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Draft Guidelines for Pre-Qualification and Prototype Testing of Seismic Isolation Systems

Harry W. Shenton III

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

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At the present time, at least in the United States, seismic isolation systems are custom designed and built on a per project basis. As a result, testing has become an essential element in the design and construction of isolated structures. Prototype and quality control tests are required by the 1991 *Uniform Building Code* and the American Association of State Highway and Transportation Officials, 1991 *Guide Specifications for Seismic Isolation Design*. Currently, however, standards do not exist for conducting these tests. The Building and Fire Research Laboratory of the National Institute of Standards and Technology has developed draft guidelines for testing and evaluation of seismic isolation systems. Presented in the report are guidelines for conducting pre-qualification and prototype tests. Pre-qualification tests are currently not required by the codes but are generally conducted during development of a new system and are aimed at evaluating fundamental properties and characteristics of the isolation system. The guidelines include general requirements of the test facility, instrumentation, calibration, data acquisition, data analysis and reporting of result. A total of twenty three tests are included in the [illegible] ~~test schedule~~: ~~all are required for pre-qualification,~~ selected tests from the schedule are required for ~~prototype testing~~. Performance criteria have been established for all tests, systems that do not meet or exceed these criteria may not function adequately in service. The guidelines are to serve as a resource document for voluntary standard/specification writing organizations, and for practitioners and researchers involved in the design, manufacture and testing of seismic isolation systems.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

base isolation; building technology; experimental; seismic isolation; standard; testing

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March, 1994
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National Institute of Standards and Technology
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U.S. Department of Commerce
Ronald H. Brown, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
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ABSTRACT

At the present time, at least in the United States, seismic isolation systems are custom designed and built on a per project basis. As a result, testing has become an essential element in the design and construction of isolated structures. Prototype and quality control tests are required by the 1991 *Uniform Building Code* and the American Association of State Highway and Transportation Officials, 1991 *Guide Specifications for Seismic Isolation Design*. Currently, however, standards do not exist for conducting these tests. The Building and Fire Research Laboratory of the National Institute of Standards and Technology has developed draft guidelines for testing and evaluation of seismic isolation systems. Presented in the report are guidelines for conducting pre-qualification and prototype tests. Pre-qualification tests are currently not required by the codes but are generally conducted during development of a new system and are aimed at evaluating fundamental properties and characteristics of the isolation system. The guidelines include general requirements of the test facility, instrumentation, calibration, data acquisition, data analysis and reporting of result. A total of twenty three tests are included in the guidelines. Performance criteria have been established for all tests, systems that do not meet or exceed these criteria may not function adequately in service. The guidelines are to serve as a resource document for voluntary standard/specification writing organizations, and for practitioners and researchers involved in the design, manufacture and testing of seismic isolation systems.

Acknowledgements

The author would like to thank the NIST Oversight Committee for their guidance and assistance in developing these guidelines. This includes Dr. Ian Buckle, Dr. Charles Kircher, Professor James M. Kelly, Dr. Ronald Mayes and Dr. Victor A. Zayas. Their time and effort are greatly appreciated.

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1. INTRODUCTION

1.1 Background

One of the most promising concepts in seismic resistant construction to come of age in the 20th century is seismic base isolation. The premise of seismic isolation is that a structure can be decoupled from the ground, thereby reducing the effect of strong ground shaking on the structure. To decouple the structure, a flexible interface is provided at or near the foundation such that during an earthquake lateral deformations are concentrated across the isolation interface and deformation of the superstructure is minimized. In effect, the superstructure responds in a rigid body mode, with greatly reduced relative displacements, member forces and absolute acceleration. Relatively high levels of damping are also provided in the isolation system to control the displacements across the isolation interface.

Seismic isolation is applicable to most types of civil engineering structures, including buildings, bridges, water towers, nuclear power plants, and other special structures. To date, isolation has been implemented most often in bridges and buildings. As of 1990, the number of buildings to be isolated worldwide was estimated at 38, and the number of bridges was estimated at 51 (Buckle and Mayes, 1990). The actual numbers at that time were most likely higher, and since then have increased dramatically. It is worth noting that base isolation has become a viable alternative for seismic retrofit of existing structures.

There are several types of isolation systems in use today, and many more which are under development or have been proposed. Some have decades of development history, while others are still in the concept stage. In either case, at least in the United States, isolation systems are not "off-the-shelf" items, they are custom designed and built on a per project basis. Consequently, testing has become an essential element in the design and manufacture of all isolation systems. Testing is required by the *Uniform Building Code* (UBC) (*Uniform*, 1991) and the American Association of State Highway and Transportation Officials (AASHTO), *Guide Specifications for Seismic Isolation Design* (*Guide*, 1991).

At the present time two classes of tests are required by UBC and the AASHTO Guide: prototype tests and quality control (QC) tests. These may be loosely defined as follows:

> **Prototype tests** are project specific and are conducted to verify the design properties of the isolation system prior to construction.
>
> **Quality Control tests** are project specific and are conducted to verify the quality of manufacture and as-built properties of the isolation system prior to installation.

A third class of tests, referred to here as Pre-Qualification tests, are defined herein as follows:

> **Pre-Qualification tests** need not be project specific and are conducted in order to establish the fundamental properties and characteristics of the isolation system, and to determine the extent to which these properties and characteristics are dependent on load and environmental factors.

Formal pre-qualification tests as defined above are not required by the codes but are usually conducted in some form or another in the early stages of development of a new system.

Presently, standards do not exist for conducting pre-qualification, prototype or quality control tests. The need for standards was reported as a critical element in the five year research plan developed following the 1986 ATC-17 Seminar on Base Isolation and Passive Energy Dissipation (*Proceedings*, 1986). Test standards would (1) ensure the systematic characterization of isolation system properties, (2) provide a systematic method for demonstrating a minimum level of acceptable performance, and (3) enable the rational comparison of different isolation systems and components.

In response to this need the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) has developed draft guidelines (i.e., pre-standard) for testing and evaluation of seismic isolation systems, as part of BFRL's National Earthquake Hazard Reduction Program (NEHRP) effort. The proposed guidelines are contained in three reports: this report, which is devoted to pre-qualification and prototype testing, and two others that are devoted to quality control testing. These documents represent the initiation of the process to develop standards for testing of seismic isolation systems (therefore the title "Draft Guideline..."). The final "Guidelines.." will be published after thorough review and evaluation of the draft guidelines. The review and evaluation process is to involve broad industry input and a testing component. The completed "Guidelines.." will then be submitted to code writing organizations and regulatory agencies in consideration for adoption.

1.2 Scope

The Guidelines are intended to be comprehensive and applicable to isolation systems regardless of the superstructure (e.g., buildings, bridges or special structures); are intended to cover all viable systems, whether they be elastomeric, sliding or hybrid; and are intended to be applicable to systems that consist of multiple isolator units, or use different components that are distributed throughout the isolation interface. The draft guidelines cover all pertinent tests of the isolation system or components, whether they be essential or of a secondary nature to the design of the superstructure. The guidelines encompass all critical isolation system and component areas related to structural, mechanical and environmental performance.

The Guidelines are intended for systems that isolate *in the horizontal plane only*, i.e., the system is assumed to be essentially rigid in the vertical direction. Guidelines for testing of vertical isolation systems are not specifically included. In addition, the Guidelines are intended for *passive* isolation systems only. Although it is likely that many of the tests are applicable to components of active or semi-active systems, the Guidelines were not written with these systems in mind.

1.3 NIST Seismic Isolation Standard Development Oversight Committee

To assist in developing the guidelines a five member Oversight Committee was formed to serve in an advisory capacity to BFRL. The committee helped to develop test requirements and identify relevant performance criteria, and review the draft guidelines. The committee included individuals with expertise in the design, fabrication and testing of seismic isolation systems, and in the design of structures that incorporate seismic isolation. The committee included:

Dr. Ian Buckle
Deputy Director, National Center for Earthquake Engineering Research
Buffalo, New York

Dr. Charles Kircher
Charles Kircher & Associates
Mountain View, California

Professor James M. Kelly
Department of Civil Engineering, University of California at Berkeley
Berkeley, California

Dr. Ronald Mayes
President, Dynamic Isolation Systems, Inc.
Berkeley, California

Dr. Victor A. Zayas
President, Earthquake Protective Systems
San Francisco, California

The committee meet three times, on November 30 and December 1, 1992 at NIST in Gaithersburg, Maryland, on April 19, 1993 in Irvine, California, and on September 20, 1993 at the University of California at Berkeley, Earthquake Engineering Research Center, Richmond, California.

1.4 Outline of the Report

Presented in Chapter 2 is a brief description of some of the isolation systems and components that are in use or under development today. This is presented to illustrate the diversity of isolation hardware available today, and to assist, where possible, in interpretation of the guidelines. The key components of the guidelines are presented in Chapters 3 through 6.

Prior to testing, the capacity of the isolation system must be "rated". The onus of responsibility is on the supplier of the isolation system to state the fundamental properties and characteristics of the system. This includes defining the range of loads and environmental conditions in which the system can be expected to operate and function properly. The concept of rated capacity is fundamental to the guidelines and carries through from pre-qualification, to prototype, to QC testing. Details of the test procedures are based on the rated capacity of the system. A standard list of properties to be rated has been developed to cover all tests and is presented in Chapter 3.

General test requirements are presented in Chapter 4. This includes the requirements of the test facility, instrumentation, calibration, data acquisition, analysis of the data and reporting of results. The schedule of pre-qualification tests is outlined in Chapter 5. Prototype tests are outlined in Chapter 6. Tests are grouped in categories, according to the type of test or load. For each test the load sequence and test parameters are specified, the test procedure is outlined and applicable performance criteria are defined. The performance criteria are a set of rules and principles against which the performance of the isolation system or component is measured. Systems that do not meet these criteria may not perform adequately in service.

In the course of developing the guidelines, and in working with the Oversight Committee, it became evident that a number of issues remain to be resolved with regard to testing of isolation systems. These issues are outlined in Chapter 7 under research needs. Some of these issues are critical to the development of sound guidelines and will need to be addressed in the near future so that results can be incorporated in a revised set of guidelines.

A summary is presented in Chapter 8. To assist the reader a table of Symbols and Notation is contained in Appendix A, a Glossary of Terms is contained in Appendix B. Schematic drawings of several test facilities are presented in Appendix C.

2. ELASTOMERIC, SLIDING AND HYBRID SEISMIC ISOLATION SYSTEMS

A seismic Isolation System is defined as the collection of Isolation Units, Isolation Components and all other structural elements that transfer force between the foundation/substructure and the superstructure. The Isolation System as a package provides the lateral flexibility and damping necessary for effective isolation, and high initial stiffness required to resist wind load. Some systems also include an ultimate restraint or "fail-safe" mechanism that is meant to engage at very large displacements or provide back-up support in case of failure of the isolation system. In these Guidelines an Isolation Unit is defined as a device that provides all the necessary characteristics in an integral device; an Isolation Component is defined as a device that provides some of the necessary characteristics (e.g., flexibility *or* damping) in a single device.

