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EXPERIMENTAL TESTS OF VARIOUS TYPES OF SEISMIC ISOLATION SYSTEMS

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Abstract

Seismic isolation is one of the most effective means of earthquake hazard mitigation. This paper summarizes experimental studies on different types of seismic isolation systems that are used for structural applications such as buildings and bridges, and for non-structural systems such as computer servers, artwork, medical equipment and other sensitive equipment. The seismic isolation systems presented in the paper include: 1) Lead rubber bearings (LRB): Extreme testing of LRBs is presented. 1410 mm diameter bearings were subjected to large lateral displacements in addition to the axial load. The same bearings were subjected to combined shear and tension, with an extreme uplift of 20 mm. Limit state performance of full-scale bearings is also presented where the bearings are subjected to more than 500% shear strain. 2) Non-structural isolation system: A patented multi-directional spring isolation system that provides damping and self-centering capabilities. The system is used mainly to isolate sensitive equipment inside a building. Shake table test results are presented in the paper showing the effectiveness of the system. 3) Elastomeric slider bearings (ESB): Test results are presented of ESBs used in a unique application in the US. A vertical expansion of an existing building was required, and the isolation bearings were introduced between the existing structure below and the addition above. 4) Sliding systems: The paper presents test results of a polyamide nylon-based sliding material that has been used significantly in Japan and has been introduced to the US recently. The material has a lower coefficient of friction than the typical PTFE. The material has been used in a building project in the US where the SEOR used extensive test results to characterize and model the isolation system.

Keywords: Earthquake, Seismic Isolation, Hazard Mitigation, Nonstructural Isolation, Shake table Testing, Lead Rubber Bearings.

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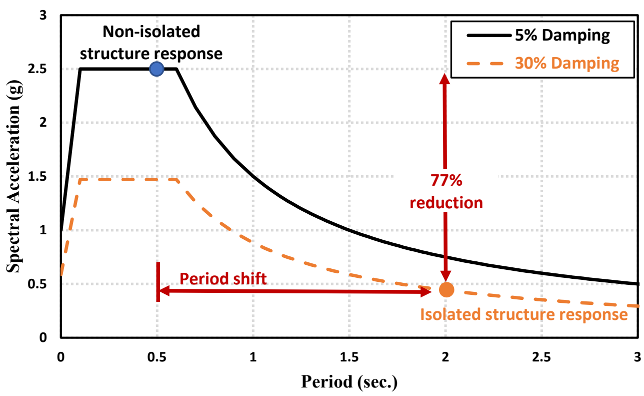
1 INTRODUCTION

Seismic base isolation is widely recognized as one of the most effective and commonly employed methods for mitigating the hazards associated with earthquakes. The basic concept of seismic isolation is to substantially decouple a structure from damaging earthquake ground motions using seismic isolators (see Figures 1a & 1b). Consequently, when a seismic isolated structure is subjected to an earthquake, the inelastic deformations occur in the seismic isolators, reducing forces/accelerations in the structure compared to conventional, fixed-base structure. The modern concept of seismic isolation originated in New Zealand in the 1970's [1], and many studies have demonstrated the advantages of seismic isolation in mitigating structural damage during severe seismic events [2,3]. In contrast, conventionally designed structures depend on the inelastic response of selected structural elements to dissipate the earthquake energy, resulting in damage to these selected elements [4, 5, 6, 7, 8, 9]. In general, a seismic isolator that is used to protect a structure against earthquakes should have the following characteristics as a minimum:

- Flexibility from the low horizontal stiffness of the isolators, which lengthens the period of vibration of the structure and reduces the seismic forces (see Figure 1c).
- Energy dissipation from the introduction of significant level of hysteretic damping, which absorbs energy from the earthquake. This limits relative displacements and deformations to acceptable levels and further reduces the seismic forces (see Figure1c).

(a)

(b)



(c)

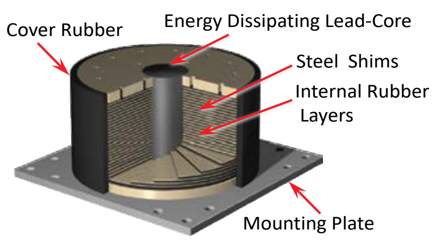
Figure 1: a) Installation of seismic isolators for a building in Taiwan. The superstructure will be connected to the isolators and decoupled from the ground, b) A completed building showing the seismic isolators fully installed, c) Effect of isolator flexibility and damping on a structure performance

