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UPLIFT IN BASE-ISOLATED BUILDINGS WITH FRICTION PENDULUM BEARINGS

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ABSTRACT

One of the main concerns in the design of base isolated buildings utilizing friction pendulum (FP) bearings is uplift in the bearings resulting from the superstructure being subject to significant overturning forces. This effect may compromise the stability of the isolation system. Many designers opt for adding weight to the structure or installing uplift restrainer devices to eliminate uplift, significantly increasing the construction cost. This paper describes the design approach utilized in the Mills Peninsula Hospital, where limited uplift of the FP bearings was allowed to occur. This hospital building is located in the city of Burlingame, California, is a new 441,000 square feet, six-story, base-isolated, steel-framed structure designed to allow for immediate occupancy after a major seismic event (M: 8.0) generated by the adjacent San Andreas Fault. Nonlinear time history analysis was performed using seven sets of ground motions for two levels of performance to evaluate the building response and uplift effects on the bearings. Analysis results indicate that maximum uplift in the bearings is less than 3/4" at the maximum capable earthquake, which corresponds to the 950-year return period event. The design assumptions were validated through testing of the FP bearing, including verification of the capacity of the bearing to undergo momentary uplift at maximum horizontal displacement (separation above sliding surface) and reengagement without ejecting the slider, or sustaining damage or failure of bearing components.

Introduction

Essential facilities such as hospitals are expected to remain operational following a major earthquake event, as they are critical for post-earthquake disaster response and recovery. The use of base isolation provides in most cases, the most cost-effective solution to achieve this performance goal, protecting the integrity of the structure and its contents.

The friction pendulum (FP) bearings provide an effective means of base isolation for the structure, decoupling the building response from the seismic ground shaking, and dissipating energy through the friction and restoring force typical of these systems. However, one of the disadvantages in the utilization of FP bearings lies in the lack of tension stiffness, resulting in bearing uplift when the superstructure is subjected to significant overturning forces, especially if

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the lateral-force resisting frames are limited to one or two bays. This behavior may compromise the integrity of the isolation system and the stability of the structure. Use of traditional design approaches to limit the uplift, such as increasing the number of frame bays or using uplift restrain devices, may be impractical and cost prohibitive for certain structures.

This paper presents a case study of the Mills Peninsula Hospital in Burlingame, California, currently under construction. It is a base isolated structure with FP bearings, where limited uplift of the bearings was allowed to occur. Nonlinear time history analysis was performed utilizing seven sets of ground motions for two performance levels to evaluate the response of the structure and uplift effects on the bearings. A prototype bearing was tested to evaluate the capacity of the isolator to undergo uplift without losing stability or sustaining damage to any of its components.

Building Description

The Mills Peninsula Hospital building is a 441,000 square-foot, 7-story, base isolated, steel frame structure located in the City of Burlingame, California. This new 243-bed acute care hospital building is part of the Mills Peninsula Hospital replacement project, which also includes an 809-car parking garage and a 200,000 square-foot medical office building. The governing code was the 2001 California Building Code, largely based on the 1997 Uniform Building Code.

The performance goal for the hospital building is to allow for immediate occupancy after a major seismic event (M8.0), occurring 2.7 km away on the San Andreas Fault. In order to achieve this performance, the lateral force resisting system was designed to remain essentially elastic in the Design Basis Earthquake (DBE), which corresponds to the 475-year return period event. The lateral force resisting system, including the isolation system, will remain stable during the Maximum Credible Earthquake (MCE), with limited ductility for other structural components. The MCE event has a 950-year return period. The projected ground motions were severe, with a spectral acceleration of 0.291g at 3 sec for the MCE.

The building is located on a sloping site, with a partial lower level on the east side of the hospital. The Lower Level has a story height of 19'-0", to best suit site topography. Level 1 above, with a story height 17'-6", encompasses the roughly rectangular building footprint of 440' in the east-west direction and 302' in the north-south direction, with a deep cutout adjacent to the main entry (see Figs. 1 and 2). The southwest quadrant does not continue above the first level to the second level, which has a 15'-0" story height. Level 3 through Level 6, with typical story height 15'-0", are set back from the second level and are composed of two 'L' shaped patient towers linked by the elevator core. There is a seismic joint separating the two towers located at the east side of the elevator core from Levels 4 through roof. The east tower terminates at Level 5. The lateral system for the superstructure is an ordinary concentric braced-frame.

