Seismic Isolation Using the Friction Pendulum System

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INTRODUCTION

An innovative seismic isolation system, the Friction Pendulum System (FPS), offers improvements in strength, versatility and ease of installation as compared to previous systems. Moreover, the approach offers several inherent performance benefits not available before. It is based on well known engineering principles of pendulum motion, and is constructed of materials with demonstrated longevity and resistance to environmental deterioration. The desirable isolation characteristics exhibited by FPS components hold the promise of an effective and practical system for significantly increasing the seismic resistance of nuclear power plants, reactor vessels, and equipment. This paper presents results from a four year research and testing program to assess the technical performance of the FPS.

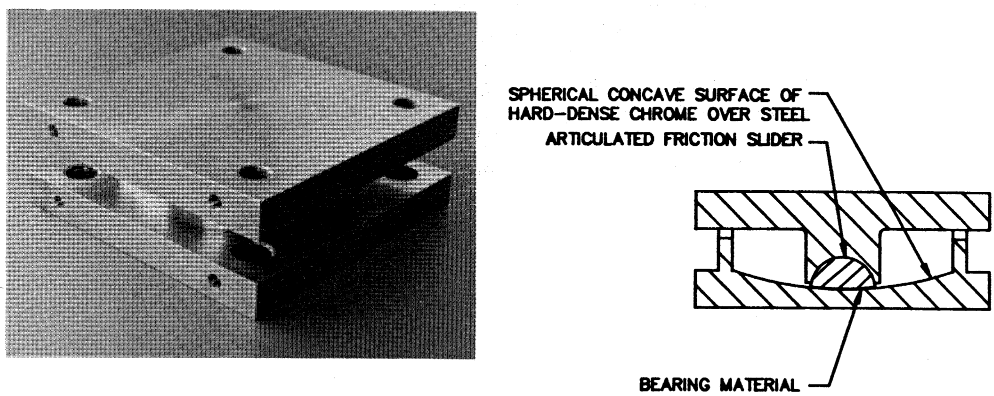
FPS SEISMIC ISOLATION

The Friction Pendulum System (FPS) uses geometry and gravity to achieve the desired seismic isolation results. A photograph and cross section view of an FPS steel connection is shown in Fig. 1. The FPS concept is based on an innovative way of achieving a pendulum motion (Fig. 2). The supported structure or equipment item responds to earthquake motions with small amplitude pendulum motions. Friction damping absorbs the earthquake's energy. The result is a simple, predictable, and stable earthquake response. The operation of the connection is the same whether the concave surface is facing up or down. Fig. 3 illustrates the operation of the connection when installed at the top of a column, with the concave surface facing downward, as tested on the shake table at U.C. Berkeley's Earthquake Engineering Research Center.

RESULTS

The FPS seismic isolation has been tested under more than 150 simulated earthquake loadings and conditions (Zayas, Low and Mahin, 1987). Seismic isolation is achieved by shifting the natural period. The natural period is controlled by the selection of the radius of curvature of the concave surface. The natural period of vibration of a rigid mass supported on FPS connections is determined from the pendulum equation, $T = 2\pi\sqrt{r/g}$, where g is the acceleration of gravity. This is the sliding period of the isolators, and the sliding or activated period of a relatively stiff structure supported on the FPS.

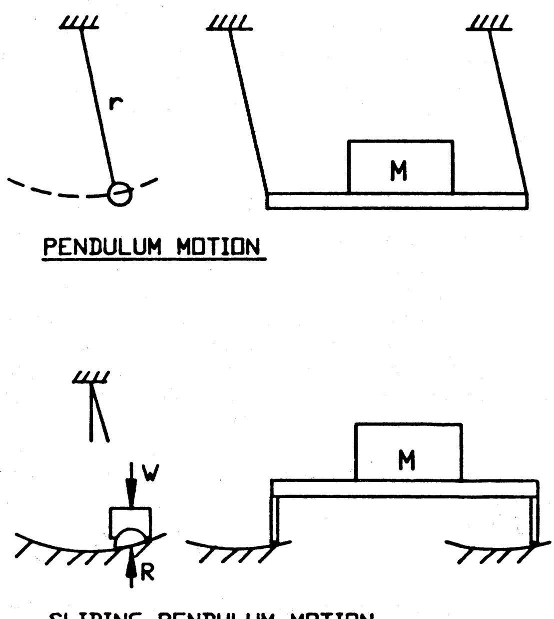
The force level at which sliding motion begins is controlled by the selection of the friction bearing material. When the earthquake forces are below the friction force level, an FPS supported structure responds like a conventionally supported structure. Once the friction force level is exceeded