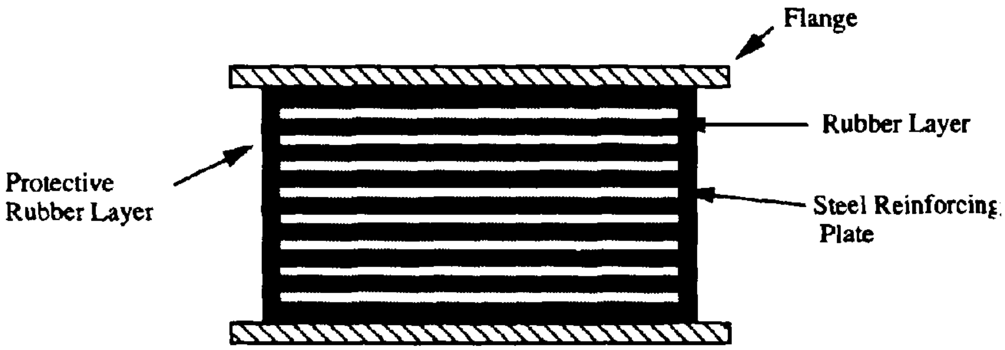
As mentioned previously, there are many different kinds of seismic Isolation Systems/Units and Components in use today and others are under development. Systems today are broadly grouped into three categories: primarily elastomeric, primarily sliding and hybrid systems. A brief description and examples from each of the three general categories will be discussed in the following. Note, this is not meant to be an exhaustive discussion of the various systems in use or under development today and should not be construed as an endorsement of any one system over another.

2.1 Elastomeric Systems

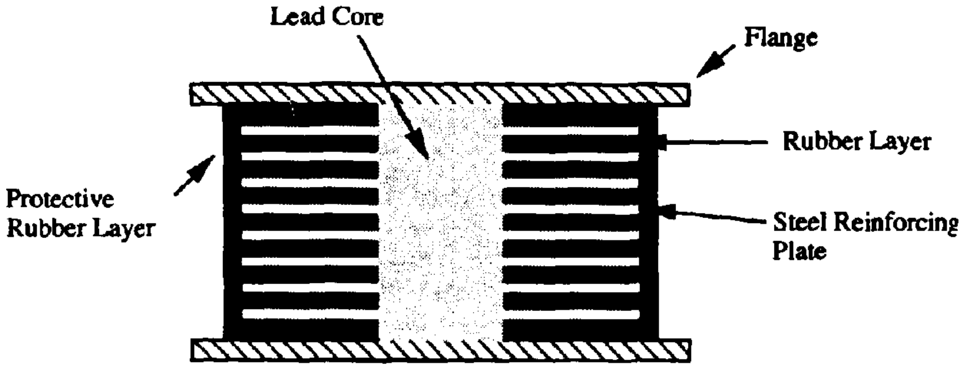
Laminated elastomeric isolation bearings are similar to elastomeric bridge bearings which have been in use for years. The bearing is fabricated by bonding alternating layers of elastomer and steel under high heat and pressure to form an integral bearing that is free of joints. The relative thickness of the elastomer to steel, overall height, plan dimensions and material properties are varied to achieve the desired horizontal stiffness, vertical stiffness, and damping characteristics. Two common types of laminated elastomeric bearings are shown in Figure 2.1. Presented in Figure 2.1 (a) is an ordinary laminated elastomeric bearing and in Figure 2.1 (b) is a Lead-Rubber-Bearing (LRB).

Different types of elastomer have been used in isolation bearings including natural rubber, filled rubber and synthetic rubbers such as Neoprene. In ordinary laminated bearings most of the damping is provided by the elastomer, consequently, great effort has gone into developing elastomers with high damping suitable for seismic isolation. These elastomers are usually referred to as High Damping Rubbers, so most ordinary laminated bearings today are simply referred to as High Damping Rubber (HDR) bearings.

The LRB is fabricated as described above, but with one or more cylindrical hollow cores through the height. After fabrication of the laminated part a lead plug is pressed into the core of the bearing. During normal operation, the weight of the structure and the steel shims provide confinement for the lead. The lead core is provided primarily to provide damping, and secondarily to provide lateral stiffness. The elastomer used in LRB's can be, but is not necessarily of a high damping composition.



(a.) Laminated Elastomeric Bearing



(b.) Laminated Lead-Rubber Bearing

Figure 2.1 Elastomeric Isolation Systems

Elastomeric bearings are usually rectangular, square or circular in plan. The connection to the foundation and superstructure can be provided by dowels or bolts, although in recent years bolted connections have become the design of choice. An elastomeric isolation bearing is an Isolation Unit, by the definition given previously, since the restoring force and damping mechanism are combined in a single integrated device.

2.2 Sliding Systems

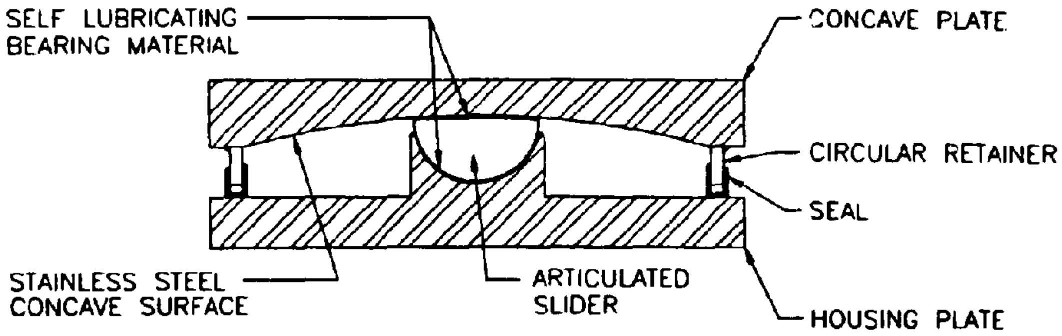
The origin of sliding isolation systems can be found in simple Coulomb friction. By the classic law, the maximum force that can be transmitted to an object that is free to slide on an accelerating foundation is limited to the normal force times the coefficient of friction. In this way the sliding interface acts as a fuse to limit the effect of ground acceleration on the system, and under cyclic motion sliding provides the necessary damping mechanism. For an isolation system a restoring/recentering force must be provided in order to limit displacements and prevent the structure from sliding or "walking" off the bearing surface. As with elastomeric bearings, pure sliding bearings also have a history of use as bridge bearings.

Examples of sliding isolation systems include the Friction Pendulum System (FPS) (Zayas, et al. 1990) and the Resilient-Friction Base Isolation (R-FBI) System (Mostaghel and Khodaverdian, 1988). The FPS uses a spherical stainless steel dish upon which slides an articulated slider. Mounted on the bottom of the slider is a low friction composite material. The restoring force of the FPS is provided by the weight of the structure as it moves in a pendulum type motion described by the dish. The FPS is illustrated in Figure 2.2 (a). The R-FBI uses alternating layers of steel and teflon centered around an elastic rubber core. The teflon-steel frictional interface acts as a fuse and provides the necessary damping. The elastic core provides the restoring/recentering force and can be fabricated with, or without steel reinforcement. The R-FBI is illustrated in Figure 2.2 (b). By the definition given previously the FPS and R-FBI are also Isolation Units, again, because the restoring force and damping mechanism are provided in a single integrated device.

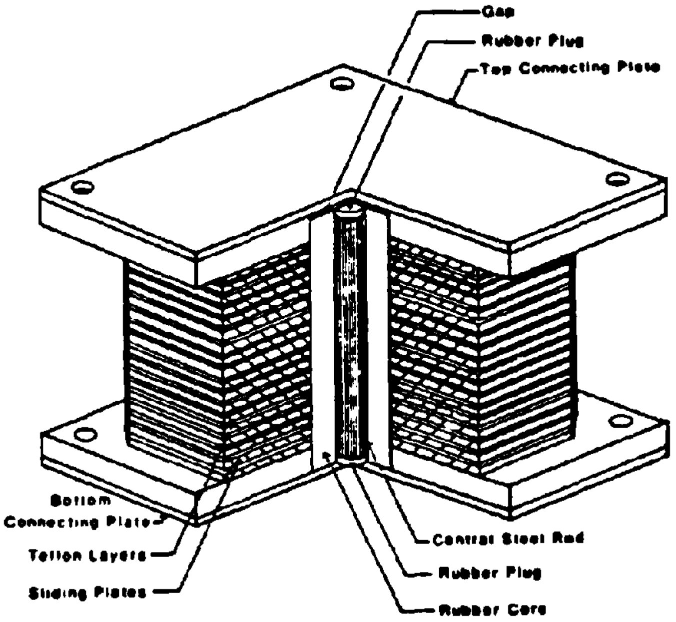
In practice the sliding interface usually consists of two dissimilar materials that have the desired coefficient of friction and wear characteristics. Throughout the years many different material combinations have been tried. Recent designs include stainless steel on teflon (including woven, filled and unfilled Teflon), stainless steel on bronze, and stainless steel on special composite materials.

2.3 Hybrid Systems

The majority of systems that are not primarily elastomeric or primarily sliding fall into the "catch-all" hybrid category. Hybrid systems generally use independent components to provide the restoring force, damping, wind restraint and ultimate restraint. Components can be integrated or in close proximity to each other, or distributed throughout the isolation interface. Hybrid systems sometimes include aspects of one or both of the previous classes of systems. There are too many



(a.) Friction Pendulum System (Zayas, et al, 1990)



(b.) R-FBI System (Mostaghel and Khodaverdian, 1988)

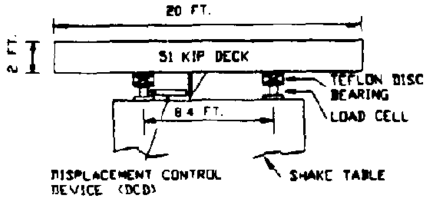
Figure 2.2 Sliding Isolation Systems

hybrid systems to present them all here. Instead, three systems are presented here just as examples.

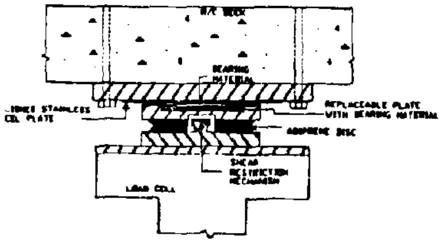
Presented in Figure 2.3 is the Sliding Bearing with Displacement Control Device system (Constantinou, et al, 1992). The sliding bearing consists of an Adiprene disc, that allows for limited rotation about a horizontal axis, a shear restraint mechanism and a Teflon-stainless steel sliding interface. The Displacement Control Device uses a combination of springs and friction to produce a tri-linear force deflection behavior.

