PERFORMANCE VALIDATION OF LARGE SEISMIC RESPONSE MODIFICATION DEVICES

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SUMMARY

In the seismic retrofit design of California’s long span toll bridges, seismic response modification devices (SRMD) such as isolation bearings, dampers, lock-up systems and other forms of mechanical fuses or energy absorbing mechanisms have been extensively employed to control and limit seismic input into vulnerable bridge components. In particular, limitations of force input into the existing sub-standard superstructures by means of isolation systems and/or mechanical fuses have been shown to be efficient retrofit solutions reducing costly superstructure retrofit measures which would require extensive bridge/lane closures and traffic interruptions. Seismic response modification devices of the size required for the retrofit of these long span toll bridges have not been built or tested to date. To fully characterize the performance of isolation bearings with over 50 MN axial load and over ±1 m horizontal displacement capacities as well as dampers with up to 9 MN force capacity under real-time 6 DOF seismic input motions, a special SRMD testing facility was developed for Caltrans in the Charles Lee Powell Structural Research Laboratories at the University of California, San Diego. The design, construction, and performance characteristics of this unique seismic testing system in direct support of California’s toll bridge retrofit program are presented.

INTRODUCTION

In the seismic retrofit of California’s long span toll bridges, seismic response modification by means of isolation bearings and/or dampers is used to limit the seismic force input into the superstructure and to avoid costly superstructure retrofit measures which would require lane closures and traffic interruptions. A summary of maximum design characteristics for these SRMDs in California’s toll bridge retrofit program is presented in Table 1.

Seismic Response Modification Devices (SRMDs) with the capacities outlined in Table 1 have not been manufactured or tested to date and questions concerning scale-up effects for these response modification devices become critical since the safety of the retrofitted bridge relies on well defined friction and energy absorption characteristics.

Only full-scale real-time dynamic testing of these new SRMDs can verify the actual response characteristics and thus validate the structural retrofit concept. This paper describes the design, construction and performance characterization of a full-scale testing facility which will allow the real-time 6-DOF dynamic characterization of these new generation of seismic response modification devices for long span bridges. The test system requires vertical load capacities of up to 50 MN at horizontal displacements of ±1.2 m and velocities of up to 1.8 m/s for full 6-DOF digital control testing under any prescribed set of load/deformation time-histories. The concept development, design, and construction of the Caltrans SRMD test system, see Fig. 1, at the University of California, San Diego (UCSD) is described in the following.

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Table 1 SRMD Design Characteristics in California's Toll Bridge Retrofit Program

Toll Bridge	Device Type	Max* Vertical Load [MN]	Max* Horiz. Load [MN]	Max* Horiz. Displ. [m]	Max* Velocity [m/s]
1. Benicia-Martinez	Friction Pendulum Bearings	22.5	3.5	±1.23	--
	Lead Rubber Bearings	5.38	2.0	±0.46	--
2. Carquinez Straits	Lock-up Devices	--	15.57	±0.025	---
3. Richmond-San Rafael	Dampers	--	2.45	±0.48	1.09
	Rubber Isolators	11.12	4.89	±0.76	---
4. San Francisco-Oakland Bay Bridge	Friction Pendulum Bearings	20.02	1.33	±0.46	--
	Dampers	--	3.11	±0.56	2.28
5. Vincent-Thomas	Dampers	--	1.3	±0.66	2.54
6. San Diego-Coronado	Dampers	--	1.6	±0.20	0.25
	Rubber Isolators	6.9	1.6	±0.64	--

