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Sept. 2003

TECHNICAL CHARACTERISTICS

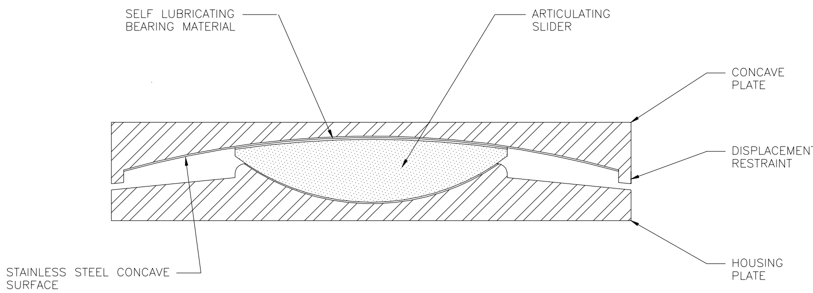
OF

FRICTION PENDULUM™ BEARINGS

GENERAL DESCRIPTION

Friction Pendulum™ bearings are seismic isolators that are installed between a structure and its foundation to protect it from damage due to earthquake shaking. The bearings reduce lateral loads and shaking movements transmitted to the structure. They can protect structures and their contents during strong, magnitude 8 earthquakes, and can accommodate near fault pulses and deep soil sites.

Friction Pendulum™ bearings use the characteristics of a pendulum to lengthen the natural period of the isolated structure so as to avoid the strongest earthquake forces. The period of the bearing is selected simply by choosing the radius of curvature of the concave surface. It is independent of the mass of the supported structure. Torsion motions of the structure are minimized because the center of stiffness of the bearings automatically coincides with the center of mass of the supported structure.



Bearing Section

The bearings offer versatile properties which can satisfy the diverse requirements of buildings, bridges and industrial facilities. The bearing's period, vertical load capacity, damping, displacement capacity, and tension capacity, can all be selected independently. Dynamic periods from 1 to 5 seconds, and displacement capacities of up to 60 inches can be provided. Dynamic frictions from 3% to 20% are available. Effective damping ranges from 10 to 40%. Individual bearings can support vertical loads up to 30 million pounds, and tension load capacities of up to 2 million pounds. The Friction Pendulum™ bearing’s versatile properties permit the seismic isolation design to be optimized for best seismic performance and lowest construction cost.

The reliability of the dynamic and sliding properties of Friction Pendulum™ bearings has been verified through hundreds of rigorous tests performed at internationally renowned earthquake engineering research centers [Refs. 1, 4, 6, 7, 9, 15, 16, 17, 18, 27, 28, 29, 30]. Test results demonstrate a consistent and reliable bi-linear response with no degradation under repeated cyclic loadings. The specified effective stiffness and damping values are accurately delivered for either unscragged or scragged bearings, new or aged bearings, and for temperatures ranging from 30 °F to 100 °F. Tests of full-size bearings show that they retain their full strength and stability throughout their displacement range, with high strength factors of safety.

DYNAMIC PROPERTIES

Friction Pendulum™ seismic isolation bearings are based on an innovative way of achieving a pendulum motion. Geometry and gravity achieve the desired seismic isolation properties. The result is a simple and stable seismic response.

The isolator period is controlled by the selection of the radius of curvature, R, of the concave surface. The natural period of vibration of a rigid structure supported on Friction Pendulum™ bearings is determined from the pendulum equation,

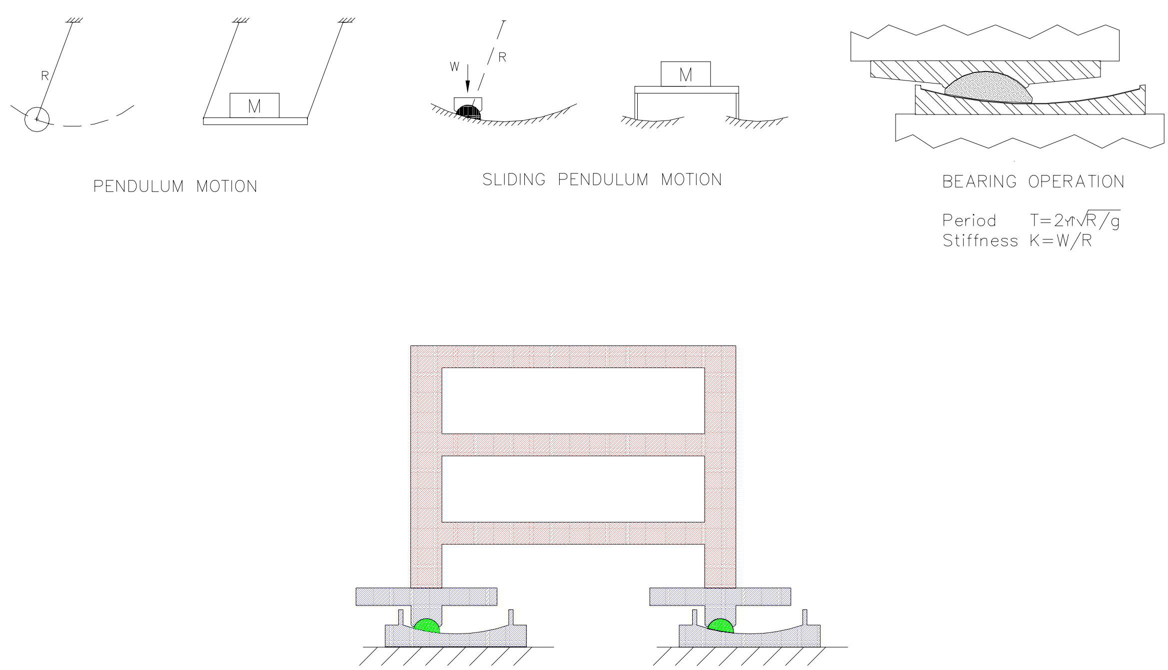
$$\mathbf{T = 2\pi\sqrt{(R/g)}}$$

where g is the acceleration of gravity.

When the earthquake forces are below the friction force level, a Friction Pendulum™ supported structure responds like a conventionally supported structure, at its non-isolated period of vibration. Once the friction force level is exceeded, the structure responds at its isolated period, with the dynamic response and damping controlled by the bearing properties.

