear-
ing displacement in this case is only 1.23 in. (31.2 mm) or 4.92 in. in
prototype scale. It should be noted that this displacement is about half the
bearing displacement recorded in tests with similar size and aspect ratio model,
but supported by elastomeric isolation systems (Griffith et al. 1988).

Another important observation to be made is related to the peak model
acceleration. The acceleration in most tests is larger than the peak table ac-
celeration. Only in the case of the strongest signal (Pacoma ST4W record)
the table acceleration was deamplified in the isolated model. The level of
acceleration in the model is about 1.5 to 2 times that recorded in similar
tests with elastomeric isolation systems (Griffith et al. 1988). It should be
noted that these results and comparisons apply for the designs of the friction-
pendulum system and elastomeric isolation system that are examined in this
study.

It has been common in the past to determine the effectiveness of an iso-
lation system by the degree to which the table acceleration is reduced in the
structure above the isolation system (e.g., Griffith et al. 1988). Indeed, in
isolated structures in which all stories move in phase, the accelerations must
be low, otherwise the first story will be subjected to excessive shear, over-
turning moment, and drift. However, in isolated structures in which the floor
accelerations are out of phase (higher mode response), the reduction of the
level of acceleration from that of the shake table is not a good measure of
the effectiveness of the isolation system. In out-of-phase response, the floor
accelerations point in opposing directions, thus leading to reduced story shear,
overturning moment, and drift. This is exactly the observed behavior of the
tested system.

Evidence of this behavior is provided in Figs. 4-6, which show accel-
eration and displacement profiles of the model at selected times for the case
of the Technet-B bearing and for three excitations of significantly different
frequency content: El Centro S00E 200% (peak table acceleration of 0.78
g), Hachinohe NS 150% (peak table acceleration of 0.36 g), and Pacoma
ST4W 100% (peak table acceleration of 0.92 g). The times at which the
profiles are plotted correspond to the instances at which the peak model
acceleration, peak base overturning moment, peak interstory drift, peak base
FIG. 4. Profiles of Story Acceleration and Displacement in Case of Techmat-B Material and for El Centro Input (0.78 g Peak Table Acceleration). Profiles are Shown at Times of Peak Model Acceleration, Peak Overturning Moment, Peak Interstory Drift, Peak Base Shear, and Peak Bearing Displacement. Solid Line Represents Acceleration.

FIG. 5. Profiles of Story Acceleration and Displacement in Case of Techmat-B Material and for Hachinohe Input (0.36 g Peak Table Acceleration).

Shear, and peak bearing displacement occur. These profiles clearly demonstrate that when the peak acceleration occurs, the response is out of phase (second or third mode). Evidently, the effectiveness of the FPS bearings could not be assessed by the level of the model acceleration in comparison with that of the shake table. Rather the peak table acceleration at the limit of elastic behavior in comparison to the corresponding table acceleration under fixed-base conditions could be used as a measure of the effectiveness of the isolation system in protecting the structural system above. Based on this criterion, the tested system has been effective in protecting the structure above under extreme loading, such as the 1940 El Centro motion scaled up in 1210.
acceleration by a factor of two. The tested system could also sustain, while elastic, other extreme loadings of significantly different frequency content, such as the 1971 Pacoima motion scaled to 0.92 g and the 1988 long-period Hachinohe motion scaled to 0.36 g peak acceleration. Similar results are obtained in the case of woven-Teflon bearing material, which has a slightly lower coefficient of friction than Techmet-B. The interested reader is referred to the report by Makris et al. (1990b) for a more detailed presentation of the results.

Figs. 7-9 show the recorded base (bearing) displacement time histories and base shear-displacement loops in the case of Techmet-B for three selected table inputs. The base shear (at the bearing level) was computed from the floor acceleration records rather than being measured directly by load cells. The loops are for the entire system of bearings. The results demonstrate increasing resistance with increasing displacement and insignificant permanent displacement at the end of free vibration response. In the case of El Centro motion (200%), the permanent offset is less than 4% of the peak bearing displacement. Furthermore, the maximum recorded permanent displacement (see Table 3) was less than 5% of the bearing design displacement (2 in. or 50.8 mm).

Of particular interest are the results of the sequence of tests with the Mexico City motion in the case of the lower friction, woven Teflon. This motion is essentially a sinusoidal wave at the fundamental frequency of the isolation system. The results of Table 3 show that the system was at resonance. For example, in the test with 0.11 g peak table acceleration, the bearing displacement was 0.263 in. (6.68 mm). A minor increase in acceleration (to 0.12 g) resulted in an almost fourfold increase in displacement. This undesirable effect could be avoided by designing the bearings with higher friction so that the ratio of maximum coefficient of friction, \( f_{\text{max}} \), to peak table acceleration in units of g is larger than the limit \( \sqrt{2} / 4 \). This ability of sliding systems to avoid resonance has been originally explained by Den Hartog (1931) and very recently extended to velocity-dependent frictional systems by Makris (1989).
FIG. 7. Experimental Time History of Base (Bearing) Displacement and Base Shear-Displacement Loop for El Centro Input (0.78 g Peak Table Acceleration)

FIG. 8. Experimental Time History of Base (Bearing) Displacement and Base Shear-Displacement Loop for Hachinohe Input (0.36 g Peak Table Acceleration)
Finally, we note that during the entire testing program no uplift occurred at the bearings and no torsional response was observed.

