SEISMIC ISOLATION FOR STRONG, NEAR-FIELD EARTHQUAKE MOTIONS

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SUMMARY

As a consequence of the strong ground motions recorded during the Kobe and Northridge Earthquakes, stronger design earthquakes are now controlling the seismic design of important structures. These stronger earthquakes include the effects of near-field pulses, fault-normal motions, and near-field deep soil site motions. It is costly to design structures to withstand these strong earthquake motions using a conventional strength approach. For non-isolated structures, structural frame drift and force demands can exceed 10 to 20 times the structure's elastic capacity, risking major structural damage. For isolated structures, the seismic isolation bearings need to have displacement capacities and isolator periods which exceed those of the typical isolation bearings used in the past.

The seismic isolation design and construction of three public works structures is presented. They include the San Francisco Airport International Terminal, the Hayward City Hall, and the Benicia-Martinez Bridge. These important structures are located near major faults in California and were designed to resist strong earthquake motions. Skidmore, Owings & Merrill, the Structural Engineer for the San Francisco Airport International Terminal, performed comparative designs and analyses for various structural systems, including; a moment frame, three braced frame schemes, one moment and three braced frame schemes with viscous dampers, and a moment frame with seismic isolators. Only the isolated structure could satisfy the design criteria. The Hayward City Hall is an essential government facility that is located 200 yards from the Hayward fault. The structure was designed by KPFF Consulting Engineers to withstand a magnitude 7 earthquake with no disruption to its operation. The Benicia-Martinez Bridge is an important transportation artery in the San Francisco Bay Area and the seismic upgrade of the bridge had to be completed without disrupting traffic flow. The seismic retrofit was designed by Imbsen & Associates for a MCE on the Green Valley Fault. The spectral accelerations are more than 30 times typical seismic lateral design forces.

These important structures were designed to avoid seismic damage, at lower construction costs than alternative construction methods. They use Friction Pendulum bearings with periods between 3 and 5 seconds, lateral displacement capacities between 20 to 53 inches, and vertical load capacities of up to 6 million pounds.

INTRODUCTION

An effective non-isolated structure design, or isolated structure design, must be able to absorb the ground displacements generated by the strong, near-field pulses so as to avoid excessive deformations and instability in thestructure. The near-field ground motion is the primary factor which dictates the seismic displacement demands and performance. The period of the isolation bearings is the primary bearing parameter which controls how much of the seismic displacement demand is absorbed by the bearings. Isolation bearings with longer periods will absorb a greater percentage of the total displacement demand. Dynamic analysis results provide the total lateral drift displacement which needs to be accommodated by the structural system (Figs. 1 and 2). Large drift displacement demands for non-isolated structures can substantially exceed the ductility capacities and stability limits of conventional framing systems.

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An example structural drift response to a near-field, deep-soil ground motion is shown in Fig. 1. The structure's essentially elastic limit is calculated to be two times the nominal first yield, accounting for material, member, and frame over-strengths while maintaining an essentially linear elastic lateral drift response. This is equivalent to using a 1.33 allowable stress increase and an Rw of 2.0, as the essentially elastic limit for a typical code based seismic design. The near-field, deep soil ground motion results in a drift displacement demand for the non-isolated structure of 48 inches. These drift demands are 4.8 times the structure's essentially elastic limit, and 9.6 times nominal first yield, with anticipated severe structural damage and a risk of collapse. For the same structure and ground motion, adding seismic isolators with a 2 second period results in shear forces and drifts 1.6 times the structure's essentially elastic limit, with anticipated repairable structural and architectural damage. For the 3 second isolator period, bearing forces remain below the structure's essentially elastic limit, with no significant damage anticipated.

An example structural drift response to a near-field, fault-normal ground motion is shown in Fig. 2. The drift displacement for the non-isolated structure is 18 inches, and seismic shear force and drift demands are four times the structure's essentially elastic limit. For the same structure and ground motion, adding isolator bearings with a 3 second period, results in shear forces and drifts 2.5 times the structure's essentially elastic limit. For the 5 second isolator period, bearing forces remain below the structure's essentially elastic limit, with no significant damage anticipated.