Presented in Figure 2.4 is the GERB system (Huffman, 1985). This system uses helical steel springs in combination with viscous dampers. The springs and dampers can be located apart, or fabricated as an integral unit.

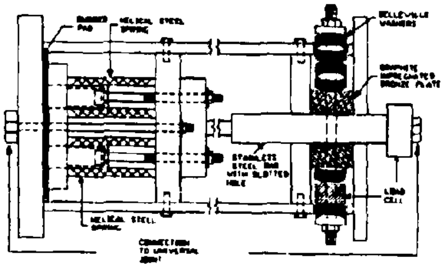
Presented in Figure 2.5 is the Alexisismon system (Ikonomou, 1985). This system consists of 3 basic elements: pot bearings, that carry vertical load and allow lateral movement and small rotations about a horizontal axis; rubber springs, that do not carry vertical load but simply provide a restoring force; and connection elements that are designed to withstand wind load and moderate earthquakes, but break or release under strong ground shaking.



(a.) Section of Bridge Deck

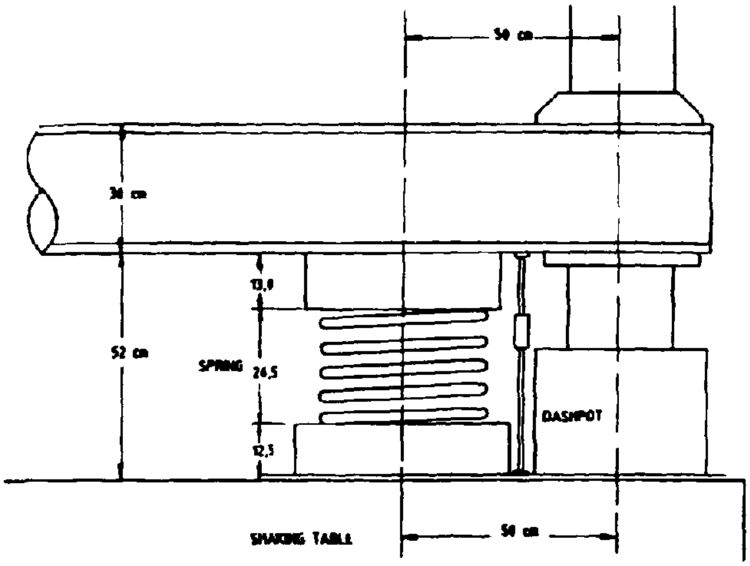


(b.) Slider



(c.) Displacement Control Device

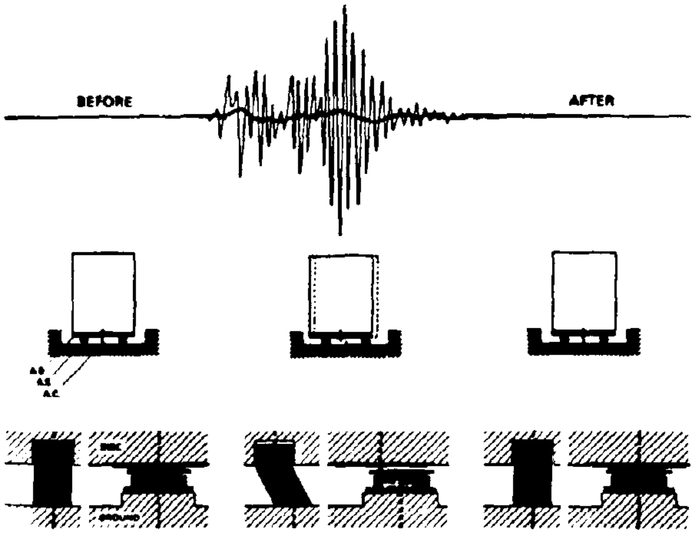
Figure 2.3. Hybrid Isolation System: Slider with Displacement Control Device (Constantinou, et al, 1992)



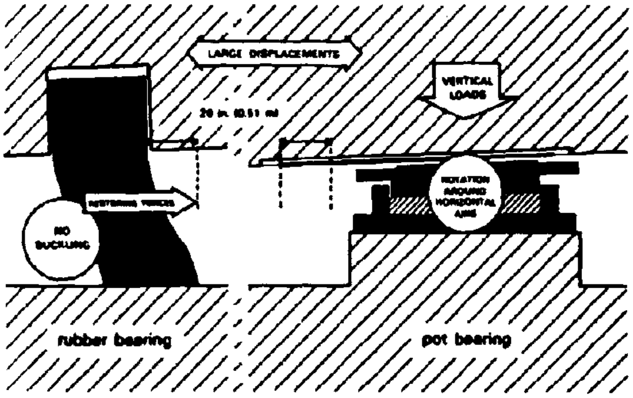
(a.) Schematic of Spring and Viscous Damper

(b.) Photograph of GERB System

Figure 2.4. Hybrid Isolation System: GERB System with Steel Springs and Viscous Dampers (Huffman, 1985)



(a.) Response Illustrated During an Earthquake



(b.) Enlarged View of System Components

Figure 2.5. Hybrid Isolation System: Alexisismon System with Pot Bearing and Rubber Spring (Ikonomou, 1985)

3. RATED CAPACITY

The nominal capacity of all Isolation Units and Components must be "rated" by the supplier prior to testing. Properties or characteristics to be rated are listed below, along with the parameter notation and a short description.

Parameter	**Notation**	**Description**
Stiffness:		
Horizontal	K_H	Effective horizontal stiffness at the Design Displacement and Design Vertical Load.
Horizontal under Wind	K_W	Effective horizontal stiffness at the Design Wind Load and Design Vertical Load.
Vertical	K_V	Effective vertical stiffness at the Design Vertical Load.
Energy Dissipation	E_H	Energy dissipated per cycle at the Design Displacement and Design Vertical Load.
Lateral Deformation:		
Design Displacement	D	Nominal displacement capacity, including that resulting from torsion, **Draft Option** **corresponding to a level of ground motion that has a 10 percent probability of being exceeded in a 50 year period.**
Maximum Displacement	D_{TM}	Total maximum displacement capacity, including that resulting from torsion, **Draft Option** **corresponding to a level of ground motion that has a 10 percent probability of being exceeded in a 100 year period.**
Thermal Displacement	D_t	Nominal thermal displacement capacity.
Vertical Deformation:		
Design Displacement	D_V	Nominal vertical displacement under the Design Vertical Load.
Creep Displacement	D_c	Creep displacement under the Design Vertical Load.

Parameter	Notation	Description
Rotation	θ	Nominal rotation capacity about an axis in the horizontal plane, and perpendicular to the direction of lateral loading under the Design Vertical load.
Compression:		
Low	P_L	Lower limit of load range of satisfactory seismic performance, includes the effect of vertical ground motion and overturning.
Design Vertical Load	P_D	Nominal capacity in compression for dead and live load.
High	P_U	Upper limit of load range of satisfactory seismic performance, includes the effect of vertical ground motion and overturning.
Tension	P_T	Nominal capacity in tension.
Lateral Load:		
Wind	F_W	Nominal wind load capacity.
Braking/Centrifugal load	F_b	Nominal braking/centrifugal load capacity.
Degradation Cycle Limit	N_D	Number of cycles to $\pm D$ with a vertical load of P_D corresponding to a ±15% change in Effective Stiffness, or a ±30% change in Energy Dissipation relative to the first complete cycle Effective Stiffness or Energy Dissipation, respectively.
Thermal Cycle Limit	N_t	Number of cycles to $\pm D_t$ with a vertical load of P_D corresponding to a ±15% change in Effective Stiffness, or a ±30% change in Energy Dissipation relative to the first complete cycle Effective Stiffness or Energy Dissipation, respectively.
Temperature:		
Low	T_L	Lower limit of operating temperature.
Design	T_D	Nominal design temperature.
High	T_U	Upper limit of operating temperature.

4. GENERAL REQUIREMENTS

4.1 Introduction

This chapter outlines the general requirements for Pre-Qualification and Prototype testing of seismic isolation systems. The topics covered include: test facility, instrumentation and instrumentation calibration, data acquisition, data analysis and reporting of results. Unless otherwise specified all tests shall be conducted in accordance with these requirements. Special requirements are presented, as necessary, in Chapters 5 and 6 in conjunction with particular test specifications.

For reference, a schematic diagram of a Unit or Component under general bi-lateral loading is presented in Figure 4.1. A definition diagram is presented in Figure 4.2. Indicated in the figures are the forces, deformations and elements of the test facility that are referenced in these guidelines.

4.2 Test Facility

Tests shall be conducted in a facility that is capable of applying simultaneously a static vertical load and a cyclic lateral load to a specimen or group of specimens. The vertical load capacity of the facility shall be at least 10% greater than the largest vertical load to be applied during the test. The test facility shall have a lateral load capacity that is at least 10% greater than the largest lateral load to be applied during the test, and a total stroke of at least twice the maximum displacement specified for the test. Tests may be conducted in a single or multiple specimen configuration. The configuration may emulate but is not limited to those illustrated in Figure 4.3.

Unless otherwise specified, the lateral load shall be applied under displacement control such that the motion of the actuator is representative of a sinusoidal wave with specified frequency. At load rates less than or equal to 250 mm/min (10 in/min), the lateral load may be applied with constant velocity such that the motion of the actuator is representative of a sawtooth wave with specified frequency. The vertical load may be applied under load control or displacement control, provided the load can be maintained within ±10% of that specified for the duration of the test. The facility shall be such that the lateral load plane will remain parallel to within ± 5° of the bottom and/or top reaction support at all times, for the duration of the test.

The vertical load system shall be verified in accordance with ASTM E4 to an accuracy of ±5%. Where possible, the lateral load system shall be verified in accordance with ASTM E4 to an accuracy of ±2.5%. Otherwise, the lateral load system shall be calibrated as described in ASTM E74 and shall have an uncertainty of not more than ±2.5% of force[1]. *Load verification or calibration shall be carried out with the actual equipment to be used in the test.* Verification or calibration shall be required after repair, replacement or relocation of test facility equipment.

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[1] The system shall be calibrated using the procedure described in the standard, but not necessarily in accordance with the standard.

