THE SUSTAINABILITY OF MOTION CONTROL SYSTEMS

by

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Abstract

With all the damage to structures due to dynamic loading in the past few decades, the demand for motion control systems in structures has skyrocketed. Many different technologies for combating wind and earthquake loads have been identified. Energy dissipation devices and base isolation are two methods that reduce the damage and minimize the response of a structure.

Energy dissipation of a structure removes energy and therefore movement from a structure by providing damping. Motion energy is converted to other types of less damaging energy. Base isolation is only effective against earthquakes. Bearings are placed under a building and stop ground motion from getting into the building.

This thesis will provide an overview of available dampers and bearings available in the market. Then it will look at how sustainable each type of device is. Sustainability of a device will be determined by its expected lifetime and required maintenance.
Acknowledgements

This thesis would not have been possible without the help of many people. I would like to thank them all.

First of all my parents, who have always supported me. They have given me their determination, their love of learning and their warped sense of humor, all of which helped in the writing process. Thanks mom and dad.

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I am forever grateful to my boyfriend Drew, who has encouraged me, helped type and provided just the right amount of distraction from my work.

My best friends Bridget and Barbora, who have always been there for me. Thanks for keeping the bonds tight even over the long distance.

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A huge thanks to my thesis advisor Professor Connor and all my other professors. Your wisdom and understanding overwhelm me.

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1 Introduction

Damage caused by dynamic loading has been staggering in recent years. The price tag on direct and indirect damages for the 1989 Loma Prieta and 1994 Northridge earthquakes was over 50 billion dollars. Wind effects of some high rises have rendered them useless due to motion sickness and even minor failure. This has shifted the design focus from life-safety to performance when it comes to structural response to motion. In response to the new demand in design, a new type of technology has come about called motion control. Motion control in structures can be broken down into three different categories. These are base isolation, passive energy dissipation, and active control.

Table 1-1 Classification of Motion Control Systems

<table>
<thead>
<tr>
<th>Base Isolation</th>
<th>Passive Energy Dissipaters</th>
<th>Active Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Damping Rubber Bearings</td>
<td>Viscous Dampers</td>
<td>Bracing Systems</td>
</tr>
<tr>
<td>Lead Rubber Bearings</td>
<td>Friction Dampers</td>
<td>Mass Systems</td>
</tr>
<tr>
<td>Elastometric Bearings with Energy Dissipation Devices</td>
<td>Hysteretic Dampers</td>
<td>Variable Stiffness and Mass Systems</td>
</tr>
<tr>
<td>Friction Pendulum Bearings</td>
<td>Viscoelastic Dampers</td>
<td>Pulse Systems</td>
</tr>
<tr>
<td>Flat Sliding Bearings with Restoring Force Devices</td>
<td>Tuned Mass Dampers</td>
<td>Aerodynamic Systems</td>
</tr>
<tr>
<td>Lubricated Sliding Bearings with Energy Dissipation Devices</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.1 Active Control

Active control differs from base isolation and passive energy dissipation in that it requires external energy to operate. Someone must literally flip the switch to turn the system on. This makes active control less reliable during a natural disaster caused blackout, where electricity is not available and motion control is most needed. Active
control is also the most adaptive motion control system available. With active control, system properties can be varied to combat motion more effectively. Hence, active control is not used as much as other technologies and will not be discussed in this report.

1.2 Passive Energy Dissipaters

Passive energy dissipation is implemented through dampers. Dampers remove energy or motion from a structure in a non-destructive way. Dampers can be configured throughout a building to minimize displacement, velocity, acceleration or a combination of two or more. By controlling a structure's response to dynamic loading, a large amount of damage to the structure and its facilities can be avoided.

Energy is represented four different ways in a structure. This is shown in the following equation:

\[ E_{t} = E_{k} + E_{s} + E_{u} + E_{f} \]

\( E_{t} \) is energy inserted into the structure by an outside force, such as wind or an earthquake. This energy input is converted into the four energy types of a structure. \( E_{k} \) is kinetic energy and it is manifested in the movement of the structure. \( E_{s} \) is elastic strain energy. Elastic strain energy is fully recoverable and stores the energy like a spring, which releases energy back into motion again. \( E_{u} \) is plastic strain energy. Plastic strain energy is not recoverable; it is trapped in the structure in the form of residual deformation or damage. The last type of energy is friction energy. A large portion of friction energy is released as heat; the remaining part is trapped as deformation.

Hysteretic dampers are designed to yield before other elements of a structure and dissipate energy through cyclic inelastic deformation. Viscous, friction and viscoelastic dampers use friction to release energy. By removing energy from the system in a non-destructive predictable way, dampers are able to protect the structures they are housed in.
Tuned mass dampers use inertia force to dissipate energy. This is a type of kinetic energy. The damper is tuned to resonate out of phase with the structural motion. By doing so, it exerts a force on the structure which cancels out the force created by the structure’s motion.

Damping in a structure is quantified as a percentage of the critical damping or damping ratio. Critical damping is the smallest amount of damping needed to inhibit oscillation completely. It is a function of the mass and stiffness of a system. Structures are always under damped. Damping ratios usually range from 2% to 30%. Wind vibration control usually provides a 5% damping ratio while seismic application ranges from 10 to 20 percent of critical damping. The reduction of displacements induced in a structure (ignoring relatively stiff energy dissipation devices) as a function of the damping ratio can be calculated.

Table 1-2 Displacement Reduction Factors

<table>
<thead>
<tr>
<th>Percent of Critical Damping</th>
<th>Displacement Reduction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>15</td>
<td>1.4</td>
</tr>
<tr>
<td>20</td>
<td>1.6</td>
</tr>
<tr>
<td>30</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Only a little bit of damping can reduce displacement significantly. Above 30% damping, there is diminished returns in system protection.
1.3 Base Isolation

Base isolation also protects structures from damaging dynamic loading effects. Base isolation is placed under a structure and keeps ground motion from acting on the structure. This is obviously only effective against earthquakes. By adding base isolation beneath a stiff building, forces and displacement can be reduced by as much as a factor of four. (Aiken, 1996) This is accomplished primarily through period shift. Base isolation uses flexible bearings under a structure to create a layer of low stiffness. When the earthquake ground motion occurs, the bearings shear and the building does not move laterally.

There are two different types of bearings, sliding bearings and laminated bearings. Bearings are designed to provide the appropriate stiffness in the vertical direction and flexibility in the horizontal direction. Laminated Rubber Bearings are made up of stacked layers of rubber and steel shims. The steel shims provide vertical stiffness while the rubber allows for flexibility in the horizontal direction. Sliding bearings use friction instead of a material to produce displacement and damping. There are many combinations of these types of bearings using a variety of materials.

---

Figure 1-1 Different Types of Bearings
2 Testing

Motion control devices are a relatively new technology. So their lifespan and maintenance requirements or sustainability is unknown. Structures are built to last decades; will the motion control devices housed within them do the same? One way to determine this is through testing.

There are already codes and guideline documents that provide design provisions for base isolation and passive energy dissipation. The Uniform Building Code and AASHTO Guide Specification both have design code requirements for base isolation that have included testing since 1991. The NEHRP Guidelines for the Seismic Rehabilitation of Buildings gives design and testing methods for base isolation and passive energy dissipation for retrofit. The code mandated testing requirements have two goals in mind. First to make sure the devices have the physical properties specified in design and that they can withstand the maximum expected earthquake and wind loading, and secondly, for quality control of devices that will be installed. No testing is specified for sustainability.

