16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2676 (Abstract ID)

Registration Code: S-T1466007904

Seismic Isolation of Sensitive Equipment

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Abstract

Seismic isolation has been used effectively over the past three decades to protect contents of structures and maintain the functionality of buildings. In recent years, there has been a growing interest in isolating only specific floors within buildings or select equipment. Isolating equipment poses unique challenges due to the relatively light mass supported by the isolators and the consequent need for isolator stiffness that is two to three orders of magnitude lower than conventional isolation. Moreover, space constraints inside the buildings and around the equipment require innovative solutions to accommodate the required isolation hardware. This paper discusses seismic isolation of equipment using a patented multi-directional spring. This innovative spring provides damping and self-centering capability while occupying much smaller space than conventional method of using orthogonal springs and dampers. This system was extensively tested on shake tables at the University of Nevada, Reno, SUNY University at Buffalo and the University of California, Berkeley. Over 300 seismic tests demonstrated the effectiveness of the system, which lowered accelerations transmitted by a factor of three or more. The system has been used in the US, Canada, Costa Rica, Venezuela and Ecuador. Size of applications ranges from a fully isolated floor of 1500 sq. m. to a single platform of 0.5 sq. m. In multiple modular format, the system was used to protect the super computers at the Lawrence Berkeley Labs where an entire 1500 sq. m. floor was isolated. In this case, the isolated floor was a physical substitute to the raised access floor (1220 mm tall). Moreover, the system provide a displacement capacity of 460 mm, while accommodating cables, cooling & sprinkler lines underneath. At the other end of the spectrum, individual platforms have been isolated to protect sensitive equipment in the Public Safety Building in Salt Lake City. These platforms provided a lateral displacement capacity of 610 mm, while measuring merely 180 mm in height. In a unique application for a control building on top of a dam in Canada, three-dimensional isolation was designed to protect critical control equipment from large accelerations generated from amplification through the extremely rigid dam structure. Other applications, such as isolation of statues located in a park and containerized data centers, show the wide potential of this system's ability to be used in outdoor conditions exposed to elements.

Keywords:

Nonstructural Isolation; Equipment Isolation; Low Mass Isolation; Multi-Directional Spring; Shake Table Testing.

1. Introduction

Seismic isolation has been implemented over the past three decades in many structures ranging from historic buildings, modern data centers, lifeline bridges, large liquid storage tanks, piers and other civil structures. It has been proven to be effective as evidenced in numerous earthquakes in Japan, US, New Zealand and Chile. In some cases, where isolation of a whole structure is not possible or practical, protection to contents and occupants can be provided by isolating specific floors or equipment within a building. Isolating equipment rather than an entire building poses certain challenges because of the low stiffness requirements and the need to allow sufficient space for movement of the isolation system within the building.

There have been some early attempts to isolate lighter units by focusing on the response of single equipment [1,2]. Ball-in-cone isolators [3,4] provide the advantage of uniform lateral force, but do not provide any initial strength or adequate damping. Other systems studied more recently [5] showed some of the limitation of using such systems for high aspect ratio equipment. These systems mostly focused on the response of individual equipment and not a whole floor.

Complete floor isolation systems enable equipment to be moved and re-located anywhere on the floor of specific rooms or areas. Some form of floor isolation systems have been used sporadically in Japan in the past 20 years. These systems are either gravity based using suspension mechanisms or linear spring based systems coupled with viscous dampers or lead plugs for damping [6]. Kaneko et al [7] report that a floor isolated system in Kansai area worked effectively during the 1995 Hyogoken-Nanbu earthquake.

The focus of this paper is to discuss a new system that can be utilized for stand-alone equipment or a complete floor. This system uses an innovative Multi-Directional Spring Unit (MDSU) that provides low stiffness, damping and self-centering capabilities to the isolated nonstructural components. These MDSUs can be used in individual modules or be combined together to isolate large floor areas. The inner workings of the multi-directional spring unit, its mechanical properties and analytical modeling, along with shake table testing of these units, are described in the first few sections of the paper. Later sections focus on applications of these units in a range of projects from individual platforms to large floors.

2. Multi-directional Spring Unit

The isolation system consists of a combination of modules and spacer or stinger members. A module is the smallest independent unit with direct vertical support, stiffness and damping elements incorporated in it. Spacer or stinger members are designed connect two modules. These transfer vertical and lateral loads to the active modules and are included to keep stiffness of the systems down and reduce overall cost. Modules for full floor system are usually 4' x 6' (1.2 m x 1.8 m) to allow easy transportation through the building, fitting within elevators. Also, they can be made as small as 4' x 4' (1.2 m x 1.2 m) for individual equipment isolation. Each module is supported on casters (rollers) or guided linear blocks, which provide vertical load transfer and unimpeded horizontal movement. Stiffness is provided by a ‘tension-only’ coil spring.