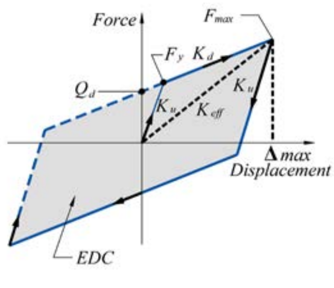
Testing is considered an essential aspect of the design and review of seismic isolation systems. Extensive experimental campaigns conducted at advanced testing facilities have greatly enhanced the confidence level in seismic isolation technologies. The availability of high-capacity testing rigs, capable of conducting full-scale testing of devices under realistic loading conditions, has deepened and improved the knowledge and behavior of existing and new seismic isolation solutions [10]. The main objective of this paper is to present experimental studies on various types of seismic isolation systems that are used for conventional structural applications such as buildings and bridges, and for non-conventional non-structural applications. The seismic isolation solutions presented in the next sections are:

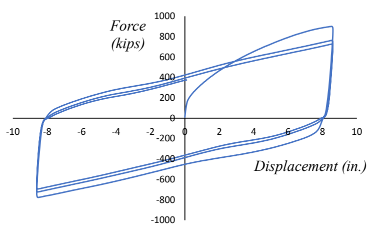
a) Lead-rubber bearings (LRB) and Rubber bearings (RB)
b) Non-structural/low mass seismic isolation system
c) Elastomeric sliding bearings (ESB)
d) Sliding system using polyamide (nylon-based) material

2 LEAD-RUBBER BEARINGS AND RUBBER BEARINGS

Lead-rubber bearings and rubber bearings are considered two of the most common seismic isolators in applications worldwide. LRBs and RBs have been extensively tested, and there are comprehensive guidelines on their design and modelling [11]. Figure 2a shows the main components of an LRB: layers of vulcanized low-damping rubber and steel shims. The rubber layers provide flexibility in the lateral direction, while the steel shims prevent bulging due to axial loads, creating high vertical stiffness. The bearing is fitted with a central lead core which is confined by the steel shims. The lead core provides resistance to service loads, then yields and dissipates energy under earthquake lateral movements. Steel mounting plates are placed on top and bottom of the bearing to connect to the substructure and superstructure. Finally, a resilient rubber compound is used as a cover rubber to protect the bearing's internal components from environmental effects. Figure 2b shows an idealized bilinear force-displacement relationship for an LRB. Figure 2c shows an actual force-displacement test loop for an LRB that was used in a bridge located in the United States. The RB is made of the same components as the LRB, except that there is no central lead core. This removes the majority of the resistance to service loads and energy dissipation, causing the RB to behave more like a simple lateral spring. RBs are commonly paired with LRBs to achieve a desired system performance and response.







(a) (b) (c)

Figure 2: a) Main components of lead-rubber isolators, b) Bilinear force-displacement relationship for an LRB, c) Actual force-displacement test results for an LRB

2.1 LRB extreme uplift testing

Extreme prototype testing was conducted for a LRB used on a bridge project. The bearing has a diameter of 1410 mm and is composed of (50) 8 mm thick rubber layers (total rubber height = 400mm). A 390 mm lead core is used to resist bridge service loads and to provide the required damping. The LRB was extensively tested at both the Caltrans SRMD (Seismic Response Modification Device) testing facility at University of California San Diego and at Dynamic Isolation Systems (DIS) testing facility in NV. The prototype test protocol included compression and shear testing up to 1051 mm (263% shear strain) at both low and high velocities. The testing velocities ranged from 20 mm/sec up to 1571 mm/sec. In addition, an extreme uplift and shear test was conducted where an uplift of 20 mm was first applied to the bearing, and then sheared to a displacement of 450 mm. Selected test loops and results are shown in Figure 3. The bearings maintained performance and stability throughout the extreme testing protocol.