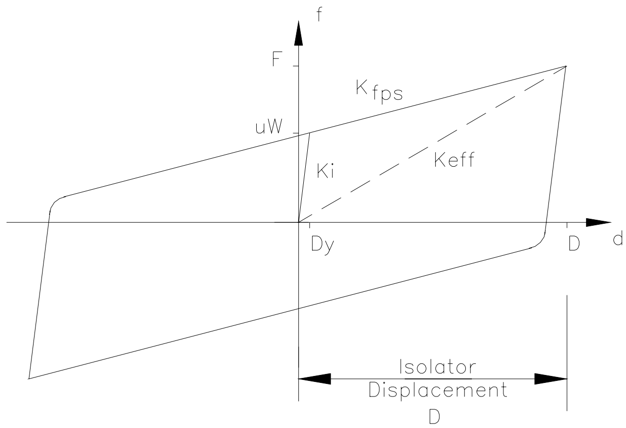
The operation of the bearing is the same whether the concave surface is facing up or down.

The Friction Pendulum™ bearing has the flexibility to achieve a wide range of properties. Changing the sliding period from 2 to 3 sec. reduces the base shear and increases the displacement. Changing the friction coefficient from 0.10 to 0.05 further reduces the base shear and increases the displacement.

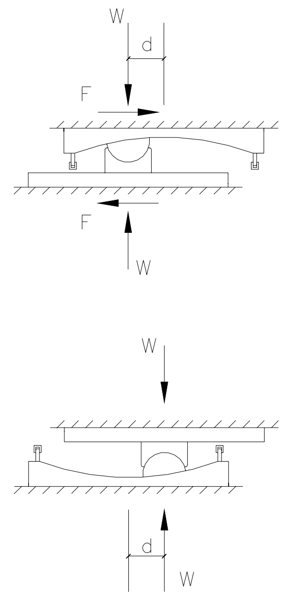


Principles of Friction Pendulum Bearing Operation

Modeling the Friction Pendulum Bearings



HYSTERETIC LOOP



BEARING

Definitions

u = Dynamic Friction

W = Vertical Load

R = Radius of Curvature

Ki = Initial Stiffness = $\frac{uW}{Dy}$

K_{fps} = Stiffness of FP Bearing = $\frac{W}{R}$

D = Design Displacement

$F = uW + \left[\frac{W}{R}\right]D$

T = Bearing Period = $2\pi\sqrt{\frac{R}{g}}$

Keff = Effective Stiffness = $\frac{F}{D}$

Teff = Effective Period = $2\pi\sqrt{\frac{W}{Keff*g}}$

B = Effective Damping = $\frac{2}{\pi}\left[\frac{u}{u+D/R}\right]$

Dy = 0.10 in.

ANALYSIS AND MODELING METHOD

The Friction Pendulum Bearings can be modeled as bi-linear hysteretic elements in programs such as 3D-BASIS, ETABS AND SAP2000.

STANDARD RADIUS (R) = 39, 61, 88, 120, 156, AND 244 IN.

STANDARD DYANMIC FRICTION RANGE FROM 3% TO 12%

The semi-spherical design of the articulated slider achieves relatively uniform pressures under the articulated slider. The relatively uniform pressure distribution reduces slip-stick motion and prevents high local bearing pressure from occurring.

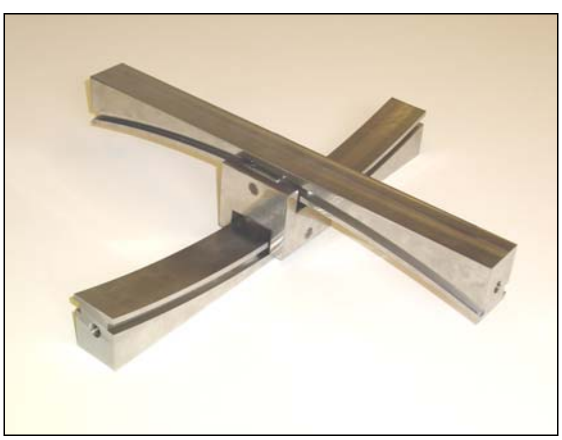
The lateral restoring stiffness of the Friction Pendulum™ bearing is,

$$\mathbf{k = W/R}$$

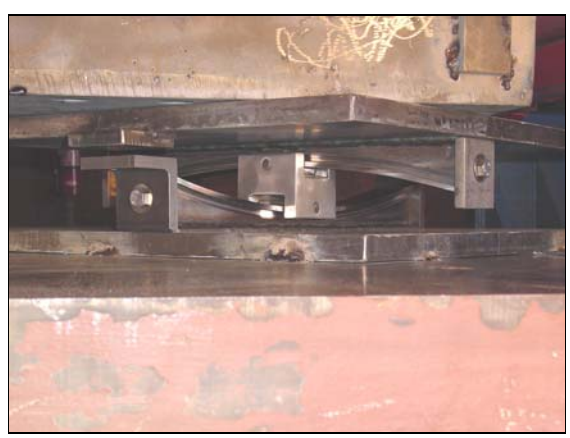
where W is the supported weight and R is the length of the radius of curvature of the concave surface. This is the stiffness of a simple pendulum. The fact that the period of the Friction Pendulum™ bearing is independent of the mass of the supported structure is an important property which has advantages in controlling the response of a structure. The desired period can be selected simply by choosing the radius of curvature of the concave surface. The period does not change for light or heavy structures, or if the weight of the structure changes or is different than assumed. The damping is controlled by the hysteretic dynamic friction which also automatically adjusts for uncertainties or changes in structure mass. This ability of the bearing to automatically adjust for uncertain or added structure mass improves safety. Larger than expected bearing displacements, that would otherwise occur with larger than expected structure masses, are avoided.

TENSION CAPACITY

EPS offers a cylindrical version of our Friction Pendulum™ bearing, that can carry tension loads. This bearing typically has two orthogonal cylindrical rails interconnected by a housing-slider assembly. The housing slider assembly contains two cylindrical sliders, and the housing unit which structurally interconnects the two orthogonal rails. When loaded in compression this cylindrical bearing has the same pendulum based seismic isolation properties, including period stiffness, and friction damping, as the spherical bearing. However the cylindrical tension bearing also maintains the pendulum based seismic isolation properties while carrying tension loads. The cylindrical tension bearing allows free multi-directional shear movements as with the non-tension spherical bearing. Bearing tension capacity provides overall structural connectivity and integrity. The cylindrical bearing is also available with a single rail, permitting sliding movements in one direction, while restraining against movement in the perpendi direction.