For the non-isolated structures, shear forces 8 to 10 times nominal first yield result in major structure yielding and loss of stiffness, with local strains which may exceed member ductility capacities. Large structural frame drifts, ranging from 18 to 48 inches, require the stiffness and stability calculations to account for the effects of eccentric gravity loads (P-delta moments). Large drift displacements reduce the structure's lateral stiffness, which can cause instability and collapse. With isolated structures, large drift displacements in the bearings can reduce the bearing lateral stiffness, and can cause bearing instability. Bearing stability should be verified using the maximum vertical bearing loads, including dead, live and seismic loads. This load differs from the code-specified average dead loads used to design the isolator's lateral stiffness and period. Large displacements in the isolation bearings can also result in large eccentric gravity load moments in the supported structures, which need to be accounted for in the structure design.

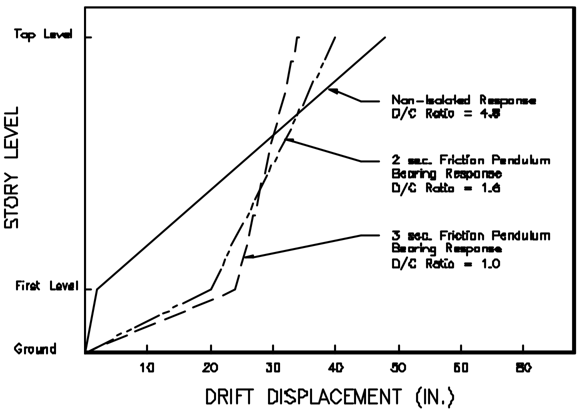


Fig. 1: Structural Response for Deep Soil Ground Motion One Mile from Fault

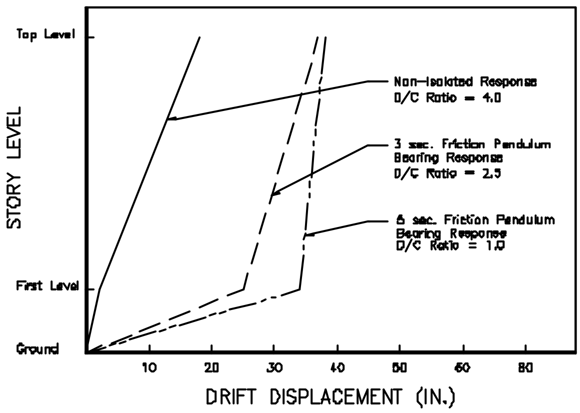


Fig. 2: Structural Response for Fault Normal Ground Motion 200 yards from Fault

APPLICATION EXAMPLES

San Francisco Airport International Terminal

The San Francisco Airport International Terminal building, with over 22 million cubic feet of interior space, is the largest isolated building in the world. The building has dramatic architectural features, including: an expansive interior lobby that spans 700 by 200 feet, with a 94 foot story height, enclosed by glass exterior walls (Fig. 3). Moreover, the building spans over the main highway access to the remainder of the San Francisco Airport. The architectural and structural design was done by Skidmore Owings, and Merrill, of San Francisco. This landmark building incorporates 267 Friction Pendulum bearings to protect it from the severe ground shaking expected to occur at this deep soil site, located 10 miles from the San Andreas fault. The Friction Pendulum bearings [Al-Hussaini 1994; Mokha 1991; Zayas 1993] use an equivalent pendulum dynamic motion to achieve the desired isolated periods and displacement capacities (Fig 5). The bearings are located at the tops of the walls which support the building over the highway, and on the grade level footings for the two sides of the building which are adjacent to the highway (Fig. 6).