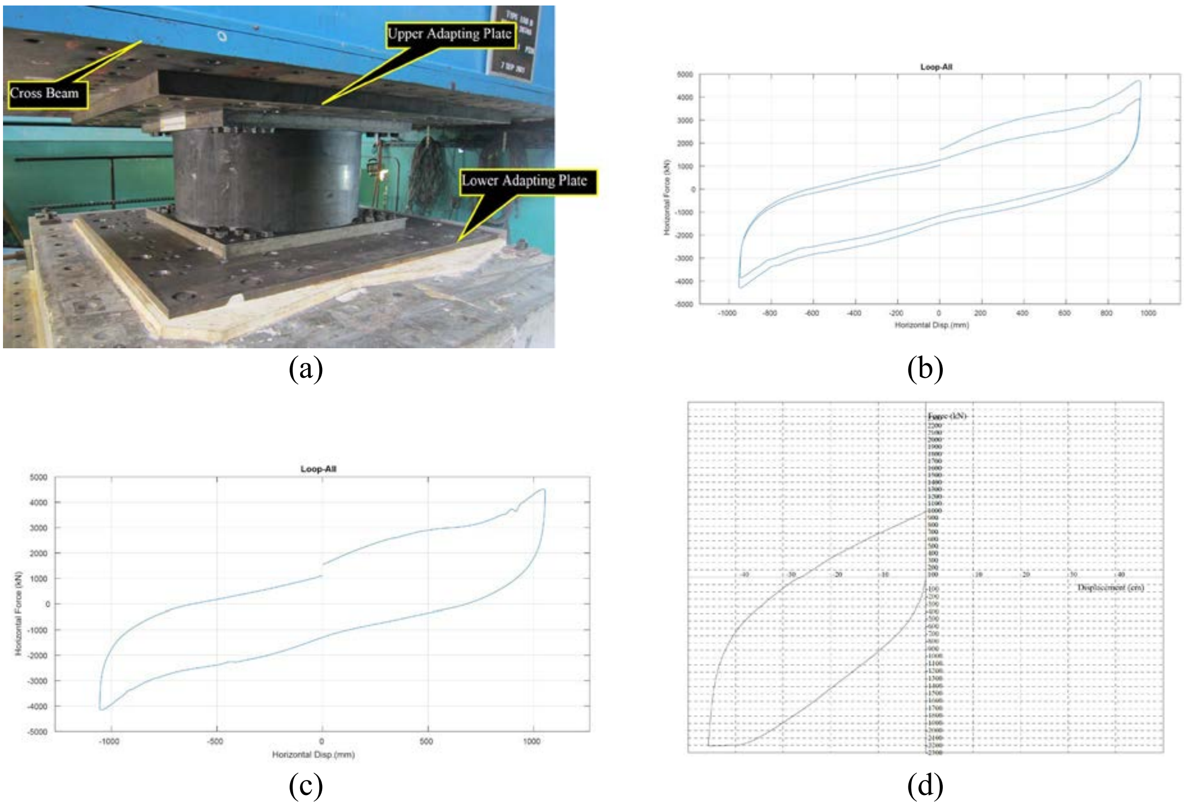


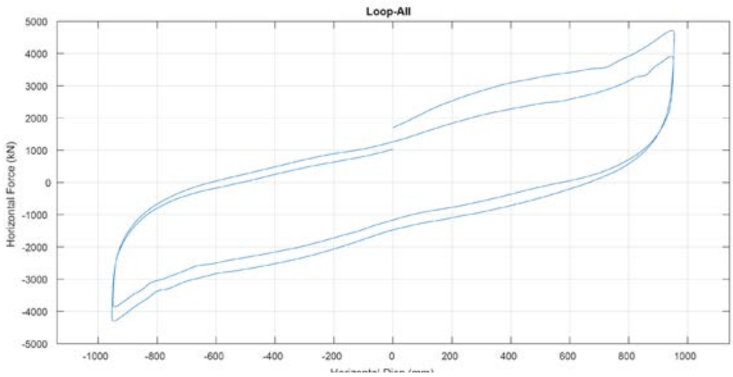
Figure 3: a) Installed bearing in the SRMD test machine, b) Force-displacement loop [axial load=3200 kN, displacement=955 mm, velocity=1571 mm/sec], c) Force-displacement loop [axial load=7000 kN, displacement=1051 mm, velocity=938 mm/sec], d) Force-displacement loop [uplift=20 mm, displacement=450 mm, velocity=20 mm/sec]

2.2 Limit state performance of rubber bearings

During strong ground motions, seismic isolation bearings are subjected to large lateral displacements that in some cases could be larger than expected in design. The designers are interested in evaluating the performance of elastomeric isolators beyond the standard design limits to ascertain the safety margin beyond the expected design displacements. This subsection evaluates the limit state performance of large rubber isolators through testing. 500 mm and 800 mm isolators were tested at DIS testing facility, and a 1300 mm isolator was tested at the SRMD facility.

a)

b)