Tension Bearing



Tension Bearing in Test Machine

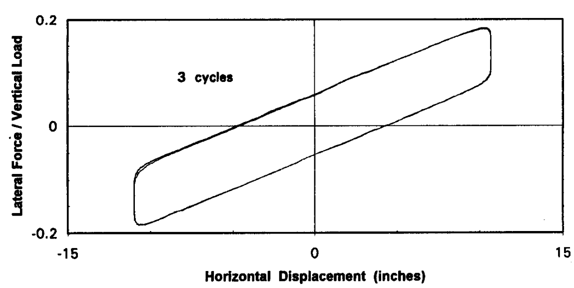
PERFORMANCE AND QUALITY ASSURANCE TESTING

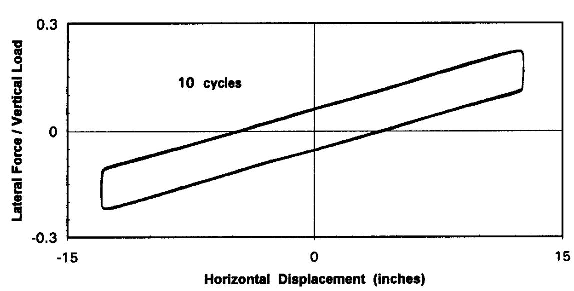
The performance and properties of Friction Pendulum™ isolators have been supported by extensive testing at internationally renowned earthquake engineering research centers, including: the National Center for Earthquake Engineering Research (NCEER), State University of New York at Buffalo (now known as MCEER); and the Earthquake Engineering Research Center (EERC), University of California, Berkeley.

The experimental hysteretic loops demonstrate an ideal bi-linear response of the Friction Pendulum™ with no observable degradation under repeated cyclic loadings. The test results of full-size bearings for the U.S. Court of Appeals building show that Friction Pendulum™ isolators retain their full strength and stability throughout their displacement range [9,17]. Friction damping reduces the seismic displacements.

The dynamic friction is measured from tests of full-size isolators. The dynamic friction coefficient is calculated by dividing the area of the hysteretic loop by the total displacement travel. The break-away friction is measured during the first movement of the tests. The dynamic friction values from tests of full-size isolators were within 20% of the specified value. Break-away friction is typically equal to, or less than, the dynamic friction value. Under no circumstances did the break-away friction exceed the specified dynamic friction value by more than 20%.

The behavior and response of Friction Pendulum™ isolators to a wide range of earthquake loadings and superstructure types have been investigated both experimentally and analytically. Physical properties of the bearings are well established and exhibited a high degree of consistency throughout the entire series of test programs.