**Analytical Prediction of Response**

The response of the tested structure was analyzed using a lumped-mass model. The equations of motion of the six-story superstructure are

\[ M \ddot{U} + C \dot{U} + K U = -M(\ddot{U}_b + \dot{U}_b) \]

where \( U = \) the vector of floor displacements with respect to the base; \( U_b = \) the base displacement with respect to the table; and \( U_t = \) the table displacement. A dot denotes differentiation with respect to time. The mass matrix, \( M \), is diagonal. The stiffness matrix, \( K \), was determined by condensation of a stiffness matrix with 288 degrees of freedom, which was constructed using a general-purpose finite element program (GTS/STRUDL). The damping matrix, \( C \), was constructed from the analytically determined frequencies and mode shapes (see Table 1) and the experimentally determined damping ratios using a procedure described by Clough and Penzien (1975) [see Mokha et al. (1990) for details].

The additional needed equation was determined from the dynamic equilibrium of the entire system in the horizontal direction:

\[ \sum_{i=1}^{6} m_i(\ddot{U}_i + \dot{U}_b + \dot{U}_t) + m_b(\ddot{U}_b + \dot{U}_b) + F_s = 0 \]

where \( m_i, i = 1, \ldots, 6 \) are the floor masses; \( m_b = \) the base mass; and
FIG. 10. Analytical Time History of Base (Ringing) Displacement and Base Shear-Displacement Loop for El Centro Input: Compare with Fig. 7

\[ F_s = \text{the force mobilized at the isolation interface. This force is given by} \]

\[ F_s = \left( \frac{w}{s} \right) u_s + \mu(u_s)WZ \]

in which \( \mu \) is described by Eq. 3 with parameters \( f_{m}, D_{f}, \) and \( s \) determined experimentally, as explained earlier; and \( Z \) is a variable governed by the following differential equation (Constantinou et al. 1990)

\[ YZ' + \gamma Z = 0 \]

in which \( Y = 0.005 \text{ in. (0.127 mm)} \) and \( \beta + \gamma = 1 \). \( Z \) replaces the signum function in Eq. 1 and is used to account for the conditions of separation and reattachment.

Eqs. 3–7 are reduced to a system of first-order differential equations and numerically integrated using an adaptive integration technique with truncation error control, which is appropriate for stiff differential equations (Gear 1971). Figs. 10–12 present analytically determined responses of the model structure for conditions identical to those that resulted in the experimental responses of Figs. 7–9. A comparison of the two sets of figures shows a very good agreement between analytical and experimental results. It should be noted that the analytical prediction is not restricted to only peak response values, but is capable of reproducing almost every detail of the observed response.

Evidently, analytical techniques are available for the prediction of the response of sliding isolation systems.
FIG. 11. Analytical Time History of Base (Bearing) Displacement and Base Shear-Displacement Loop for Hachinohe Input. Compare with Fig. 8

FIG. 12. Analytical Time History of Base (Bearing) Displacement and Base Shear-Displacement Loop for Pacoima Input. Compare with Fig. 8

1215
CONCLUSIONS

Shake-table tests have been performed to evaluate the behavior of the friction-pendulum system installed in a tall, flexible structure with large aspect ratio of height to distance between bearings. The tests show that:

1. The system is effective in protecting the structural system from extreme seismic-loading conditions with significantly different frequency content. In all tests (two of which had a peak table acceleration of almost 1 g) the model remained elastic.

2. The maximum recorded permanent displacement at the bearings was very small and, in particular, less than 6% of the bearing design displacement.

3. No bearing uplift occurred despite the model's large ratio of height to distance between bearings.

4. High-frequency response at the second and third modes of vibration of the six-story model with peak model acceleration larger than the table acceleration was observed. Owing, however, to the higher-mode response the floor accelerations point to opposing directions, leading to reduced story shear, overturning moment, and drift.

5. In tests with the El Centro motion, it was shown that the isolated structure could sustain, while elastic, a peak table acceleration six times greater than that it could sustain under fixed-base conditions.

6. The system has quantifiable properties, and analysis techniques are available for the reliable prediction of its response.

ACKNOWLEDGMENTS

The research reported herein was supported by the National Center for Earthquake Engineering Research under contract number 88-2002A, the National Science Foundation under grant number CES-8857001, and by Earthquake Protection Systems, Inc.

APPENDIX. REFERENCES


In partial fulfillment of the requirements for the degree of Master of Science.