The building is supported by a total of 171 friction pendulum isolators (FP). The plane of isolation is under the Lower Level for the extent of its footprint and stepped up to just under Level 1 for the balance of the plan. There were 80 bearings at the Lower Level and 91 at Level 1. The bearings are supported by concrete pedestals on isolated spread footings, which are founded in the native soil (Colma Formation) of the site. The FP bearings were fabricated by Earthquake

Protection Systems (EPS) in Vallejo, California. The bearing (Fig. 3) consists of an inner articulated slider with two inner concave spherical surfaces, which will slide along the two main concave spherical surfaces. The isolator bearings have a maximum displacement capacity of 32 inches, with radius of curvature of the main concave surface of 88 in, resulting in a nominal period of 4.1 sec. The nominal value of dynamic coefficient of friction is 0.05. Upper and lower bound values of the coefficient of friction are 0.04 and 0.07, respectively, and are utilized in the analysis to account for fabrication tolerances, aging, temperature and surface contamination. Two different types of isolators were provided based on the maximum gravity and vertical earthquake loads acting on the bearing: Type A with a maximum load capacity of 1050 kips and type B with a maximum capacity of 2700 kips.

Since the displacement demand at the near-fault site was large, 32 linear viscous dampers with maximum force capacity of 250 kips were provided. These dampers reduced the maximum displacement in the isolation system, reducing the size of the bearing, as well as the foundation pedestal and perimeter moat. The upper and lower bound values for the damping coefficient are 6 and 4 kip-sec/in, respectively.

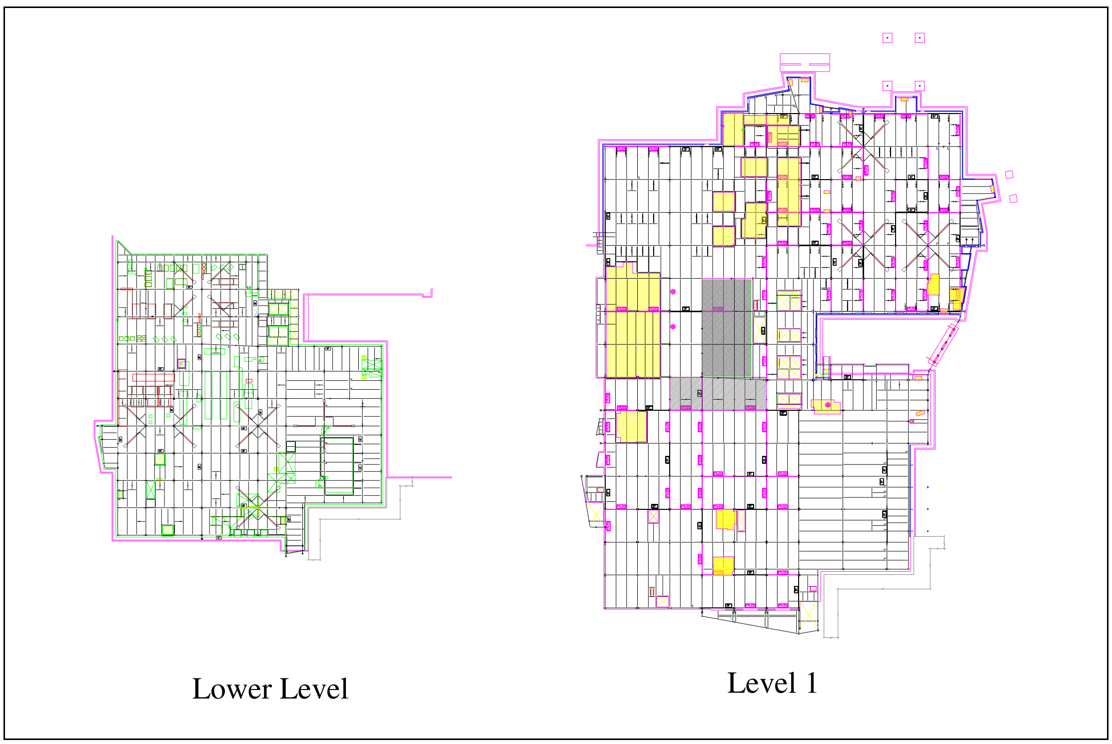

Figure 1. Floor plan at the isolation level.

Above the isolation system, the lateral force-resisting system consists of steel concentric braced frames in both single bay diagonal and chevron configurations to accommodate space-planning requirements. Outrigger trusses (see Fig. 4) are provided at the roof level and Level 1 of single bay braced frames to improve distribution of overturning forces, and reduce bearing uplift at braced frame columns. The trusses were designed to remain elastic at 1” differential vertical displacement within a single bay.