*Note: Maxima do not necessarily occur in the same device or at the same time

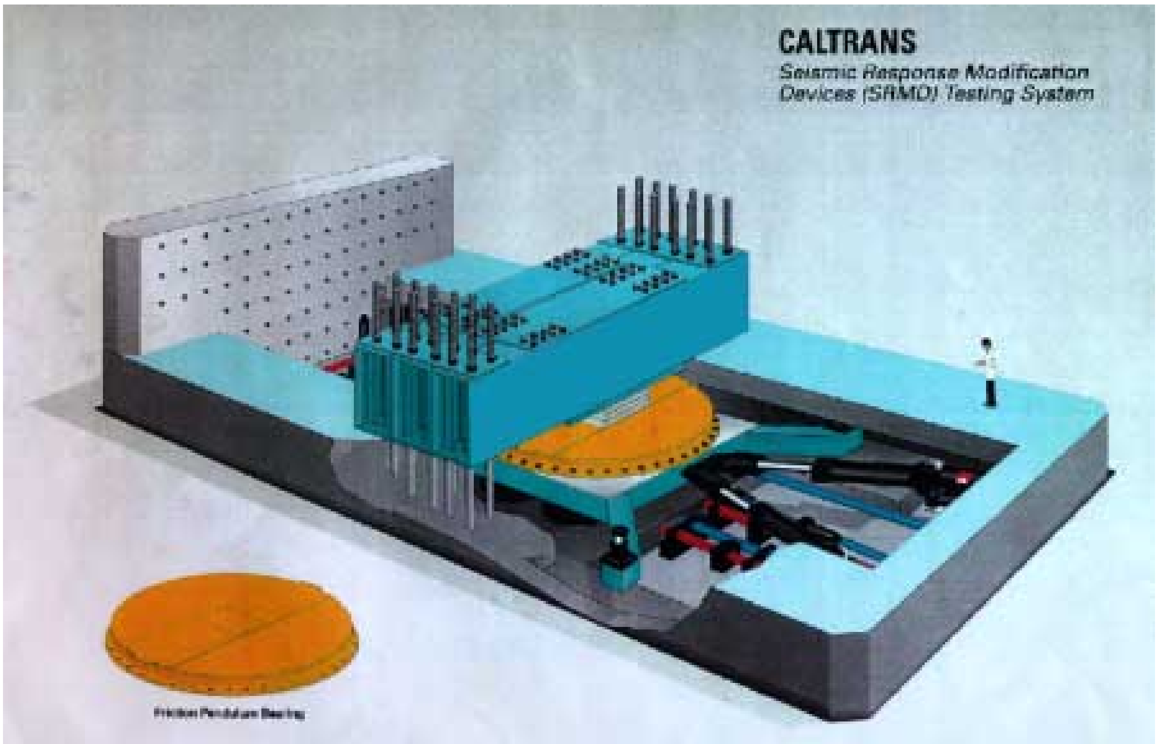


Figure 1. SRMD Test System

TESTING OBJECTIVES AND REQUIREMENTS

Technical requirements for the Caltrans Seismic Response Modification Device Test System (SRMD) were developed on the basis of current design projects for the California Toll Bridge Retrofit Program, as well as the new AASHTO T-3 Guide Specification for Seismic Isolation Design [Mellon 1997]. Specifications have been adjusted during the design phase to provide a very flexible test system, open to a wide spectrum of devices and testing possibilities.

Targeting the possibility of testing the SRMD devices that will be installed in the first of the Caltrans toll bridge retrofit projects (Benicia-Martinez bridge), the design and construction of the testing facility was put on a fast track 2 year schedule. This challenging time frame did not allow any time for construction of a new building space for the SRMD testing machine. For this reason the University of California, San Diego located and obtained a portion of the existing laboratory building as permanent space for the testing machine. The building is located on the UCSD campus directly adjacent to the Powell Structural Research Laboratories, with the advantage of direct access to the support services of these labs. The available space comprises about 300 square meters (3,200 ft2) and is already serviced by a 20 ton (40 kips) overhead crane. The exceptional demand of hydraulic power for this test system requires about 19,000 litres (5,000 gal) of oil storage and pressurization through nitrogen gas up to 34 MPa (5,000 psi). For safety reasons, the pumps and the 100 accumulators are located in a separate building. Direct pumping, designed for long duration tests and for accumulator charge, will provide 720 and 417 litres per minute (190 and 110 gpm) at 21 and 34 Mpa (3,000 and 5,000 psi), respectively.

The main technical requirements of the 6-DOF system are summarized in Table 2. These specifications, the different types of isolating devices and dampers to be tested, and the testing objectives and procedures, drove the overall design approach. The isolating devices selected for the Benicia-Martinez and Coronado bridges were friction pendulum system (FPS), see Fig. 2, and elastomeric isolation bearings, respectively, as well as viscous dampers, common to almost all the toll bridge retrofit projects. Testing objectives ranged from slow speed uni-directional testing for basic performance characterization to high speed, 3-D testing for energy based analysis. The investigation of the effect of wear and aging was also an important issue in the proposed test program, through re-characterization of the performance of the prototype SRMDs already exposed to the actual bridge loads, deformations and environmental conditions.