In a conventional arrangement, sets of coil springs with one end attached to the module and other to the ground will provide the required stiffness component. However, such an arrangement will require at least 4 springs per module, in orthogonal directions and to account for movement in + and – directions. The multi-directional spring unit eliminates the need for four independent spring thus improving the arrangement: A steel cable connects the coil spring to the active module on one side and anchors to the ground on the other side. This steel cable passes through a bushing that is attached to the module. The purpose of the bushing is to provide smooth transition from horizontal spring to vertical contact at the ground. Due to the placement of the bushing and spring, any horizontal movement of the module results in vertical pull of the cable, which in turn through the bushing causes extension in the spring. The extension of the spring provides stiffness and restoring force for the module. Schematic of the multi-directional spring unit is shown in Fig. 1.

As shown in Fig. 1, the surface of the bushing is the revolution of a semi-circle around an external axis parallel to its diameter. This surface is capable of accommodating 180º rotation of the cable in vertical plane and 360º rotation in the horizontal plane. The sliding of the cable on the bushing results in significant damping, as seen from the force-displacement (F-D) loop in Fig. 2. Another bushing that is a revolution of quarter circle is provided at the anchor point of the cable. This bushing accommodates rotations up to 90º vertically and 360º horizontally, thus allowing the cable to move without a sharp bend at the connection point. No sliding of the cable occurs at this bushing.

With both bushings lined up vertically in the starting position, there is no overall horizontal force on the module because the cable is vertical. As a result the F-D loop passes through the origin. As the module moves in any horizontal direction, there are two distinct regions of movement: (1) wrapping of the cable around the bushings, changing the cable angle from vertical to horizontal in a few inches of displacement. This manifests itself as the rapid increase in force in the early part of the F-D loop; (2) constant horizontal angle of the cable and steady pulling of the spring once the cable is completely wrapped around the bushings. This is seen as the steady secondary slope. The force applied by the spring is amplified or reduced as per the belt friction formula depending on loading or unloading directions. That is, the cable from ground anchor to the bushing is tight-side or slack-side depending on the movement away from the center or towards the center. This results in four distinct segments of the F-D loop, two each for loading and unloading branches.

The area between the loading and unloading branches contributes to damping in the system. Depending on the displacement, the equivalent viscous damping ratio is in the range of 10% to 15%. Detailed description of the multi-directional spring unit is provided in Cui et al 2010 [8].

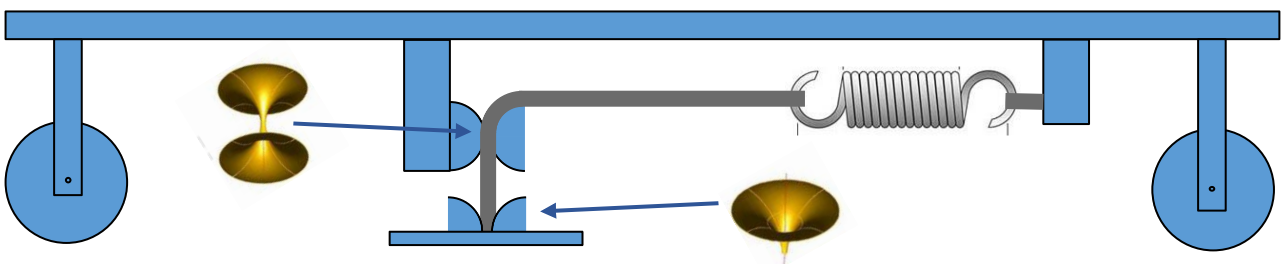


Figure 1: Schematic of the Multi Directional Spring Unit

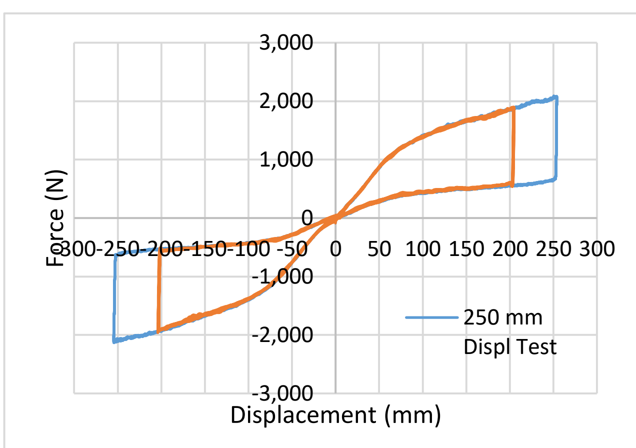


Figure 2: Force – Displacement Loop of a Multi-Directional Spring Unit

3. Combination of Modules to Isolate Larger Spaces

An individual module can be used to isolate a stand-alone unit such as sensitive equipment, artwork or server. Alternatively, several modules can be combined to form a large platform or a full floor as shown in Fig. 3. In the complete floor isolation configuration, the system is a physical substitute for the raised floor (or computer access floor). Such a configuration will include edge details and flexible connections. Multiple shake table tests were conducted on configurations consisting of single module, modules joined with connectors and modules with edge details. These tests are described in the section below.