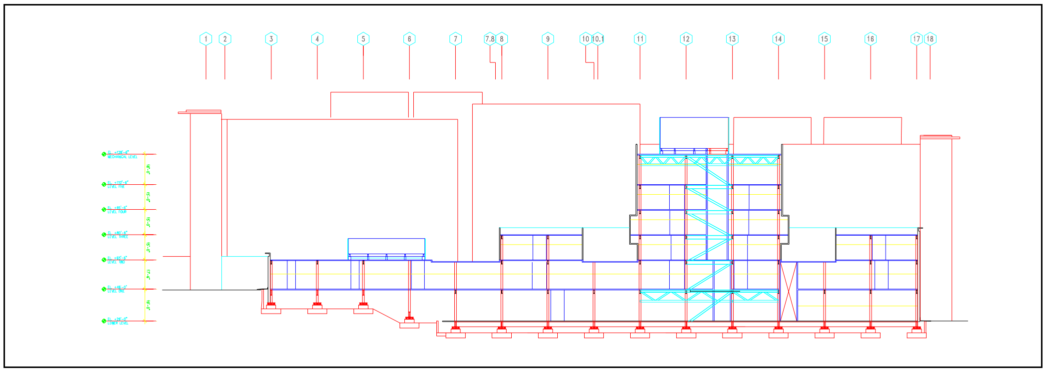

Figure 2. Section through the hospital building.

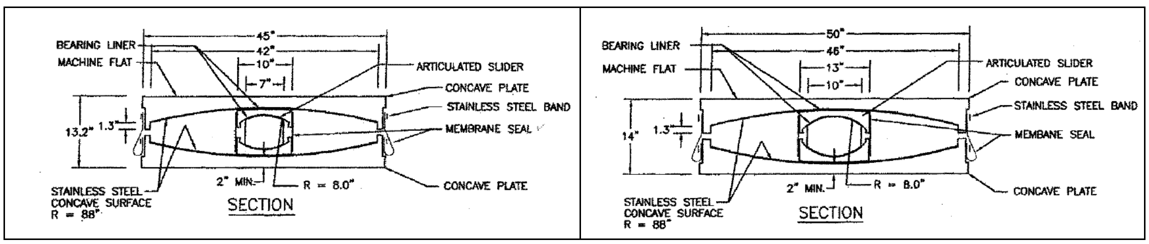

Figure 3. Cross section of isolator type A (left) and type B (right).

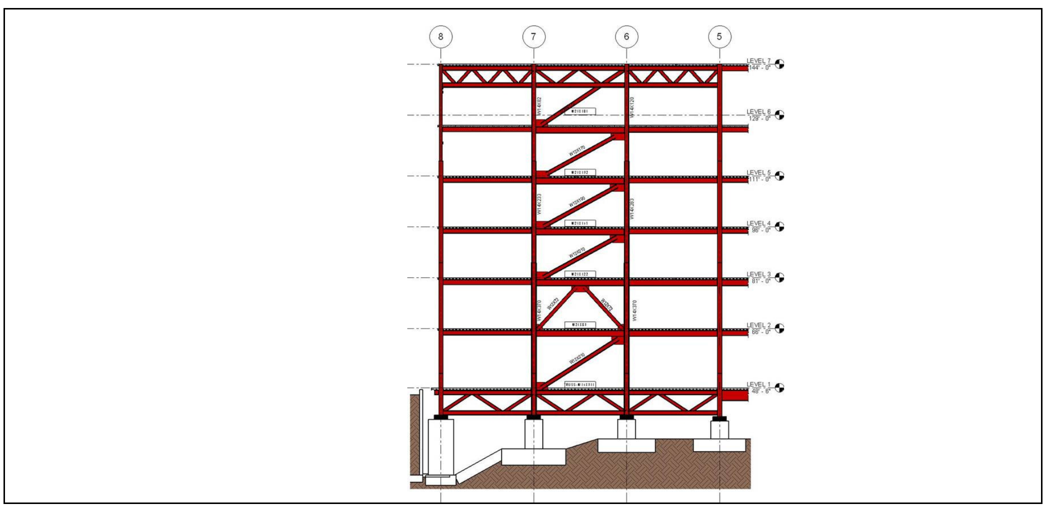

Figure 4. Outrigger truss at typical braced frame.