2.1 Testing Methods

2.1.1 Reduced-Scale Dynamic Testing

Reduced-scale dynamic testing is the most common test for research on base isolation and passive energy dissipation. It is possible to test scaled down devices with existing shake tables at large test labs. These tests are small enough to not require hydraulic pumps or accumulators, which drive up energy costs. Tests machines at the University of California at Berkeley and State University of New York at Buffalo can test bearings under vertical loads up to 200 kips and horizontal loads in one direction up to 75 kips. The maximum deflection of these machines is plus or minus 6 inches and the maximum
velocity is 25 inches per second. Additional features include axial tension loads, horizontal moments and the ability to measure bearing force directly with load cells. Both schools also have machines to test passive energy dissipation devices dynamically. Berkeley and SUNY’s machines, which were originally made to test viscous dampers, have force output of 100 and 50 kip respectively. With maximum displacements of plus or minus 10 inches and velocity of 20 inches per second, they are able to test small velocity driven dampers.

Reduced-scale dynamic testing was used in the Golden Gate Bridge Seismic Retrofit. The full-size dampers for the project will produce an average power of 261 kW and a peak power of 5.41 MW under design loading. Dynamic testing on this scale would be way too expensive and produce an enormous amount heat, so reduced-scale dampers were designed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reduced-Scale</th>
<th>Full-Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Stroke</td>
<td>±152 mm (±6 in.)</td>
<td>±660 mm (±26 in.)</td>
</tr>
<tr>
<td>Maximum Design Force</td>
<td>445 kN (100 kips)</td>
<td>2890 kN (650 kips)</td>
</tr>
<tr>
<td>Maximum Design Velocity</td>
<td>508 mm/sec. (20 in./sec.)</td>
<td>1900 mm/sec. (75 in./sec.)</td>
</tr>
</tbody>
</table>

The test program ran an endurance test that simulated wind-induced high-cycle loads to test the damper’s seals and moving parts. Data from this type of testing could be used to determine sustainability. Other tests included sinusoidal and constant velocity tests with the design earthquake input and design considerations with various displacements, amplitudes, velocities and loading frequencies. The cyclic test was done at temperatures of 40, 70 and 125 degrees F. Each damper took two to three weeks to test. The total cost of the program was $150,000, with the dampers provided by the manufacturers at no cost.
Passing the reduced-scale dynamic test pre-qualified devices for use. The full-size dampers would still need to be tested by other methods for quality control.

2.1.2 Large-Scale Quasi-Static Testing

Quasi-static testing is the least expensive way to test large devices. It is a reasonable method if the device is not dependant on the rate of loading or thermodynamic effects. Quasi-static testing works well for elastomeric isolation bearings and dampers that are not velocity driven, for example, yielding steel dampers. Rates of loading are in the
magnitude of 8-12 in/min, which requires much smaller equipment than a faster test. Sliding bearings, such as the friction pendulum system requires at least a rate of 1-4 in/sec, which is sometimes possible with this type of testing.

Most manufacturers for elastomeric bearings have quasi-static testing capability. In order to apply vertical loads to a fixed platen, two bearings are stacked and a shear load is applied in the middle. This gives average results for the two bearings. Larger machines are capable of vertical compression loads of 4000 kips and shear loads of 1000 kips in one direction only. Bearings up to 72 in square and 36 in high can fit into these machines.

Quasi-static testing of high-damping rubber bearings was used for the LAC/USC Medical Center Replacement Project. The basic testing requirements were defined in the 1994 UBC. The testing loads and displacements were very high, a 4000 kip vertical load combined with a shear displacement of 20 inches. Because the design involved uplift at some of the columns which called for a loose-bolt connection between the bearing and structure, additional tests were run to determine the connection’s effect on the bearing.

This type of testing verifies the design specifications of a device, but does little to estimate the sustainability of the device. If wear developed after such a short loading time, some extrapolation could be done. Although such wear would most likely be due to a quality defect and be deemed not acceptable.

2.1.3 Large-Scale Dynamic Testing

Drop testing, which was originally developed for shock and impact applications, has been applied to viscous dampers. Like its name implies, the test involves dropping a weight onto the damper, which causes a high impact force at a known velocity. This type of test is usually done in conjunction with reduced-scale dynamic testing in order to calibrate the test. Drop testing applies impact loads of up to 2000 kips at a maximum of 450 in/sec.
With the damper's piston in different starting positions, drop tests can load a damper in both extension and retraction directions.

![Figure 2-2 Drop Test Machine at Taylor Devices](image)

The short duration of the impact loading in a drop test limits the test ability to determine sustainability. Forces in the device dissipate before the next load is applied. ETEC is one of two large-scale dynamic testing facilities opened just recently in California. The Energy Technology Engineering Center (ETEC) Facility in Canoga was originally designed to rest large bearings for base isolation of nuclear power plants. The machine could test bearings with vertical and one direction of horizontal loading and uniaxial energy dissipation devices. The machine was enhanced as a part of an extensive testing program for Highway Innovative Technology Evaluation Center (HITEC). The details of this testing program will be explained later on. The testing capabilities of the ETEC machine are as follows.
Table 2-2 Capacity of ETEC Test Machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>±1180 kN (±265 kips)</td>
</tr>
<tr>
<td>Displacement</td>
<td>±380 mm (±15 in.)</td>
</tr>
<tr>
<td>Velocity</td>
<td>± mm/sec. (± in./sec.)</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>3,560 kN (800 kips)</td>
</tr>
<tr>
<td>Displacement</td>
<td>±102 mm (±4 in.)</td>
</tr>
<tr>
<td>Velocity</td>
<td>±254 mm/sec. (±10 in./sec.)</td>
</tr>
</tbody>
</table>

Caltrans' SRMD Test System at University of California, San Diego

The new California Department of Transportation Seismic Response Modification Device (SRMD) Test System was built to test various devices to be used in 6 major toll bridge retrofits planned by California. The size of some of these devices is unprecedented. The devices play a key role in the dynamic response of the bridges. This raises concerns about their seismic performance, as well as sustainability. This is why Caltrans designed the SRMD test system, which will be able to test large-scale bi-directional horizontal and vertically loaded bearings in real-time, and actual size uni-axial dampers.

Table 2-3 Capacity of SRMD Test Machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical force</td>
<td>44,500 kN (10,000 kips)</td>
</tr>
<tr>
<td>Horiz. force: longit. / trans.</td>
<td>±8900 kN / ±4450 kN (±2,000 kips / ±1,000 kips)</td>
</tr>
<tr>
<td>Vertical displ.</td>
<td>254 mm (10 inches)</td>
</tr>
<tr>
<td>Horiz. displ.: longit. / trans.</td>
<td>±1220 mm / ±610 mm (±48 inches / ±24 inches)</td>
</tr>
<tr>
<td>Vertical velocity</td>
<td>±254 mm/sec. (±10 inch/sec.)</td>
</tr>
<tr>
<td>Horiz. velocity: longit. / trans.</td>
<td>±1780 mm/sec. / ±760 mm/sec. (±70 inch/sec. / ±30 inch/sec.)</td>
</tr>
<tr>
<td>Maximum specimen size</td>
<td>3.66 m x 3.66 m in plan x 1.52 m high (12 ft. x 12 ft. in plan x 5 ft. high)</td>
</tr>
</tbody>
</table>
The machine will have an accumulator bank of 150 gal. of displaced oil volume. During a 20 second test, the system will produce an average power of 8040 hp with a peak output of several times more. This will be able to simulate actual earthquake loading for even the largest devices to be used on the toll bridges. The facility opened in August of 1999 and is scheduled to test the bearings for the Benicia-Martinez retrofit in three phases. The first phase will test slow-speed uni-directional shear loads with a constant vertical load. The next phase will involve actual earthquake inputs and have six degrees of freedom. The final phase of the test will look at sustainability. These tests will include using devices that have been removed from the bridge after use. The total cost of the system is around 15 million dollars.