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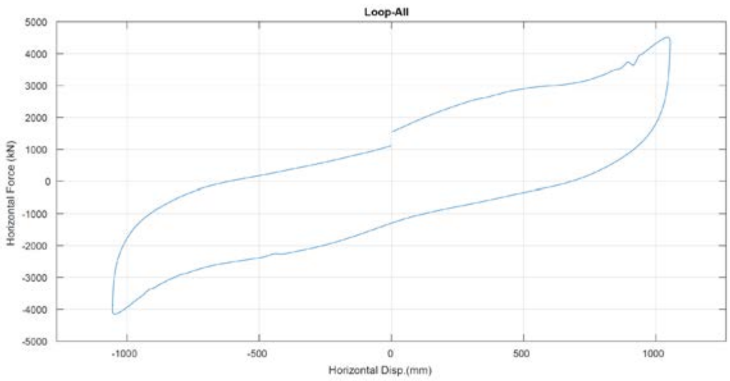

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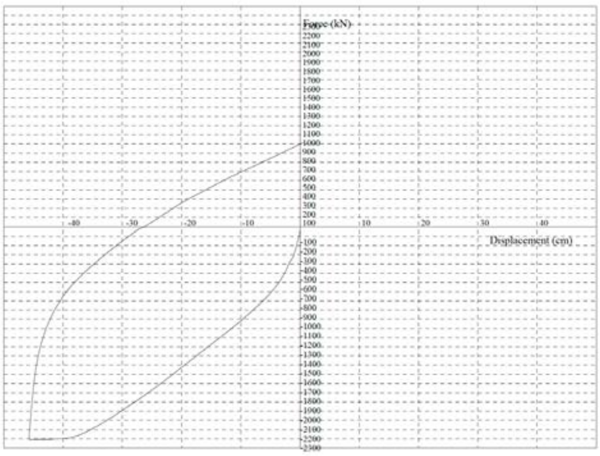


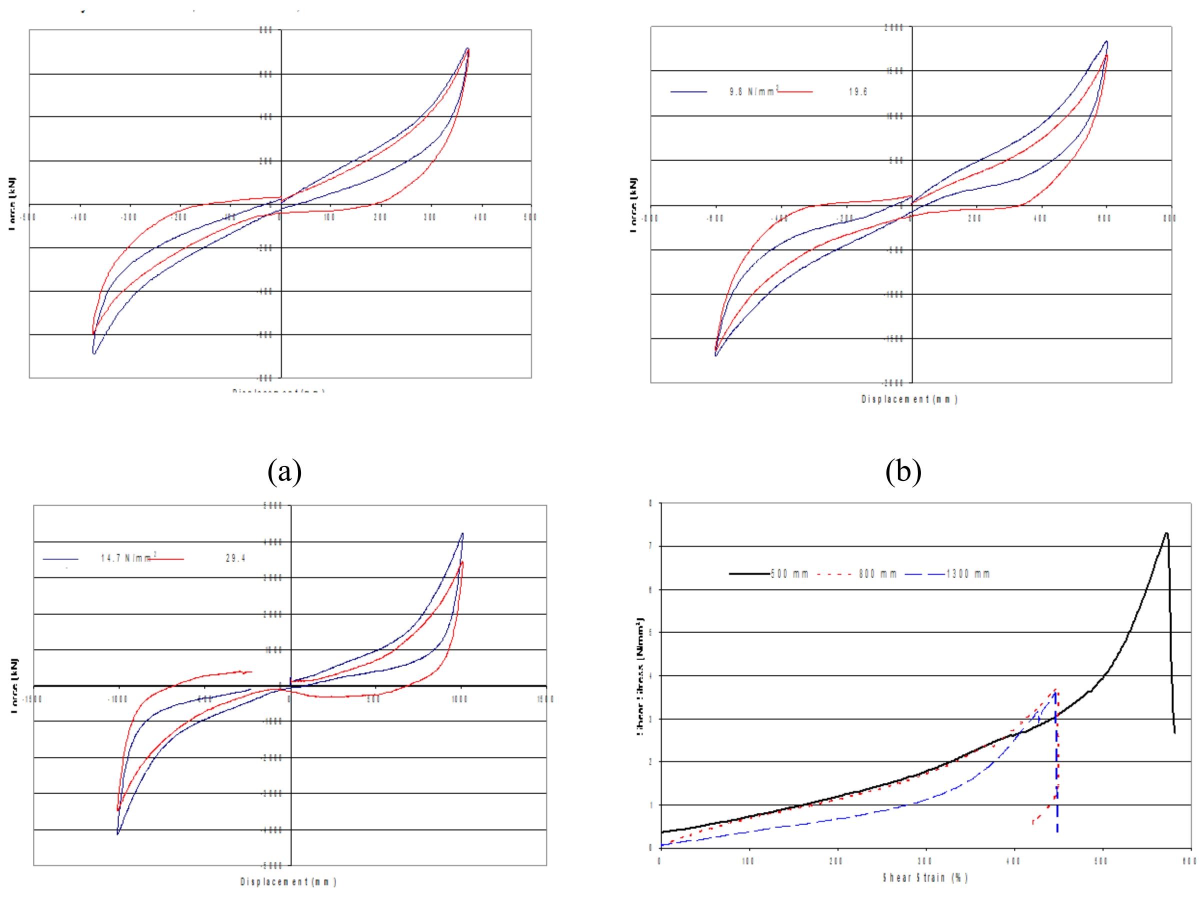
Figure 3: a) Installed bearing in the SRMD test machine, b) Force-displacement loop [axial load=3200 kN, displacement=955 mm, velocity=1571 mm/sec], c) Force-displacement loop [axial load=7000 kN, displacement=1051 mm, velocity=938 mm/sec], d) Force-displacement loop [uplift=20 mm, displacement=450 mm, velocity=20 mm/sec]