Analytical Model

The building was analyzed utilizing the computer program ETABS v8.4.6 (Computers and Structures, 2004). The lateral resisting system was explicitly modeled with beams, diagonal and column elements, using rigid diaphragms to represent the building floors. Double concave FP bearings were modeled utilizing *Isolator 2* properties, based on an equivalent radius of sliding calculated for a single FP isolator (Fenz and Constantinou, 2006). Linear viscous dampers were modeled utilizing the *Damper Element*. Design of the superstructure, isolation framing and foundation was based on the results from the DBE time history analysis, assuming that the system will remain essentially elastic. The isolation system, superstructure and foundation were checked for stability with the results from the MCE time history analysis. At this performance level, limited nonlinearity was expected to occur (ϕ=1.0 and use of expected strength of 25% above nominal) at the superstructure and outrigger trusses. The maximum and minimum response parameter of interest from the time history analysis were taken as the maximum or minimum absolute value for each earthquake pair and then averaged over the 7 pairs of ground motion records. Each earthquake pair was rotated 90 degrees. Upper bound isolator and damper properties were used to develop maximum uplift and lateral seismic forces. Lower bound values were used to develop maximum lateral displacements at the plane of isolation.

Since correct characterization of uplift effects was important for isolator performance, the computer program 3DBASIS-ME-MB (Tsopelas et al., 2005) was utilized to validate the results obtained from the ETABS program. The program 3DBASIS-ME-MB is an excellent benchmark for this comparison, since its results correlate very well with experimental results, as well as with results obtained from more sophisticated analysis programs such as ABAQUS.

Analysis Results

Output obtained from a nonlinear response-history analysis of the seismically base isolated building subject to bidirectional excitations, utilizing computer programs ETABS and 3DBASIS-ME-MB, was compared to validate accuracy of the uplift prediction. Fig. 5 shows the good correlation between the two programs in the reported values of axial load and uplift occurrence at every instant in time. Although both programs predict similar isolator maximum displacement, 3DBASIS-ME-MB predicts slightly more axial load and shear on the isolators. One possible explanation for this difference is that ETABS models explicitly the superstructure stiffness, as well as the rocking effects in the structure, providing additional energy dissipation mechanisms not present in 3D-BASIS-ME-MB. In general, the results demonstrate that programs ETABS and 3DBASIS-ME-MB produce comparable output, and that ETABS adequately represents uplift effects of the base isolated structure.

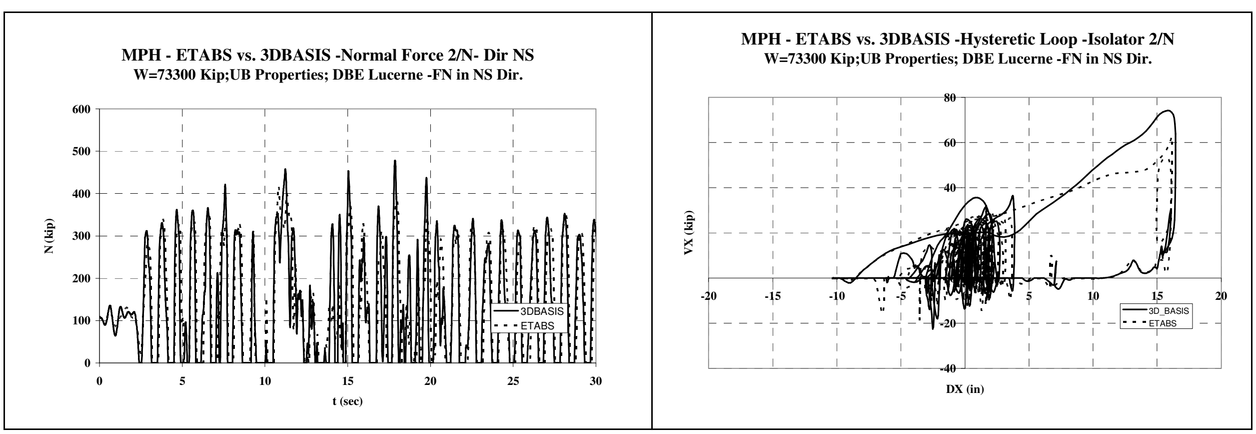

Figure 5. ETABS vs. 3DBASIS-ME-MB- comparison.

