EXTREME DYNAMIC TESTING OF FRICITION PENDULUM BEARINGS WITH VARIOUS RESTRAINING RIM DESIGNS

Yu BAO1, Tracy BECKER2, Takayuki SONE3, Hiroki HAMAGUCHI4

ABSTRACT

Friction pendulum isolation bearings are commonly used around the world. They consist of multiple components with spherical surfaces that slide relative to each other during ground motion, dissipating energy through friction. Motion in the bearing may or may not (as in the case of Eurocode conforming bearings) be stopped by a restraining rim. In order to understand the safety margin within the design of these bearings as well as the necessary design forces for the surrounding structure, it is necessary to understand the bearing’s behavior under extreme conditions, including reaching and going beyond the displacement capacity. There have been very few experimental studies focusing on the extreme behavior of sliding isolation bearing. Thus, a series of shake table tests was conducted at McMaster University using model-scale double friction pendulum bearings. To investigate the influence of restraining rims on the extreme behavior of sliding isolation bearing, four different restraining rims are considered in this study: no rim, bolted rim, and fully connected rims of different thicknesses. These restraining rims represent typical designs of sliding isolation bearings in Europe, Japan, and the United States. Experimental observations through high speed cameras showed that the restraining rim design has a profound influence on the extreme behavior of sliding isolation bearing. Measurements of the forces transmitted to the surrounding structure are also presented.

Keywords: isolation; sliding; friction; shake table; failure

1. INTRODUCTION

Excessive displacements are a potential concern for the safety of isolated systems. They can result in the failure of isolation bearing itself or cause the superstructure to impact against the surrounding moat wall, which either of which may damage or even induce collapse of the superstructure. Sliding isolation bearings consist of one or more sliders with friction liners and corresponding concave sliding plates. Often there is a restraining rim along the perimeter of the sliding plate to prevent the slider from exceeding the displacement capacity and dropping off the sliding surface. The study here focuses on a non-articulated double friction pendulum bearing, which has one slider with concave sliding plates on the top and bottom. A previous study (Bao et al. 2017a) on the failure mechanism of double friction pendulum bearings with fully connected restraining rims showed two types of failure modes for the bearings: one due to uplift and the other due to yielding of the restraining rim. Yielding versus uplift behavior was dependent on the mass of the superstructure. However, this study did not consider other restraining rim designs.

Past experimental studies have primarily focused on the sliding isolation response under typical conditions, either to examine seismic performance or verify bearing model theories. There has been very limited experimental study on the extreme behavior of sliding isolation bearings. Sarlis et al. (2013) tested the triple friction pendulum bearing until the isolation bearing impacted its restrainer. In

1Post-doctoral Researcher, Dept of Civil Eng, McMaster University, Hamilton, Canada, baoy7@mcmaster.ca
2Assistant Professor, Dept of Civil Eng, McMaster University, Hamilton, Canada, tbecker@mcmaster.ca
3Chief Researcher, Earthquake Eng Dept, Takenaka R&D Institute, Chiba, Japan, sone.takayuki@takenaka.co.jp
4Structural Dynamics Group Leader, Earthquake Eng Dept, Takenaka R&D Institute, Chiba, Japan, hamaguchi.hiroki@takenaka.co.jp
their experiment they observed the isolation bearing uplifted due to the impact. However, impacts were minor and the isolation bearing was never tested to failure. Additionally, the effect of the restraining rim design was not investigated. Becker et al. (2017) experimentally and numerically investigated the extreme performance of a steel frame isolated on six triple friction pendulum bearings. This investigation looked at the failure of triple friction pendulum bearings which included both bolt shear and slider uplift. Again this study looked only at one type of restraining rim.

This paper presents an experimental study on the extreme behavior of double friction pendulum bearings with the intent of better understanding the margin of safety available in designs. Four sliding isolation bearings all with identical friction coefficient, sliding radius, and displacement capacity were tested. However, each bearing had a different restraining rim design, representative of sliding bearings in Europe, Japan and the United States. In Europe sliding isolation bearings are not permitted to include a restraining rim (European standard 15129, 2009) to ensure that no impact force will be transferred to superstructure. However, there is nothing to limit the internal slider from sliding beyond the bearing causing loss of functionality of the isolator. In the United States, sliding isolation bearings include fully connected restraining rims to limit the displacement of the bearing in an extreme event. In Japan bearings with separate restraining rims bolted to the sliding surface are available as well as bearings with no restraining rims. Experimental observations and measured responses are used to discuss the significant influence that the different restraining rim designs have on the extreme behavior of double friction pendulum bearings.