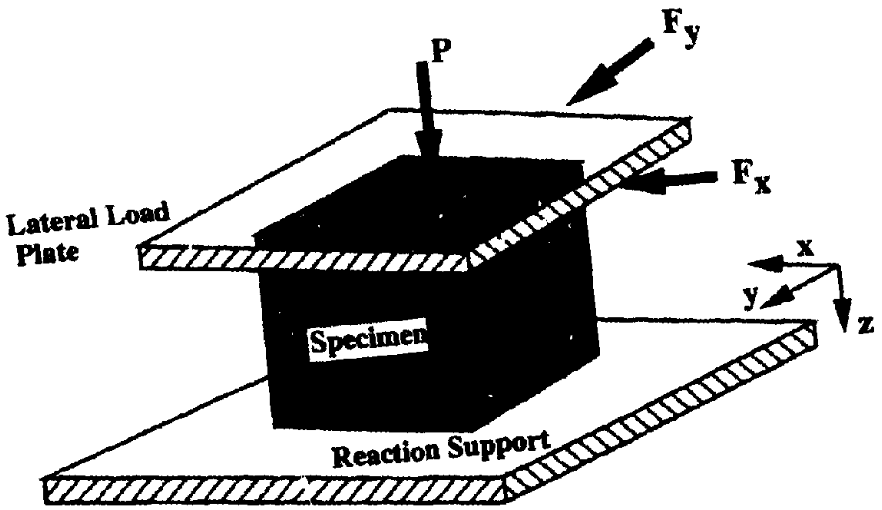


Figure 4.1 Unit or Component Under Bi-Lateral Loading

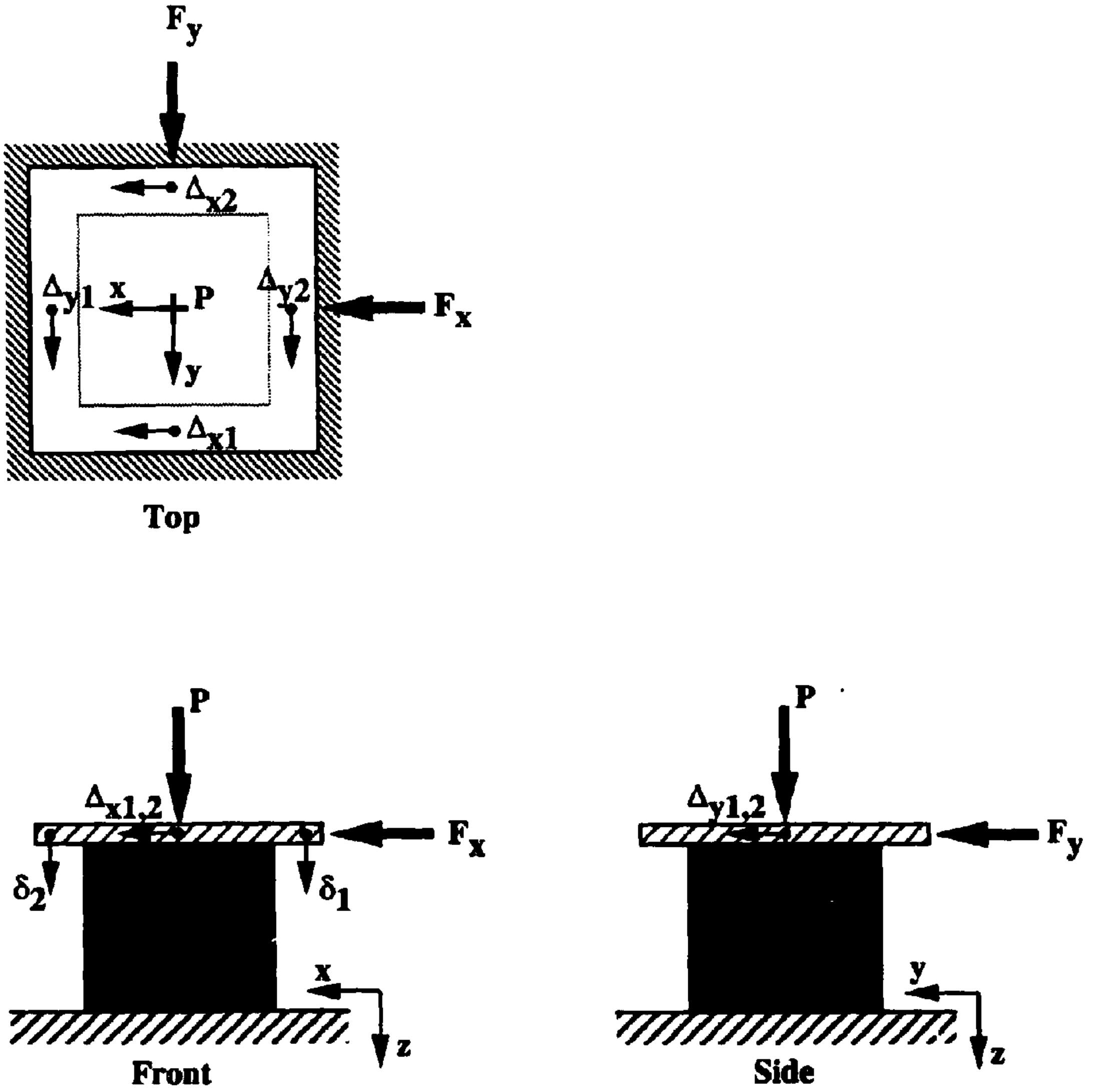
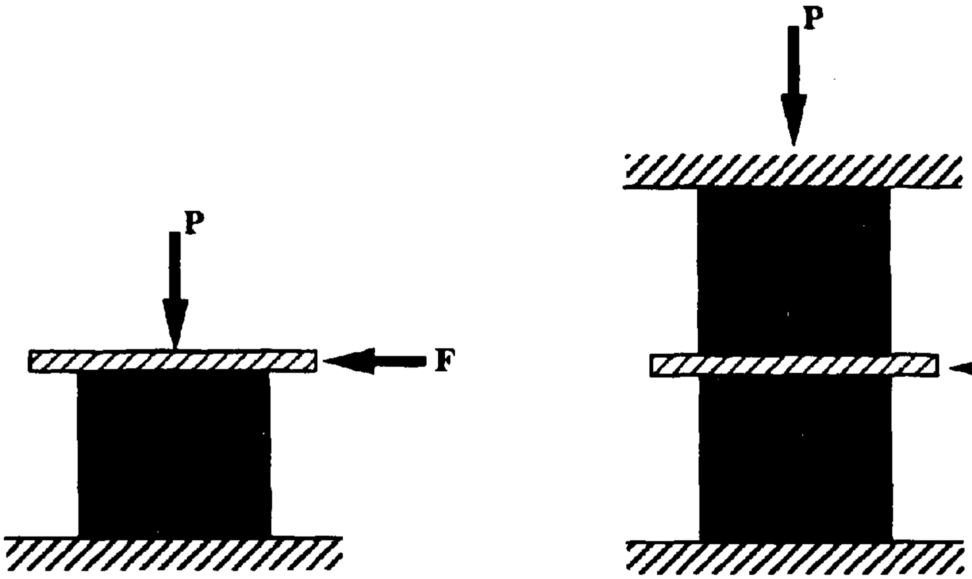
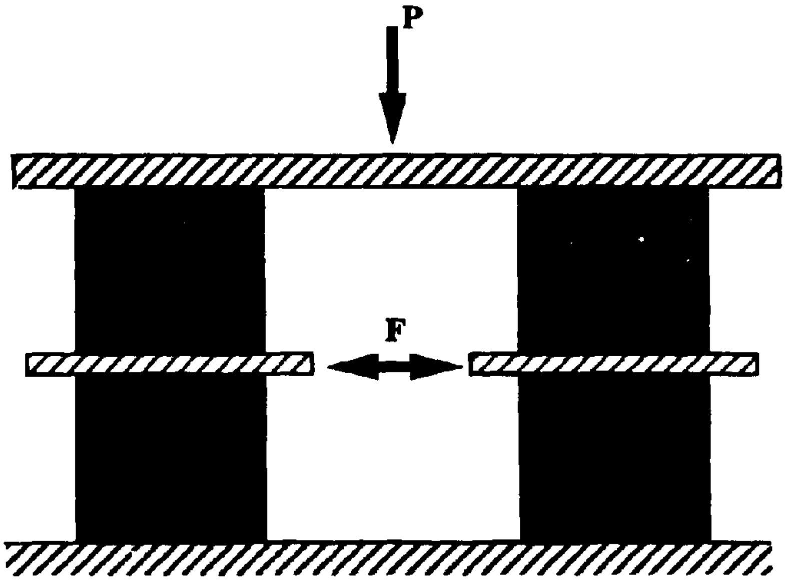


Figure 4.2 Definition Diagram



(a.) Single (b.) Dual



(c.) Quadruple

Figure 4.3 Test Configurations

4.3 Instrumentation and Calibration

Transducers shall be in place to measure, at a minimum, lateral load, lateral displacement, vertical load and vertical displacement. A thermometer shall be in place to record the temperature of the testing environment.

Loads on the test specimen may be measured via the test machine read-out, load cells in the force train of the actuator or via a force transducer between the specimen and reaction support. Transducers shall be such that loads are resolved to within 1% of the specified full load. Load cells in the force train of the actuator shall be verified or calibrated as outlined in Section 4.2. Other force transducers shall be calibrated periodically as described in ASTM E74 and shall have an uncertainty of not more than ±2.5% of force.

For actuator velocities less than or equal to 125 mm/min (5 in/min), load measurements may be made via a calibrated pressure differential across an actuator servo valve. The pressure differential shall be calibrated using a similar procedure as that stated for the load cell or force transducer.

Vertical displacement shall be measured at 2 points on the lateral load plane at opposite sides of the specimen, along a line parallel to the direction of lateral loading (δ_1 and δ_2 in Figure 4.2). Lateral displacement shall be measured at 2 points on the lateral load plane, at opposite sides of the specimen, along a line orthogonal to the direction of lateral loading (Δ_{x1} and Δ_{x2}, or Δ_{y1} and Δ_{y2} in Figure 4.2). Transducers shall be of sufficient precision to resolve the displacement to within 1% of the specified full displacement. Displacement transducers shall be calibrated periodically and shall have an uncertainty of not more than ±2.5% of displacement. Suitable displacement transducers include but are not limited to Linear Variable Differential Transformer (LVDT), Direct Current Differential Transformer (DCDT) and Linear Resistance Potentiometer.

4.4 Data Acquisition

An analog or digital data acquisition system shall be used to record time, lateral and vertical loads, two lateral displacements and two vertical displacements, for the duration of the test. Data shall be digitized or sampled at a rate not less than 100 times the frequency of loading. A digital data acquisition system shall be capable of sampling all data channels nearly simultaneously: the maximum time skew between channels shall be less than 1% of the sampling time interval.

4.5 Data Analysis

Data analysis is specified for a typical compression-shear test, assuming lateral load in one direction (x) only. For clarity, subscripts denoting the direction of lateral loading have been dropped. Properties measured or computed that pertain to lateral behavior are for that direction (x) only.

Unless otherwise specified the analysis of results shall include but is not limited to the following. The time history of lateral displacement (Δ) shall be computed as the average of the measured lateral displacements (Δ_1, Δ_2), i.e.,

$$\Delta(t) = \frac{1}{2}(\Delta_1(t) + \Delta_2(t)) \tag{4.1}$$

The time history of vertical displacement (δ) shall be computed as the average of the measured vertical displacements (δ_1, δ_2), i.e.,

$$\delta(t) = \frac{1}{2}(\delta_1(t) + \delta_2(t)) \tag{4.2}$$

Hysteresis loops for lateral deformation shall be constructed by plotting the measured lateral load (F) versus the lateral displacement (Δ) for the n cycles of the test. Hysteresis loops for vertical deformation shall be plotted in a similar manner, i.e., vertical load (P) is plotted versus vertical displacement (δ) for the n cycles of the test.