For the 500 mm isolators, linear force-displacement loops were observed until shear strains of 250% and then stiffening of the rubber was clearly observed. The isolators exhibited satisfactory behavior up to 550% shear strain and under a compression stress of 19.6 N/mm^2. During the final test with 9.8 N/mm2, the isolators failed at 574% shear strain.

For the 800 mm isolators, linear force-displacement loops were observed until shear strains of 250% and then stiffening of the rubber was clearly observed. The stiffness in the range of 300 to 400% was three to four times compared to stiffness under 200% strain. The isolators failed at 450% shear strain with a compression stress of 9.8 N/mm^2.

For the 1300 mm isolator, similar behavior was observed up to the 250% shear strain. The isolator successfully carried a compression stress of 29.4 N/mm^2 at 400% shear strain. The isolator failed at 446% shear strain with a compression stress of 14.7 N/mm^2.

Figure 4 presents selected force-displacement loops for the tree bearing sizes. Table 1 shows the isolator dimensions and ultimate strain test results.



(a) (b)

(c) (d)

Figure 4: a) 500 mm isolator [strain:400%, stress 9.8 & 19.6 N/mm^2], b) 800 mm isolator [strain:400%, stress 9.8 & 19.6 N/mm^2], c) 1300 mm isolator [strain:400%, stress 14.7 & 29.4 N/mm^2], d) Shear stress vs shear strain behavior at failure

All bearings performed at displacements and strains well in excess of their design values and well beyond values used in design practice worldwide. This highlights that individual elastomeric bearings, produced by qualified, high quality manufacturers, have significant robustness and resiliency.

Isolator		500 mm	800 mm	1300 mm
Bearing Diameter	mm	500	800	1300
Layer Thickness	mm	3.7	6	9
Number of Layers		25	25	28
Shear Modulus of Rubber	N/mm^2	0.39	0.39	0.39
Shape Factor (S)		33.6	33.9	36.1
Stress at Failure	N/mm^2	9.8	9.8	14.7
Strain at Failure	%	574	450	446

Table 1: Rubber bearing dimensions and ultimate strain test results.

2.3 LRB instability in bridge shake table testing

A reduced-scale model (2/5th scale) of a three-span, curved girder bridge isolated with a 12 LRBs was tested on four shake tables. The bridge was subjected to ground motion excitations exceeding the design level earthquake to initiate instability of the seismic isolators (up to three times the design level). The displacements at selected locations exceeded the diameter of the isolators and triggered their instability. Shear strains exceeding 400% were observed which was more than 4 times the design level strain. The bridge did not collapse, the overall stability of the system was maintained, and full recovery of the unstable seismic isolators was observed [12]

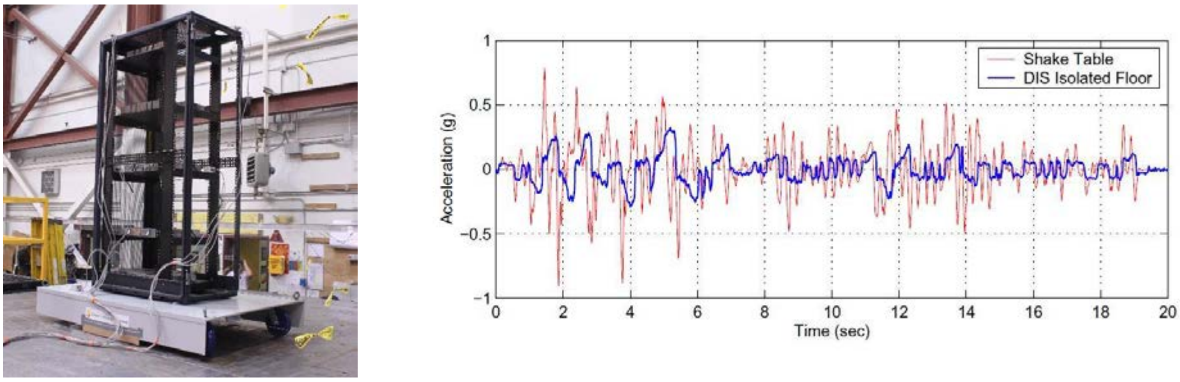
Figure 5: Video snapshots showing the LRB during the extreme testing that caused the instability [12]