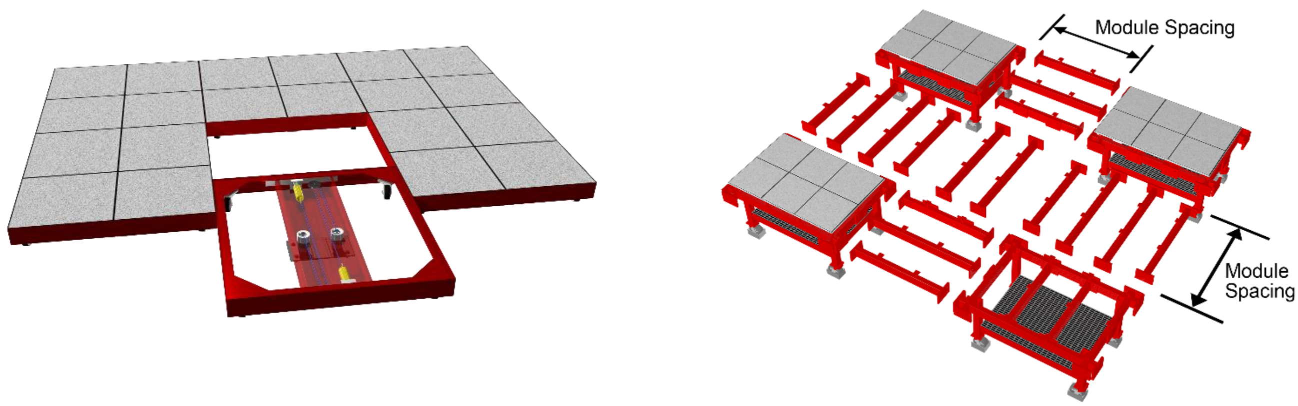


Fig. 3: Individual Modules connected to form larger floors (a) low profile configuration (< 12" or 300 mm), and (b) higher profiles for heights up to 48" (1.2 m)

4. Shake Table Testing

Early testing performed at University of Nevada, Reno in 2007 focused on establishing the behavior of the system, followed by a later testing in 2010 to evaluate the effectiveness of a single module in reducing the seismic forces on servers (Fig. 4). Over 200 tests were conducted using the bidirectional shake table at UNR on test specimens up to 6 feet x 12 feet in plan size. Results showed that the isolated platform reduced accelerations by a factor of 3 to 4.

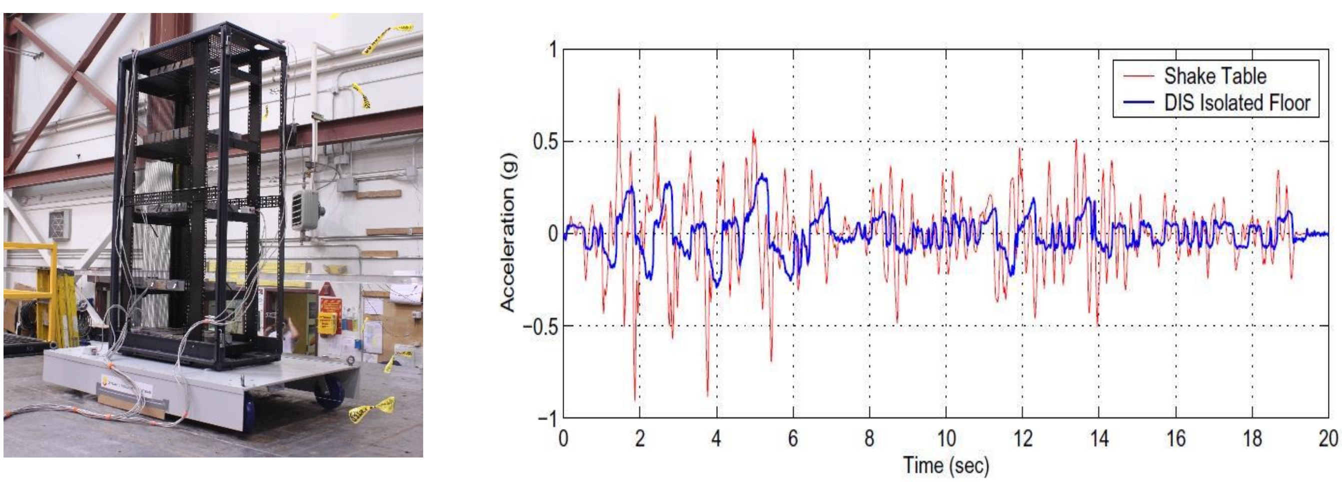


Fig. 4: (a) Testing of Single Server Rack at UNR; (b) Reduction of Input Accelerations by a factor of 3 to 4

Characterization of individual multi-directional spring units was conducted at State University of New York (SUNY), University at Buffalo (UB), in 2007 (Cui et al. 2010 [8]). In addition, effect of edge details and cover plates around the system were explored further in this testing (Figure 5). Overall, 35 tests were conducted covering a range of load conditions, X- and Y-eccentricities of load and stiffnesses of the springs, for uni- and bidirectional input. Results from these tests established the effect of friction from edge cover plates (Cui et al. 2016 [9]).