2. EXPERIMENTAL SETUP

The experiments were conducted at the Applied Dynamic Laboratory at McMaster University using a bidirectional shake table with a displacement capacity of 350 mm. Only uniaxial input was used in the North-South direction. The schematic drawings showing the instrumentation are presented in Figure 1. To concentrate on the extreme behavior of the isolation bearings only two isolators were tested at a time, aligned in the North-South direction, and a rigid block, weighing approximately 110 kN, was used to provide adequate pressure on the bearings. The setup was inherently unstable in the East-West direction, so two reaction frames with four roller bearings on each frame were used to restrain the concrete blocks while allowing them to move in the North-South direction. The roller bearings did cause non-negligible forces on the blocks that were unfortunately not able to be measured. Two high speed cameras, measuring at 350 frames per second were used to capture the bearing behavior during the tests.

2.1 Sliding bearing specimens

A length scale \( L = 3.5 \) was selected for designing the sliding bearing specimens in consideration of the shake table capacity. The geometric properties of prototype bearing, based on the dimensions of a commercially available bearing and the scaled model bearing are listed in Table 1. While the properties for the sliding surfaces remained the same, four different types of restraining rims were designed for this experiment:
1) Specimen A does not have a restraining rim, instead it has a flat periphery with 10 mm width beyond the sliding surface, similar to those allowed in Europe. These bearings are also available in Asia.
2) Specimen B has a stopper ring bolted at eight points around the perimeter using M3 screws (M8 bolts in prototype bearing). These bearings are available in Japan.
3) Specimen C has the sliding surface and rim milled from a single piece of steel; thus, the restraining rim is fully connected, as is common in sliding bearings in the United States. The rim thickness was selected to be 5 mm. Preliminary finite element analysis results suggested that the significant yielding would be expected during impact.
4) Similar to Specimen C, Specimen D also has a fully restraining rim; however, the rim thickness was selected to be 10 mm for comparison. Preliminary finite element results suggested that significant uplift would be expected during impact.
Table 1. Geometric properties of prototype bearing and model bearing.

<table>
<thead>
<tr>
<th>Bearing property</th>
<th>Prototype Bearing</th>
<th>Model bearing with length scale $L = 3.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of curvature $R$ (m)</td>
<td>2.5</td>
<td>0.714</td>
</tr>
<tr>
<td>Inner slider diameter $D_{sl}$ (mm)</td>
<td>200</td>
<td>57.1</td>
</tr>
<tr>
<td>Inner slider height $h_{sl}$  (mm)</td>
<td>104</td>
<td>29.7</td>
</tr>
<tr>
<td>Plate inner diameter $D$ (mm)</td>
<td>670</td>
<td>191.4</td>
</tr>
<tr>
<td>Restraining rim height $h$  (mm)</td>
<td>12</td>
<td>3.4</td>
</tr>
<tr>
<td>Displacement capacity (mm)</td>
<td>450</td>
<td>130</td>
</tr>
<tr>
<td>Second stiffness period (s)</td>
<td>4.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Properties provided by the bearing manufacturer state that under 60 MPa pressure, 100 mm/s, and 20 °C the friction coefficient is nominally 0.06. However, in these test, the pressure on the slider was only 22 MPa; thus, the friction coefficient was expected to be larger. Manufacturer data predicts an increase of 15% (i.e. $\mu \approx 0.08$); however, from the experimental hysteresis loop the friction coefficient was estimated as 0.125.

2.2 Input motion and test procedure

The East-West component of the 1995 Kobe earthquake recorded at Takatori station was selected as
the input ground motion. This is a near-fault motion which contains a strong velocity pulse. In the unscaled ground motion, the pseudo-acceleration at the model-bearing second stiffness period (i.e. 2.4 s) is 0.11 g. All the input ground motions were amplitude scaled based on the unscaled ground motion.

There were two aims to this experimental study: (1) to study the behavior of sliding bearings when they reach their maximum displacement; and (2) to compare the performance of the bearings with different rims at maximum displacement. When the bearing impacts its restraining rim, it is possible to damage the rim and affect further performance. Thus, it was desirable to limit the number of input motions that involve impact to avoid cumulative damage. As a result, the following test protocol was used: for the bearings with rims, Specimen B, C, and D, 70% of the baseline motion was run and then scaled up with an increment of 20%. At 110% the bearings had just reached or were very close to their maximum displacement. Then, 115% of the motion was run to observe minor impact. After, the ground motion was amplified considerably (155% for Specimen C and D and 135% for Specimen B) to observe the extreme behavior. For Specimen A, there was no rim to damage, and thus the ground motion was amplified from 110% in increments of 5% until the slider displaced outside of the sliding surface.