The maximum values of selected response parameters from the ETABS model are presented in Table 1 for the DBE and MCE time history analyses. These analyses were performed utilizing upper bound isolation properties for all reported parameters except the vector sum displacement, which was determined by utilizing lower bound properties. The little difference observed between the two performance levels are due to scaling of the time histories, resulting in the DBE parameters to be very close to those of the MCE level. Note that the maximum uplift values at the MCE and DBE performance levels are 0.65 inches and 0.59 inches, respectively.

Table 1. Maximum response parameter values from ETABS model.

Level	**Base Shear (V/W)**	**Vector Sum Displ (in)**	**Max Isolator Normal Force (kip)**	**Uplift (in)**
DBE	0.17	-	2308	0.59
MCE	-	27.6	2352	0.65

Fig. 6 depicts a representative result of the percentage of total supports uplifting for each increment of uplift, as well as the percentage of isolators experiencing uplift at each time instant subject to the scaled Landers-Lucerne record at MCE level. It can be observed that for this particular case, approximately 43.8% of the isolators (75 in total) will experience uplift at any instant in time during the seismic event. The uplift is limited to columns that are part of the lateral force resisting system. Less than 5% of the isolators (approximately 9 bearings) will experience uplift values greater than 0.32 inches. Fig. 6 also shows that in general only a small fraction of the bearings (about 12% or 20 isolators) undergo uplift at any time instant, with a maximum peak value of 15% occurring at the most intense seismic excitation pulse. The relatively low number of isolators and uplift values reported in these examples are within reasonable limits that do not compromise the stability of the isolation system.

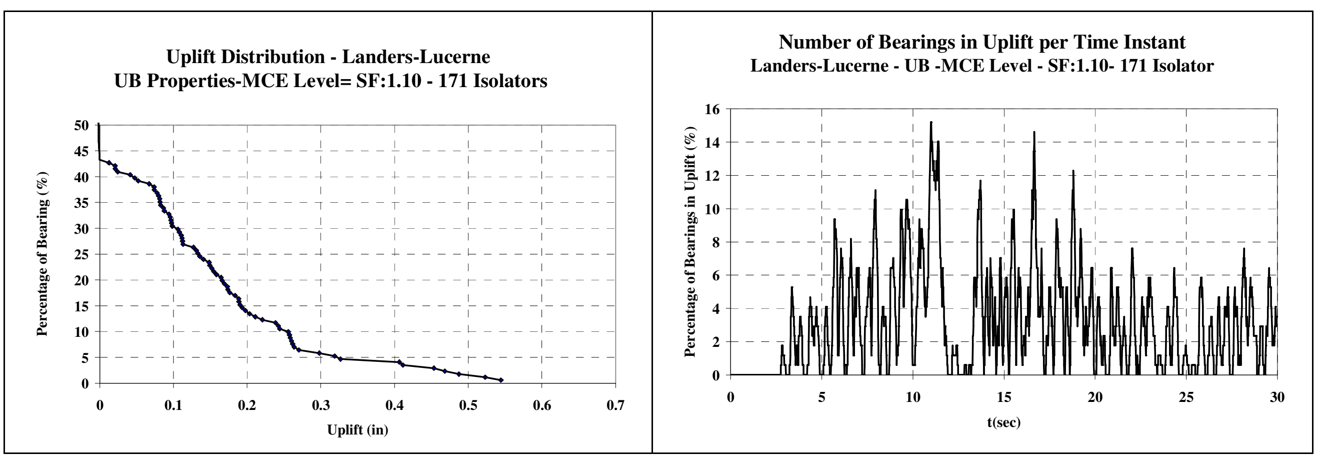

Figure 6. Percentage of uplifting supports vs. uplift and number of bearings in uplift per time instant for the scaled Lucerne-Landers record at the MCE level.

FP Bearing Pre-prototype Test

Two separate prototype tests were conducted to verify the stability of the isolator uplifting during estimated response from the analysis. The testing was performed at the EPS test facility located in Vallejo, California, utilizing their testing machine shown on Fig. 7. The machine consists of a moving table connected to five horizontal hydraulic actuators and the steel horizontal reaction frame. The table slides over a low friction-sliding surface attached to the vertical reaction frame. The vertical load is applied by 15 vertical actuators connected to the vertical reaction frame and platen. The machine is capable of testing bearings under controlled conditions of vertical load and lateral movement.