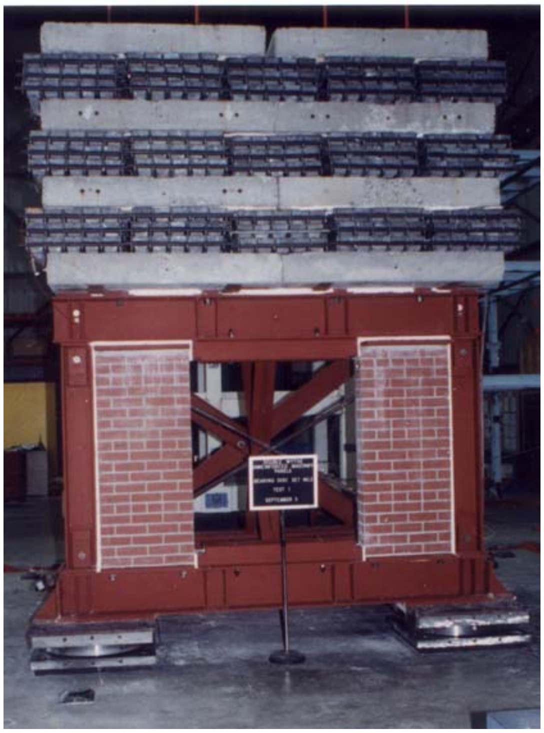




Test Results for 3 and 10 Cycles, respectively, at 1.2x Design Displacement

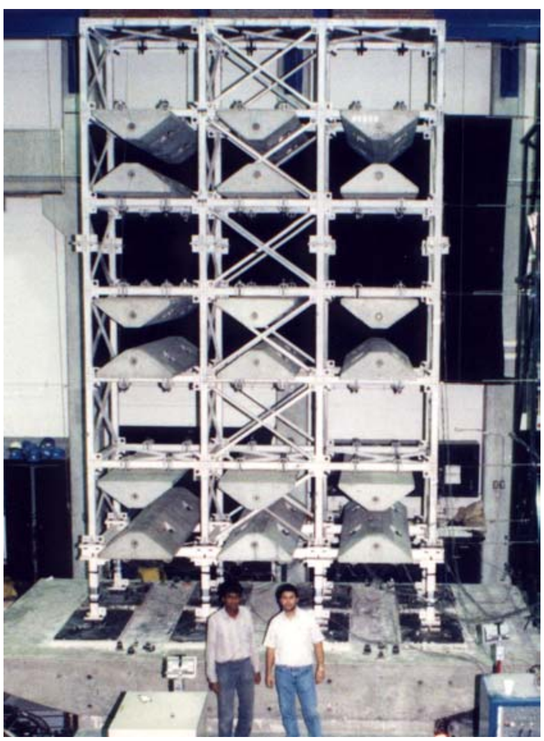
EPS Test Machine

Bearing in Test Machine

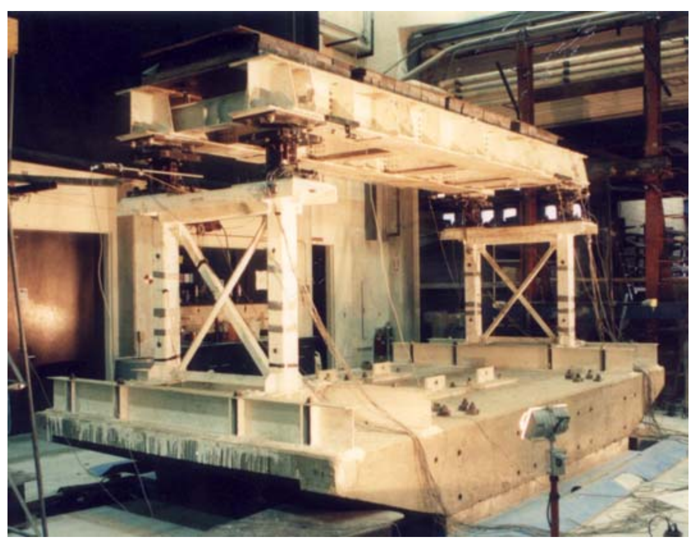


1992 URM Tests: Isolated structure remains undamaged after 58 earthquakes including magnitude 8 earthquake loadings.

1992 URM Tests: Non-Isolated structure fails after 3 earthquakes of magnitudes 5, 6 and 7, respectively.



1991 Shake Table Tests of 7 Story Frame



1992 Shake Table Tests of Bridge on Flexible Piers

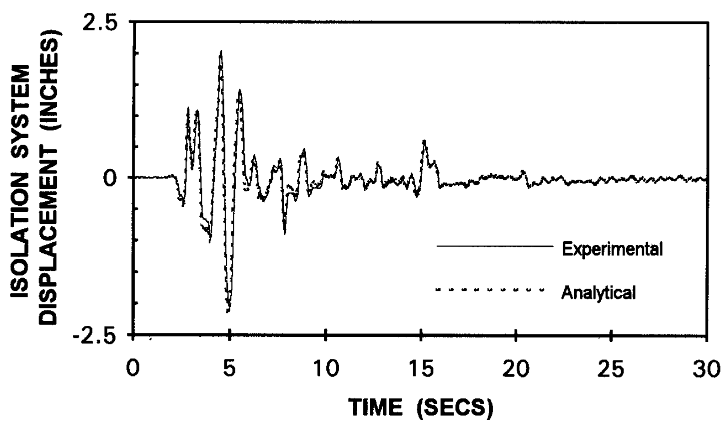
The following table lists chronologically the research test programs on the Friction Pendulum™ seismic isolation bearings performed at University and Government sponsored laboratories.

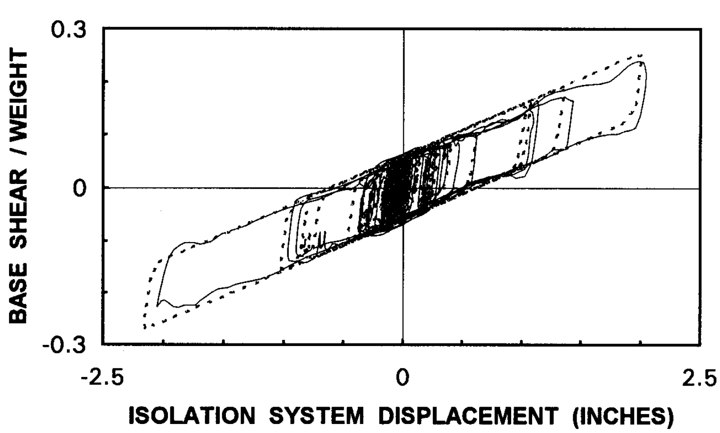
Year	Location	Description	Principal Investigator	Ref. No.
1986	EERC	Compression-shear tests of model bearings.	Prof. Mahin	16
1986	EERC	Shake table tests of 2-story steel frame structure. Test Structures modeled full-size buildings with periods ranging from 0.3 to 3.0 sec. and torsional eccentricities of 0% to 45%	Prof. Mahin	16
1989	EERC	Compression-Shear testing of model low friction bearings at velocities up to 20 inches per second.	Prof. Mahin	15
1989	NCEER	Shake table tests of a 6-story steel moment frame (quarter scale model) using bearings below a rigid base.	Prof. Constantinou	7,8
1989	NCEER	Compression-shear tests of model bearings.	Prof. Constantinou	7
1990	EERC	Compression-Shear tests of full-size 2.0 sec. bearings used in the seismic retrofit of a 4-story apartment building.	Dr. Zayas	13
1990	NCEER	Shake table tests of a rigid slab bridge on bearings.	Prof. Constantinou	
1991	NCEER	Shake table tests on 7-story steel moment and braced frame buildings (quarter scale) with bearings below individual columns.	Prof. Constantinou	1,17
1992	EERC	Shake table tests of unreinforced brick/granite masonry panels using full-size 2.5 sec. period bearings.	Prof. Mahin	9,17
1992	NCEER	Shake table tests of a highway bridge on flexible piers with the bearings isolating the bridge deck from the piers.	Prof. Constantinou	6
1993	EERC	Compression-Shear testing of full-size 2.75 sec. period bearings. Vertical loading 44 to 1275 kips; sliding velocities from 0.1 to 20 inches per sec.; temperatures from –20°F to 90°F; simulated aging to 100 years.	Dr. Zayas	3,17
1994	NCEER	Shake table tests of computer equipment supported on bearings.	Prof. Constantinou	27
1995	NCEER	Tests of temperature, longevity and reliability using model bearings.	Prof. Constantinou	29
1997	ETEC	HITEC Compression-Shear tests and 10,000 cycle wear tests of full-size bearings for Caltrans and the Federal Highway Administration (FHWA).	Armand Onesto	30
1999	EERC	Caltrans shake table tests with bi-directional interaction for bridge applications.	Prof. Mahin	
1999	NCREE Taiwan	Shake table tests of model bearings for use in power transmission towers.	Prof. Shinozuka	
2000-2001	UCSD	Caltrans High Speed Compression-Shear tests of large (13 feet diameter) bearings for retrofit of the Benicia-Martinez Bridge.	Prof. Seible	
2001	WA State Univ.	Shake table tests of a three story structural model with FP bearing and dampers (NSR Grant project).	Prof. Symans	31
2001	UCSD	Caltrans, High Speed Compression-Shear tests of large Cylindrical Uni-directional FP bearing for retrofit of West Span of Oakland Bay Bridge.	Prof. Seible	32
2001	UCSD	Government of Turkey, Bolu Viaduct Project, High Speed Compression-Shear Prototype tests on large FP bearings.	Prof. Seible	33
2001	UCSD	Tennessee DOT, I-40 Project High Speed Compression-Shear tests of large FP bearings with vertical loads of up to 10,000 Kips	Prof. Seible	34
2002	MCEER	Shake table tests of cylindrical tension bearings	Prof. Constantinou	35

The performance and design of the Friction Pendulum™ isolation system for the U.S. Court of Appeals was verified with shake table tests of unreinforced masonry structural models at the Earthquake Engineering Research Center, in August 1992. The isolated models were subjected to over 200 earthquake tests, including large, magnitude 8 earthquakes, without sustaining any damage to the masonry panels. The isolation bearings were then locked in place, and the non-isolated structural model was tested. After 3 small magnitude earthquakes, all of the masonry panels in the non-isolated structure were severely damaged, and testing was stopped.