Fig. 3: San Francisco Airport International Terminal

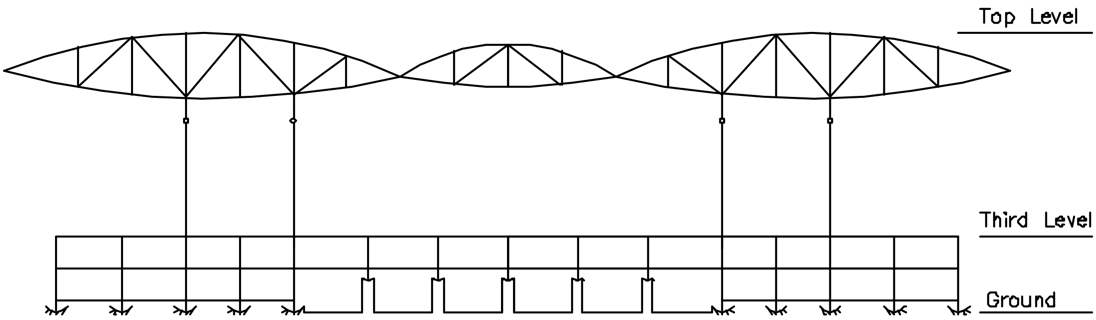


Fig. 4: San Francisco Airport International Terminal Structural Frame

The seismic performance objective was no structural damage, and minimum architectural damage, during the magnitude 8, site specific Maximum Credible Earthquake (MCE). The critical seismic design criteria was the 10 inch maximum drift deflection that could be accommodated by the glass exterior walls enclosing the lobby level. Falling glass posed a serious safety consideration for the public loading and boarding areas. An important structural consideration was the low redundancy in the structural frame of the lobby story (Fig. 4). An essentially elastic response was desirable for both controlling drift and to offset the low structural redundancy.

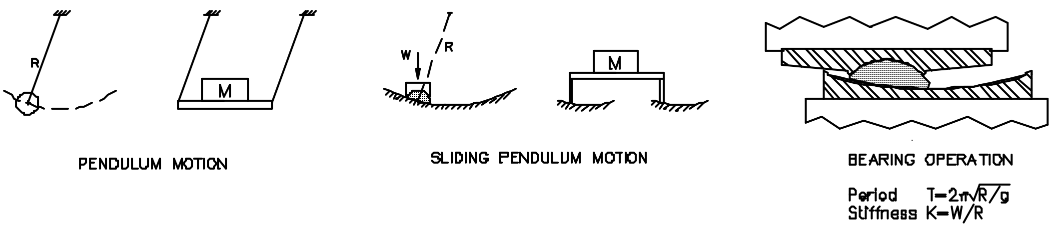


Fig. 5: Basic Principles of the Friction Pendulum Bearing

Skidmore Owings and Merrill performed comparative designs and analyses for various structural systems, including; a moment frame, three braced frame schemes, one moment and three braced frame schemes with viscous dampers, and a moment frame with seismic isolators. Although a moment frame was preferable to maintain the open space architecture in the lobby, several braced frame schemes were also investigated to reduce the drift and over-stress ratios. The seismic shear forces and story drifts for the primary structural systems considered are shown in Figs. 7 to 9. For the moment frame design, the story shear in the lobby level was 3.0

times the elastic strength capacity, and the story drift was 43 inches; four times the deflection capacity of the window walls. For the 100% braced frame design, the story shear in the lobby level was 2.4 times the elastic strength capacity, and the story drift was 23 inches; twice the deflection capacity of the window walls. With the braced and moment frame designs, the increase in member and joint sizes required to meet the performance objectives exceeded practical steel fabrication limits, and would have been prohibitively expensive.

Since the conventional frames could not satisfy the performance criteria, the addition of viscous dampers to the braced and moment frame designs was then investigated. For the braced frame with viscous dampers, the story shear in the lobby level was 2.3 times the elastic strength capacity, and the story drift was 30 inches; three times the deflection capacity of the window walls. For the braced frame, adding dampers in line with the diagonal braces, reduced the stiffness of the braces, and increased the frame drift by 30%. For the moment frame with viscous dampers, the story shear in the lobby level was 1.8 times the elastic strength capacity, and the story drift was 28 inches; three times the deflection capacity of the window walls. For the moment frame, adding dampers increased the frame stiffness and shear forces, but reduced drift by 35%.

Since the frame designs with added viscous dampers still did not satisfy the performance criteria, the use of seismic isolators was then investigated. Isolation bearing designs were done for lead-rubber, high damping rubber, and Friction Pendulum seismic isolators. For the moment frame design, with seismic isolators added, the story shear in the lobby level was 1.0 times the elastic strength capacity, and the story drift was 10 inches; within the deflection capacity of the window walls. This satisfied the seismic performance objectives, and maintained the preferred open architecture of the moment frame.