Table 2. Technical Specifications

Vertical Force	53,400 kN
Longitudinal Force	8,900 kN
Lateral Force	4,450 kN
Vertical Displacement	±0.127 m
Longitudinal Displacement	±1.22 m
Lateral Displacement	± 0.61 m
Vertical Velocity	±254 mm/s
Long. Velocity	±1,778 mm/s
Lateral Velocity	±762 mm/s
Height of Specimen	Up to 1.52 m
Relative Platen rot.	±2°

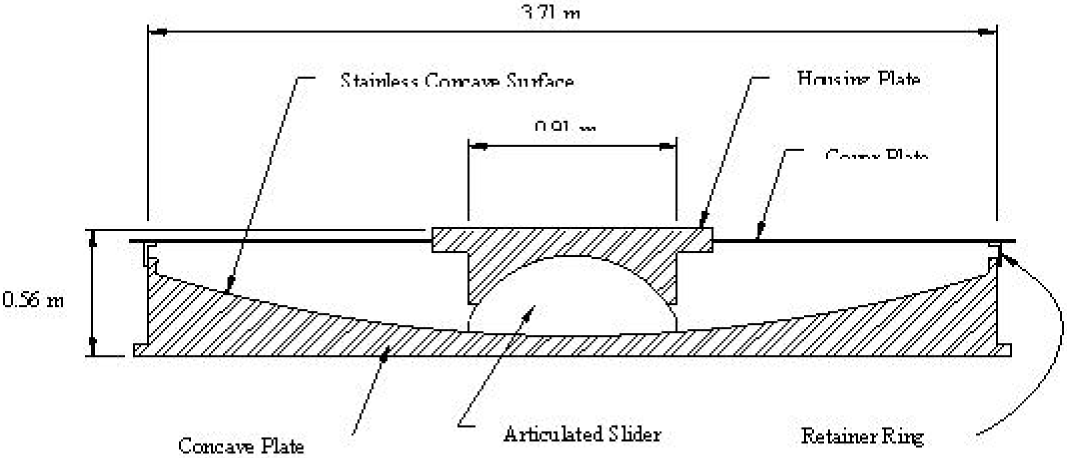


Figure 2. Typical FPS Bearing for Benicia-Martinez Bridge

DESIGN CONCEPT

The design of the test facility was developed jointly by Caltrans, UCSD, and MTS. Many preliminary configurations were re-visited and modified due to the complexity of the project, driven by the large demand of vertical forces and displacements, as indicated in Table 2. The final design configuration of the testing system is shown in Figure 3. The testing system consists of a horizontal prestressed concrete reaction frame (concrete box), and of a moving platen, connected by four horizontal actuators to the concrete box. The platen slides over four hydraulic hydrostatic low friction bearings attached to the floor of the concrete structure. The platen also extends with four steel outrigger arms that support four low friction-sliding actuators at their tops. The testing system is completed by two additional reaction structures: a steel cross beam, removable and linked to the concrete box through a tie-down rod system, and a heavily prestressed reaction wall on one end of the machine. Figure 3 shows a plan view and cross sections, with key dimensions.

Due to the large displacements of the test specimens in the longitudinal and transverse directions, the traditional solution of a platen with hinge connection to horizontal and vertical actuators was not practical. This configuration would have required very long stroke vertical actuators, with deep excavation inside the existing building. Space limitations, difficulties of access for tall excavating equipment and the need to maintain the rest of the existing laboratory in working condition during construction made this solution impractical. The adopted solution was the use of 4 vertical hydraulic sliding bearings which support the moving platen, apply the vertical load, and allow horizontal motion and swivel capacity with very low friction (less than 0.2% of vertical force). The four horizontal actuators have a 2.5m stroke, 800 ton capacity and dual 20m^3/min. servo-valves, and the 4 vertical low friction bearing actuators have 0.25m stroke, 2,000 ton capacity and 11m^3/min. servo-valves each.