Shake table tests carried out at the National Center for Earthquake Engineering Research in 1991 investigated the response of a 7 story steel framed structure having various lateral load resisting systems. Friction Pendulum™ seismic isolators reduced the structure base shears, story shears, and story drifts in this test structure by factors of 4 to 6. These tests showed that the Friction Pendulum™ isolators were effective in reducing the earthquake loads on multi-story structures having a large overturning aspect ratio and with different structural configurations.

The dynamic analysis models used to predict the behavior of the isolated structures have been verified with the results of shake table tests performed at EERC and NCEER. Comparisons of analysis models with test results show that the analysis results reliably and accurately predict the response of Friction Pendulum™ isolated structures.





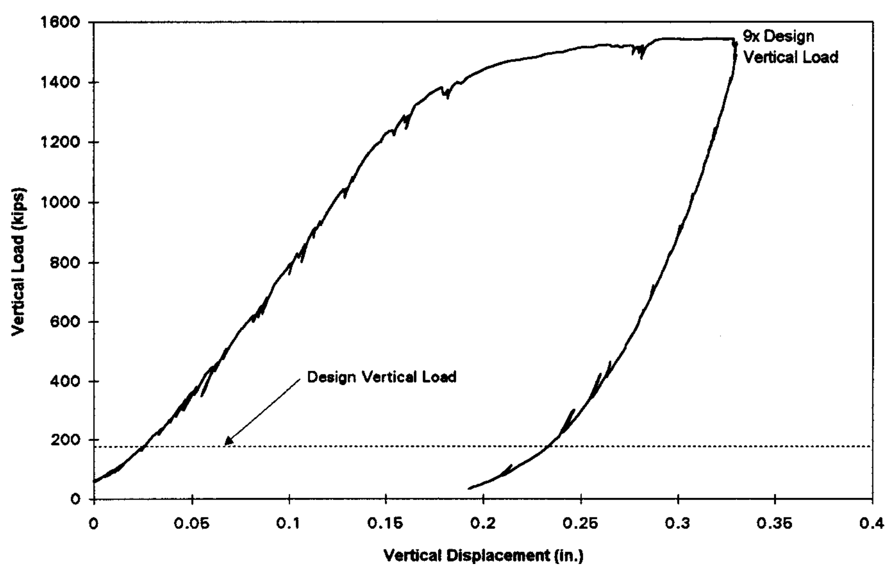
Comparison of Experimental Results and Analytical Prediction

TORSION PROPERTIES

Their pendulum properties make Friction Pendulum™ bearings particularly effective at minimizing adverse torsion motions which result from accidental mass eccentricities. The bearing's dynamic stiffness is directly proportional to the supported weight, so that the center of lateral stiffness of the bearings always coincides with the center of mass. Since the friction force is also proportional to the supported weight, the center of the friction forces of the bearing group also coincides with the center of mass of the structure. Hence, the stiffness and friction forces automatically adjust for accidental mass eccentricities. Shake table tests have shown that these torsion properties significantly reduce torsion motions and stresses in the structure, improving structure safety, and reducing bearing displacements at the isolator level [7, 15, 16, 17]. Smaller isolator displacements reduce seismic gap requirements and expenses.

BEARING COMPRESSION STRENGTH

Friction Pendulum™ bearings offer strength and stability that exceed those of any other seismic isolation bearing. An isolator from the U.S. Court of Appeals project in San Francisco, was compression load tested to nine times its design vertical load at the design lateral displacement and at the centered position. The bearing was then cyclically tested under compression and shear, and the results show the bearing retained its operational ability for lateral stiffness, damping, and vertical load capacity.



Compression Load Test at Lateral Displacement of 11 inches

Individual bearings can support service level loads of 30 million pounds. Moreover, the bearings retain high strength factors of safety above the service load capacities. Vertical earthquake motions and seismic overturning moments make the bearing's vertical load factors of safety a critical life safety consideration. Bearings which resist seismic overturning moments experience the maximum vertical loads when they are at the maximum lateral displacement. While laterally displaced, the bearings must also sustain additional vertical loads due to vertical earthquake motions. Furthermore, the reduced vertical stiffness of the bearing, occurring at the design lateral displacement, increases the dynamic amplification of vertical motions, further increasing bearing loads. The vertical earthquake motions can increase bearing vertical loads by factors of 2 or more and should be accounted for in the design. During the Northridge Earthquake, dynamic amplifications exceeding 2 were observed for the vertical seismic motions within buildings supported with elastomeric bearings.

Vertical bearing loads due to vertical earthquake motions are usually not explicitly accounted for in the UBC and ASHTO seismic isolation guidelines. To adequately resist vertical earthquake motions and other load uncertainties, EPS recommends the isolation bearings should provide strength factors of safety for compression loads of at least 2.0 at the maximum lateral displacement. UBC and ASHTO seismic isolation guidelines and typical seismic isolation designs with elastomeric bearings have required a vertical load factor of safety of only 1.0 at the maximum lateral displacement. Under combined vertical and lateral earthquake motions, a low strength factor of safety can result in overturning and collapse of the structure during the design seismic event. The most important life safety consideration in the design of seismic isolation bearings is vertical load stability in the laterally displaced position; at this position, isolation bearings perform their intended function and support their maximum loads.