The maximum and minimum lateral displacements, Δ_i^+ and Δ_i^- respectively, shall be established for each complete cycle of the test. The maximum and minimum lateral loads, F_i^+ and F_i^- respectively, shall be established for each cycle of the test. Effective Stiffness (K_{H_i}) for each complete cycle i shall be computed as follows,

$$K_{H_i} = \frac{F_i^+ - F_i^-}{\Delta_i^+ - \Delta_i^-} \tag{4.3}$$

The Average Effective Stiffness (K_H) shall be computed for the n cycles of the test, as given by

$$K_H = \frac{1}{n}\sum_1^n K_{H_i} \tag{4.4}$$

Energy Dissipation shall be determined for each complete cycle of the test. The energy dissipated in cycle i (E_{H_i}), is equal to the area enclosed by the hysteresis loop for that cycle and should be expressed in units of force-length (e.g., kN-mm, or kip-in, etc.). The area enclosed by the loop may be determined by numerical integration for digital data, or by other suitable means for analog data. The Average Energy Dissipation (E_H) shall be determined for the n cycles of the test, as given by

$$E_H = \frac{1}{n}\sum_1^n E_{H_i} \tag{4.5}$$

4.6 Report of Results

Results of the tests shall be documented in a clear and concise report. Unless otherwise specified the report should include but is not limited to the following.

Name of the laboratory or institution conducting the test, name of the technician or engineer present for the test, name of the engineer responsible for the test, date and time at the start of the test, test configuration (single, dual, quadruple or other), test designation, specimen designation, temperature of the test environment, specimen scale (full or some fraction thereof). Pertinent test parameters shall be clearly indicated in the report, including number of cycles, displacement D, frequency of loading, vertical load, and temperature of the specimen. The report shall include or reference a sketch of the test configuration, with load and transducer positions indicated.

Report Effective Stiffness and Energy Dissipation for each complete cycle of the test, listed by cycle number in increasing order. Report the Average Effective Stiffness and Average Energy Dissipation for the n cycles of the test. Report the calculation of criteria associated with the test. The report shall include hysteresis plots for lateral deformation and vertical deformation under the specific test conditions.

4.7 Commentary

C4.1 Introduction.

The test procedures outlined in these Guidelines are generally classified as either "cyclic lateral load" or "ultimate or reserve capacity" tests. A cyclic lateral load test requires applying simultaneously a constant vertical load and a cyclic lateral load to a test specimen. The test is conducted for a specified vertical load, maximum lateral displacement, number of cycles and frequency of loading. The ultimate or reserve capacity test requires applying a monotonically increasing load until failure is observed, as indicated by overstress, buckling, fracture, rupture, or other event, or until a specified reserve capacity is demonstrated. The ultimate capacity test is conducted for load in the vertical or lateral plane, and may also require imposing a static load or displacement in a direction that is not coincident with the primary load direction.

The majority of tests specified in Chapters 5 and 6 can be classified as cyclic lateral load tests and have similar equipment and data analysis requirements. Therefore, rather than duplicate material, general requirements are outlined in this chapter and exceptions or special requirements for a particular test are noted in the later chapters.

C4.3 Test Facility.

As a minimum the test facility must be capable of subjecting a specimen to combined compression/shear. In a few tests the specimen is sheared laterally in 2 orthogonal directions, in which case, the facility must apply a bi-directional or bi-lateral shear load, as illustrated in Figure 4.1. For a specified vertical load and lateral displacement the most convenient control system combination is, vertical under load- and lateral under displacement-control.

There are several options in test configuration but the most common include the single, dual and quadruple configurations, as illustrated in Figure 4.3. The three configurations have certain advantages and disadvantages that offer trade-offs between complexity of the test facility and uniqueness of the experimental data:

- In the single specimen configuration the bottom of the specimen is held fixed and the top is sheared laterally (Figure 4.3a), or visa-versa. Single specimens may also be tested by shearing both top and bottom planes in alternating directions (see Figure C.4 in Appendix C). The data obtained in the single specimen configuration is unique to that specimen; however, the test set-up is the most complex of the three because both lateral load and moment reaction support must be provided.
- In the dual configuration the lateral load is applied to a plate that is sandwiched between two specimens, the other ends of which are held fixed (Figure 4.3b). The data obtained in the dual configuration is the average of the two specimens. This test set-up eliminates the need for a moment reaction support.
- In the quadruple configuration four specimens are tested in stacks of two, with the lateral load applied between the stacks (Figure 4.3c). The data obtained in the quadruple configuration is the average of four specimens: however, the test set-up is the simplest of the three and eliminates the need for both the moment and lateral load reaction supports.

Of the five facilities illustrated in Appendix C, four test in a single specimen configuration and one uses a dual configuration.

It is important that the test facility and equipment be periodically verified or calibrated. Verification refers to establishing the accuracy[2] of a test machine or facility over a specified load range using a load measuring device that is traceable to NIST (i.e., a Secondary Standard). ASTM E4 addresses load verification, but is intended for ordinary laboratory tension/compression test machines. At this time, a standard does not exist for load verification of tension/compression/shear test facilities. Nevertheless, ASTM E4 may be applied to the vertical load system independent of the lateral, if interaction between the two systems is assumed or shown to be negligible.

ASTM E4 may also be used for the lateral system independent of the vertical system, however, the following difficulties may arise: (1) this may require the fabrication of special fixtures to load a tension/compression Secondary Standard using the lateral system, (2) it may not be appropriate or possible to verify a system operating under displacement control. The alternative to ASTM E4 is to calibrate the lateral system using the procedure described in ASTM E74. Calibration refers to determining the calibration factor and uncertainty of an instrumentation package. The calibration factor is subsequently used during testing to convert, typically, an analog output to engineering units. It is not necessary to conform to ASTM E74, since it is actually intended for calibration of Primary and Secondary Standards used in ASTM E4, however, the procedure and data analysis is applicable and easily followed. Note, the actual equipment "package" to be used in the test should be calibrated. At a minimum this would include load cell and data acquisition system. Calibration of the complete test package, however, is highly recommended. This would include servo-value, actuator, load cell and data acquisition system.

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[2] maximum error of the test machine relative to the true load, over the specified load range.

C4.4 Instrumentation and Calibration.

Vertical loads are typically measured via the test machine read-out in facilities that use a universal test machine or press to apply the axial load. Otherwise, loads (vertical and lateral) are measured via a load cell in the actuator train, or by a force transducer located directly beneath the specimen. A load cell in the actuator train is suitable provided dynamic effects of the test facility are negligible, i.e., the measured load *is equal to* the load on the specimen. As an alternative, or for verification, loads can be measured via a transducer between the specimen and reaction frame. In either case, care should be taken to ensure that the frequency response characteristics of the load cell or transducer are properly matched to the test conditions, particularly for higher frequencies of loading. Transducers should be calibrated periodically using an appropriate procedure. If the transducer is sensitive to combined shear, axial and moment load conditions, the calibration procedure should take this into account.

At load rates less than or equal to 125 mm/min (5 in/min), i.e., pseudo-static loading, load can be measured via a calibrated pressure differential across the actuator servo valve. This eliminates the need for a load cell in the actuator train. This is not, however, an accurate or reliable technique for dynamic testing and should not be used at actuator velocities greater than that stated.

In a cyclic bi-lateral load test a minimum of six displacement measurements are required: 2 vertical displacements and 2 lateral displacements in each of the orthogonal directions (see Figures 4.1 and 4.2). Two measurements are required on opposite sides of the specimen in each direction. Mechanical dial gages are not recommended, except as back-up or for quick reference while the test is being conducted.

Displacement transducers should be calibrated periodically using an appropriate procedure. The procedure should include, as a minimum, 3 measurements at 5 displaced positions within the stroke range of the instrument to be used during testing. The true displaced position should be determined using a stable measuring instrument that has a resolution at least an order of magnitude smaller than the device being calibrated. A linear or second order curve should be fit to the data using a least squares technique and the uncertainty of the fit established. Once again, proper calibration involves the complete transducer "package" to be used during testing. This includes transducer, signal conditioning equipment, power supply and data acquisition system.

The uncertainty to be permitted in the measured Effective Stiffness and Energy Dissipation dictates the uncertainty allowed of the load cells and displacement transducers. Noting Eq. (4.3), Effective Stiffness is a ratio that involves four independently measured quantities. It can be shown that the uncertainty in K_{H} may be estimated by the square-root, sum-of-squares of the uncertainties of each of the measured quantities, i.e.,

$$U_K = \left\{ U_{F^+}^2 + U_{F^-}^2 + U_{\Delta^+}^2 + U_{\Delta^-}^2 \right\}^{1/2} \tag{3.6}$$

in which $U_{(\,)}$ denotes the uncertainty of the measured values. Assuming the desired uncertainty in measured Effective Stiffness is ±5.0%, force and displacement must be measured with an uncertainty of ±2.5%. A similar result is obtained for the calculation of Energy Dissipation.

C4.5 Data Acquisition.

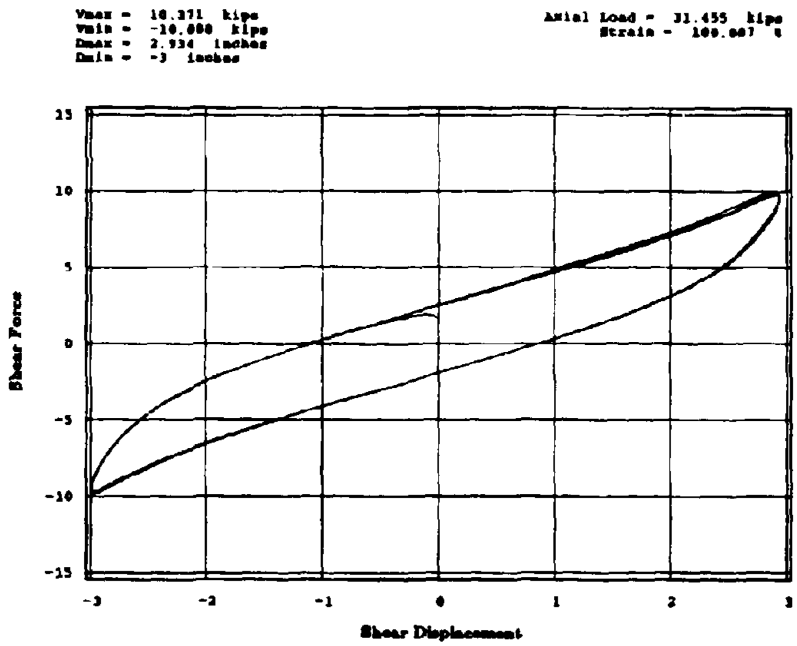
Data is to be recorded with an analog or digital data acquisition system. Although digital data acquisition systems are becoming the norm, analog devices are still in use. For ease of subsequent computer analysis, data recorded using an analog device is often digitized from the analog record. In either case it is important to digitize or sample test data at a rate that will accurately resolve the load-deformation hysteresis loop. A rate of 100 times the frequency of loading (e.g., 50 samples/sec for a frequency of loading of 0.5 cyc/sec) will resolve a typical hysteresis loop into approximately 100 data points. This is a recommended minimum: a higher sampling rate may be required to accurately resolve loops with sharp peaks, and to get an accurate measure of Effective Stiffness and Energy Dissipation.