![Figure 2-3 SRMD Test Machine](image)

### 2.2 HITEC Testing Program

The evaluation of seismic isolation and energy dissipater devices was conducted by the Federal Highway Administration (FHWA), California Department of Transportation (Caltrans) and the Highway Innovative Technology Evaluation Center (HITEC) in 1998.
These are some of the few published test results to include sustainability and will be referred to often in the following text. The tests consisted of a range of dynamic testing on full-scale devices in order to determine range, capacity, resilience, performance under service and dynamic loads, energy dissipation, functionality in extreme environments, resistance to accelerated aging (salt spray), predictability of response, fatigue and wear, and size effects. These properties were determined by nine different tests on five similar devices.

Table 2-4 Example of Test Article Physical Properties

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1</td>
<td>50</td>
<td>19</td>
<td>6.0</td>
<td>2.0 (+/- 1.0)</td>
<td>450</td>
<td>65.50</td>
<td>3.0</td>
</tr>
<tr>
<td>TA #2</td>
<td>150</td>
<td>28</td>
<td>9.0</td>
<td>3.0 (+/- 1.5)</td>
<td>1600</td>
<td>87.75</td>
<td>3.0</td>
</tr>
<tr>
<td>TA #3</td>
<td>150</td>
<td>28</td>
<td>9.0</td>
<td>3.0 (+/- 1.5)</td>
<td>1600</td>
<td>87.75</td>
<td>3.0</td>
</tr>
<tr>
<td>TA #4</td>
<td>150</td>
<td>28</td>
<td>9.0</td>
<td>3.0 (+/- 1.5)</td>
<td>1600</td>
<td>87.75</td>
<td>3.0</td>
</tr>
<tr>
<td>TA #5</td>
<td>240</td>
<td>38</td>
<td>12.0</td>
<td>4.0 (+/- 2.0)</td>
<td>2800</td>
<td>103.00</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Test 1 Performance Benchmark: To verify experimentally the initial response characteristics, damping, and number of loading cycles required to stabilize response.

Test 2 Compressive Load Dependent Characterization: To quantify experimentally the effects of varying compressive loads on the performance characteristics, specifically stiffness, damping, and energy dissipation per cycle (EDC). This test is only applicable to isolators.

Test 3 Frequency Dependent Characterization: To determine experimentally dynamic performance characteristics at varying frequencies in the primary direction of operation. This test is only applicable to isolators.
Test 4 Frequency Dependent Characteristics: To determine dynamic performance characteristics and verify the constitutive laws. This test is only applicable to dampers.

Test 5 Fatigue and Wear: To evaluate the potential seismic performance changes resulting from 10,000 cycles of service movements (temperature and live load fluctuations).

Test 6 Environmental Aging: To verify experimentally seismic performance after exposing the device to a salt spray environment.

Test 7 Dynamic Performance Characteristics at Temperature Extremes: To assess the effects of extreme temperature on the performance characteristics.

Test 8 Durability: To assess component durability resulting from a moderate number of strong motion cycles.

Test 9 Ultimate Performance: To determine experimentally ultimate displacement and margins of safety.

Table 2-5 HITEC Program Example Test Matrix

<table>
<thead>
<tr>
<th>TA #1 (50 kip)</th>
<th>Test 1</th>
<th>Test 4</th>
<th>Test 8</th>
<th>Test 9</th>
<th>N/A</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #2 (150 kip)</td>
<td>Test 1</td>
<td>Test 4</td>
<td>Test 7</td>
<td>Test 8</td>
<td>Test 9</td>
<td>N/A</td>
</tr>
<tr>
<td>TA #3 (150 kip)</td>
<td>Test 1</td>
<td>Test 4</td>
<td>Test 7*</td>
<td>Test 8</td>
<td>Test 9</td>
<td>N/A</td>
</tr>
<tr>
<td>TA #4 (150 kip)</td>
<td>Test 1</td>
<td>Test 4</td>
<td>Test 5</td>
<td>Test 6</td>
<td>Test 4</td>
<td>Test 9</td>
</tr>
<tr>
<td>TA #5 (240 kip)</td>
<td>Test 1</td>
<td>Test 4</td>
<td>Test 8</td>
<td>Test 9</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: Test numbers do not correspond to the testing sequence. Table 3.1 shows the actual test sequence, left to right, for each test article submitted.

* Test 7 (for hot temperatures) was performed on TA #3 only if it was fabricated from different materials than TA #2.
In order to determine the sustainability, only the relevant test results will be considered.
In most cases, this will primarily be test 5, test 6, test 7, test 8 and test 9.
3 Viscous Dampers

A typical viscous damper is a telescoping piston/cylinder filled with fluid. The piston head has voids in it to allow the fluid to move through it. The damper usually also includes an external guide sleeve, extender and attachment clevises. The guide sleeve increases buckling resistance and protects the piston rod from the outside environment. A seal on the sleeve can be added to scrape contaminants from the damper cartridge.

![Figure 3-1 Taylor Devices Viscous Damper](image)

Force is generated in the device by the pressure differential across the piston head and the fluid compressibility. Viscous dampers transform energy into heat, like most dampers. Viscous dampers are unique in that their force output is directly related to velocity. Velocity is out of phase with displacement in the structure, so the amount of force applied to the structure at any particular moment is minimized in this arrangement.

\[ ma + cv + kd = F \]
Where $a$, $v$ and $d$ are acceleration, velocity and displacement respectively. $M$ is the mass of the structure; $c$ is the damping coefficient; and $k$ is the stiffness. The inertia forces $(ma)$ are directly related to the acceleration of the structure and act in phase with the stiffness force $(kd)$. Without any damping at all, a structure would continue to oscillate due to inertia and stiffness forces indefinably. Fortunately, all systems contain some damping usually in the form of friction and yielding of materials. But by increasing damping, even just a little, a structure will stop moving much quicker.

The viscous damper, by being out of phase, applies the necessary forces to stop the movement in the structure when the inertial and stiffness forces are not being applied. This reduces the total forces on the structure at any given time.

### 3.1 Materials

There are five major parts that make up a typical viscous damper. These are the fluid, seal, piston rod, pressure cylinder and end caps. The materials which make these components play a big part in the sustainability of a damper. By researching the sustainability of the materials of a product, the sustainability of the whole can be estimated. Although, this method does not account for poor mechanical design.

**Fluid** – Silicon which is a pure fluid polymer that will not settle out or breakdown into components. It is prone to oxidation but this is prevented by permanently sealing the silicon inside the damper. Silicon is heat resistant to 418 degrees F.

**Seal** – High strength polymer which is high strength and wear resistant. It makes it possible for no needed periodic seal changes or seal exercising.

**Piston Rod** – Stainless steel is a type of steel that contain more than 10% chromium, with or without other alloying elements. Stainless steel resists corrosion, maintains its strength at high temperatures, and is easily maintained.
Pressure Cylinder and End Caps – Alloy Steel which is an iron-based mixture with manganese is greater than 1.65%, silicon over 0.5%, copper above 0.6%, or other minimum quantities of alloying elements such as chromium, nickel, molybdenum, or tungsten. An enormous variety of distinct properties can be created for the steel by substituting these elements in the recipe. This application’s alloy is designed for a high burst pressure.

3.2 Testing

Two different bands of viscous dampers were subjected to the HITEC testing program. Failure of four of the ten devices was caused for various reasons. These failures give insight to the possible weaknesses of viscous dampers. Observed property changes during the testing will also help to estimate functional lifetime of a device.

During the first test, ETEC applied 10 fully reversed cycles at the design displacement (DD) at a frequency corresponding to a 2.0 second period. This caused two devices to fail by a seal burst causing hydraulic fluid to spray from the devices. The failure was determined to be because a small relief orifice had been inadvertently omitted. Without the orifice, the internal pressure increased as the test progressed until a tie rod stretched, causing the seal burst. This can be corrected by heightened quality control during production.