COMPRESSION STIFFNESS

The compression stiffness of the Friction Pendulum™ bearings is typically about 7 to 10 times greater than elastomeric isolation bearings. Most importantly, Friction Pendulum™ bearings retain these vertical stiffness values at their design lateral displacement. Typical elastomeric isolation bearings have approximately one half the vertical stiffness at the design displacement as compared to the undeformed position. Thus, the vertical stiffness that resists the overturning moment loads is about 14 to 20 times greater for Friction Pendulum™ bearings than that of elastomeric bearings. This higher vertical stiffness minimizes loss of the structure's shear wall stiffness due to rocking about the base, reduces uplift displacement demand on the bearings, and reduces the need for spreader trusses or walls across the base of the building to spread out the overturning moments. These factors can significantly reduce the isolator installation costs.

The higher vertical stiffness of the Friction Pendulum™ also results in a lower vertical period, which is less susceptible to dynamic amplification of the vertical motion. The vertical period of a typical Friction Pendulum™ bearing is approximately 0.03 sec. From the UBC spectra, the dynamic amplification factor is 1.3. The vertical period of the typical elastomeric bearing, at the design lateral displacement, is approximately 0.1 sec. with a dynamic amplification factor of 2.0. The lower dynamic amplification factor for the Friction Pendulum™ bearing reduces vertical bearing loads due to vertical earthquake motions, improving vertical load stability and safety as compared to the specified elastomeric design.

UNSCRAGGED AND SCRAGGED PROPERTIES

Scragging is the repeated lateral loading of an isolation bearing, to achieve a softening of the bearing stiffness. Elastomeric isolation bearings typically recover 70 to 90% of the unscragged properties within 3 months to 2 years after scragging.

EPS recommends that structure shear force designs be based on unscragged bearing properties, which are measured from three or fewer cycles of lateral loading to the design lateral displacement applied to a previously untested bearing. Multiple cycles of loading at lesser displacements have a progressive scragging effect and should be avoided when measuring design stiffness and shear values. Basing the structure shear force design on stiffness properties measured after significant prior loading results in unconservative designs. Averaging four or more cycles of loading has a similar unconservative effect.

The first cycle of loading on each new virgin bearing tested for the U.S Court and the Revithoussa LNG Tanks, was recorded and reported, as were the subsequent loading cycles. The Friction Pendulum™ bearings demonstrated relatively consistent stiffness and damping properties for either unscragged (virgin) or scragged (previously loaded) bearings. The first cycle of lateral loading on the virgin bearing resulted in friction coefficients approximately 1/2 % higher than those obtained from subsequent cycles. The first cycle virgin properties did not effect the tangent stiffness values. The bearings satisfied the design stiffness and damping requirements for the first and subsequent loading cycles.

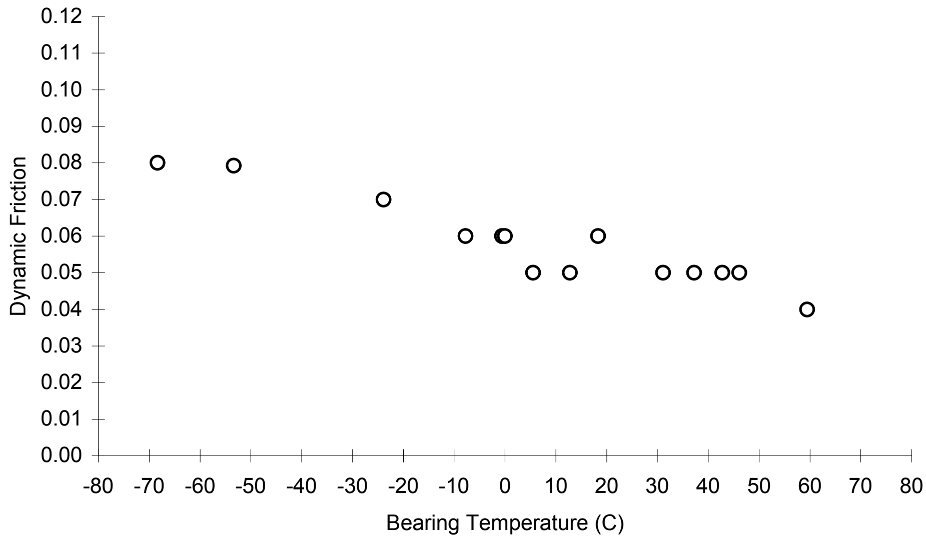
Since first cycle unscragged properties are stiffer than subsequent cycle properties, they result in higher seismic shear forces in the structure above. For the U.S. Court of Appeals and Revithoussa LNG Tanks, the first cycle properties were used for the structure shear force designs. Since the subsequent cycle properties are less stiff, the subsequent cycle properties were used to check maximum bearing displacement requirements. This approach results in a conservative design for both structure seismic shear forces and bearing displacements.

TEMPERATURE EFFECTS

Low temperatures increase the stiffness of isolation bearings, and high temperatures reduce the stiffness. This applies to both elastomeric and sliding bearings. EPS recommends that the structure shear force design be based on the cold temperature bearing properties, as applicable to the structure site. Since tests of material samples can produce significantly different results for temperature effects as compared to tests of full size bearings, EPS recommends that bearing temperature effects be based on tests of full size bearings.

In order to quantify the effects of temperature on the properties of Friction Pendulum™ isolators, full-size isolators were cooled or heated to the target temperatures at the bearing core, then subjected to combined compression and shear testing. A full-size bearing was cooled to -70 °F, then tested as the temperature gradually rose. Another bearing was heated to 90 °F, then tested as the temperature gradually lowered. The aerospace bearing liner is rated for operation from temperatures ranging from -320°F to +400 °F.

The temperature tests showed that friction decreases as the temperature rises, and increases as the temperature decreases. There is no effect of temperature on the bearing dynamic stiffness or period. There is a small effect of temperature on the effective stiffness and period due to the friction coefficient change.



Effect of Temperature on Dynamic Friction

MATERIAL LONGEVITY AND AGING

The sliding interface components of the Friction Pendulum™ bearing are constructed of materials with demonstrated longevity and resistance to environmental deterioration and aging [20, 21, 22, 23]. The bearing liner is a high strength, self-lubricating composite material that was developed for use in critical aerospace applications. It meets stringent specifications for use in military applications [21]. The concave sliding surface is a high grade stainless steel with exceptional corrosion and environmental resistance. The durability and long-term material reliability of Friction Pendulum™ bearings result in an expected bearing life exceeding 100 years.