C4.6 Data Analysis.

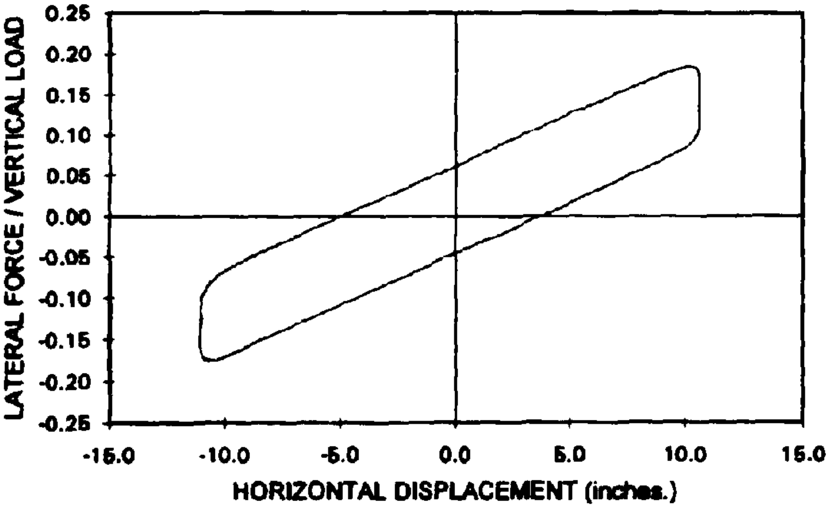
The analysis of data from a cyclic lateral load test involves, at a minimum, (1) construction of hysteresis loops, (2) determination of the Average Effective Stiffness and, (3) determination of the Average Energy Dissipation. For a quick qualitative evaluation of the general strength and stiffness characteristics of the Isolation Unit or Component, a hysteresis plot is most valuable. A few examples of measured hysteresis loops are presented in Figure 4.4.

The key parameters derived from the experimental data are Average Effective Stiffness and Average Energy Dissipation. These parameters characterize the Isolation System and, in design, determine the magnitude of lateral load transmitted to the superstructure. The Effective Stiffness of a cycle is the difference in maximum and minimum forces divided by the difference in maximum and minimum displacements, as given by Eq.(4.3). Energy Dissipation is the area enclosed by the loop. These are illustrated in Figure 4.5 for a hypothetical hysteresis loop. Effective Stiffness and Energy Dissipation should only be determined for *complete* cycles of loading. Data from the first half cycle and the last half cycle should not be used in the determination of the system properties.

For many Units and Components Effective Stiffness represents the slope of the line that connects the points of maximum force (displacement) and minimum force (displacement), as illustrated in Figure 4.5. The stiffness calculation in this case is intuitively obvious. In some cases, however, the maximum (minimum) force and maximum (minimum) displacement in a cycle *are not coincident.* This tends to occur when hysteresis loops are very rounded: examples of this type are illustrated in Figure 4.6. In this case, Effective Stiffness computed according to equation (4.3) is some average measure of the force-deflection behavior.



(a.) Laminated Elastomeric Bearing (Aiken, Kelly, Tajirian 1989)



(b.) Friction Pendulum System (Zayas, et al 1990)

Figure 4.4 Sample hysteresis loops

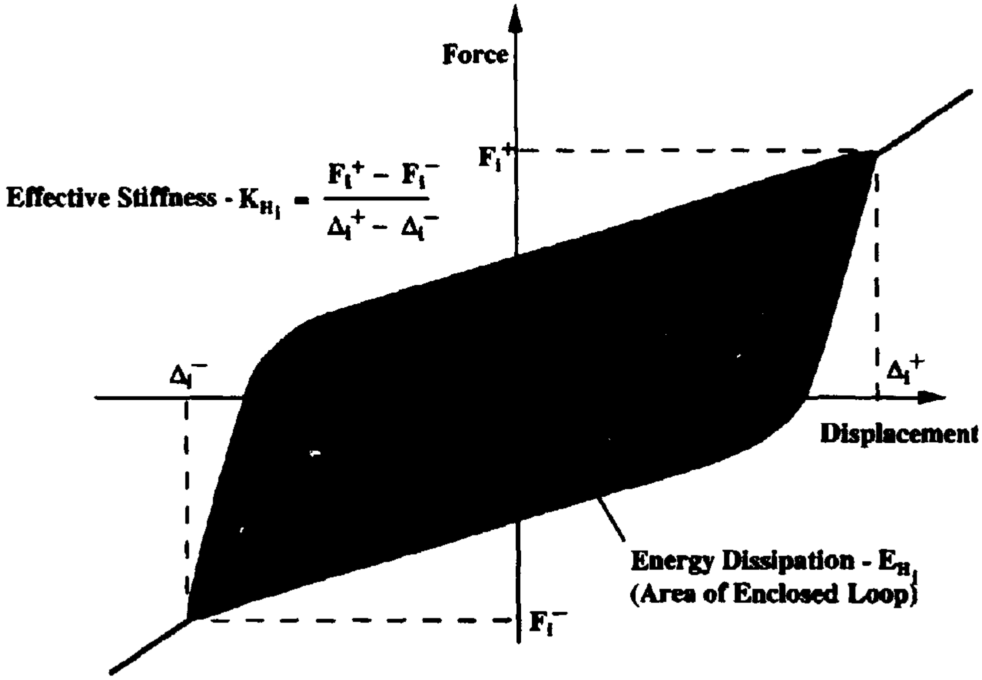


Figure 4.5 Effective Stiffness and Energy Dissipation for Typical Hysteresis Loop

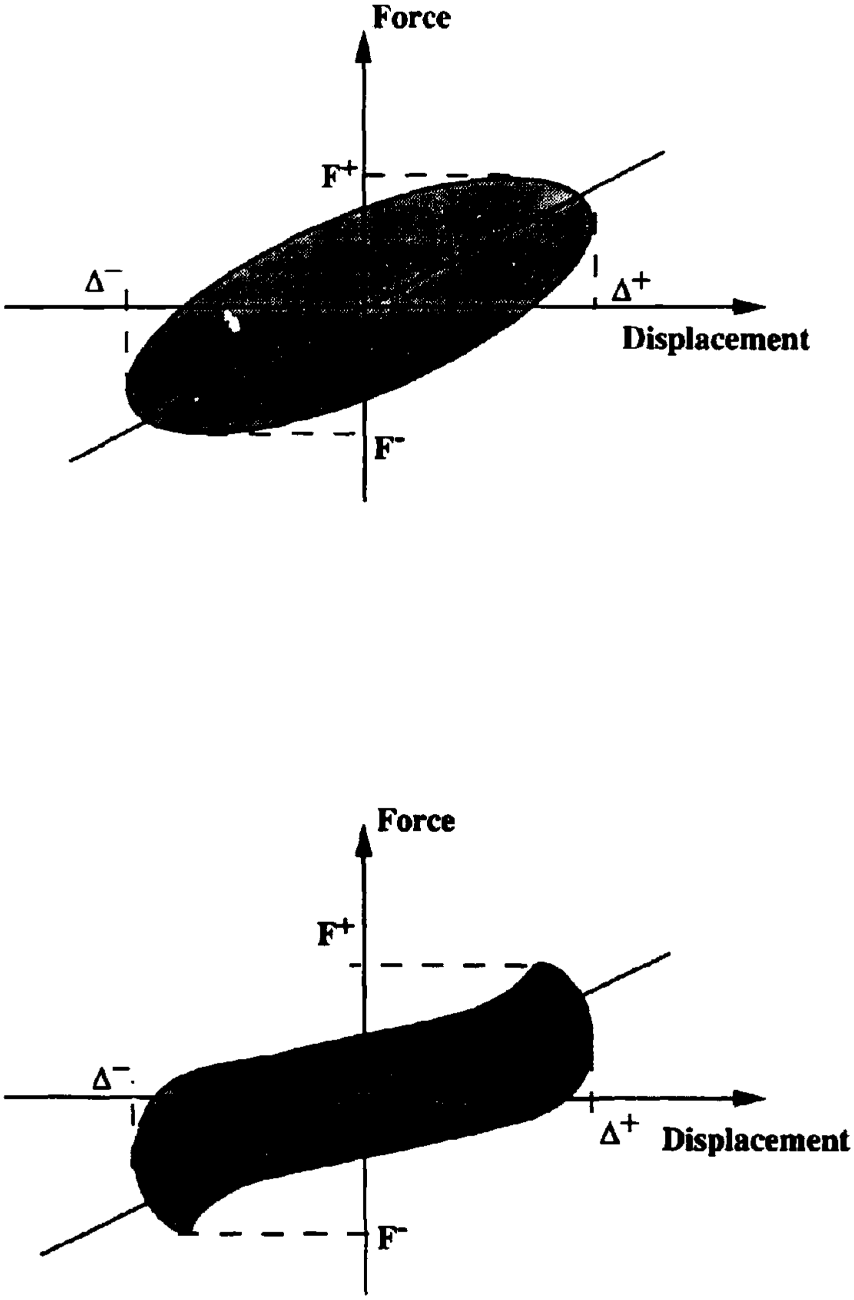


Figure 4.6 Effective Stiffness as Measured in Various Loops

5. PRE-QUALIFICATION TESTS

5.1 Introduction

This chapter outlines the requirements for pre-qualification testing. A total of sixteen test procedures are outlined in this chapter. Tests are grouped into two categories: Preliminary Characterization (Category I) and Ultimate and Reserve Capacity (Category II). Seven other test procedures are outlined in chapter 6 under prototype testing. The tests in chapter 6 are also grouped into two categories: Seismic Loads (Category III) and Non-Seismic Loads (Category IV).

The purpose of the Preliminary Characterization test (Category I) is to establish if, and the extent to which the properties and characteristics of a System, Unit or Component are dependent on virgin loading, frequency of load, load cycle history, load cycling, vertical load, load direction, load plane rotation, bilateral load, temperature, creep and aging. The Average Effective Stiffness and Average Energy Dissipation of the isolation system are evaluated for a limited range of displacements under varying load and environmental conditions.