The selected seismic isolators were Friction Pendulum bearings, with a dynamic period of 3 seconds, a dynamic friction of 6%, and a displacement capacity of 20 inches. An important feature of the Friction Pendulum bearings is that during seismic events, the spherical articulated slider remains at the column centerline, which maintains the structure's gravity loads concentric on the steel frame above. This feature of Friction Pendulum bearings resulted in a significant savings in the structural steel frame costs for the International Terminal. Rubber isolation bearings resulted in eccentric gravity loads on the steel frame, and corresponding increased stresses in the columns and beams. The use of Friction Pendulum bearings also maintained higher vertical load factors of safety in the displaced positions, and the inherent fire resistance of heavy steel members. The unique features of the Friction Pendulum bearings saved 680 tons of structural steel compared to the steel structure required to accommodate the rubber isolation bearings

Fig. 6: San Francisco Airport Bearing Installation

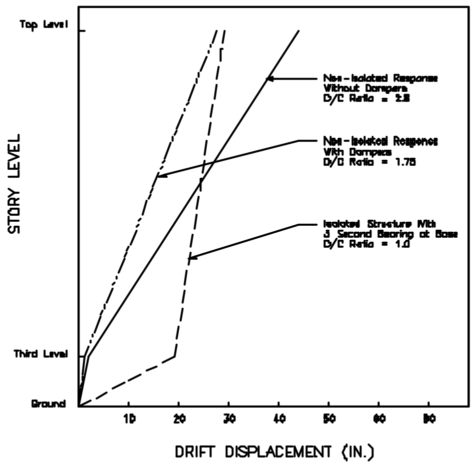
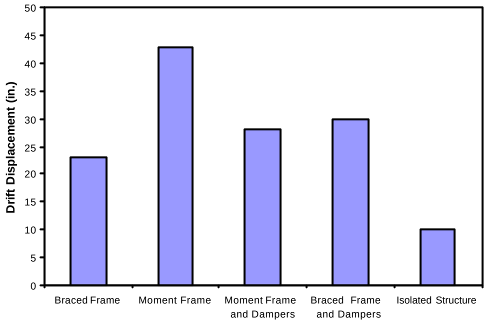


Fig. 7: San Francisco Airport Structure Response



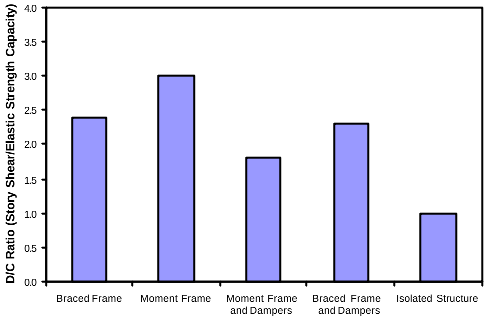


Fig. 8: Story Drift for Main Lobby, SF Airport Terminal

Fig. 9: Demand/Capacity Ratio for Lobby Columns, SF Airport Terminal

Benicia-Martinez Bridge

The Benicia-Martinez Bridge is one of the largest bridges to date to undertake a seismic isolation retrofit (Fig. 10). The seismic retrofit design was done by Imbsen & Associates, under contract with the State of California, Department of Transportation. The seismic retrofit was designed for a MCE on the Green Valley Fault (Fig 11). The spectral accelerations of 7 and 8 g's, are more than 30 times typical seismic lateral design forces. The Friction Pendulum bearings for this large toll bridge have a dynamic period of 5 seconds, a dynamic friction of 6%, and a displacement capacity of up to 53 inches (Figs. 12 & 13). Individual bearings have a 6 million pound design vertical load capacity, measure 13 feet in diameter, and weigh 40,000 pounds. These bearings are the largest seismic isolation bearings ever manufactured.