3. EXPERIMENTAL FINDINGS

3.1 Forces and Displacements

Figure 2 shows the hysteresis loops for each specimen. The bearings have a nominal displacement limit of 130 mm. The vertical displacement time histories for each bearing’s maximum scaled ground motion are shown in Figure 3. The dotted line in Figure 3 is the vertical displacement of the bearing when it reaches its 130mm with no uplift, determined through the bearing’s geometry.

Bearing Specimen A had the smallest peak shear forces. This is expected as the lack of restraining rim means that no impact forces can be induced. For Specimen A, as the slider exceeded the spherical sliding surface, the vertical displacement increased while the shear force dropped due to the slider rotating as it moved onto the flat periphery which does not provide any secondary stiffness. From the geometry of bearing Specimen A, which has a flat 10 mm wide rim past the concave surface, the maximum horizontal displacement is between 180 mm and 210 mm before it is no longer statically stable. At 150% of the motion this limit was already reached but the inertia force drove the slider back. At 155% of the motion the slider moved beyond the bottom plate and sat on a connection bolt. The forces and vertical displacements were consistent between the north and south bearings; the difference in vertical displacements was only 1.4 mm. This indicates that no significant rocking or uplift occurred.

For bearing Specimen B, C, and D, the horizontal displacement histories and shear forces for the maximum motion were very similar, all had three impacts during the ground motion. The maximum horizontal displacements for them were 150.2 mm, 147 mm and 145.5 mm, respectively. Compared to the physical displacement limit of 130 mm, the large horizontal displacement may come from a combination of rim yielding and slider rotation during uplift. While Specimen B had the smallest input motion (135% as compared to 155% for the other two specimens), it had the largest plastic deformation. Specimen D had the smallest rim deformation. The yielding in the restraining rim acted as a damper; after the third impact, Specimen C had a smaller rebound displacement than Specimen D. Specimen B has a much smaller rebound; however, this may come from the stopper ring dissipating more kinetic energy or due to the smaller ground motion input.

For Specimen B, C, and D, although their horizontal displacements were very similar, their vertical displacement varied. The vertical displacement difference between the north and south bearings was only 0.7 mm for Specimen B but was as large as 14.6 mm for Specimen C and 15.9 mm for Specimen D. For all bearings, the south isolation bearing consistently had a larger peak shear force than the north isolation bearing. While this may come from minor misalignment during the construction, it is more
Figure 2. Bearing hysteresis under largest input motion
Figure 3. Bearing vertical displacements under largest input motions

likely due to the rocking of the concrete mass, which distributed significantly larger axial load to the south isolation bearing. Specimen B had a peak shear force of 117 kN or 1.06 g. Specimen C had a peak shear force of 158 kN or 1.44 g, and Specimen D had a peak shear force of 174 kN or 1.58 g.
3.2 Qualitative Behavior and Bearing Damage

3.2.1 Specimen A: No Rim

For the bearing with no restraining rim, during the test at 115% of the motion, the inner slider reached the displacement limit of the spherical sliding surface and just began to move on to the flat 10 mm wide rim. The motion was then incremented at 5%. At 140% of the motion, there was severe abrasion of the friction liners on the inner slider; this was due to the shearing mechanism of flat periphery against the convex slider when excessive horizontal displacement occurred. After this motion, a new set of sliders was installed. At 150% of the motion, high speed cameras show the center of the slider moved past the bottom plate, but inertial forces caused the bearing to reverse; thus, the isolation bearing remained functional after the test. At 155% of the baseline motion, the slider displaced completely beyond the bottom plate, but, interestingly, the sliders sat on the adjacent connection bolts and the top plate continued to slide, much like a single friction pendulum bearing, until the test was stopped. Figure 4 shows a bearing after motion was stopped as well as damage to the bearing. After removing the isolation bearings, inspection showed the surfaces of the inner sliders were severely damaged; the friction liner was sheared and there were indents from where the sliders sat on the connection bolts.

3.2.2 Specimen B: Bolted Rim

As the stopper ring of Specimen B is connected with only eight M3 screws, Specimen B was not expected to carry as large a shear force as Specimen C or D. In reality, impact can occur at any place along the stopper ring; however, in this study the rim was oriented so that the impact occurred directly between two bolts. At 115% of the baseline motion, the south bearing experienced slight impact which cause a permanent uplift of the stopper ring so that there was 0.25 mm gap between the ring and the sliding plate. Afterwards, the input motion was then directly scaled up to 135% baseline motion to observe the extreme behavior. During the impact, the stopper rings of both isolation bearings experience large yielding, two screws from the stopper ring of the south isolation bearing were sheared off, and the sliders were significantly damaged to the point that, in a run of 70% of the motion conducted immediately afterwards, they gouged the steel sliding surfaces. The damage is shown in Figure 5. The damage to the slider surface and scratched concave surface resulted in a higher friction coefficient. When comparing the hysteresis loops from the damaged and undamaged slider under the 70% motion seen in Figure 6, the friction coefficient increased by 10% to 15%.