The purpose of the Ultimate and Reserve Capacity test (Category II) is to establish the ultimate capacity, or demonstrate reserve capacity, of the System, Unit or Component under various load conditions. The tests include ultimate compression under zero lateral load, compression in the displaced position, ultimate tension under zero lateral load, tension in the displaced position, and lateral load and displacement capacity under the design vertical load. Tests denoted as "ultimate" are proof tests and are conducted to failure.

Performance criteria have been established for most of the tests in the guidelines. The criteria are rules or principles against which the performance of the isolation system or component is tested. Criteria in Category I tests are "benchmarks", and simply provide a method for characterizing the response of the System, Unit or Component (e.g., "frequency dependent", "temperature dependent", etc.). The criteria in Category II (and categories III and IV in chapter 6) are performance standards. Systems that do not meet these minimum criteria may not perform adequately in service. The performance criteria are generally in the form of simple expressions that are to be evaluated based on the results of the test. Others are descriptive in nature and require a subjective evaluation of test results.

Tests procedures are presented in a standard format that includes the following elements:

Test Designation:	For reference tests are designated using the notation "C.#", where C denotes the category in Roman numerals and # denotes the test number. For example, II.2 refers to test number 2 of Category II.
Purpose:	A brief statement of the purpose or objective of the test.
Sequence:	Test parameters are specified and the sequence is outlined, e.g., number of cycles, loads, rates, etc.
Procedure:	The procedure for conducting the test is described in detail.
Criteria:	Performance criteria described previously.
Special	

PRECEDING PAGE
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Requirements: Other requirements or exceptions to those presented in Chapter 4 (e.g., facility, instrumentation, data analysis, etc.)

Exception: In certain cases exceptions to the recommended procedure are allowed.

In that these guidelines are "draft" some details of the test procedures remain to be determined. Where possible, different options, or the range of parameters that have been considered or are proposed for a particular test are presented. Draft options are preceded or enclosed in a shaded box like the one shown below:

Draft Option

In certain instances the test procedure is complete, with the exception of "hard" numbers for some parameters. In this case variables, usually α and β, are shown in place of the hard numbers and the expected range of the parameter is presented in the shaded draft option box. This occurs with the performance criteria for a number of tests.

The general requirements for pre-qualification testing are discussed in Section 5.2. Guidelines for conducting Preliminary Characterization tests (Category I) are presented in Section 5.3. Guidelines for conducting Ultimate and Reserve Capacity tests (Category II) tests are presented in Section 5.4. Limited commentary is presented in Section 5.5.

5.2 General Requirements of Pre-Qualification Tests

Unless otherwise specified Pre-qualification tests shall be conducted in accordance with the following:

(a) Pre-qualification shall include all tests outlined in Table 5.1. Pre-qualification shall also include a complete series of prototype tests, as outlined in chapter 6 (Table 6.1), and applicable quality control tests (not addressed here).

(b) Tests shall be conducted on Isolation Units and Components. Components may be tested individually, or in combination with other Components in the Isolation System provided the assembly and connection of the tested Components is representative of the full System detail. It may be necessary to substantiate, either theoretically or by additional tests, the overall behavior and stability of the Isolation System when the tests described herein are conducted only on individual Components.

(c) Tests shall be performed separately on two specimens of the Isolation Unit or Component. A sufficient number of specimens shall be used such that 2 independent data sets are obtained when testing in a multiple specimen configuration. Specimens are to be new and previously never tested, however, the same specimens may be used for the complete series of tests. Unless otherwise specified, all tests shall be conducted on full scale specimens. In certain instances scale model specimens are acceptable, provided they are not less than 1/4 full scale and are representative of the full scale prototype.

> *Note - it is recognized that facilities do not yet exist to test full size Units or Components under some of the conditions outlined in the guidelines, because of the size and load carrying capacity of the specimen. This is true in particular for ultimate capacity tests, and compression-shear tests under real-time loading. In this case scale model specimens are acceptable.*

(d) The nominal capacity of the specimen to be tested must be "rated" by the supplier prior to testing. Properties to be rated are presented in chapter 3.

(e) Unless otherwise specified the frequency of isolation (f_i) (i.e., inverse of the isolated period $f_i = 1/T_i$) shall be determined from the rated Horizontal Stiffness (K_H) and the Design Vertical Load (P_D).

(f) Category I tests shall be conducted in the order in which they are listed in the Guidelines.

(g) Properly documented Pre-qualification tests previously conducted on a Unit or Component may be used to satisfy the requirements of this section, provided the Unit or Component to be tested is similar in design, materials and construction as that tested previously.

Table 5.1. Schedule of Pre-Qualification Tests[1]

Category	Test	Purpose
I	I.1	Establish dependence on virgin loading
	I.2	Establish dependence on frequency of load
	I.3	Establish dependence on load cycle history
	I.4	Establish dependence on load cycling
	I.5	Establish dependence on vertical load
	I.6	Establish dependence on load direction
	I.7	Establish dependence on load plane rotation
	I.8	Establish dependence on bilateral load
	I.9	Establish dependence on temperature
	I.10	Establish dependence on creep
	I.11	Establish dependence on aging
II	II.1	Ultimate compression under zero lateral load
	II.2	Compression in displaced position
	II.3	Ultimate Tension under zero lateral load
	II.4	Tension in displaced position
	II.5	Lateral load and displacement capacity under design vertical load

[1] Pre-qualification shall also include a complete series of prototype tests (chapter 6) and quality control tests.

5.3 Category I - Preliminary Characterization

Draft Option

Parameters α and β, present throughout Category I, pertain to performance criteria associated with Effective Stiffness (α) and Energy Dissipation (β). These criteria may be viewed as "benchmarks" and simply provide a means for characterizing the performance of an Isolation System. The criteria, however, ultimately determine the extent of prototype testing required.

Parameters α and β are generally expected to range from 10 to 35 (%). It is not clear whether α (β) should be constant for all tests in Category I, or whether it should vary from one test to the next (although the same parameter value is used throughout Category I, ***this is not meant to imply that*** α ***(***β***) is to be constant for all tests***), or, what the relative ratio of α and β should be for a particular test. Parameters α and β should be chosen, taking into consideration the fact that manufacturing tolerances on materials are typically in the ±10% range, and that a ±20% variation in stiffness results in a ±10% variation in isolator displacement and base shear (UBC, 1991).

5.3.1 Test for dependence on Virgin Loading.

Test Designation: I.1

Purpose: To establish the effect of virgin loading on the response in subsequent cycles.

Sequence: Denoting two specimens as "A" and "B", tests shall be conducted in accordance with the following:

(a.) *Specimen A only* - 5 fully reversed cycles to a peak displacement of ±*D*; then

(b.) *Specimens A and B* - 3 fully reversed cycles at each of the displacement increments ±0.25*D*, ±0.5*D*, ±0.75*D* and ±1.0*D*.

Tests shall be conducted in the order listed, with a vertical load corresponding to P_D and at a frequency of loading of not less than 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test shall be run continuously without pause between cycles, or without pause between changes in displacement increments in (b). Sufficient time shall be allowed between sequences (a) and (b) to dissipate any heat developed during the previous test.

Criteria: The System, Unit or Component response is considered to be independent of virgin loading if:

(1.) the Average Effective Stiffness of specimen A and the Average Effective Stiffness of specimen B are within α% of each other, for each increment of displacement in test sequence (b), i.e.,

$$\frac{\left| K_H^A - K_H^B \right|}{\min\left\{K_H^A,\ K_H^B\right\}} \le 0.01\alpha \qquad (5.1)$$

where K_H^A and K_H^B is the Average Effective Stiffness at a given displacement of specimen A and B, respectively, and $\min\{K_H^A,\ K_H^B\}$ denotes the minimum of K_H^A and K_H^B.

(2.) the Average Energy Dissipation of specimen A and the Average Energy Dissipation of specimen B are within β% of each other, for each increment of displacement in test sequence (b), i.e.,

$$\frac{\left| E_H^A - E_H^B \right|}{\min\left\{E_H^A,\ E_H^B\right\}} \le 0.01\beta \qquad (5.2)$$

where E_H^A and E_H^B is the Average Energy Dissipation at a given displacement of specimen A and B, respectively, and $\min\{E_H^A,\ E_H^B\}$ denotes the minimum of E_H^A and E_H^B.

5.3.2 Test for dependence on frequency of loading.

Test Designation: 1.2

Purpose: To establish dependence of system response on the frequency of loading, and to determine the lower and upper threshold frequencies, f_L and f_U, respectively.

Sequence: (a.) Three fully reversed cycles to peak displacements of $\pm D$ at a frequency corresponding to f_i (the isolation frequency).

(b.) three fully reversed cycles to peak displacements of $\pm D$ at increments of frequency less than f_i, as needed, to determine the lower threshold frequency f_L. The test shall include a series of three cycles at a frequency of $f_i/2$. In no case shall the frequency of loading be less than 0.004 cyc/sec.

(c.) three fully reversed cycles to peak displacements of $\pm D$ at increments of frequency greater than f_i, as needed, to determine the upper threshold frequency f_U. The test shall include a series of three cycles at a frequency of $3f_i/2$. Tests need not be conducted at frequencies greater than $2f_i$.

Tests shall be conducted with a vertical load equal to P_D.

Procedure: Sequence (a.): Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test without pause between cycles.

Sequence (b): Same as sequence (a); the frequency of loading shall be decreased in increments, to the limit of 0.004 cyc/sec, until the lower threshold frequency (f_L) is established. The lower threshold frequency is the minimum frequency that satisfies Criteria (1) and (2) below.

Sequence (c): Same as sequence (a); the frequency of loading shall be increased in increments, to the limit of $2f_i$, until the upper threshold frequency (f_U) is established. The upper threshold frequency is the maximum frequency that satisfies Criteria (1) and (2) below.

Sufficient time shall be allowed between tests at the different rates to dissipate any heat developed during the previous test. The vertical load shall be maintained between tests.

Criteria: The System, Unit or Component response is considered to be independent of frequency of loading over the range of frequencies f_L to f_U, if:

(1.) the Average Effective Stiffnesses measured at frequencies corresponding to f_L and f_U are within $\pm\alpha\%$ of the Average Effective Stiffness measured at a frequency corresponding to f_i, i.e.,

$$\frac{\left| K_H^{f_L} - K_H \right|}{K_H} \leq 0.01\alpha \quad \textit{and} \quad \frac{\left| K_H^{f_U} - K_H \right|}{K_H} \leq 0.01\alpha \qquad (5.3)$$

where K_H is the Average Effective Stiffness measured at a frequency of f_i, $K_H^{f_L}$ is the Average Effective Stiffness measured at a frequency of f_L and $K_H^{f_U}$ is the Average Effective Stiffness measured at a frequency of f_U.

