Protective Systems for Buildings: Application of Spherical Sliding Isolation Systems

by Michael Constantinou

Abstract

The friction pendulum system (FPS) bearing is a form of spherically shaped, articulated sliding bearing. Movement of one part of the bearing with respect to others resembles pendulum motion in the presence of friction The lateral force needed to induce a lateral displacement, μ, consists of a restoring force equal to Wμ/R and a friction force equal to μW, where R is the radius of curvature of the spherical sliding surface, μ is the coefficient of friction and W is the vertical load on the bearing. The lateral force is proportional to the vertical load, a property which minimizes adverse torsional motions in structures with asymmetric mass distribution. The stiffness of the bearing (W/R) is proportional to the supported mass so that the period of vibration is only dependent on the radius of curvature and acceleration of gravity. This allows designs with large period of vibration, which has distinct advantages in applications to light weight structures and soft soil conditions.

In 1989, NCEER and Earthquake Protection Systems, Inc. collaborated on the shake table testing of a large, six-story steel moment frame model with FPS isolators installed below a rigid diaphragm. Under moderate to severe level ground motions, no uplift of the bearings was observed despite the large overturning aspect ratio of the model. The isolated structure could sustain, while elastic, a peak ground acceleration about six times larger than it could sustain under non-isolated, fixed-base conditions. The tests also revealed that the isolated structure did not respond as a "rigid block", but rather it exhibited response with higher mode participation, as a result of the nonlinearity of the isolation system and flexibility of the superstructure (nearly one second period in prototype scale).

In 1991, tests were conducted with a seven-story, 47.5 kip steel model under fixed-base and isolated conditions, and with various braced and moment frame configurations. Moreover, tests were conducted with the isolators placed directly at the base of individual columns, rather than having a rigid base above the isolators. In severe seismic loading, large overturning moments developed, which resulted in up to ±100% variation on the axial bearing load. The tests provided a wealth of data, which were used to refine analytical models for the isolation bearings and verify simplified analysis procedures. The analytical model has been later implemented in the computer program 3D-BASIS-ME.

The research on the seismic isolation of buildings, together with research conducted in parallel on the seismic isolation of bridges, established the FPS system as a highly researched, well understood and effective seismic isolation system. As a result of this research, the FPS system was selected for the seismic isolation of two major structures: the U S. Court of Appeals building in San Francisco and two liquefied natural gas storage tanks in Greece.

Collaboration

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Objectives and Approach

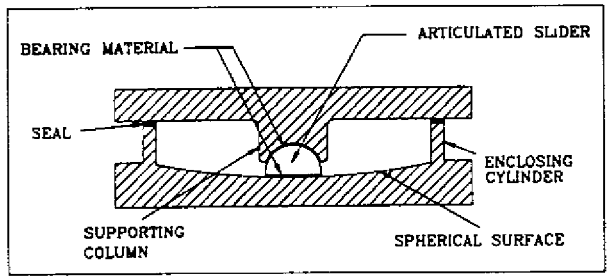
The primary objective of this project was to perform an analytical and experimental study of sliding seismic isolation systems. The Friction Pendulum System (FPS) has been given particular attention as being a low profile, compact and highly stable form of isolation system. The research focused on conducting shake table experiments of isolated building models, utilizing a variety of structural and isolation system configurations, and applying severe seismic loading. The experimental results revealed the limits of the effectiveness of the isolation system, and exposed its features, advantages and disadvantages. A second objective was to use the experimental results to develop and verify an analytical model for the bearings, and implement the model in dynamic analysis computer codes.

This research task is part of NCEER's Building Project. Task numbers are 87-2002A, 88-2002A, 89-2101 and 90-2101.

Accomplishments

Selected Shake Table Test Results

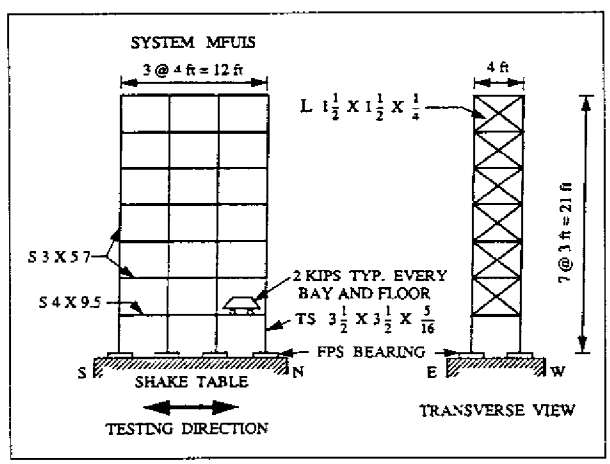
Testing of the isolated seven-story building model was unique in many ways: for example, isolators were placed directly below the columns without forming a rigid isolation basemat, large overturning aspect ratio, and significant variation in bearing axial load and bearing uplift. Figure 1 shows the friction pendulum bearing. Figure 2 shows a diagram of the moment frame configuration of the isolated model structure. The size of the model is illustrated in figure 3.