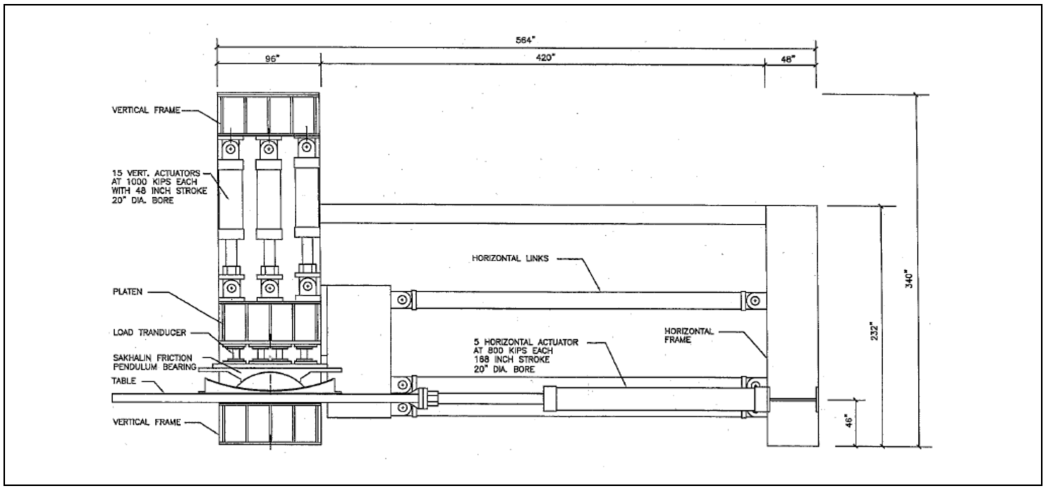

Figure 7. Bearing testing machine.

Both prototype tests were conducted at low velocity (>0.1 in/sec) to observe the behavior of the inner slider. The testing load corresponds to the average long term compression load (dead plus 50% of the live design load), and subject to 94% of the maximum horizontal displacement capacity of the isolator (Dmax) and maximum uplift value at the MCE level. In this particular case, compression loads are 290 kips and 740 kips for isolator type A and B, respectively. The maximum displacement (0.94Dmax) was 28 inches and the maximum uplift was 1". This value is conservative and was defined based on the uplift values obtained from time history analysis at the MCE level.

Fig. 8 shows the various stages of lateral and vertical movement associated with the first uplift test. The first uplift test consisted of applying the specified minimum compression load to the bearing (Fig. 8a), then displacing it to the MCE maximum distance, which is estimated at 0.94Dmax (Fig. 8b) and returning it to zero position. At zero position, the bearing is unloaded and the top concave plate is uplifted by 1 inch as shown on Fig. 8c. Maintaining it in its uplifted position, the top plate is displaced 0.47Dmax (14 inches) as shown on Fig. 8d. At this position, the bearing is reloaded to its minimum compression load and displaced another 0.47Dmax in the same direction (Fig. 8e), for a total displacement of 0.94Dmax. Maintaining the applied load, the isolator is returned from the maximum displaced position to the zero position, as shown on Fig. 8f. The acceptance criterion for this test is that the slider remains inside the retainer ring of the top and bottom concave plates.