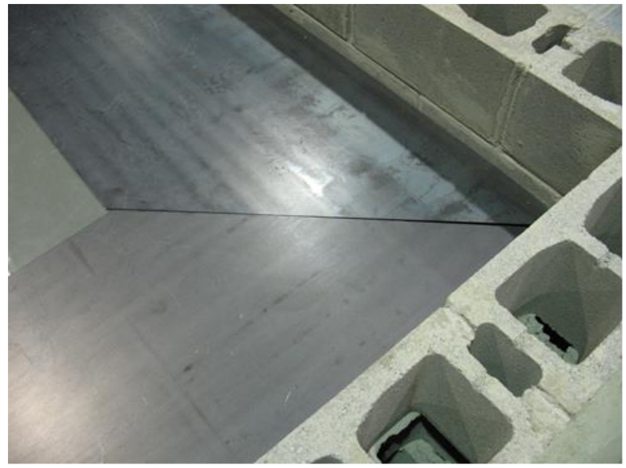



Fig. 5: (a) Overall View of the System tested at UB (lighter grey surface is the movable isolated floor; darker grey is the set of edge plates attached to the concrete wall); (b) Close-up of Corner Configuration of Edge Plates

Further testing was done on a larger connected modules at University of California, Berkeley's three dimensional shake table at Richmond Field Station in 2014. The tested system had an overall isolated area of 140 square feet featuring two spring modules, numerous stringers and extensions. The standard tile-stringer-pedestal system with 35 standard tiles was directly integrated onto the isolated platform. In addition, three fully equipped computer racks were placed on the tiles and were part of the shake table testing (Fig. 6). The focus of this study was to examine the behavior of multiple modules in fully loaded, partially loaded and unbalanced loaded conditions. Test results (Fig. 7) demonstrated the effectiveness of the system from 500 psf (24 kPa) to 175 psf (8.5 kPa) in uniform and unbalanced configurations (PEER STI/2014-12 [10]).

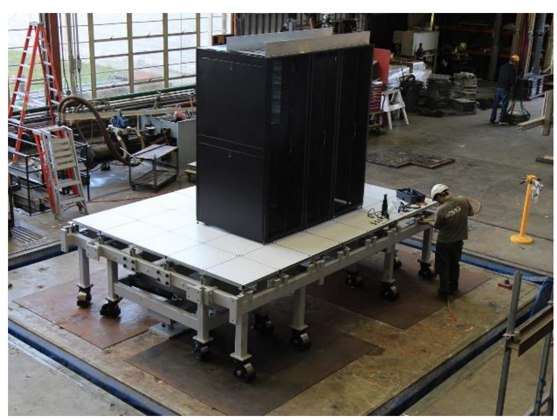



Fig. 6: Shake Table Testing of the Floor Isolation System at UC Berkeley: (a) Bare floor frame, and (b) Tile-stringer-pedestal system installed on top of the floor along with server racks