■ Figure 1
FPS Bearing Section. Bearing May Be Installed with the Spherical Surface Facing Either Up (As Shown) or Down.

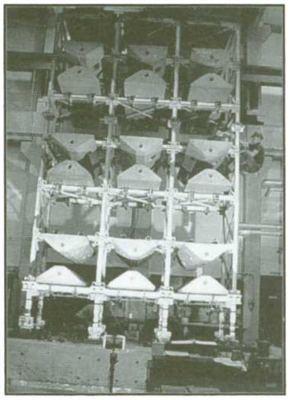
At quarter length scale, the seven-story model with a fixed base (non-isolated) had a fundamental period of 0.45 seconds. When isolated, the bearings had a 9.75 inch radius of curvature, resulting in a 1.0 second rigid body mode period. The coefficient of friction in the bearings under high sliding velocity conditions was 0.06.

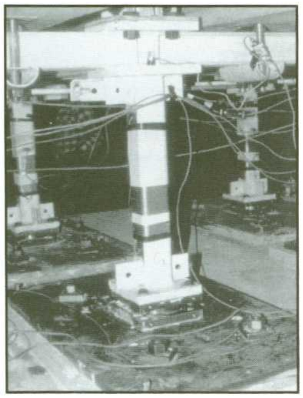
In a test, the model was excited with the 1940 El Centro earthquake, component S00E. In the isolated condition, the actual earthquake was scaled up by a factor of 2.0, whereas in the non-isolated condition the earthquake was scaled by a factor of 0.35. In another test, the 1952 Taft earthquake, component N21E, was applied to the two models with scale factors of 3.0 and 0.75,



■ Figure 2
Diagram of Tested Isolated Seven-Story Moment Frame Building Model.

■ Figure 3
View of Isolated Model on Shake Table and Close-up View of Bearing Connection to Column.





respectively. A comparison of recorded story shear forces and drifts is presented in table 1. The comparisons show that the isolated structure can withstand earthquake shaking four to six times stronger than the non-isolated structure, while remaining within its elastic drift limit. The bottom story drift is expressed with respect to the exterior and interior column base. This isolation story drift for the isolated structure is much larger than its counterpart, because the column bottom is free to slide and rotate and is not fixed to the shake table as in the fixed-base structure.

The very good performance of the isolated model in the El Centro earthquake was achieved under conditions of severe loading. Figure 4 shows the recorded response of the isolation system in terms of bearing displacement history and loops of shear force vs displacement for individual bearings and for the isolation system. It may be observed that the two exterior bearings (designated as C0 and C3) developed shear force at extreme displacement in the range of zero to nearly 2.5 kips. Since the shear force is proportional to the axial load, it indicates a severe variation of the axial load on the exterior bearings, from zero to about twice the gravity load. The C0 exterior bearing experienced some limited uplift.

Story	Non-Isolated		Isolated		Non-isolated		Isolated	
	El Centro S00E 35%		El Centro S00E 200%		Taft N21E 75%		Taft N21E 300%	
	Shear / Weight	Drift / Height (%)	Shear / Weight	Drift / Height (%)	Shear / Weight	Drift / Height (%)	Shear / Weight	Drift / Height (%)
7	0.077	0.231	0.083	0.318	0.06	0.187	0.065	0.194
6	0.138	0.339	0.143	0.42	0.111	0.278	0.097	0.267
5	0.181	0.387	0.159	0.453	0.147	0.34	0.127	0.316
4	0.21	0.458	0.168	0.501	0.184	0.401	0.141	0.358
3	0.218	0.46	0.206	0.569	0.212	0.463	0.148	0.364
2	0.22	0.361	0.226	0.435	0.224	0.36	0.149	0.264
1	0.235	0.281 Ex 0.284 In	0.24	1.396 Ex 0.875 In	0.235	0.328 Ex 0.294 In	0.175	0.753 Ex 0.519 In

Ex: Exterior Column, In: Interior Column, Weight = Total Structural, Weight Height = Story Height

■ Table 1
Comparison of Response of Non-Isolated and Isolated Structure