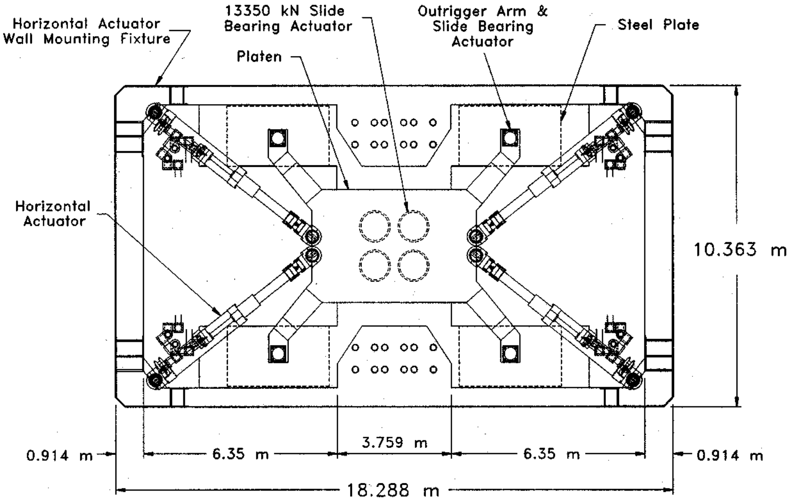
The dimensions and strokes of the horizontal actuators determined the shape of the support structure. Its closed box-like geometry, together with the property of self-reacting horizontal forces, was desirable also for providing containment of oil leakage and testing of specimens to failure. The large vertical loads which the testing machine can apply are transferred to the test specimen by the 4 vertical hydrostatic actuators through the platen and reacted against an assembled tubular cross-beam. A self-reacting frame in two directions is thus obtained, as illustrated in Figure 4.

PERFORMANCE RANGE

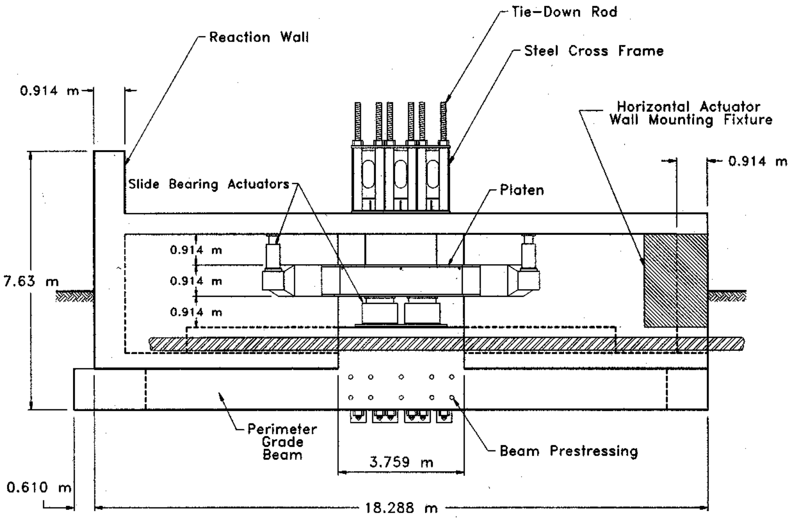
An initial analysis of the overall stability of the platen, at the most critical conditions of loads and displacements, showed the limits of the solution of a platen supported on four sliding bearings, which provide vertical force only in compression. A large improvement in stability was achieved by adding eccentric points of vertical reaction through the four steel outrigger arms connected to the platen. On top of each of these extensions a sliding bearing provides extra vertical force needed to balance the overturning moment applied to the platen. One of the main issues was the location of the reaction structure for these actuators, given the large range of displacements they are required to cover. The solution of mounting these actuators to slide in pockets, which are part of the surrounding concrete box, was adopted. The pockets in the lateral walls are covered on the inside top face with polished steel plates, providing the finish conditions required for the optimum performance of the sliding actuators. The outrigger's arms will be equipped with 534 kN hydrostatic bearings, applied above the steel arms. They allow 0.5 m of stroke. For design purposes, their service capacity has been assumed at 490 kN. The design of the system took into account also the possibility of more powerful actuators, up to 1,470 kN, applied above and/or below the outrigger arms.