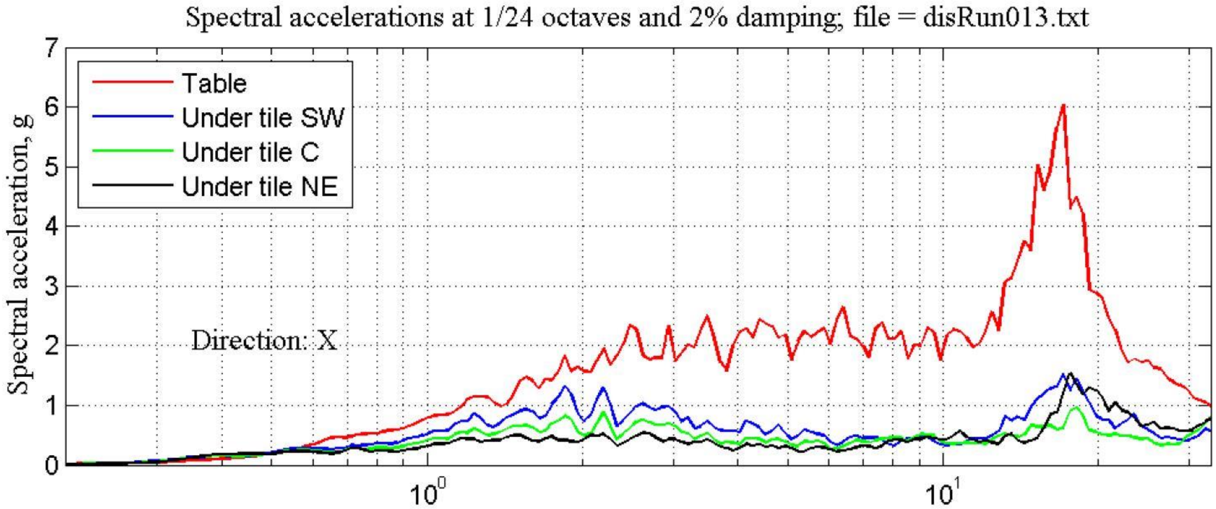


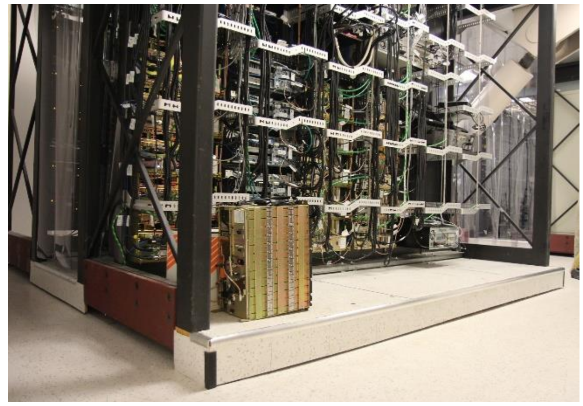
Fig. 7: Reduction of accelerations over a wide range of frequencies. Red line is the shake table input, other three plots are response spectra of accelerations on the isolated platform measured at three different locations.

5. Individual Modules – SLC and Union City Projects

5.1 Salt Lake City Public Safety Building

The new Salt Lake City Public Safety Building [11], completed in 2014, houses the city's police, fire and emergency management departments (Fig.8). This 4-story, 172,000 sq. ft. building was designed to remain operational after the maximum considered earthquake (2475 year return period). The lateral force resisting system consisted of steel moment frame with viscous dampers as well as perimeter SidePlate moment frames. These structural features ensured that the building achieved the Immediate Occupancy objective for the MCE and Life Safety objective for the 84% deterministic earthquake. Special attention was paid to the nonstructural component design. Nevertheless, the accelerations at the sensitive transmission components located in second floor level were higher than the equipment's rated limits. These components were isolated using individual platforms to reduce these accelerations in the 0 to 0.5 second period range.

Isolation platforms were designed to meet challenging constraints. Physically, the platforms needed to be 7" (175 mm) or shorter to eliminate the need for handrails and to accommodate the cables above. Laterally, the platforms were designed to 24" of movement in any horizontal direction. Finally, the spectral accelerations on top of the platform were limited to 1 g (maximum) and 0.75 g (average between periods of 0 and 0.5 sec). To meet the physical constraints, the platform was supported on low-profile, high-capacity casters and required specially designed low profile multi-directional spring units. To meet the design goals, the platforms were designed to have an isolated period of 2 seconds with an equivalent damping ratio of 13%. Nonlinear time history analyses were performed with seven records in SAP2000 [12] using Pivot elements to model the multi-linear elastic behavior of the spring element.



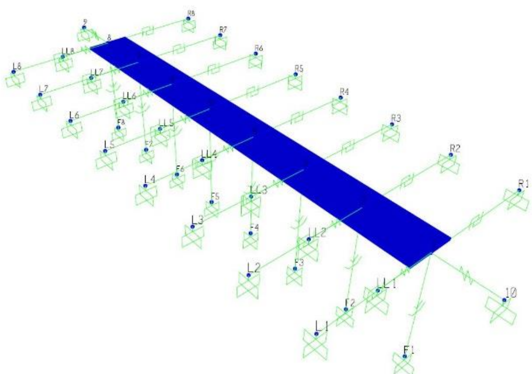


Fig. 8: (a) Salt Lake City Public Safety Building;

(b) Isolated platform to protect sensitive equipment (viscous dampers used to protect the structure can be seen in the upper right corner); (c) Analycial model of a long isolated platform.

5.2 Union City Plaza Statues

Three tall bronze-sculpted “Danseurs,” which were previously displayed on the north side of the Louvre in Paris, are now the centerpiece of the civic plaza in Union City, CA (Fig. 9). Each statue is 16 feet (5 meters) tall and weighs about 4,000 pounds (1,800 kg), with ankles that are only 6 inches (150 mm) in diameter. With Hayward fault 1 km from the site, analyses showed that the fixed-base sculptures will be subjected to 1.3 g in a design earthquake (DE) with demand-to-capacity (DCR) ratio of 4.95 at the ankles of the statues [13].