3 NON-STRUCTURAL/LOW-MASS SEISMIC ISOLATION SYSTEM

Lately, there has been an increasing interest in isolating particular floors within buildings or specific equipment and not isolating the whole structure. The unique challenges of isolating equipment arise from the relatively low mass supported by isolators, necessitating isolator stiffness that is significantly lower compared to conventional isolation. This section discusses seismic isolation of equipment using a patented Multi-Directional Spring Unit (MDSU) that provides damping, low stiffness, and self-centering capabilities. The MDSUs can be used for stand-alone equipment or to isolate a complete floor. More details about the inner workings of the MDSU, mechanical properties, and analytical modeling can be found in [13, 14].

Extensive bi-directional shake table testing was conducted at the University of Nevada Reno (UNR) to evaluate the effectiveness of the system in reducing the seismic forces/acceleration on server racks (see Figure 6a). Results showed that the isolation platform reduced accelerations on the server racks by a factor of 3 to 4. A sample acceleration history showing the input shake table motion and the isolation platform response is shown in Figure 6b.

Additional shake table testing was conducted on larger connected modules at University of California Berkeley. The system that was tested had a total isolated area of 140 square feet, which included two spring modules and many stringers. Three fully equipped computer racks were part of the shake table testing (see Figure 7). The objective of the study was to evaluate the behavior of multiple spring modules in fully loaded, partially loaded, and unbalanced loaded conditions. Test results showed effectiveness of the system where reduction of accelerations over a wide range of frequencies was achieved (see Figure 8).



(a) (b)

Figure 6: a) Shake table testing of single server rack at UNR [14], b) Sample acceleration history showing reduction of input accelerations by a factor of 3 to 4 [14]

(a) (b)

Figure 7: Shake table testing of a floor isolation system at UC Berkeley [14] a) Floor isolation system with no tiles or server racks on top, b) Floor isolation system showing the tile -stringer-pedestal system installed on top along with server racks