The stability mechanism of the platen is shown in Figure 5 for elastomeric and friction pendulum bearings. In the figure, P represents the vertical load and H the applied shear force at mid-height of the specimen, Δ the total platen displacement, O1 and O2 the vertical forces applied by the outrigger actuators, V1 and V2 the vertical forces applied by the sliding bearings mounted below the platen, and W the total weight of platen, specimen and outrigger actuators. For simplicity, the model is here reduced to a 2-D system however, the response of the platen has been analyzed with a 3-D finite element model which allowed the application of several critical combinations of loads and displacements.

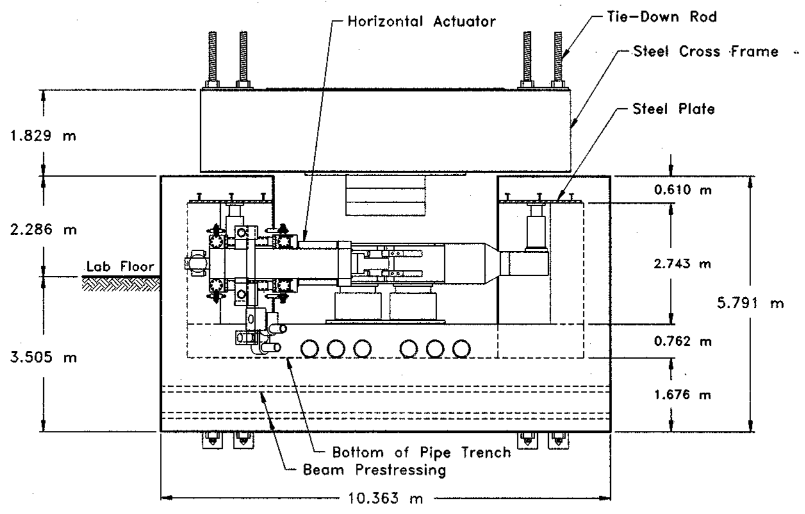
The two types of isolation devices present substantial differences in terms of forces transferred to the machine during a test. The elastomeric rubber bearings represent the most critical case for platen stability as well as for structural demand. In fact, due to their capacity to carry shear and end moments, they introduce a large overturning moment into the platen. This contribution is, as shown in Figure 5, increasing with the size of the



a) Longitudinal Cross-Section



b) Plan View



c) Transverse Cross-Section

Figure 3. SRMD Plan View and Cross-Section

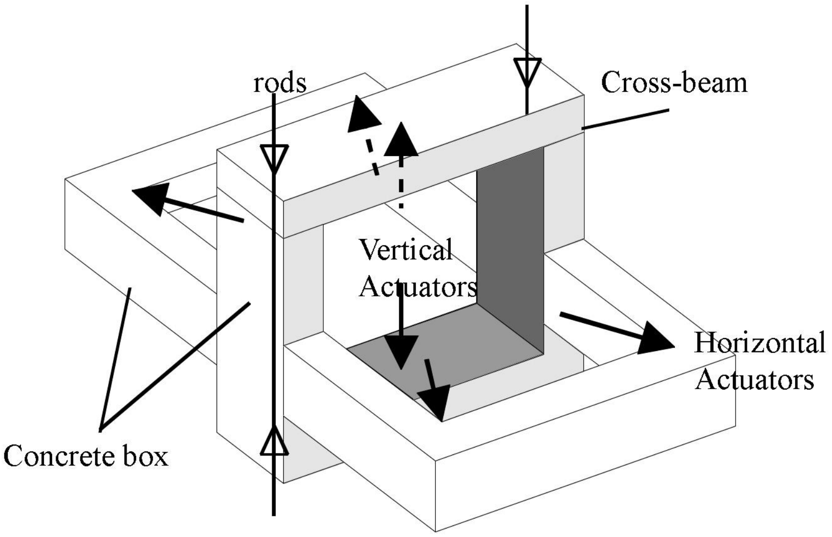
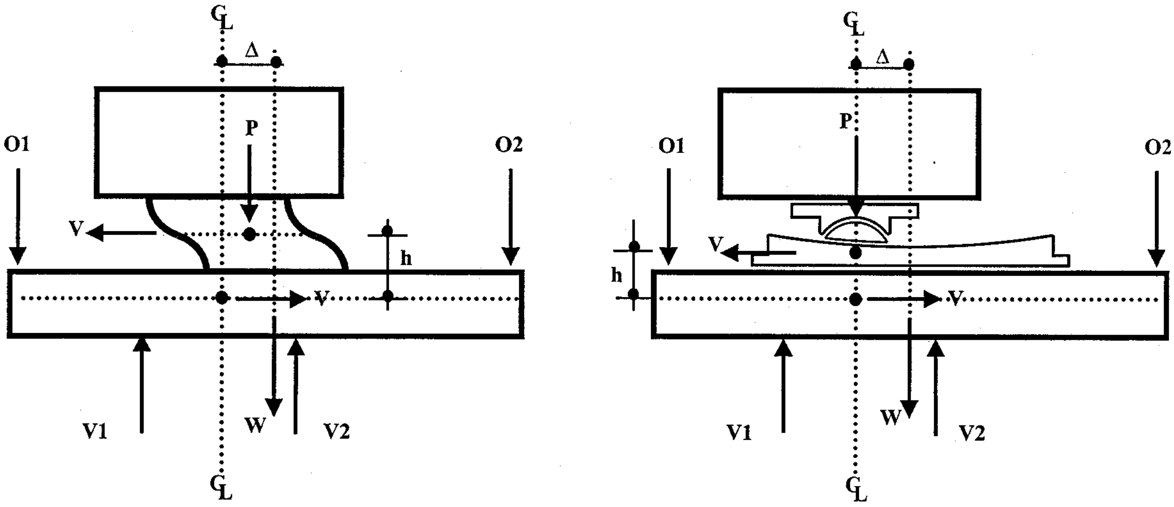