Isolated platforms measuring 8 feet x 8 feet (2.4 m x 2.4 m) were placed under each statue to reduce the seismic demand. The high aspect ratio of the statues required tensile load capacity from the platform. Four cross-linear bearings were used to carry the vertical load as well as provide tensile load capacity. These bearings have a coefficient of friction of less than 0.5% and were designed to move freely in any horizontal direction up to 30 inches (760 mm). An analytical model of the sculptures over the platforms was developed using SAP2000. Sculptures and the steel platform were modeled as linear elastic elements and the multidirectional spring unit was modeled with nonlinear elements to simulate the springs’ force-displacement loop. Force in the cross-linear bearings was ignored as they provide little resistance to movement (< 20 lb). Average displacement for seven (7) time history records was 20 inches (500 mm) with the average acceleration reduced to 0.2 g. Moreover, the Demand-Capacity-Ratio (DCR) for the stress in the ankles was reduced to 1.04, with little to no damage expected during the DE event.

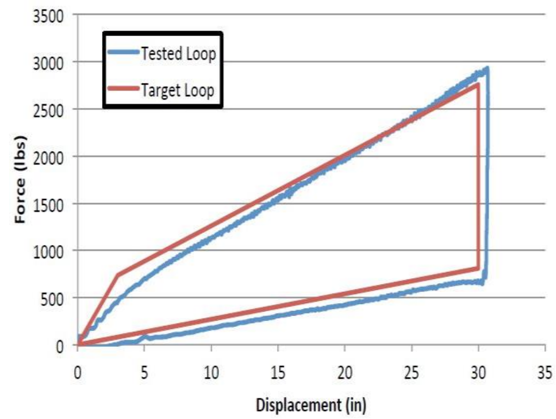


Fig. 9: (a) Statues on isolated platforms at Union City Plaza; (b) Verification test to confirm the properties of the full-scale isolated platform.

6. Floor isolation by Connecting Several Modules – UCB project

The new Shyh Wang Hall or Computational Research and Theory Facility (CRTF) at the Lawrence Berkeley National Laboratory is located less than 1 km from the Hayward fault. This facility will house National Energy Research Scientific Computing Center (NERSC), one of the leading supercomputing centers that serves nearly 6,000 researchers in the US and abroad. It's 20,000 sq. ft. machine room houses two Department of Energy (DOE) supercomputers. Steep hillside location of the building precluded the use of seismic isolation for the whole building, therefore, to protect the supercomputers, 16,000 sq. ft. (1,500 sq. m.) of the floor was isolated [14].

One of the key challenges of this project was the variable loading on the isolated floor over the life of different supercomputers. Some of the new generation supercomputers are water-cooled and weigh up to 500 psf. However, during changing of one system to the other, there are large chunks of floor that would have no load at all, other than the dead load. This required careful consideration of torsional effects of the unbalanced system. Other demands on the system were the requirement to remove any tile independent of other tiles, requirement to have clear accesses under all tiles (not have any cross bracing under the tiles), sufficient space (4' or 1.2 m) under the floor to allow cooling water lines, power, network cables and sprinklers and class 8 clean room requirements above the floor.

The final solution consisted of 139 basic modules, each measuring 6' x 4'. These modules were interconnected with 6' long stringers or beams. A conventional access floor (tile-stringer-pedestal) system was integrated into the base frame members (Fig. 10). The system was designed to move 18" (450 mm) in any horizontal direction and all utilities were attached to translate with the system and joined the surrounding structure via flexible connections. Behavior of the system for unbalanced/asymmetrical loading was validated by performing three-dimensional shake table tests at Richmond Field Station (Fig. 6). Spring module's bushings were tested for wear to ensure that class 8 clean room requirements were met. The finished floor is identical in its appearance to typical raised access floors used in data centers, with the exception of gap cover plates around the perimeter designed/included to maintain continuity in a seismic event.