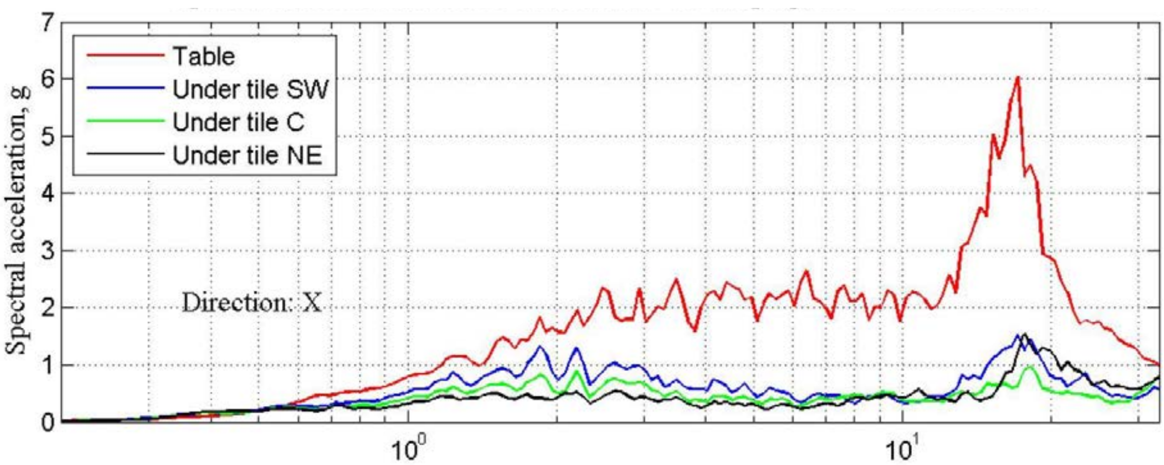


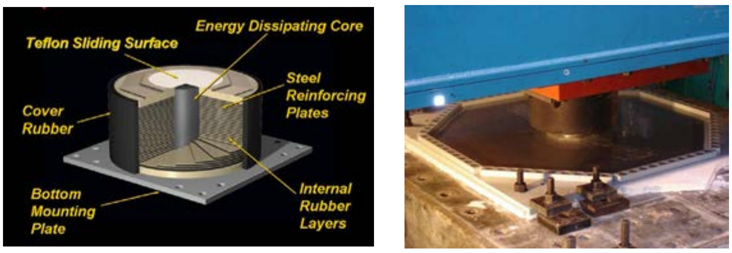
Figure 8: Response of the seismic isolation floor showing reduction of accelerations over a wide range of frequencies. The red line is the shake table input, and the other three plots are response spectra of accelerations on the isolated platform measured at three different locations [14]

4 ELASTOMERIC SLIDING BEARINGS

Elastomeric Sliding Bearings (ESB) were used as part of the seismic isolation system for a unique application in San Francisco. They were used in the first application of seismic isolation in the world that permits the vertical expansion of an existing structure by introducing isolation bearings between the existing structure and the addition (see Figure 9). More information about the building and the design can be found in [15].

Two different types of isolation bearing were used, a conventional LRB and an elastomeric sliding bearing (ESB) consisting of PTFE slider in series with an elastomeric bearing. A schematic showing the ESB's main components is presented in Figure 10a. The elastomeric bearing is intended to provide an initial lateral flexibility before sliding starts and provide additional flexibility if the EQ displacements exceed the dimensions of the sliding plate. Extensive testing have been conducted at the University of California San Diego to characterize the performance of the ESBs (see Figure 10b). Test results of one of the ESBs are presented in Figure 11.

Figure 9: The 185 Berry St. building showing the vertical expansion of the existing structure by introduce seismic isolation bearings between the existing structure and the addition



(a) (b)

Figure 10: a) Schematic of the ESB showing the main components, b) Testing of an ESB at UCSD [15]

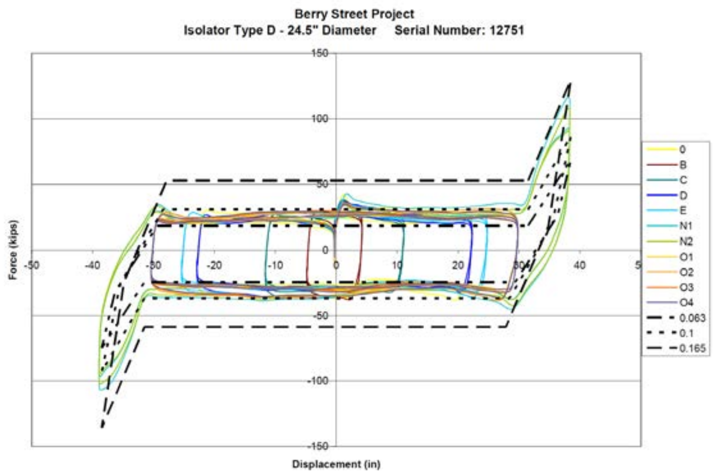
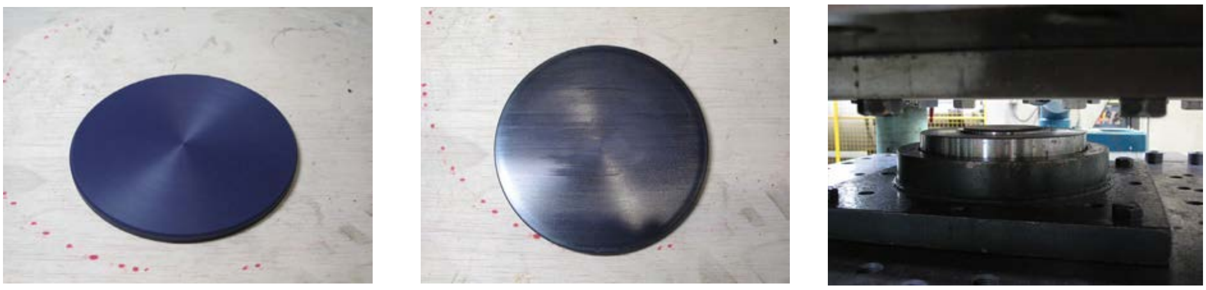


Figure 11: Force-displacement loops of one of the ESBs tested at UCSD [15]