a.) Photograph

b.) Section

Fig. 1 FPS Isolator



EQUATIONS PERIOD $T=2\pi\sqrt{r/g}$

STIFFNESS $k = W/r$

Fig. 2 Basic Principles

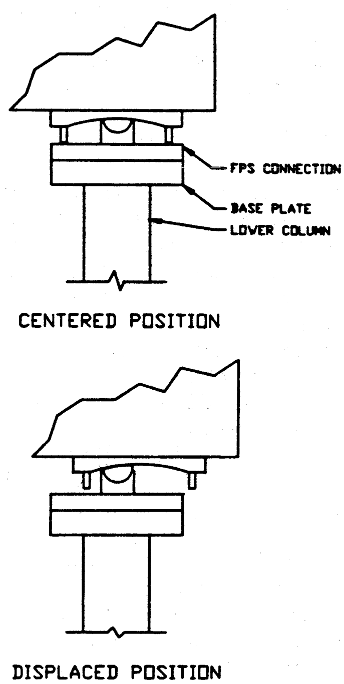


Fig. 3 FPS Operation

the dynamic response is controlled by the FPS isolators. The steady state response of the FPS to harmonic ground motions is plotted in Fig. 4. As the strength of the ground accelerations increase, the percentage of acceleration transmitted to the structure decreases. When considering long period earthquake ground motions, or near field pulses, the friction coefficient and natural period can be chosen such that there is no amplification of motions with periods greater than .707 times the FPS period.

The experimentally measured hysteretic loops for the lateral force versus displacement response of the FPS are shown in Fig. 5. The results are shown for test Structure II, subjected to an earthquake loading scaled to twice the strength of the 1940 El Centro record. The experimental hysteretic loops demonstrate ideal bi-linear responses with no observable degradation under repeated cyclic loading. The base shear loads measured for the various test structures are plotted in Fig. 6, together with the elastic response spectra for non-isolated structures. The initial elastic structure period of the test structures (the non-isolated period) can be read from the horizontal axis.

During the earthquake simulation tests, the test structures underwent small amplitude pendulum motions which were hysterically damped by the friction bearing materials. The hysteretic friction damping minimized the seismic drifts and displacements. The drifts occurring in the FPS and the structure above are plotted in Fig. 7. The results reported in Figs. 5, 6, and 7 are for the test structures supported on FPS isolators with a 2 sec. period and a friction coefficient of 0.10. Of primary interest are the results for the test structures with initial elastic periods of less than 0.9 sec.

The FPS approach has the flexibility to achieve a wide range of isolator properties. The effect of varying the period and friction coefficient of the FPS isolators is shown in Fig. 8. Changing the FPS 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.

The lateral restoring stiffness of the activated FPS connection is, 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 stiffness is directly proportional to the supported weight, is an important and unique property of the FPS which has advantageous effects on the torsion response of a structure. The center of lateral stiffness of the FPS connections coincides with the center of mass. Since the friction force is also proportional to the supported weight, the center of rigidity of the connections acting as a group always coincides with the center of mass of the structure. This property makes the FPS connections particularly effective at minimizing adverse torsional motions which would otherwise occur in asymmetrical structures. The torsion responses for test Structure I, with different imposed mass and stiffness eccentricities, are shown in Fig. 9.