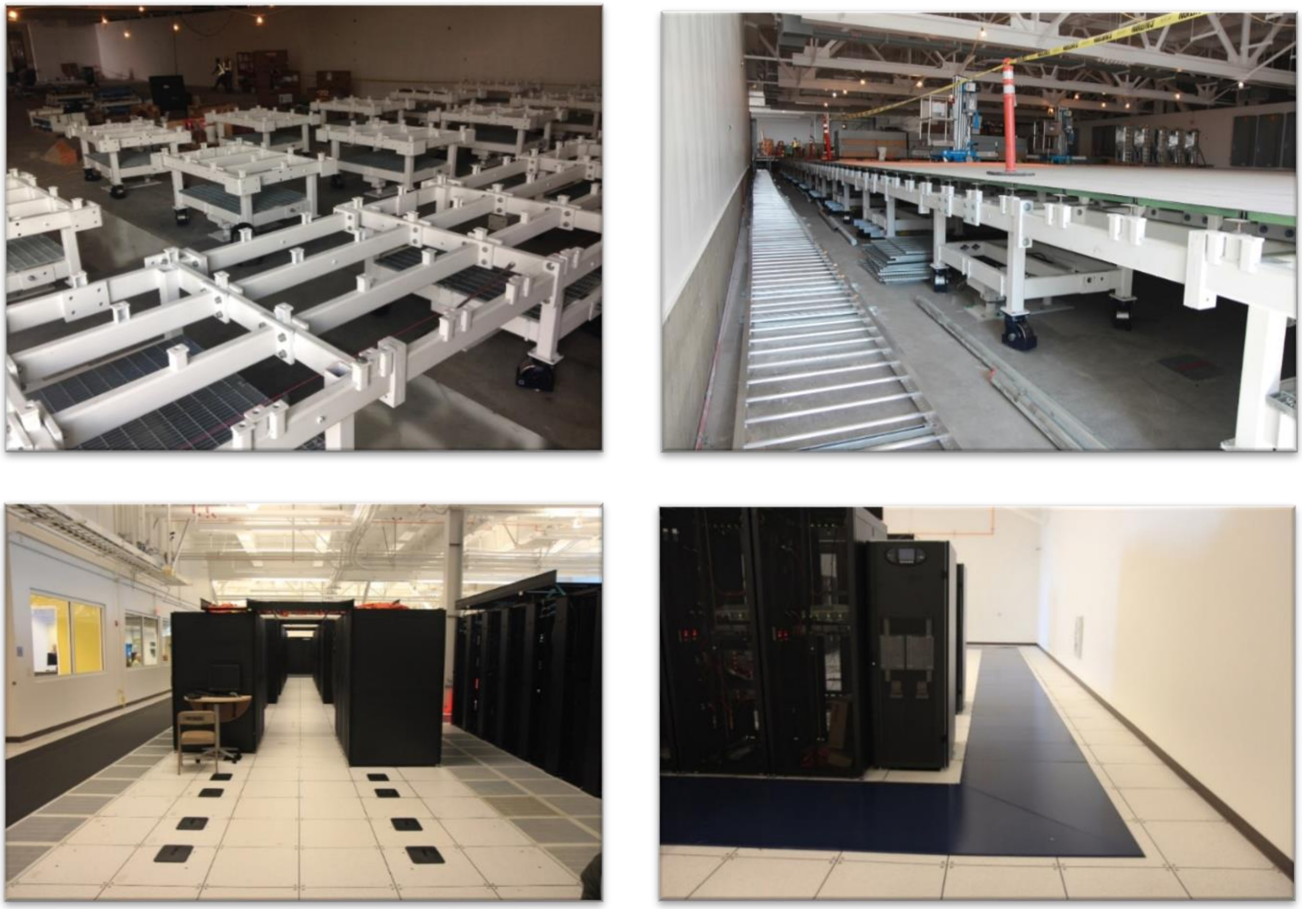


Fig. 10: (a) Individual modules placed and being connected with stringers, (b) floor tiles installed on the frame, (c) Completed Floor with super computers, and (d) Seismic gap covers around the perimeter.

7. 3-D Isolation of Tall Equipment

Many sensitive components undergo seismic qualification tests in accordance with AC156 or NEBS specified shake table tests. These tests ensure that the equipment can survive input motion over a wide range of frequencies (0.3 to 33 Hz) and remain operational. In many applications with high local seismicity, or unfavorable placement of equipment within the structure (such as in upper floors of stiff building) the motion reaching the equipment exceeds the qualification threshold. By selecting the correct period of isolation, these motions can be reduced by an order of magnitude and be brought within the qualification threshold. The reduction in force and acceleration transmitted enables the equipment to be used safely during and after the earthquakes. Examples of such cases for a large utility company in Canada requiring isolation in horizontal as well as vertical directions are provided below. Furthermore, electrical equipment had high aspect ratios (in the range of 3 to 5), which resulted in higher accelerations at the top due to rocking and pitching motions.

Three dimensional floor isolation systems developed in Japan (Arima et al. 1997 [6], Kaneko et al, 1995 [7]) were found to be complex and not practical for this application. Also, systems tested by Fathali and Filiatrault, 2007 [[5] were found to have amplification of motion due to rocking. Therefore, a new vertical isolation system was developed that consisted of compression springs, viscous dampers and linear guides. Use of linear guides enabled the system to translate in the vertical direction while fixing the rotational degrees of freedom. This vertical isolation system can be used independently (Fig. 11 a) or in conjunction with a horizontal isolation system (Fig. 11 b). Both configurations were thoroughly tested on shake table to validate their seismic performance.

Fig. 12 shows the effectiveness of the 3D isolation platform. The blue IEEE 693 High Performance line is the qualification threshold of the equipment. The red plot is the acceleration response reaching the equipment prior to being isolated and can be seen to exceed the threshold at different frequencies in X, Y and Z directions. The green plot is the acceleration response spectrum above the 3D isolation platform. Improvement of performance by an order of magnitude can be seen in X and Y directions. Static deflection associated with vertical isolation limited the reduction of acceleration in this axis due to space constraints. In this project, a vertical period of 0.5 sec was utilized. The addition of significant damping, provided by fluid viscous dampers in the vertical direction, ensured good performance was achieved despite the short period in this axis.