The principal properties that affect the performance of seismic isolation bearings are the stiffness, period, and damping. For Friction Pendulum™ bearings, the stiffness and period are controlled by the radius of curvature of the concave surface. The radius of curvature does not change with time. Aging effects on the dynamic stiffness and period of the Friction Pendulum™ bearings are, therefore, not significant.

The bearing liner is a high load/low friction composite, which provides non-degrading and low friction sliding, without the use of liquid lubricants. This composite material has been used in the U.S. aerospace industry for over 35 years for high load/high torque bearing applications. The rated static load capacity is 60,000 psi. The rated operating temperature range is -320°F to +400 °F. It provides much higher strength and wear durability than the PTFE materials used in typical bridge or structural bearings.

U.S. aerospace applications of this bearing material have very demanding performance and quality control requirements. They include: wing pivot bearings, landing gear bearings, helicopter blade bearings, aircraft engine bearings; and bearings in actuator systems for hydraulics systems; among others. The load requirements in the U.S. military aerospace applications are similar to, or exceed, those of the Friction Pendulum™ bearings. Furthermore, the wear requirements exceed those of the Friction Pendulum™ bearings.

U.S. Military Specifications set no age limit or shelf life limit for the use of this bearing material. The bearing material components have been identified as chemically stable and inert, with no noticeable effect of aging. A ten year old sample of the bearing material has been tested and found to show no noticeable deterioration due to age. It's resistance to industrial chemicals is rated as excellent.

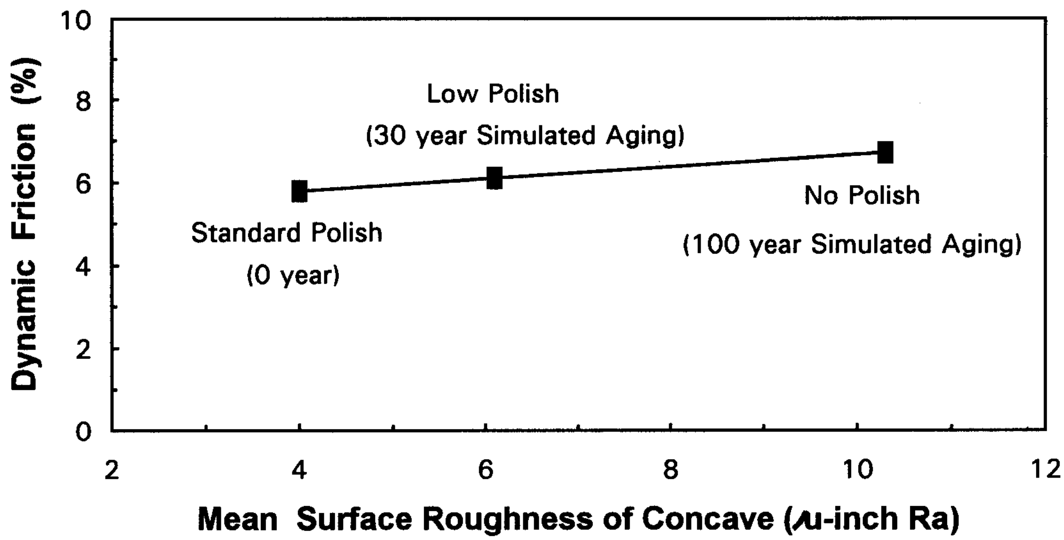
The other component of the sliding interface is the main stainless steel concave surface. ASTM A240 stainless steel, austenetic grade 300 series with a polished finish, is used for the concave surface.

The "Corrosion of Stainless Steels" section of the Metals Handbook Ninth Edition, Vol. 13 Corrosion, ASM International, reports results of observed corrosion of AISI 300 series stainless steels in a marine atmosphere [24]. Stainless steel samples were left exposed for 15 years, 250 meters from the sea. After 15 years, the Type 316 stainless steel exhibited extremely slight rust stains on 15% of the surface. The rust stains were easily cleaned to reveal a bright surface, and would have only a minor effect on the surface roughness and friction coefficient. For a sealed Friction Pendulum™ bearing, installed in a building, similar rust stains would take more than 50 years to develop. Changes in the surface roughness of the concave surface have a modest effect on the dynamic friction value, primarily in the first cycle of loading.

To simulate long term aging effects, Friction Pendulum™ bearings were tested with different surface roughnesses, including high mirror polish, low polish, and no polish. The tests were correlated to aging based on the ASM exposure tests, and stainless steel exposure tests by Taylor Devices [20] of stainless steel samples with outdoor and indoor exposure times ranging from 10 to 39 years. The no polish specimen included surface contamination from the steel mill, and was considered a conservative simulation of the worst case 100 year aging effect.

The effects of the simulated 100 year aging are shown in the figure on the following page. The figure shows the friction coefficients measured in the first cycle of loading. The 100 year simulated aged bearing demonstrated a 1% increase in the friction coefficient, as compared to the high mirror polish bearing. The friction increase was observed only for the first cycle of loading. Friction results for subsequent cycles were equivalent to the polished bearings.

The dynamic friction values of full-size bearings have remained within specification when subjected to repeated loadings during a single test, or over a series of earthquake tests, reaching the design life of the bearings. The wear life of Friction Pendulum™ bearings exceeds thirty design basis earthquake loadings. The friction coefficients of bearings subjected to more than fifty cycles of loading in a single test, and more than fifty sequential earthquake loadings have remained stable and within the design specification.



Effect of Aging

The test results for the Friction Pendulum™ composite bearing liner differ from those for soft PTFE materials used in typical structural and bridge bearings. The softer materials creep and impregnate themselves into the mate plates, causing break-away friction values that exceed the dynamic friction values [26]. In contrast, hundreds of tests on Friction Pendulum™ bearings demonstrate the static break away friction coefficient is consistently less than, or equal to, the dynamic friction coefficient [1, 7, 15, 16, 18].

Moreover, Friction Pendulum™ bearings were selected for the Revithoussa LNG Tanks over elastomeric bearing types, because they demonstrated the ability to satisfy the stringent performance requirements set for the effects of aging, temperature, and virgin (unscragged) properties. All bearings were required to satisfy the seismic performance requirements under the combined effects of 35 years aging, low temperatures of 10°F, and virgin unscragged properties, as well as the combined effects of new bearing properties, high temperatures of 86°F, and scragged run-in properties. Satisfaction of these performance requirements were required to be demonstrated by performing full-size bearing tests under the specified range of conditions. Elastomeric bearings were tested, but were not able to satisfy the performance requirements. Friction Pendulum™ bearings satisfied all performance requirements.