3.3.3 Specimen C: Thin Restraining Rim

For this bearing, the rim thickness is only 5 mm. The first minor impact was observed at 115% of the baseline motion, and then the motion was scaled directly up to 155%. Compared to Specimen A and B, there are some distinct features associated with behavior of Specimen C: 1) after impact, the slider immediately rebounded; 2) the north and south bearings exhibited different behavior from pronounced rocking. The north isolation bearing experienced noticeable uplift during impact while the south bearing did not. Figure 7 shows the condition of the bearings after the test. As expected, the restraining rims on both the top and bottom plates experienced considerable plastic deformation during the impact. The condition of the sliders was significantly better than Specimen B after the extreme motion, only the edges that hit the rims suffered some damage; the remainder of the slider was undamaged.

3.3.3 Specimen D: Thick Restraining Rim

Like bearing Specimen C, bearing Specimen D also has a fully connected restraining rim, but it is twice as thick, with a thickness of 10 mm. The isolation bearing first exhibited minor impact at 110% of the baseline motion, a very minor dent was noticed in the rim under 115% of the motion. The motion was then directly scaled to 155%. Similar to Specimen C, the north and south bearings had different behavior: the north isolation bearing underwent substantial uplift during the impact while the
Figure 4. Damage to Specimen A: no rim bearings

Figure 5. Damage to Specimen B: bolted rim bearings

Figure 6. Comparison of 70% motion hysteresis before and after maximum input motion (135% for Specimen B and 155% for Specimen D)
south isolation bearing maintained contact. One observation for the north isolation bearing is that the impact force was large enough to cause the bearing support, designed primarily to transfer the shear force to the table, to rotate, which was only noticeable in the high speed camera footage. After the 155% motion, 70% of the motion was run, and the bearings were completely functional. Comparing the hysteresis loops in Figure 6 shows the friction coefficient increased around 5% due to the damaged slider surface. The relatively smaller increase in friction coefficient compared to Specimen B with the bolted rims was consistent with the extent of slider surface damage. Physical inspection of Specimen D after testing is shown in Figure 8; compared to Specimen C this bearing specimen had significantly less plastic deformation.
5. CONCLUSIONS

A series of shake table tests were conducted in the Applied Dynamic Laboratory at McMaster University to investigate the influence of restraining rim design on the extreme behavior of sliding isolation bearings. Four different types of restraining rims, representative of typical sliding bearings found in Europe, Japan, and the United States, were tested beyond their displacement limit. It is of note that the bearings were tested with motions up to 25% larger than those causing initial impact; the margin of safety between the design ground motion displacement and the bearing limit varies greatly depending on the regional design code. From the tests, several key observations can be made which can be used in verification of bearing models as well as for information about appropriate structural design forces.

1) For the bearings with no restraining rim, as there is no impact force, the peak axial force, shear force, and floor response spectra were the lowest among the four rim designs. However, this bearing was no longer functional after the 155% motion unless the building was physically reset and the inner sliders were replaced. In contrast, the bearings with fully connected rims were operational after 155% of the motion.

2) For the bearings with bolted rims, the impact force caused substantial plastic deformation of the stopper ring and sheared some of the connecting rim bolts. No significant uplift was observed during the impact. After 135% of the baseline motion was run, the bearing still functioned for a 70% motion, although there was significant damage to the slider which, in turn, gouged the sliding surface.

3) For the bearings with fully connected rims, large rotations were observed. As expected, a thinner restraining rim had significantly more plastic deformation than a thick rim. The thicker rim also led to relatively larger peak shear, 1.58 g, while the thinner rim had a peak shear of 1.40 g. The impact force increased steadily with the magnitude of the input motion.

Further experimental details and results can be found in Bao et al (2017b).

6. ACKNOWLEDGMENTS

The authors would like to express their gratitude to Mr. Griffin Dow as well as Mr. Kent Wheeler and Mr. Paul Heerema of the Applied Dynamic Laboratory for their support with the experimental study and Dr. Masashi Yamamoto and Dr. Masahiko Higashino of the Takenaka Research and Development Institute for their advice and feedback. The funding for this research was provided by Takenaka Corporation. The authors would also like to thank Nippon Steel & Sumikin Engineering Co. Ltd. for supplying the scale bearings for testing.

7. REFERENCES