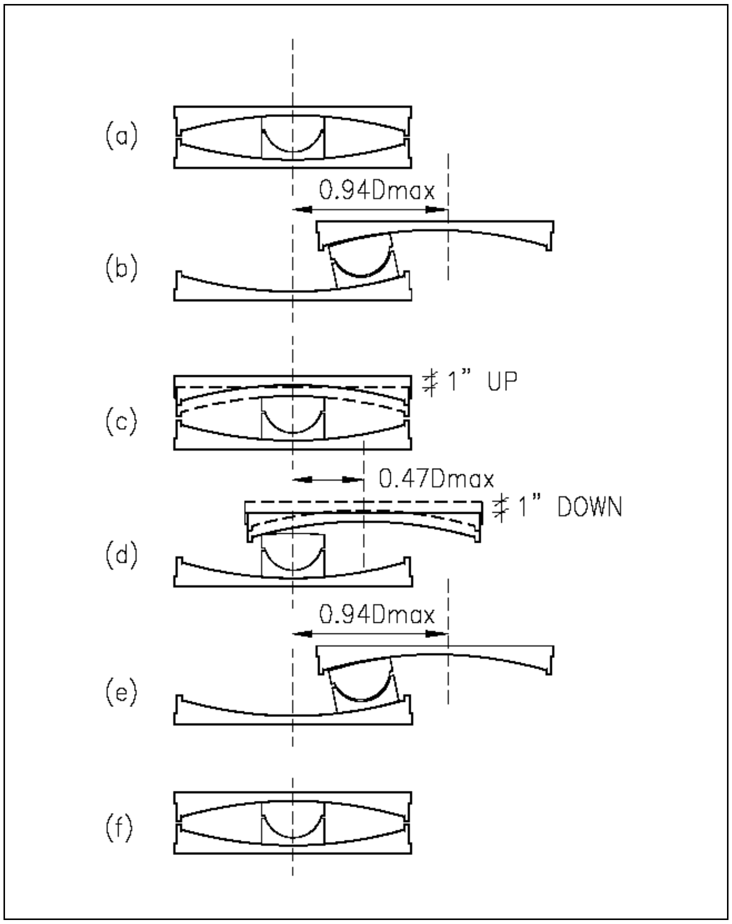

Figure 8. Cross section of FP bearing at various stages during test 1 (MPTA1.15).

Fig. 9 shows the various stages of lateral and vertical movement associated with the second uplift test. For this uplift test, the bearing was loaded to the specified minimum compression load (Fig. 9a) and then displaced to 0.94Dmax (Fig. 9b). From this displaced position, the bearing is unloaded and then the upper concave plate is uplifted by 1 inch, as shown on Fig. 9c. Maintaining the uplifted position, the top concave plate is recentered to the undisplaced position (Fig. 9d). Then the minimum compressive load is reapplied to the bearing and a three-cycle compression-shear test is performed with amplitude of 0.65Dmax (19 inches), as shown on Fig. 9e. Finally, the bearing is returned to the undisplaced center position as shown on Fig. 9f. The acceptance criterion for this test is that the slider remained inside the retainer ring of the top and bottom concave plates and that the average 3-cycle dynamic friction shall be in the range of $\mu_{fast,nom} \pm 0.01$, where $\mu_{fast,nom}$ is the nominal coefficient of friction. In this particular case, the nominal coefficient of friction is 0.05.

Hysteretic loops for the first and second uplift tests of isolator type A are shown on Fig. 10, with letters identifying the different test steps per Figs. 8 and 9. It can be observed that the bearing maintains the force-displacement relationship once the uplift is eliminated and the bearing is in compression. In all cases, the bearing maintained capture of the slider. The average 3-cycle dynamic friction was not less than 4% and not greater than 6%, validating the upper bound and lower bound coefficient of friction values utilized in the analysis of the structure.