Figure 4. The Self-Reacting Frames

specimen. Additional moments are transferred to the platen when displacements occur. Due to P-Δ effect, the applied vertical load P introduces a moment with the same direction of the one due to the horizontal forces. Opposing effects are exerted, in this case, by the platen self-weight and the vertical load eccentricity with respect to the center of sliding bearings (centerline of the machine). The remaining force components need to be balanced by the actions exerted by the installed vertical actuators (V, O). Several combinations of loads analyzed showed the difficulty of establishing a general rule for the governing force component in the stabilizing mechanism. Generally, the axial load P represents the main reason for instability at significant displacement, whereas the horizontal shear governs for limited strokes.

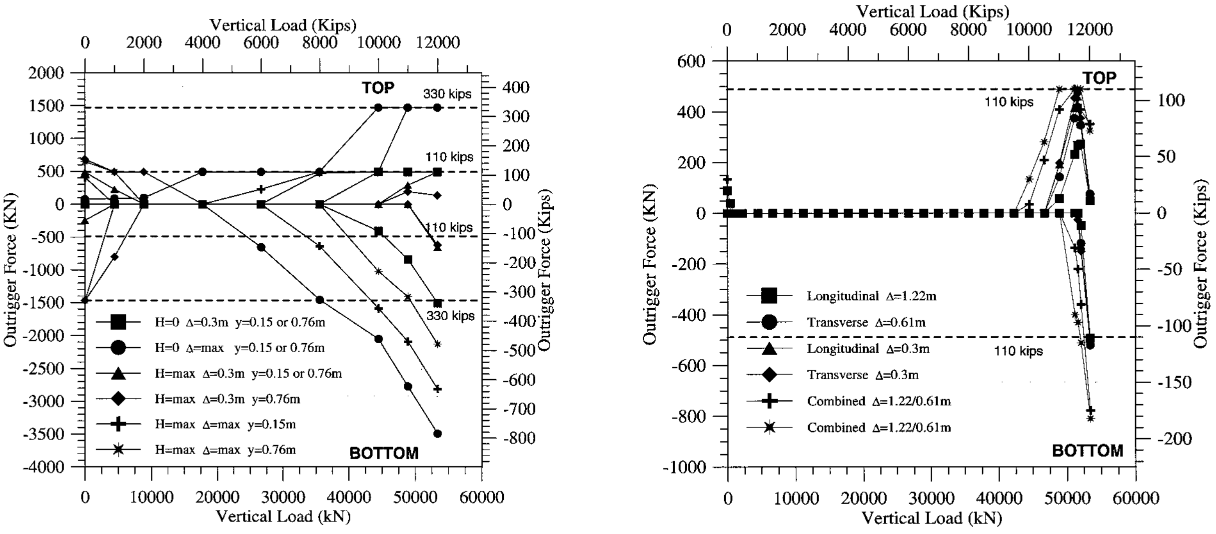


a) Elastomeric Bearings **b) FPS Bearings**

Figure 5. Platen Stability Models

The balancing effect from the sliding actuators depends on the proportions between applied external forces and displacement. It must be noted that in several conditions only the actuators on one side of the platen are active (under "compression" force) while the other ones are instead following the displaced position of the platen without providing any force contribution.