Test seven, dynamic testing at temperature extremes, caused another device to fail when an unnatural ice build up was forced into the seal. The last failure was caused by test number eight, durability, by seal rupture as another relief orifice had been omitted. Following test five and six, the 10,000 cycle durability and salt spray tests, it was found that the damping coefficients and EDC increased slightly, while the velocity coefficients decreased slightly.
Overall, the devices that were manufactured properly held up very well and promised long lifetimes with little to no maintenance. They showed no wear after 10,000 cycles and were able to sustain two times their design velocity without failure. The weak spot in the device is defiantly the seal, but as long as it is well protected from foreign objects it should last. The properties of the device will most likely shift slightly over time, but this will not hamper the performance significantly. Some viscous dampers have lasted 50 years with no maintenance.

Table 3-1 Tests 5 and 6 – Fatigue and Wear and Environmental Aging

<table>
<thead>
<tr>
<th>Period (Seconds)</th>
<th>Velocity Coeff — n</th>
<th>Damping Coeff — C</th>
<th>EDC (in-kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before **</td>
<td>After</td>
<td>Before **</td>
</tr>
<tr>
<td>20.0</td>
<td>1.05</td>
<td>0.91</td>
<td>5.4</td>
</tr>
<tr>
<td>5.0</td>
<td>0.88</td>
<td>0.82</td>
<td>7.2</td>
</tr>
<tr>
<td>1.0*</td>
<td>0.70</td>
<td>0.61</td>
<td>10.6</td>
</tr>
<tr>
<td>0.5*</td>
<td>0.70</td>
<td>0.69</td>
<td>10.6</td>
</tr>
</tbody>
</table>

* Performed at reduced displacement.
** "Before" data are obtained from Table 4.2.
4 Viscoelastic Dampers

Viscoelastic dampers exhibit both viscous and elastic properties. Therefore the forces produced in a viscoelastic damper are dependent on velocity and deformation. There are several types of viscoelastic materials. Shimizu Corporation has developed a bitumen rubber compound, Bridgestone Corporation has developed a visco-plastic rubber and 3M has a viscoelastic copolymer. There are a number of factors that affect the performance of viscoelastic materials. Stiffness and damping properties are influenced by the level of shear deformation, temperature and frequency of loading. The temperature sensitivity of viscoelastic dampers would make external applications, such as bridges, problematic.

![Viscoelastic Damper](image)

**Figure 4-1 Viscoelastic Damper**

Double layer shear dampers using the material by 3M where used in the twin towers of the World Trade Center in New York City. The dampers were located at the lower chord of trusses that supported the floors. There were 100 dampers per floor in the top 100 floors for a total of 10,000 dampers in each of the two towers. The dampers were non-structural components that damped out wind-induced dynamic response. The extension of VE dampers to seismic application has occurred more recently.

Wind vibration control only requires about 5% of critical damping while seismic targets damping ratios in the order of 10 to 20 percent. Tests of viscoelastic dampers under
simulated earthquake events show that both the acceleration responses and the inter-story drifts were reduced by up to 50%. The ambient temperature effect on seismic performance was also studied. Results showed 80% reduction of floor accelerations at 25 degrees C and over 40% reduction at 42 degrees C.

No direct testing of sustainability could be found for viscoelastic devices. Their inherent simplicity prevents any type of mechanical failure. The major risk is aging of the material, such as decomposition and the unbonding of the device. The World Trade Center in New York was built in the early 70s and before they were destroyed, no severe increase of wind vibrations was ever documented. Therefore we can assume that viscoelastic dampers have a lifetime of at least 30 years in a wind application.
5 Friction Dampers

Friction dampers, like their name indicates, dissipate energy through friction. Different devices have various methods for achieving this. There are two main types of friction damping, coulomb and structural. Coulomb friction damping produces a force that is constant in magnitude, while structural friction damping is proportional with displacement. Almost all friction dampers have an initial slip force that needs to be overcome before the device will move. The friction spring seismic damper is a relatively new device that uses a ring spring, also known as a friction spring, to dissipate energy. The device is able to self-center after displacement. The self-centering is actually strong enough to help a structure return to its pre-earthquake shape. The friction spring damper produces forces most similar to structural damping and is designed to remain elastic during an earthquake.

The friction spring damper was tested by a program inspired by HITEC literature. This program included a durability test similar to the HITEC test. The test showed that the energy dissipated per cycle decreased by less than 4% over the duration of the test. The peak force decreased by less than 3% at the same time. While this is minimal degradation, it is still much larger than what was described with viscous dampers.
Coulomb devices can be much simpler. A typical scheme involves brake pad material on steel friction interface or to allow slip in bolted connections. The Friction Damper Device is made up of three steel plates and two friction pads sandwiched in between them. They are clamped together with a pre-stressed bolt and disc springs. The nominal slip capacity or force needed to move the steel plates relative to each other can be adjusted by changing the bolt pre-stress level or by adding more steel plates and friction pads to the bolt.

Figure 5-2 Degradation Ratio VS Cycle Number
The maintenance and protection from deterioration of a device like this which is required to slip at a specific load during an event even after years of non-use is essential. That is why the placement of coulomb friction damper is usually inside of structures, protected from the elements. This type of device may also require maintenance to center it again after a quake. Even though friction dampers, both structural and coulomb, are not as sustainable as viscous dampers, they are used often because of their lower unit price.
6 Viscous Shear Damper

The Oiles Corporation makes a hybrid viscous and friction damper. The viscous shear damper is box-shaped with interlaced steel plates enveloped in fluid. The device is unidirectional and dissipates energy through the frictional resistance caused by motion of steel plates in the entrapped fluid.

![Figure 6-1 Oiles Viscous Shear Damper](image)

This device was tested by the HITEC testing program. The viscous-shear damper is velocity dependant.

\[
F = 0.42 \times e^{(-0.0420 \times v/d)} \times (v/d)^{0.59}
\]

Although during testing it was found that the maximum force would occur at maximum displacement not maximum velocity. The increase in force was most likely due to the fact that fluid was becoming trapped as the plates moved closer to the side of the device.
During 10,000 cycle and salt spray tests, the velocity coefficient and EDC increased. This became more significant for the higher velocity tests. This was not the only thing that changed the dampers' properties. The normal operating temperature of the viscous-shear damper is 23 to 120 degrees F. It was found that at 23 degrees F the velocity coefficient and EDC increased significantly. The opposite was true for 120 degrees.

Table 6-1  Test 7- Dynamic Performance Characteristics at Temperature Extremes

<table>
<thead>
<tr>
<th>Performance Parameters</th>
<th>Cold Temperature 55 hrs @ 23° F (TA #2)</th>
<th>Ambient Temperature 70° F (TA #2)*</th>
<th>Hot Temperature 24 hrs @ 120° F (TA #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity Coeff — n</td>
<td>2.3</td>
<td>0.55</td>
<td>0.77</td>
</tr>
<tr>
<td>Damping Coeff — C</td>
<td>1.1</td>
<td>12.3</td>
<td>4.8</td>
</tr>
<tr>
<td>EDC (in-kips)</td>
<td>1384</td>
<td>407.0</td>
<td>270.2</td>
</tr>
</tbody>
</table>

* Data obtained from Table 4.2 for TA #2, 2.0 second period.

Besides one device loosing a bit of fluid in the ultimate performance test when its load plate lifted up, the viscous-shear damper is a very durable device. The temperature of the device should be monitored to insure proper function during an event. Other than extreme temperature changes, the device was able to stand up to a variety of challenges without wear.
7 Hysteretic Dampers

Hysteretic dampers dissipate energy by yielding materials in the device, this is also known as plastic deformation. The magnitude of the damping force depends on the stress-strain relationship of the yielding material.

Devices have been developed that harness plastic deformation in flexural, shear or extensional modes. There are three main types of hysteretic dampers: Lead Extrusion Devices (LED), shape memory alloys (SMAs) and yielding steel systems.