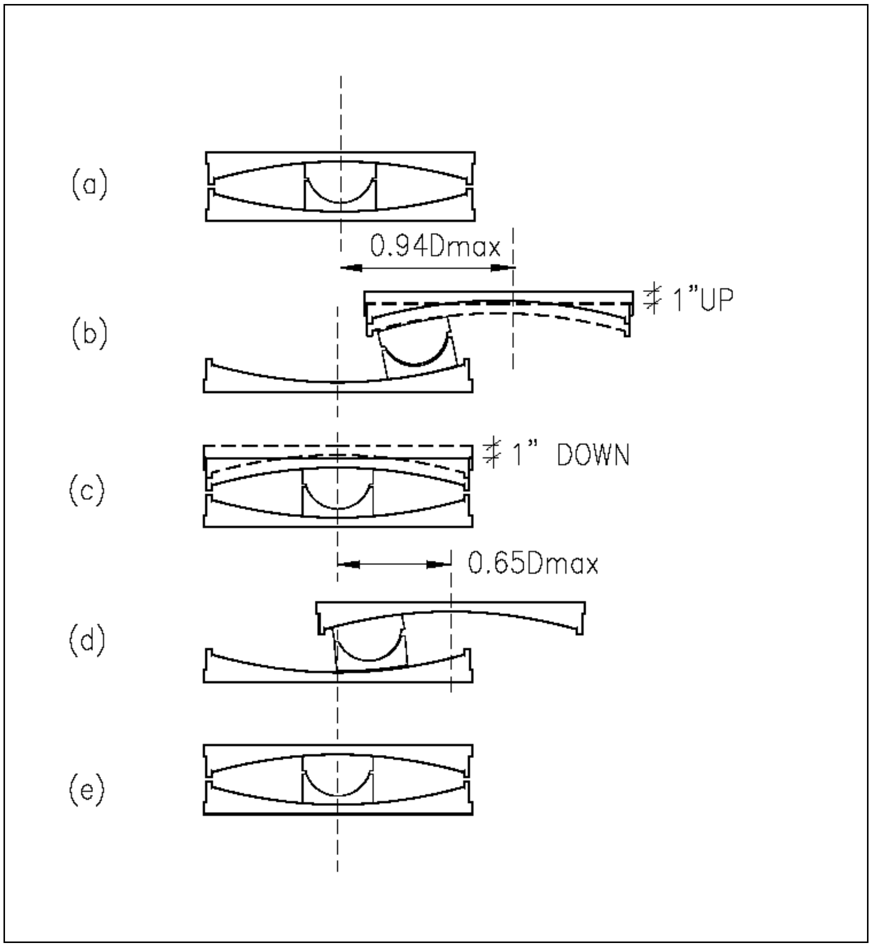

Figure 9. Cross section of FP bearing at various stages during test 2 (MPTA2.16).

After completion of the tests, the bearings were disassembled for inspection and the slider and stainless overlay were examined. No visible signs of structural yielding or permanent structural deformation were observed in the slider or in the concave plates.

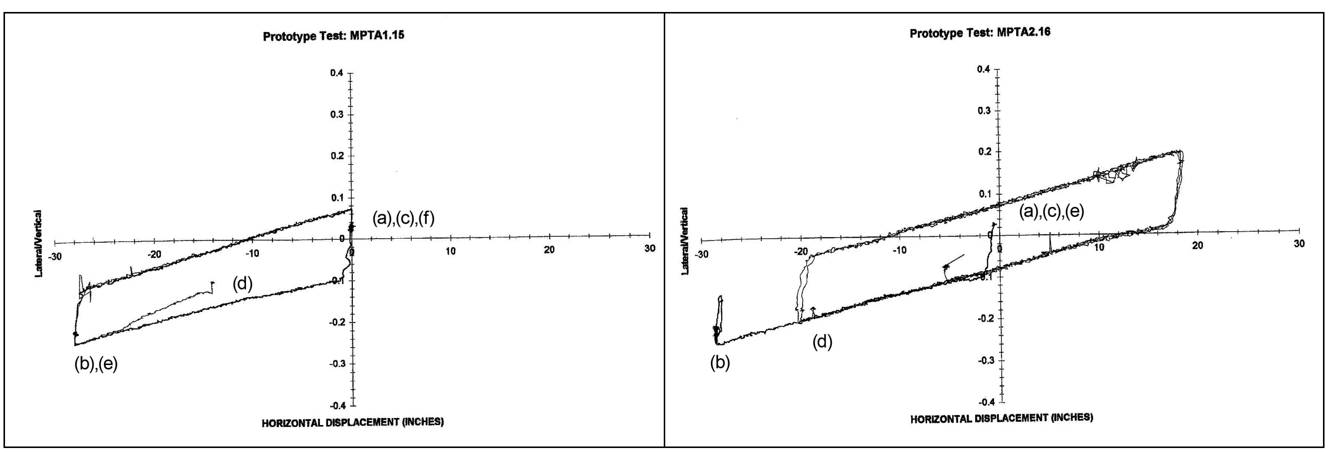

Figure 10. Force- Displacement hysteretic curves for prototype bearings tested under uplift.

Conclusions

Uplift in the bearings is a major concern when friction pendulum bearings (FP) are utilized to provide base isolation in buildings that are subject to significant overturning forces. This effect may compromise the stability of the isolation system if not properly accounted for in the design. There are several options to eliminate uplift such as adding weight to the structure or installing uplift restrainer devices to eliminate uplift. In many cases, these solutions are not practical and will significantly increase the construction costs. In response to this concern, a different design approach was utilized where limited uplift of the FP bearings was allowed to occur. This approach was implemented in the Mills Peninsula Hospital building in Burlingame, California, which was designed to allow for immediate occupancy after a major seismic event (M:8.0) generated by the nearby San Andreas fault.

Nonlinear time history analysis was performed to evaluate the building response and uplift effects on the bearings. The capacity of the FP bearing to undergo the design maximum uplift deformation without compromising the stability of the isolation system was validated through testing. Test results indicated that the FP bearings may experience uplift separation above the sliding surface up to 1" at the maximum horizontal displacement and reengagement without ejecting the slider. No appreciable damage of the bearing components were observed during the test.

Acknowledgments

The authors recognize the contribution of Dr. Charles Kircher, who developed the specification for the uplift prototype test utilized in this study. His advice during the design process and later preparation of the quality control testing criteria of the bearings is greatly appreciated.

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