Hayward City Hall

The Hayward City Hall (Fig. 14) is an essential government facility that is located 200 yards from the Hayward fault. The structural design was done by KPFF Consulting Engineers, San Francisco, to withstand the Maximum Credible Earthquake with no disruption to its operation. The design spectra, incorporating fault normal effects, are shown in Fig 15. The seismic isolation design incorporated 53 Friction Pendulum bearings and 15 Taylor viscous dampers to mitigate the effects of strong near-field earthquakes. The isolation bearings were installed at the tops of the basement columns (Fig. 16). The Friction Pendulum bearings have a vertical load capacity of 1,900,000 lbs., a dynamic period of 3 seconds, a dynamic friction of 7.5%, and a displacement capacity of 22.5 inches (Fig 17). The Hayward City Hall was the first fast-track, design/build project to incorporate seismic isolation bearings. The design/build contractor , DPR Construction of Redwood City, California, completed the construction within 16 months. The Friction Pendulum bearings were manufactured, tested, delivered and installed within 4 months of the award of the bearing supply contract.

CONCLUSIONS

Friction Pendulum isolation bearings can permit structures to safely resist strong, near-field fault, earthquake ground motions on an essentially elastic basis. In order to accommodate these severe ground motions, the seismic isolation bearings need to have isolator periods and displacement capacities greater than those of typical isolation bearings used in the past. Friction Pendulum seismic isolation bearings can provide the isolator periods and displacement capacities necessary to mitigate the strongest near-field ground motions, including the effects of fault normal and deep soil ground motions. These bearings remain inherently stable at large displacements, and maintain high vertical load factors of safety. An important factor for economical structure design, is that the isolation bearings retain concentric gravity loads on critical structural elements. For the application examples presented, seismic isolation with Friction Pendulum bearings provided the lowest cost of construction to achieve the desired, essentially elastic, no-damage designs.

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Fig. 10: Benicia-Martinez Toll Bridge

Fig. 12: Concave Plate for Benicia-Martinez Bridge Bearing

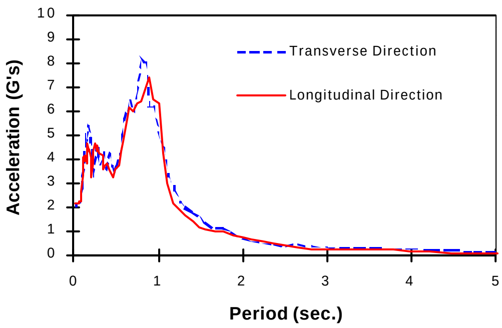

Fig. 11: Ground Motion Spectra at Pier 6 Footing

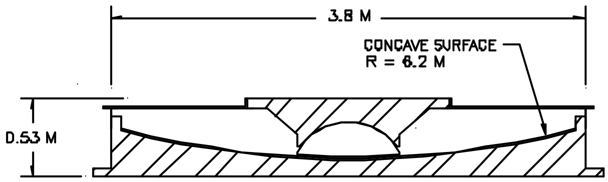

Fig. 13: Section of Benicia-Martinez Bridge Bearing

Fig. 14: Hayward City Hall

Fig. 16: Installed Bearing, Hayward City Hall

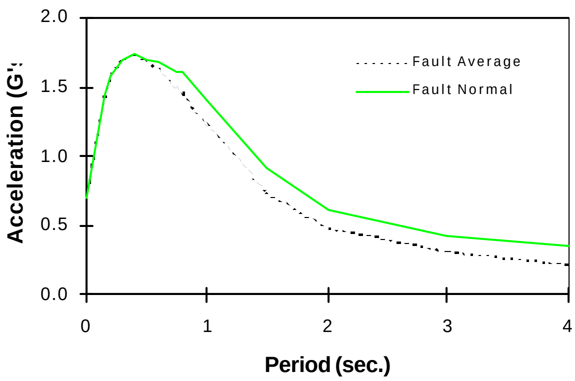

Fig. 15: Hayward City Hall Site Spectra

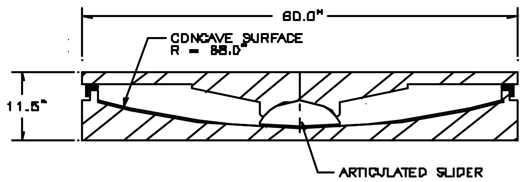

Fig. 17: Section of Hayward City Hall Bearing