7.1 Lead Extrusion Devices

Lead Extrusion Devices, as their name indicates, use lead to dissipate energy. LEDs are very similar to coulomb friction damping in that the damping force produced is not displacement dependent. Lead damping is often used to provide damping in rubber bearings. Testing has shown that LEDs are very sustainable. They are not sensitive to environmental conditions and have a very slow aging process. They are very durable. Their load-deformation relationship is stable, repeatable, and almost unaffected by the number of cycles (Aiken, 1996).

Figure 7-1 Robinson Seismic LED
7.2 Shape Memory Alloys

Shape memory alloys (SMAs) are able to deform plastically without having any permanent deformation. This is because the non-linear deformation is metallurgically reversible. The SMA goes through a crystal phase transformation that can be temperature induced or stress induced. Some types of SMAs, along with excellent fatigue resistance, have amazing corrosion resistance, superior even to stainless steel. This makes SMAs an ideal candidate for passive energy dissipation.

Shape memory alloys have both shape memory characteristics and super-elastic characteristics which can be used for energy dissipation. During shape memory the SMA first deforms elastically and then yields at constant stress due to detwinning of crystal layers. When the SMA is unloaded the plastic strain remains. This strain is eliminated by heating the SMA. It has been found that if the SMA is strained beyond 8%, all deformation may not be reversible. During super-elasticity there is a stress induced crystal formation which is reversed when the stress is removed. The recovery occurs at a lower stress level due to transformation hysteresis. Both of these characteristics of shape memory alloys have been tested in an energy dissipation application.

7.2.1 Steel Connectors using the Shape Memory Characteristic

This application uses SMA tendons, exhibiting the shape memory behavior, in a beam-column joint. The tendons are connected to the column from the top and bottom flanges of the beam. The connection was then tested at increasing cycles up to 4% drift.
The testing showed that the SMA tendons had a very stable and repeatable hysteresis, with excellent energy dissipation. Heat tape was then used to heat the tendons, but was ineffective at inducing the shape memory effect. Then two butane torches were used to heat the tendons and 80% of their original shape was recovered. When retested the hysteresis was nearly identical to the first round of testing. The testing continued through seven cycles of 4% drift when a tendon fractured.
7.2.2 Bridge Restrainers Using Super-Elastic Shape Memory Alloys

Super-elastic SMAs have an elastic strain capacity of nearly 6% and at large strains the material strain hardens. This makes SMAs ideal for restrainers in bridges. They can act as both restraint devices and dampers.

To test this application, a prototype restrainer was designed and tested. The restrainer had to be machined and then heated to produce the super-elastic properties. The prototypes were then subjected to several tension loading cycles at 6% and 8% strain. The residual strain left in the bars was less than 1%. Then to evaluate the SMA restrainers’ effectiveness in a bridge, a model of a typical bridge with SMA restrainers was produced in a nonlinear analysis program.
The study compared SMA restrainers to the as-built conditions and to conventional restrainers. The SMA dampers were able to yield repeatedly without permanent deformation, leading to significant energy dissipation. While the conventional restrainers suffered from residual deformation, which reduces their energy dissipation capacity. The results of the analysis of the multi-span simply supported bridge are shown below.

<table>
<thead>
<tr>
<th>Table 7-1</th>
<th>Results of Time History Analysis of Bridge with SMA Restrainers</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Oakland Harbor (1989 Loma Prieta), Scaled to 0.70g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pier 1 µ</td>
</tr>
<tr>
<td>As built</td>
<td>5.12</td>
</tr>
<tr>
<td>Typical restrainers</td>
<td>5.41</td>
</tr>
<tr>
<td>SMA re-strainers</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Shape memory alloys make very sustainable passive energy dissipation devices. By undergoing a crystal phase-change during plastic deformation, they experience very little fatigue or permanent deformation. Their energy dissipation force is very stable over their
lifetime and they are more resistant to corrosion than almost any other type of material. Unfortunately, shape memory alloys are very expensive.

### 7.3 Yielding Steel Systems

Mild steel is able to sustain many cycles of plastic deformation which makes it able to dissipate seismic energy. Devices that are designed with yielding mild steel often use triangular or hourglass shapes so that yielding is uniformly spread throughout. This allows for stability during repeated plastic deformations and prevents premature failure.

![Yielding Steel Section](image)

**Figure 7-5 Yielding Steel Section**

One of the most important factors that determines the sustainability of yielding steel systems and hysteretic dampers in general is that the appropriate post-yield deformation range is identified.

Design studies and large scale tests have been carried out on tension/compression yielding steel braces or “unbonded braces”. The steel core for the brace yields under reversed axial loading to provide stable energy dissipation. The core is surrounded by a concrete-filled steel tube which prevents buckling. The steel is separated from the concrete for the brace by a slip surface so that yielding is not hampered due to the shearing and Poisson’s effect.
The advantages of this type of device are its low cost, lack of dependence on mechanical components and long-term sustainability. The designer is able to independently specify the strength, stiffness and yield displacement of each device. Each property is determined by varying the cross-sectional area of the steel core, the yield strength of the steel and the length of the core which is allowed to yield. This makes it possible to incorporate unbonded braces easily into a structure. The unbonded braces will have smaller steel cross-section than conventional braces, therefore the structure will have a longer elastic period.

Along with other tests, this device was subject to a low-cycle fatigue test. The brace had a very stable behavior with virtually no degradation of strength or stiffness until failure. The steel core fractured inside the confining tube after 17.5 cycles of 2% strain. This is shown in the following graph.
Brace Slippage (min/max) = -2.03 / 2.12 \% 
Brace Def (min/max) = -2.39 / 2.5 in. 
Peak Force (min/max) = -462.9 / 424.3 kips

Figure 7-7 Force VS Displacement

This figure shows the sustainability of the unbonded brace even after severe loading.
8 Tuned Mass Dampers

A tuned mass damper uses motion to create a force and reduce dynamic response of a structure. A simplified version would consist of a mass, spring and one of the dampers previously discussed. The frequency at which the mass will resonate is tuned to be out of phase with a particular structural frequency. The out of phase inertial forces dissipate energy.

Tuned mass dampers were installed in structures as early as 1975. Most systems are specially designed and have many moving parts. An example is the tuned mass damper located in the Citicorp Center in New York. The 400 ton concrete mass reduces building sway by 40 percent.

Figure 8-1 The Tuned Mass Damper of the Citicorp Center

Located on the sixty-third floor in the crown of the structure, it is supported on twelve hydraulic pressure-balanced bearings. The mass has a peak displacement of 1.4 m in each direction.
TMDs have also been designed as pendulums where the weight is hung and the springs and dampers are attached to the lever arm.

The Petronas Towers in Kuala Lumpur, Malaysia have twelve 100 kg TMDs in the legs of the sky bridge between them.