Slightly different is the stability mechanism for friction pendulum bearings. The main reason is the low coefficient of friction between moving components, that results in reduced overturning moment to the platen. Also due to the articulated configuration of FPS devices, the applied vertical load always remains aligned with the resultant of the actions introduced by the vertical hydrostatic bearings. This condition eliminates the overturning moment due to P-Δ effect. Figure 6 shows the stability response of the platen for combined transverse and longitudinal displacements, for elastomeric and FPS bearings.



a) Elastomeric Bearing **b) FPS Bearings**

Figure 6. Combined Envelope of Platen Stability Curves

The envelope curves show the outrigger forces necessary to stabilize the platen, assuming the vertical actuators below the platen are at their maximum level of reaction. In Figure 6a the most critical conditions of horizontal loads (H), displacements (Δ), and half of the bearing height (y) are combined. The values of H and Δ are the same in both longitudinal and transverse direction. The maximum of y=0.76m as indicated in the plot, corresponds to the highest specimen allowed with cross-beam installed, i.e., 1.52m clearance. Also, the condition of zero shear force was analyzed for elastomeric bearings. This limit state can be postulated to exist when an elastomeric bearing has failed in shear, while still being subjected to vertical load. Displacements and height of the specimens range from a moderate level to the peak values allowed by the system. The dashed horizontal lines correspond to the capacity of the outrigger actuators. The present configuration will include four actuators capable of 490 kN each, mounted on top of the outrigger arms. In order to complete the analysis of stability performance of the platen, two other possible scenarios are reported in the same plot: the presence of 1,470 kN actuators on top of the outriggers and/or extra actuators installed below the platen extensions (negative values of outrigger force). For instance, the configuration of zero horizontal load and maximum displacement in both directions (black circle in Figure 6a) does not present any stability problems up to a maximum vertical load of 17,800 kN. At this level, the capacity of the 490 kN top outrigger actuators is exceeded and to reach stability at the vertical force of 26,700 kN (next data point) an extra force is needed from below the platen (about 650 kN). Above 35,600 kN of vertical load, the capacity of the outrigger actuators is exceeded for any elastomeric bearing under maximum horizontal displacement or load conditions. In the graph, unstable conditions in case of very low vertical load, maximum horizontal capacity and very tall specimens can be seen.

Figure 6b shows the difference in behavior of FPS bearings with respect to the elastomeric devices. The stability of the system becomes an issue only at very low or very high vertical loads. For a large intermediate range of vertical forces, the outrigger actuators are not required for stability purposes. The designed system configuration with 490 kN actuators above the platen outrigger arms allows stable tests at maximum displacement in both longitudinal and transverse direction with vertical load up to a maximum of about 50,000 kN.

A photograph of the completed SRMD test system without the reaction cross-head and horizontal actuators is provided in Figure 7.

The Caltrans SRMD test system was completed in July 1999 and is currently undergoing full systems characterization and shakedown testing.

Figure 7. Completed Horizontal Reaction Frame, Platen and Hydraulic Distribution System

CONCLUSIONS

The concept, design, and construction of a full-scale 6-DOF seismic response modification device test system has been presented. The test system is currently under the final phase of construction at UCSD for the California Department of Transportation (Caltrans) and will allow real-time dynamic testing of isolation bearings, dampers, and displacement limiting devices for long span bridge structures. Load displacement and velocity capacities of the new Caltrans SRMD test system significantly exceed any other bearing or isolator test facility in existence to date.

REFERENCES

Mellon, Dorie, “Caltrans Proposed Testing of Seismic Response Modification Devices for the Toll Bridge Retrofit Program,” *Proceedings, National Seismic Conference on Bridges and Highways*, Federal Highway Administration, Sacramento, CA, July 8-11, 1997.