FIRE RESISTANCE

The Friction Pendulum™ bearing offers the innate fire resistance of heavy steel joints. Bearings for bridges typically weigh from 2000 to 10,000 lbs, making a concentrated mass which heats slowly, and maintains stability at temperatures exceeding 1500°F. The aerospace bearing liner can withstand temperatures of 600 °F without damage, and maintains operational ability up to 400°F. All materials are non-combustible, except for the ethyleyne propylene seal which can withstand temperatures up to 350°F. The seal is replaceable after a fire if needed.

The bearings can be fire protected using standard fire protection methods for structural steel members. The exterior may be field sprayed with standard fire proof aggregate. Prior to spraying, the bearing's seismic movement joints should be fitted with expansion joint material to allow bearing movements.

The bearing can also be supplied with pre-encased fire board, which can meet the fire rating requirements of an individual project. The fire board is fitted to allow bearing seismic movements, and is removable and replaceable.

INSTALLATION DETAILS AND REQUIREMENTS

The Friction Pendulum™ bearings offer many installation benefits compared to elastomeric bearings:

- The bearing does not require upper or lower base plates. This saves base plate material costs, handling costs, and installation time.

- The FP bearing is vertically stiff, minimizing the vertical deflections of columns that occur during bearing installation in retrofit applications. This avoids damage to architectural finishes in the upper floors, and reducing bearing installation time and cost.

- In retrofit applications, the FP bearing does not require flat jacks. This results in savings in flat jack costs and installation time.

- The low profile bearing can be installed in constrained locations, saving foundation and structure disruption costs and time.

- The FP bearing connection can be welded, offering flexibility and cost savings in connection details.

- The tension and side plates of the FP bearing provide the necessary temporary lateral force resistance needed during construction, avoiding the cost, time and space constraints of installing temporary bracing.

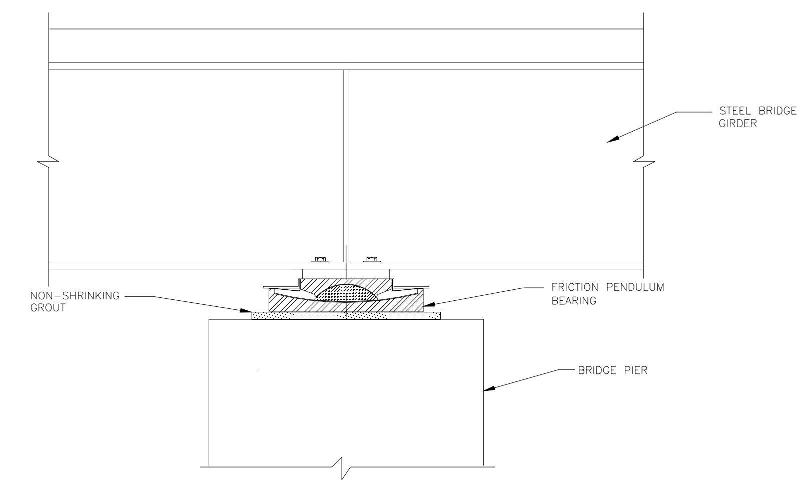
- The bearings can be installed with the concave surface facing either up or down. P-Delta moments are avoided for the structural members below the isolator, when the concave surface is facing down. This reduces the seismic forces transmitted to the foundation. P-Delta moments are avoided for the structural members above the isolator when the concave surface is facing up. This reduces the seismic forces transmitted to the upper structure.

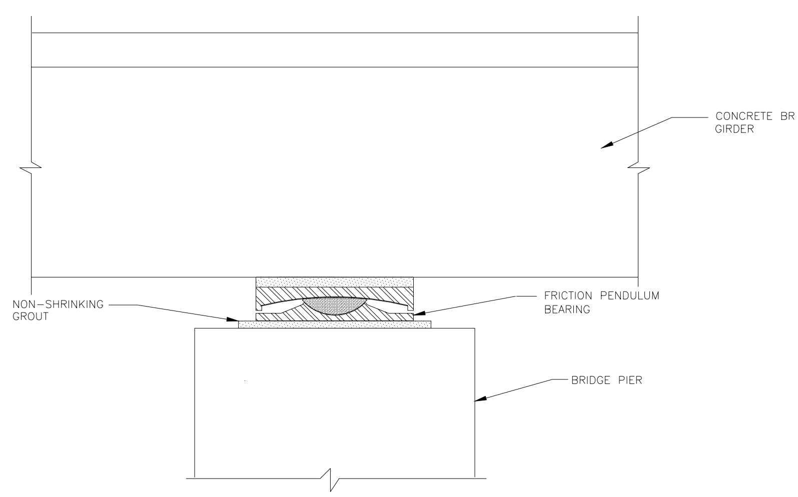
The installation benefits of the Friction Pendulum™ bearings have saved millions of dollars in project construction costs and time.

The compact Friction Pendulum™ bearing can accommodate constrained and difficult installation conditions. This often results in substantial savings in the costs of construction installation details.
The relatively small height of the Friction Pendulum™ isolator makes it preferable for installation in constrained crawl spaces, or at elevator and stair locations. The isolators are vertically rigid, retaining their full height after installation and loading. This avoids long-term creep concerns.

The isolators can be installed either with the concave surface facing up or down. The articulated joint allows relative rotations between the structure above and below the isolators, and reduces the isolator moment loads on the structure. P-Delta moments are avoided for the structural members below the isolator, when the concave surface is facing down. P-Delta moments are avoided for the structural members above the isolator when the concave surface is facing up. The cylindrical retainer ring of the Friction Pendulum™ provides a redundant support system capable of supporting the full design vertical and lateral loads.

Friction Pendulum™ isolators need less clear space around them to allow for isolator distortions. Only the sliding plane of movement needs to be accommodated. These installation details offer important advantages at locations such as exterior or interior walls, elevators, stairs, or entry ways. Seismic gap details are simplified because the slight rise of the isolators as they laterally deflect lifts overlapping plates in seismic gap joints away from expansion gap materials.





Typical Installation Details

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