One of the most recent highly publicized applications of TMDs is the Millennium Bridge in London, England. The Millennium Bridge was opened first time for general pedestrian traffic between St. Paul's Cathedral and the New Tate Gallery in summer 2000, but was closed only 3 days after its grand opening ceremony due to excessive motion, such as horizontal bridge motion of up to 100 mm. At the end of February 2002 it was opened for the public again.
In the final solution 58 TMDs in 12 different sizes and shapes were developed, designed, manufactured and installed, together with a couple of other shock absorbers. Eight horizontal and fifty vertical tuned mass dampers are hidden in the bridge structure. The horizontal TMD are 2.5 ton heavy steel blocks suspended by pendulums, their reaction to any bridge motion guided by internal viscodampers. The fifty vertical TMD consist of one to two ton heavy steel plates supported by 4 helical springs each and controlled by viscodampers in the same way as the horizontal TMD.
The parameters of each TMD, as for example its natural frequency and damping coefficient, were fixed by the Ove Arup engineers after extensive tests and calculations. Based on these functional requirements and geometrical limitations the GERB specialists had to find proper and reliable solutions, to design the actual TMD and to manufacture them. They are tuned exactly to the trouble causing bridge natural frequencies. Hidden in the bridge structure they do not disturb the elegant character of the bridge designed by star architect Sir Norman Foster. (gerb.com)

Due to the fact that each tuned mass damper is so specially designed, a testing program for each type would be impractical. The complex nature of the device suggests the need for routine maintenance. Because there are usually a very limited number of large complicated TMDs in a structure, regular check-ups are not as cumbersome as for other smaller and more widely dispersed devices. Tuned mass dampers have been used for over 25 years and have held up during that time. So they should have a long lifetime if properly maintained.
9 Laminated Bearings

Laminated bearings are made up of stacked material that provides the necessary stiffness in the vertical direction and flexibility in the horizontal direction. The material is almost always a rubber or rubber-derivative. The number of laminated layers can be adjusted along with the material properties to produce the desired device characteristics. In order to add damping to the laminated bearing, a yielding core is usually added to the bearing.

9.1 High Damping Rubber Bearings

Scougal makes a steel reinforced high damping rubber bearing. The bearing is made up of layers of high damping rubber with steel reinforcing shims to provide vertical load capacity. On the top and bottom of the bearing are thick steel load plates which distribute vertical loads and transfer shear. The bearing has a rubber cover for protection from contaminates. During an event, the bearing deforms horizontally and absorbs energy through shear displacement. The bearing was tested by the HITEC testing program.
After the combined 10,000 cycle and salt spray test, the stiffness and EDC increased while the damping decreased. The changes were most likely due to the 10,000 cycles because it is known that rubber is not affected by salt spray. The overall changes in performance were not considered significant.

The dynamic testing done at temperature extremes showed that high damping rubber becomes very stiff at low temperatures. The rubber became so stiff that the testing equipment’s capacity was reached at a displacement of less than two inches. The rubber was not affected nearly as much with high temperatures, stiffness, damping, and EDC all decreased slightly (3 - 10 %).

All of the test specimens survived the durability test with very little force degradation. The ultimate performance test only managed to fail the smallest of the bearings. The bearing failed at a displacement of 10.6 inches when the bottom laminate sheared from the mounting plate. The design displacement for the bearing was 6 inches, so it had a safety margin of 1.76. All of the other bearings had a safety margin over 2.44.

Table 9-1 Test 9 – Ultimate Performance

<table>
<thead>
<tr>
<th>Test Article ID</th>
<th>Design Disp. (DD) (in)</th>
<th>Failure Disp. (FD) (in)</th>
<th>Safety Margin (FD/DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>6.0</td>
<td>10.6</td>
<td>1.76</td>
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<tr>
<td>TA #2 (500 kip)</td>
<td>9.0</td>
<td>&gt;22</td>
<td>&gt;2.44</td>
</tr>
<tr>
<td>TA #3 (500 kip)</td>
<td>9.0</td>
<td>&gt;22</td>
<td>&gt;2.44</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>9.0</td>
<td>&gt;22</td>
<td>&gt;2.44</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>12.0</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Failure displacement was not determined due to limits of test equipment.

This is a very sustainable bearing. The bearing remained undamaged and unchanged significantly during every test except for cold temperatures. As long as cold temperatures are avoided this bearing should last a long time without maintenance.
9.2 Lead-Rubber Bearings

Lead-Rubber bearings have a similar appearance to high-damping rubber bearings. The difference is that damping is provided by a yielding lead core and not by the rubber. The steel shim located between the layers of rubber not only provides vertical load capacity but also confines the lead core. During an event, the rubber shears to reduce forces on the structure and lead core yields to dissipate energy.

Two different brands of lead-rubber bearing were tested in the HITEC testing program. During the first test the protective outer cover of all ten test bearings separated from the top and bottom load plates. The cover separation was not visible in the neutral position and there were no holes in the cover.

After the 10,000 cycle and salt spray test there were small changes in bearing characteristics which depended on the brand. Dynamic Isolation Systems’ bearing had increased damping and decreased stiffness while Skellerup’s bearing had increased stiffness and EDC for long period response and decreased stiffness, damping and EDC for short period response. The cause of the changes was assumed to be fatigue because rubber is not affected by salt spray.
The temperature tests showed that in general stiffness, damping and EDC increased at low temperatures and decreased at high temperatures. Only damping in the Skellerup bearing was unaffected by temperature variance.

All the bearings held up during the durability test. The ultimate performance test failed six of the ten test bearings. The two largest bearings did not fail because their failure displacement was beyond the limits of the test equipment. All four of the Skellerup’s smaller bearings failed with safety margins ranging from 1.7 to 2.2. The DIS bearings failed at safety margins of 2.44 and higher. All failures occurred when delamination occurred at the top or middle of the stack.

Table 9-2 Test 9 – Ultimate Performance (Skellerup)

<table>
<thead>
<tr>
<th>Test Article ID</th>
<th>Design Disp. (DD)</th>
<th>Failure Disp. (FD)</th>
<th>Safety Margin (FD/DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>6.0</td>
<td>13.2</td>
<td>2.2</td>
</tr>
<tr>
<td>TA #2 (500 kip)</td>
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<td>15.0</td>
<td>1.7</td>
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<tr>
<td>TA #3 (500 kip)</td>
<td>9.0</td>
<td>17.1</td>
<td>1.9</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>9.0</td>
<td>20.0</td>
<td>2.2</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>12.0</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Failure displacement was not determined due to limits of test equipment.

Table 9-3 Test 9 – Ultimate Performance (DIS)

<table>
<thead>
<tr>
<th>Test Article ID</th>
<th>Design Disp. (DD)</th>
<th>Failure Disp. (FD)</th>
<th>Safety Margin (FD/DD)</th>
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<td>20.0</td>
<td>3.33</td>
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<tr>
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<tr>
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<td>&gt;22.0</td>
<td>&gt;2.44</td>
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<tr>
<td>TA #4 (500 kip)</td>
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<tr>
<td>TA #5 (750 kip)</td>
<td>12.0</td>
<td>*</td>
<td>*</td>
</tr>
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</table>

* Failure displacement was not determined due to limits of test equipment.
Lead rubber bearings are very sustainable as long as their maximum deflection is not exceeded by too much. They are not significantly affected by temperature changes and require no maintenance.

9.3 Steel Rubber Bearings

Steel rubber bearings made by Tekton like the previous bearings discussed have alternating layers of rubber and steel shims. There are twelve tapered steel pins that protrude into the stack of rubber vertically from the top and bottom load plates. The pins intersect a steel plate located in the middle of the stack and are surrounded by sand. The device has a protective neoprene cover. In an event, the rubber shears laterally and the steel pins yield to dissipate energy.

![Figure 9-3 Tekton Steel Rubber Bearing](image)

Five devices were tested by the HITEC testing system. The smallest of the five was tested first and showed unstable performance, excessive compression and extensive distortion after just 10 cycles. This was deemed a failure. The remaining four bearings were then modified by the manufacturer. The sand was removed from around the pins and the design displacement was decreased by 2 inches.

Testing continued on the remaining four bearings. All had a rapid rate of degradation (40 – 50%) of lateral force until the fifth or sixth cycle. The test articles finished the test but
delaminations were observed on 3 bearings, the fourth had a protective cover that prevented visual inspection. The delaminations continued to propagate throughout the testing and at times caused a bearing to rock during testing but the bearings did not fail until pushed past their design limits. The 10,000 cycle test caused the stiffness, damping and EDC to increase. Stiffness, damping and EDC increased dramatically with low temperatures. At high temperatures the damping and EDC decreased, and stiffness increased slightly.