Another unique property of the FPS connections, as compared to other sliding supports, is the design of the articulated slider. The semi-spherical design of the slider results in uniform contact pressures between the slider and the concave surface for any combination of lateral and vertical loads. This avoids edge gouging, and reduces high frequency stick-slip motions which occur with other sliding support systems. The floor spectra for the second story in-structure response of test Structure I is shown in Fig. 10.

The fact that the period is independent of the structure mass is another important and unique property of the FPS which has advantages in controlling the response of a supported structure. The desired period can be selected by simply choosing the radius of curvature of the concave surface. The period does not change if the structure weight changes or is different than assumed.

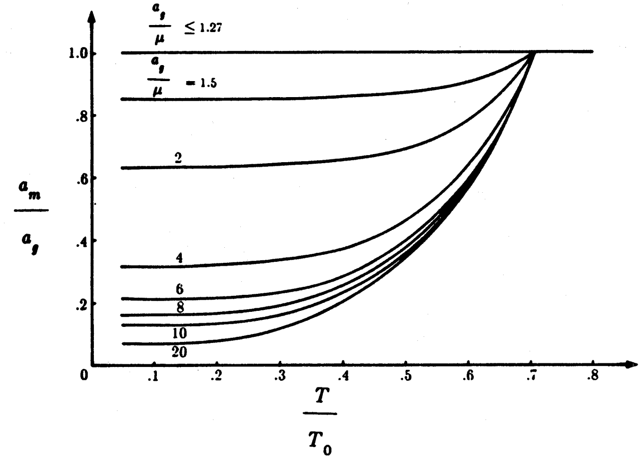


Fig. 4 Acceleration Transmissibility

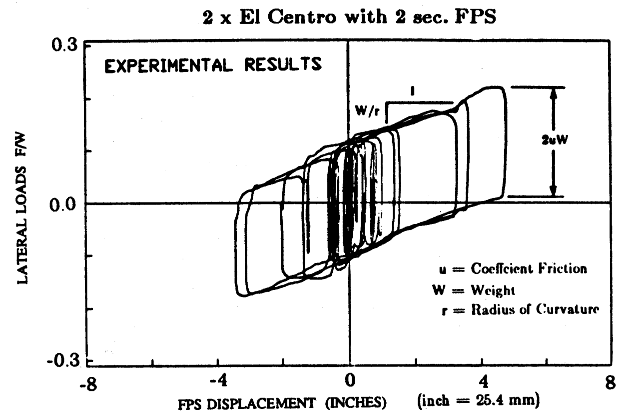


Fig. 5 Hysteretic Loops for the FPS

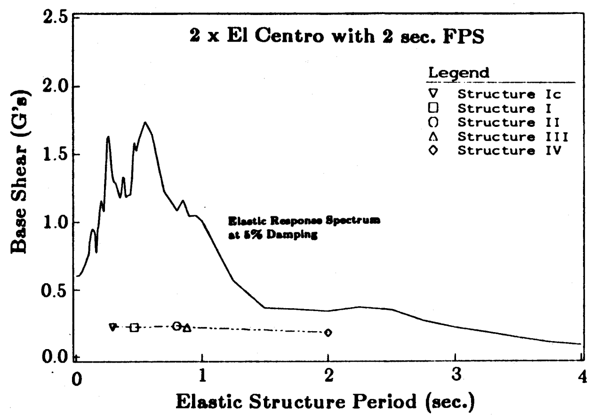


Fig. 6 Base Shear Response

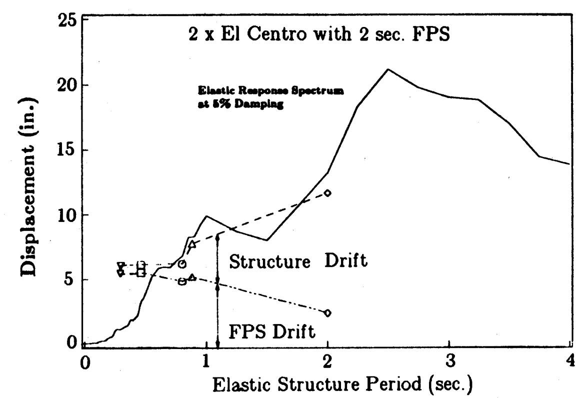


Fig. 7 Drift Response

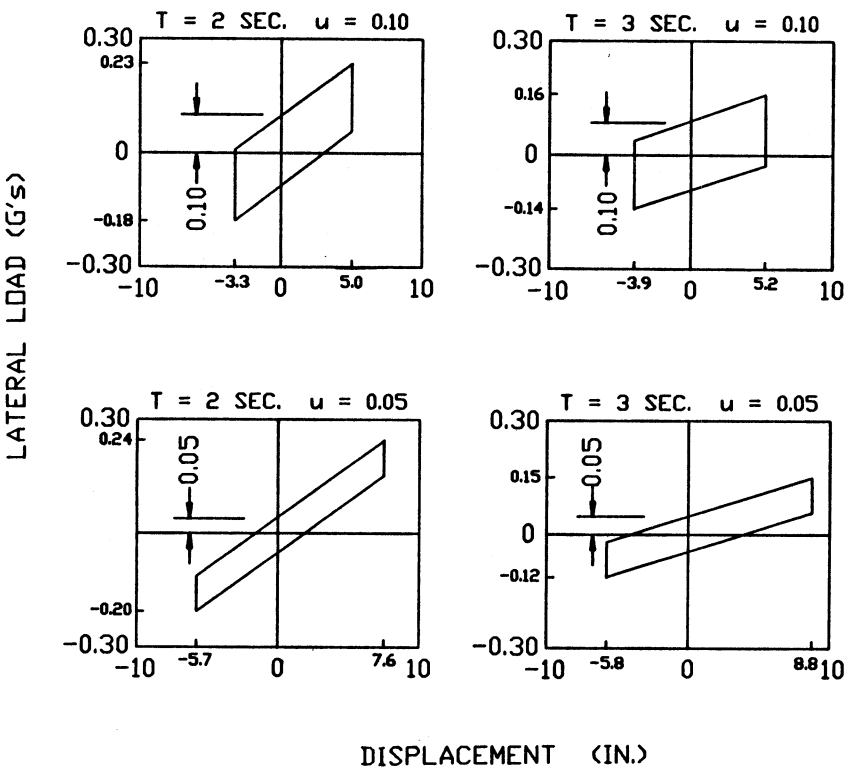


Fig. 8 Responses for Different FPS Periods and Friction Coefficients (2 x El Centro)

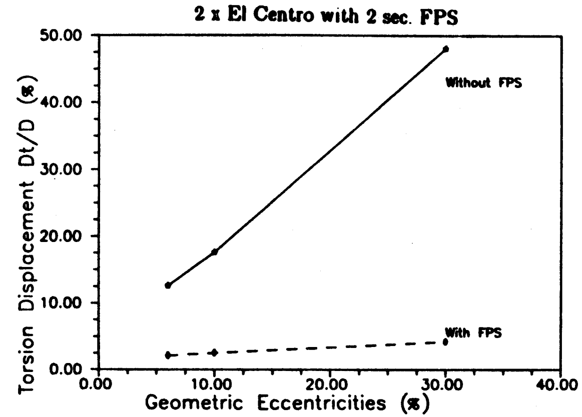


Fig. 9 Torsion Response

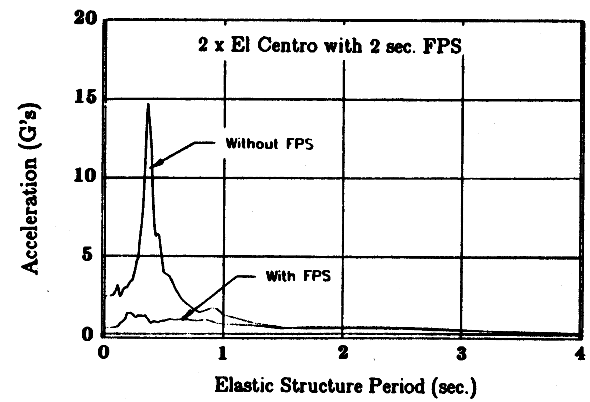


Fig. 10 Floor Spectra

The FPS approach permits the construction of compact isolators with small or very large load capacities, and which retain full strength and stability throughout their displacement range. The approach can be used to isolate light equipment items (Fig. 11), or heavy reactor buildings (Fig. 12).