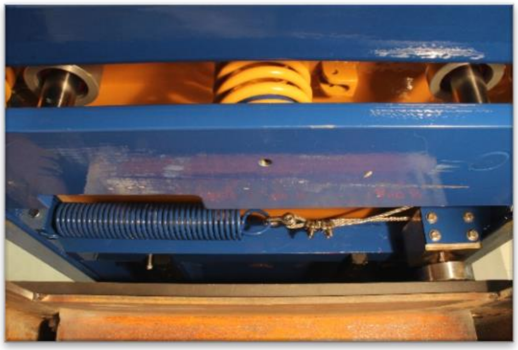


Fig. 11: (a) Individual Vertical isolation platform;

(b) 3-D Isolation Platform – horizontal and vertical springs can be seen in the photograph.

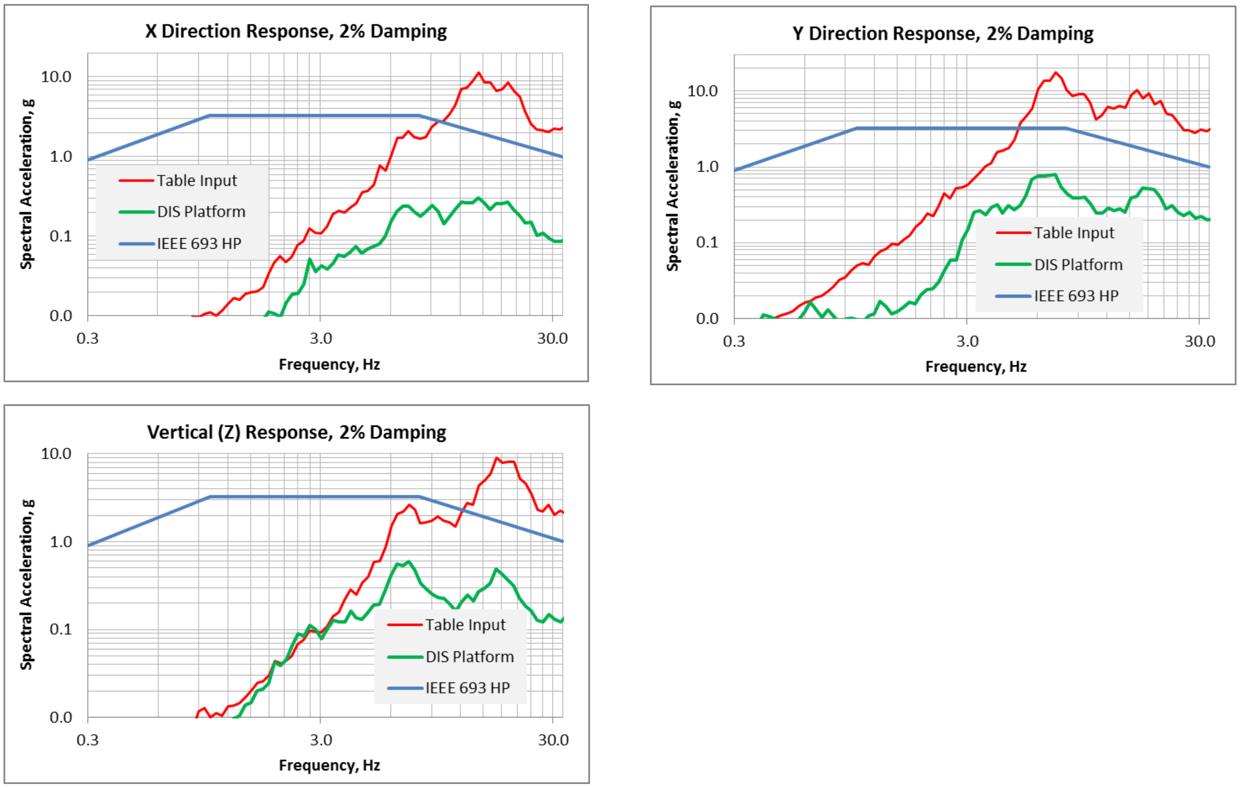


Fig. 12: Effectiveness of 3-D isolation system in X, Y and Z directions

8. Conclusions

Effective, economical and practical isolation of nonstructural components and equipment was achieved using the multi-directional spring units (MDSU). This technology has been utilized in isolating multiple floors, platforms and individual components with excellent results. Comprehensive shake table tests were conducted on this system to validate the performance over a wide variety of loading configurations and edge conditions. In addition, a simple and practical solution was developed for vertical isolation of equipment utilizing a combination of MDSUs, linear guides, and viscous dampers. This technology shows a clear method for preventing damage to and downtime of critical equipment for life safety and continued operations when faced with extreme seismic events.

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