Failure finally occurred during the ultimate performance tests due to delamination. The bearings had safety margins of 1.9 to 2.5 over their new reduced design displacements. It is interesting to note that sand escaped during failure of one of the bearings.

Table 9-4 Test 9 – Ultimate Performance

<table>
<thead>
<tr>
<th>Test Article D</th>
<th>Design Disp. (DD) (in)</th>
<th>Failure Disp. (FD) (in)</th>
<th>Safety Margin (FD/DD)</th>
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<tbody>
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<td>TA #1 (150 kip)</td>
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<td>*</td>
</tr>
<tr>
<td>TA #2 (500 kip)</td>
<td>6.75</td>
<td>14.5</td>
<td>2.15</td>
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<tr>
<td>TA #3 (500 kip)</td>
<td>6.75</td>
<td>16.7</td>
<td>2.47</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>6.75</td>
<td>13.1</td>
<td>1.94</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>10.0</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

* Failure displacement was not determined due to failure during Test 1.
** Failure displacement was not determined due to limit of test equipment.

One can easily conclude that tapered steel pins are not a good way to add damping to a bearing. They were most likely the cause of the rapid force degradation during the initial tests. The rest of the bearing held up rather well considering. This type of device needs a major redesign to improve sustainability.
10 Sliding Bearings

Sliding bearings are designed to provide the needed lateral flexibility by sliding. They usually also have a damping mechanism incorporated into the device. Sliding bearings vary much more in design than laminated bearings. The sliding surface can be flat or concave. Damping can be provided by friction or yielding elements or not at all.

10.1 Flat Sliding Bearings

10.1.1 Yielding Steel Damping

FIP makes a slider bearing that utilizes steel yielding elements for damping. The vertical load sits on a guided pot bearing which slides on a dimpled, lubricated stainless steel plate. When the bearing experiences lateral loading the shock transmission units engage the yielding steel elements. The yielding steel elements undergo plastic deformation and dissipate energy. This device is unique in that the vertical load carrying component is independent of the horizontal load carrying element.

Figure 10-1 Flat Sliding Bearing with Yielding Steel Damping
This device was tested by the HITEC testing system. The first test showed that the device had a stable and repeatable performance with very little force degradation. After 31 cycles of testing a crescent moon steel damper on one of the test devices developed a crack. After the 10,000 cycle and salt spray tests the stiffness decreased slightly and the damping increased slightly. Temperature test showed that the device was not greatly affected by changing temperatures.

Another crescent moon steel damper cracked during test 8 which was the 60th cycle on this device. This was considered to be a failure for this device. The other four devices failed during the ultimate performance test. Two failed when a crescent moon steel damper broke in half. Other failures involved slipping and stalling of the plate connections and reaching the physical limits of the bearing.

<table>
<thead>
<tr>
<th>Test Article ID</th>
<th>Design Disp. (DD) (in)</th>
<th>Failure Disp. (FD) (in)</th>
<th>Safety Margin (FD/DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>6.0</td>
<td>12.9</td>
<td>2.15</td>
</tr>
<tr>
<td>TA #2 (500 kip)</td>
<td>9.0</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>TA #3 (500 kip)</td>
<td>9.0</td>
<td>21.5</td>
<td>2.39</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>9.0</td>
<td>14.2</td>
<td>1.57</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>12.0</td>
<td>14.5</td>
<td>1.21</td>
</tr>
</tbody>
</table>

* Failure displacement was not determined due to earlier failure.

Overall this device is pretty sustainable as long as the design displacement is not exceeded. The one weakness is the yielding steel dampers. They have a limited lifetime. This could be overcome by monitoring and perhaps the periodic replacement of a crescent moon after a large earthquake.
10.1.2 Friction Damping

The EradiQuake System bearing is made by R. J. Watson. It is a steel and composite sliding bearing that uses friction to dissipate energy. The bearing is made up of a block that slides on a stainless steel sole plate. The sole plate has a perimeter guide box that centers the device. During an event, mass energy regulator (MER) springs compress and allow the bearing block to slide.

![Flat Sliding Bearing with Friction Damping](image)

Figure 10-2 Flat Sliding Bearing with Friction Damping

Five test devices were subjected to the HITEC testing system. During the first test the bearing seal on one of the devices tore after four cycles, this was the only bearing with a bearing seal. The 10,000 cycle and salt spray test provided no viable results because the device being tested was damaged when removed from the test rig.

The temperature tests showed that stiffness and EDC increased while damping decreased at low temperatures. Stiffness and EDC also increased with high temperatures. All four remaining bearings failed during the ultimate performance test. Failure was due to the
MER springs either rupturing or crushing. There was never any metal-to-metal contact during failure and safety margins ranged from 1.7 to 2.1.

Table 10-2 Test 9 – Ultimate Performance

<table>
<thead>
<tr>
<th>Test Article D</th>
<th>Design Disp. (DD) (in)</th>
<th>Failure Disp. (FD) (in)</th>
<th>Safety Margin (FD/DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>2.5</td>
<td>5.2</td>
<td>2.1</td>
</tr>
<tr>
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<td>5.0</td>
<td>9.3</td>
<td>1.9</td>
</tr>
<tr>
<td>TA #3 (500 kip)</td>
<td>5.0</td>
<td>9.3</td>
<td>1.9</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>5.0</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>5.0</td>
<td>8.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

* Failure displacement was not determined due to cancellation of Test 6.

This is a very sustainable device. It only failed when design displacements were exceeded and showed very little wear. One should note that the design displacements for this device are much smaller than other sliding bearings.

10.2 Curved Surface Sliding Bearings

10.2.1 Friction Pendulum

A friction pendulum bearing is made up of polished stainless steel concave bottom plate and a smaller stainless steel convex top plate that is usually surfaced with a lubricating liner. The small convex plate slides around in the convex plate with a pendulum-like motion. Energy is dissipated through the friction between the two plates. The smaller plate is called an articulated slider.
A friction pendulum manufactured by EPS was tested by the HITEC testing program. After the 10,000 cycle and salt spray test, damping, stiffness, and EDC all decreased. This is most likely due to the polishing of the friction surface over time. The temperature tests showed that temperature extremes had no effect on the device. During the durability test, one of the test bearings made a large noise followed by smoke and burning odor, but the cause was never determined. The failure displacement for the test bearings was found to be 20 inches which is the physical limit of the bearing. A visual inspection after the testing revealed burnt liner material and various degrees of wear and scratching on all of the devices. During the testing EPS had already made significant design revisions to the liner of their bearing to avoid this kind of damage in the future.

Table 10-3 Test 9 – Ultimate Performance

<table>
<thead>
<tr>
<th>Test Article ID</th>
<th>Design Disp. (DD) (in)</th>
<th>Failure Disp. (FD) (in)</th>
<th>Safety Margin (FD/DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>6.0</td>
<td>20*</td>
<td>3.38</td>
</tr>
<tr>
<td>TA #2 (500 kip)</td>
<td>9.0</td>
<td>20*</td>
<td>2.22</td>
</tr>
<tr>
<td>TA #3 (500 kip)</td>
<td>9.0</td>
<td>20*</td>
<td>2.22</td>
</tr>
<tr>
<td>TA #4 (500 kip)</td>
<td>9.0</td>
<td>20*</td>
<td>2.22</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>12.0</td>
<td>20*</td>
<td>1.67</td>
</tr>
</tbody>
</table>

* Failure displacements were determined from the point where the articulated slider met its physical limit.
With an improved liner this becomes an even more sustainable device. All friction devices are expected to see some wear, but this was a relatively small amount and did affect performance. One caution is that if the physical limits of the device were actually surpassed, catastrophic failure would occur.

10.2.2 Roller Bearing

The roller bearing is composed of a steel ball in-between two conical steel load plates. During an event, the ball rolls around on the constant slopes of the load plates. The device is not laterally flexible and provides no damping. The original design of this device called for friction damper to be installed on the device, but the dampers did not function properly and were left off.