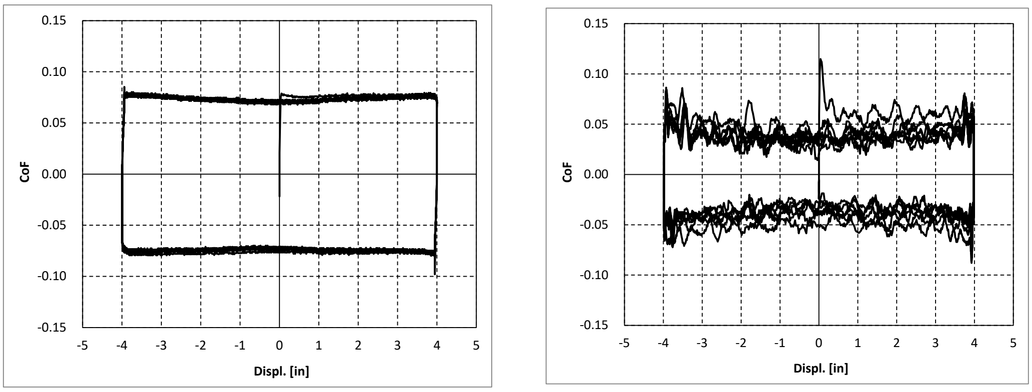
5 SLIDING SYSTEM USING POLYAMIDE (NYLON-BASED) MATERIAL

This section presents test results of a polyamide (nylon-based) sliding material that has been extensively used in different applications in Japan. Thorough characterization tests under various axial stresses and testing velocities have been conducted, and the sliding material has been introduced and used in several seismic isolation applications in the US. The material test specimen and test setup are shown in Figure 12. Selected test results are shown in Figure 13, and a summary of all the characterization testing is shown in Figure 14. Like PTFE sliding materials, the measured COF is dependent on both velocity and axial pressure. The polyamide COF is consistently lower than the expected COF for PTFE for all combinations of velocity and pressure.



(a) (b) (c)

Figure 12: a) Polyamide test specimen before testing, b) polyamide test specimen after testing, c) test setup



(a) (b)

Figure 13: Sample test loops for the polyamide material at stress = 4 ksi (27.6 MPa) a) test velocity = 1 in/sec (25.4 mm/sec), b) test velocity = 24.8 in/sec (630 mm/sec)

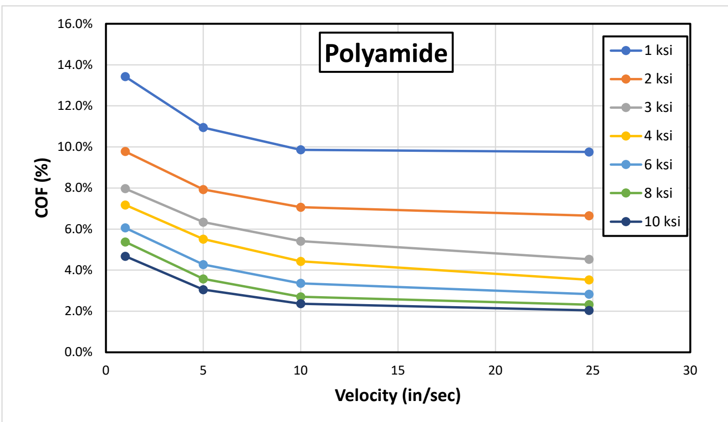


Figure 14: Summary of the characterization test results for the polyamide material conducted using various axial stresses and testing velocities

6 CONCLUSIONS

The paper summarized experimental testing of various types of seismic isolation systems. The test results demonstrate that the elastomeric isolators that are produced by qualified, high-quality manufacturers can undergo very large shear strains and axial demands and still exhibit stable hysteretic behavior. This demonstrates that individual Lead-Rubber Bearings (LRB) and Rubber Bearings (RB) are highly robust and resilient. The testing of a continuous curved bridge well in excess of the design displacement demonstrated that when placed in a system with other elastomeric bearings, an additional system robustness is achieved such that instability of individual isolators at one or two supports does not lead to bridge collapse. The system is able to fully recenter on its own and repeated instability of the LRBs does not cause permanent deformation in the isolation system or for the entire bridge. Effective seismic isolation of nonstructural equipment was achieved using the Multi-Directional Spring Units (MDSU). The MDSU has been utilized in seismically isolating individual equipment, server racks and full floors with excellent results in reducing the seismic forces and accelerations on the equipment. Different sliding products like the Elastomeric Sliding Bearings (ESB) or the Polyamide sliding material proved to be effective and has been recently used in many projects in the US.

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