The enclosing cylinder of the FPS isolator provides a lateral displacement restraint, and protects the interior components from environmental contamination. An uplift displacement restraint as used in an installation of the FPS is shown in Fig. 13. The displacement restraint provided by the enclosing cylinder provides an important safety feature in the event that earthquake loadings greatly exceed the design loads. In overload tests, when the isolator reached the lateral displacement restraint, the base shear loads increased, but the seismic loads and damage were always substantially less than would have occurred to the same structure without the FPS. Fig. 14 shows the response of Structure IV, with a 2 sec. FPS, subjected to the 1985 Mexico City earthquake.

CONCLUSIONS

The use of gravity and geometry to provide the restoring force achieves an effective and versatile seismic isolation system. FPS isolated structures demonstrate excellent seismic responses when subjected to severe earthquake ground motions including near field pulses, long period motions, and severe vertical motions. For properly designed structures, seismic loads are reduced by factors of 8 and greater. Torsional motions of eccentric and irregular structures are substantially reduced or eliminated. Because of the inherent simplicity, versatility, stability and durability of the FPS concept, it should become a major tool for the seismic resistant design of nuclear power facilities.

Reference: Zayas V.A.; Low S.S., and Mahin S.A., "The FPS Earthquake Resisting System: Experimental Report," UCB/EERC-87/01, Earthquake Engineering Research Center, University of California, Berkeley, June 1987.

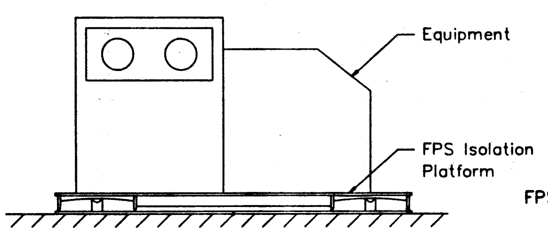


Fig. 11 Equipment Isolation

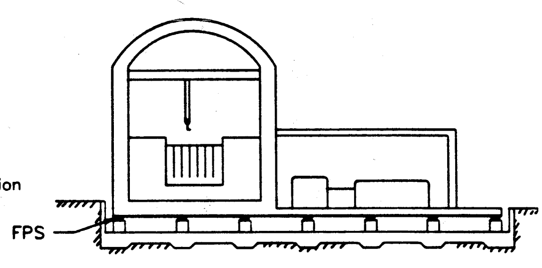


Fig. 12 Reactor Building Isolation

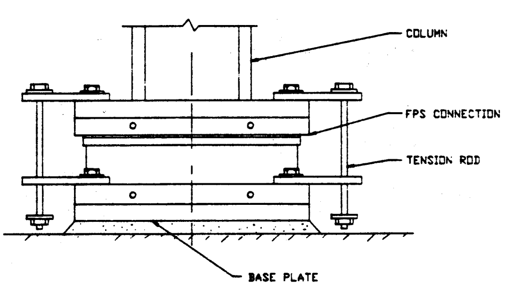


Fig. 13 FPS With Uplift Restraint

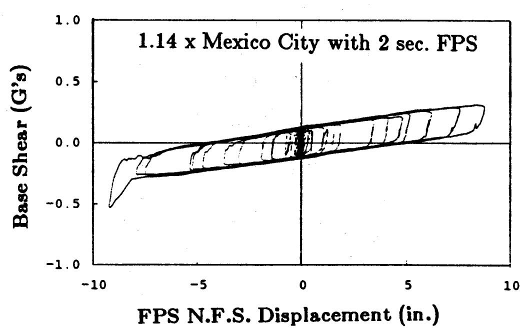


Fig. 14 Response of Displacement Restraint