![Figure 10-4 Roller Bearing](image)

The Tekton Ball-N-Cone roller bearing was tested by the HITEC testing system. The design displacement had to be reduced for this device after the first test because the ball
was hitting the retaining edge. Also during the first test the smallest element’s ball ended up denting its two conical plates.

The fatigue and environmental aging (salt spray) were not performed on this device due to late delivery and the late test bearing was no longer subjected to testing. The temperature tests showed that the only property of the roller bearing that is temperature dependant is EDC which increases during hot temperatures. Even though no major temperature dependency was found, one of the test bearings developed cracks on the steel ball and plates soon after being placed in the hot thermal chamber. Another bearing was placed in the hot thermal chamber and was not affected by the temperature. The durability test was performed on all the remaining devices. The bearing survived the 20 fully reversed cycles at design displacement with no lateral force degradation. After the test cracks were found on all test bearings except for the largest one. An estimate of when the racks first occurred was not possible. The ultimate performance test was not conducted because the limits of the device were already reached in the first test.

Table 10-4 Test 9 – Ultimate Performance

<table>
<thead>
<tr>
<th>Test Article D</th>
<th>Design Disp. (DD)*</th>
<th>Failure Disp. (FD)</th>
<th>Safety Margin ♦</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA #1 (150 kip)</td>
<td>5.5</td>
<td>**</td>
<td>1.09</td>
</tr>
<tr>
<td>TA #2 (500 kip)</td>
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<td>1.09</td>
</tr>
<tr>
<td>TA #3 (500 kip)</td>
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<td>**</td>
<td>1.09</td>
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<tr>
<td>TA #4 (500 kip)</td>
<td>8.25</td>
<td>**</td>
<td>1.09</td>
</tr>
<tr>
<td>TA #5 (750 kip)</td>
<td>11.0</td>
<td>**</td>
<td>1.09</td>
</tr>
</tbody>
</table>

* Revised design displacement based on results from the first test.
** Failure displacement was not determined due to earlier reduction of design displacement. See Section 4.8, Test Variances.
♦Safety margins calculated per Section 4.8, Test Variances.

Since the only device that did not develop cracks was the largest, one could guess that the lateral design loads for the other devices were too large. If the design loads or the devices’ strength were modified this would be a very sustainable device. It had the most
stable lateral force of all the bearings tested, although this could be due to the fact that it had no damping. The roller ball has a great potential to be a very durable device.
11 Finite Element Modeling of Motion Control Devices

Testing is required on all types of motion control devices to verify the physical properties specified with the certain device, to determine if it can withstand the maximum expected earthquake and wind loading and for quality control. Finite element analysis (FEA) can help to minimize the needed testing for these devices. Testing of devices of this size is very costly and FEA provides a large cost savings.

Finite element analysis was used for the Los Angeles Police Department Recruit Training Center Retrofit. Extensive linear and nonlinear analysis was preformed on the viscoelastic dampers including modeling of the deformation-frequency-temperature properties with a finite element program. By comparing computer model predictions to the actual test results, dampers were either accepted or rejected. The FEA model was able to determine temperature effects so accurately that test requirements for testing in a range of temperatures was waived.

This is an example of a design and testing of a natural rubber bearing and lead rubber bearing using the finite element program ADINA. The natural rubber bearing consists of laminated layers of rubber and steel, in the form of thin steel shims. The lead rubber bearing is the same bearing with an added lead core. No design was done for the size of the lead core. Testing of the lead rubber bearing was done just for comparison with the natural rubber bearing.

11.1 Design

The building is six stories with floor masses of 10,000 kg and a roof mass of 20,000 kg. Including the base isolation, the structure can be modeled as a seven degree of freedom system. The designed relative displacement of the bearing compared to the rest of the building or the relative displacement factor is two. Given this, the scaled stiffness profile of the building can be calculated. Selecting a damping ratio of 0.05 and maximum base
displacement of 0.3 meters, the stiffness can be calibrated for seismic excitation. The necessary stiffness of the bearing is 566,056 N/m.

The layers of the bearing have a diameter of 0.5 meters and a height of 0.25 meters. The rubber has a storage modulus of 4 MPa and loss factor of 0.15. With these material properties and dimensions, the bearing will need six layers. This will give a stiffness of 523,467 N/m, the remaining needed stiffness will have to be added elsewhere or by a lead core.

### 11.2 Testing

The steel shims were idealized in a motion constraint in the model. The top of each layer of rubber is restrained from any type of rotation. The natural rubber used was compressible, unlike soft rubber, and had a poisson's ratio of 0.35. In order to simulate the shape of the bearing in two dimensions, axi-symmetric elements were used.

Here is a picture of the mesh for one layer of rubber. The restraint C represents the base plate and the restraint B represents the steel shim.
This is the displacement of the six layers of rubber. The maximum displacement is located at the top of the device. The maximum deflection is 0.001007 meters with a pressure of 523,467 N applied laterally at the top. Displacements are starting to develop at the bottom of the device as well.

### 11.3 Lead Core

It is common practice to increase the shear resistance of a laminated rubber damper by adding a lead core. To see what adding a stiff core to the rubber layers would do to the displacement patterns of the device, a lead core with a 0.1 meter diameter will be added to the six layer model. The model was subjected to the same loads as before and has the same mesh density.
The maximum displacement of 0.0005754 is half of the displacement experienced by the natural rubber bearing. At the top, the displacement concentrations are split in two by the lead. Even though the lead makes the device stronger, it will still fail in the same place.

The DIS isolator discussed earlier failed when the rubber laminate sheared near the top of the stack of layers. This is where the finite element model predicted failure would occur. The other bearings failed at times by delamination in the middle or bottom of the stack. One can conclude that this was mostly likely due to defects in the device and not the build up of maximum deflection.
12 Summary and Conclusion

Overall, motion control devices are designed to be very sustainable and promise to protect the structures they are in for many, many years. The devices are made from wear and corrosion resistant materials and have simplified mechanical designs which contribute to long lives and low maintenance. The advantages and disadvantages of each device should be carefully weighted before one is selected for a particular structure. Some devices are more suited to certain applications than others. One should be well aware of a devices limitations and required maintenance before installing it.

Testing of the motion control device to be placed in a structure should be included in the design specifications. Most devices are custom built to the structure and the properties of the device need to be verified. Some type of quality control testing needs to be done also. If testing has not already been done to assess the sustainability of the device, this should be done as well. The cost of testing can be greatly reduced by using reduced-scale devices, quasi-static testing or finite element modeling. With the increasing use of motion control devices, more testing is being done and some jobs can even have pre-qualified vendors for their devices.

Even though most devices require little to no maintenance, the importance of a properly functioning motion control system should inspire owners to invest in some sort of monitoring of the devices. This could be as small as a visual inspection every couple of years. For hard to reach devices, one could use a gauge that measures strain, pressure, tilt or temperature and warn of possible damage. At very least, devices should get a checkup after a major earthquake.

There is no doubt that the applications of motion control systems will only expand in the future. These devices provide great benefits for relatively low costs. The true test of their sustainability will only come with the passage of time.
References

Introduction


Testing


Viscous Dampers


Friction Dampers


Viscous Shear Damper

Hysteretic Dampers

2. Booker, C. A. and Goel, R. K., “Effects of Supplemental Viscous Damping on Inelastic Seismic Response of Asymmetric Systems,” Department of Civil and
Environmental Engineering, California Polytechnic State University, San Luis Obispo, November 6, 2000.


**Tuned Mass Dampers**


   http://www2.bcee.concordia.ca/bldg481/Winter2002/letmein/myweb/Tuned%20mass%20damper.htm

**Laminated Bearings**


**Sliding Bearings**


**Finite Element Modeling of Motion Control Devices**


References