(2.) the Average Energy Dissipation measured at frequencies corresponding to f_L and f_U are within ±β% of the Average Energy Dissipation measured at a frequency corresponding to f_i, i.e.,

$$\frac{\left| E_H^{f_L} - E_H \right|}{E_H} \leq 0.01\beta \qquad \mathit{and} \qquad \frac{\left| E_H^{f_U} - E_H \right|}{E_H} \leq 0.01\beta \tag{5.4}$$

where E_H is the Average Energy Dissipation measured at frequency of f_i, $E_H^{f_L}$ is the Average Energy Dissipation measured at a frequency of f_L and $E_H^{f_U}$ is the Average Energy Dissipation measured at a frequency of f_U.

(3.) The System, Unit or Component is said to be "dependent on frequency of loading in the range of (f_i)" if

$$f/2 \leq f_L \qquad or \qquad f_U \leq 3f/2 \tag{5.5}$$

Note - the commentary section provides further clarification on the threshold frequencies.

5.3.3 Test for dependence on load cycle history.

Test Designation: 1.3

Purpose: To establish the dependence of system response on the history of load cycling.

Sequence: (a.) 3 fully reversed cycles at each of the displacement increments ±0.25*D*, ±0.5*D*, ±0.75*D* and ±1.0*D*; then

(b.) 3 fully reversed cycles at each of the displacement increments ±1.0*D*, ±0.75*D*, ±0.5*D* and ±0.25*D*.

Tests shall be conducted in the order listed, with a vertical load corresponding to P_D and at a frequency of loading of not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test shall be run continuously without pause between cycles, or without pause between changes in displacement increments. Sufficient time shall be allowed between test sequence (a) and test sequence (b) to dissipate any heat developed during the previous test. The vertical load shall be maintained between sequences (a) and (b).

Criteria: The System, Unit or Component response is considered to be independent of load cycle history if:

(1.) the Average Effective Stiffness measured in test sequence (a) and the Average Effective Stiffness measured in test sequence (b) are within α% of each other, at equal increments of displacement, i.e.,

$$\frac{\left| K_H^a - K_H^b \right|}{\min\left\{K_H^a, K_H^b\right\}} \le 0.01\alpha \tag{5.6}$$

where K_H^a and K_H^b is the Average Effective Stiffness measured at equal displacement increments in (a) and (b), respectively, and $\min\{K_H^a, K_H^b\}$ denotes the minimum of K_H^a and K_H^b.

(2.) the Average Energy Dissipation measured in test sequence (a) and the Average Energy Dissipation measured in test sequence (b) are within β% of each other, at equal increments of displacement, i.e.,

$$\frac{\left| E_H^a - E_H^b \right|}{\min\left\{E_H^a, E_H^b\right\}} \le 0.01\beta \tag{5.7}$$

where E_H^a and E_H^b is the Average Energy Dissipation measured at equal displacement increments in (a) and (b), respectively, and $\min\{E_H^a, E_H^b\}$ denotes the minimum of E_H^a and E_H^b

5.3.4 Test for dependence on load cycling (system degradation)

Test Designation: 1.4

Purpose: To establish dependence on repeated cycling.

Sequence: Fifty fully reversed cycles to a peak displacement of $\pm D$. Tests shall be conducted with a vertical load corresponding to P_D and at a frequency of loading of not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test shall be run continuously without pause between cycles.

Criteria: The System, Unit or Component is considered to be independent of load cycling (i.e., is non-degrading) if:

(1.) the Effective Stiffness of cycle i is within $\pm\alpha\%$ of the 1st complete cycle Effective Stiffness, for the 50 cycles of the test, i.e.,

$$\frac{\left| K_H^i - K_H^1 \right|}{K_H^1} \leq 0.01\alpha \tag{5.8}$$

in which K_H^1 and K_H^i denote the 1st cycle and ith cycle Effective Stiffness, respectively;

(2.) the Energy Dissipation of cycle i is at least $\beta\%$ of the 1st complete cycle Energy Dissipation for the 50 cycles of the test, i.e.,

$$E_H^i \geq 0.01\beta \; E_H^1 \tag{5.9}$$

in which E_H^1 and E_H^i denote the 1st cycle and ith cycle Energy Dissipation, respectively.

Special Requirements: <u>Report of Results</u>: Report the Effective Stiffness and Energy Dissipation for each cycle i of the test, listed by cycle number in increasing order. Report the percent increase or decrease in Effective Stiffness relative to the first cycle Effective Stiffness. Report the ratio of the ith cycle to 1st cycle Energy Dissipation for each cycle of the test.

5.3.5 Test for dependence on vertical load.

Test Designation: I.5

Purpose: Establish dependence on vertical load.

Sequence: Three fully reversed cycles to peak displacements of $\pm D$. Tests shall be conducted for vertical loads corresponding to P_L, P_D, P_U. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. Remove the vertical load. The test shall be run continuously without pause between cycles. The test shall be conducted at the vertical loads specified in the order P_L, P_D and P_U. Sufficient time shall be allowed between tests at the different vertical loads to dissipate any heat developed during the previous test.

Criteria: The System, Unit or Component response is considered to be independent of vertical load if:

(1.) the Average Effective Stiffnesses measured at vertical loads corresponding to P_L and P_U are within $\pm\alpha\%$ of the Average Effective Stiffness measured at the vertical load corresponding to P_D, i.e.,

$$\frac{\left| K_H^P - K_H \right|}{K_H} \le 0.01\alpha \tag{5.10}$$

where K_H is the reference Average Effective Stiffness measured at a vertical load corresponding to P_D, and K_H^P denotes the Average Effective Stiffness measured at vertical loads corresponding to P_L and P_U.

(2.) the Average Energy Dissipation measured at vertical loads corresponding to P_L and P_U are within $\pm\beta\%$ of the Average Energy Dissipation measured at the vertical load corresponding to P_D, i.e.,

$$\frac{\left| E_H^P - E_H \right|}{E_H} \le 0.01\beta \tag{5.11}$$

where E_H is the reference Average Energy Dissipation measured at a vertical load corresponding to P_D, and E_H^P denotes the Average Energy Dissipation measured at vertical loads corresponding to P_L and P_U.

5.3.6 Test for dependence on load direction.

Test
Designation: I.6

Purpose: Establish dependence on loading direction.

Sequence: (a.) *Primary (0 °) direction* - 3 fully reversed cycles to peak displacements of ±D;
(b.) *45 ° direction* - 3 fully reversed cycles to peak displacements of ±D, loading in a direction that is 45° relative to the direction of loading in (a);
(c.) *90 ° direction* - 3 fully reversed cycles to peak displacements of ±D, loading in a direction that is 90° relative to the direction of loading in (a), and 45° relative to the direction of loading in (b).
The tests shall be conducted with a vertical load equal to P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and orient such that lateral loading takes place along the selected primary (0 °) direction; the primary direction should correspond to a principal axis of symmetry, should one exist for the test specimen. Secure the specimen as necessary to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. Remove the vertical load. The test shall be run continuously without pause between cycles. Rotate the specimen 45°, such that the line of action of lateral load in the new position is 45° relative to the original orientation. Apply the full vertical load and repeat the test. Rotate the specimen an additional 45°, such that the line of action of lateral load is 90° relative to the original line of action of lateral load. Apply the full vertical load and repeat the test. Sufficient time shall be allowed between tests at the different orientations to dissipate any heat developed during the previous test.

Criteria: The System, Unit or Component response is considered to be independent of load direction if:

(1.) the Average Effective Stiffnesses for loading in the 45° and 90° directions are within ±α% of the Average Effective Stiffness measured in the primary direction, i.e.,

$$\frac{\left| K_H^o - K_H \right|}{K_H} \le 0.01\alpha \qquad (5.12)$$

where K_H is the reference Average Effective Stiffness for loading in the primary direction and K_H^o denotes the Average Effective Stiffness for loading at 45° and 90° relative to the primary direction.

(2.) the Average Energy Dissipation for loading in the 45° and 90° directions are within ±β% of the Average Energy Dissipation measured in the primary direction, i.e.,

$$\frac{\left| E_H^o - E_H \right|}{E_H} \le 0.01\beta \qquad (5.13)$$

where E_H is the reference Average Energy Dissipation for loading in the primary direction and E_H^o denotes the Average Energy Dissipation for loading at 45° and 90° relative to the primary direction.

5.3.7 Test for dependence on load plane rotation.

Test Designation: I.7

Purpose: Establish dependence on lateral load plane rotation.

Sequence: (a.) *Lateral load plane parallel* - 3 fully reversed cycles to peak displacements of ±*D* with the lateral load plane parallel to the bottom plate;

Draft Option

(b.) *Lateral load plane rotated* - 3 fully reversed cycles to peak displacements of ±*D* with the lateral load plane rotated $+\theta^\circ$ relative to the bottom plate, about an axis that lies in the plane of lateral loading and is orthogonal to the direction of lateral loading; 3 fully reversed cycles to peak displacements of ±*D* with the lateral load plane rotated $-\theta^\circ$ relative to the bottom plate, about an axis that lies in the plane of lateral loading and is orthogonal to the direction of lateral loading.

or

(b.) *Lateral load plane rotated* - 3 fully reversed cycles to peak displacements of ±*D* with the lateral load plane rotated $+\theta^\circ$ relative to the bottom plate, about an axis that lies in the plane of lateral loading and is orthogonal to the direction of lateral loading; additionally, for non-symmetric systems, 3 fully reversed cycles to peak displacements of ±*D* with the lateral load plane rotated $-\theta^\circ$ relative to the bottom plate.

The tests shall be conducted with a vertical load equal to P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure as necessary to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles with the lateral load plate parallel to the bottom plate. Remove the vertical load. Repeat the test with the lateral load plane in the specified rotated position. Sufficient time shall be allowed between tests at the different orientations to dissipate any heat developed during the previous test.

Criteria: The System, Unit or Component response is considered to be independent of load plane rotation if:

(1.) the Average Effective Stiffnesses measured with the lateral load plane rotated to $+\theta^\circ$ and $-\theta^\circ$ are within $\pm\alpha\%$ of the Average Effective Stiffness measured with the lateral load plane parallel, i.e.,

$$\frac{\left| K_H^R - K_H \right|}{K_H} \leq 0.01\alpha \qquad (5.14)$$

where K_H is the reference Average Effective Stiffness for the lateral load plane parallel and K_H^R denotes the Average Effective Stiffness for the lateral load plane rotated to +θ° and -θ°.

(2.) the Average Energy Dissipation measured with the lateral load plane rotated to +θ° and -θ° are within ±β% of the Average Energy Dissipation measured with the lateral load plane parallel, i.e.,

$$\frac{\left| E_H^R - E_H \right|}{E_H} \leq 0.01\beta \tag{5.15}$$

where E_H is the reference Average Energy Dissipation for the lateral load plane parallel and E_H^R denotes the Average Energy Dissipation for the lateral load plane rotated to +θ° and -θ°.

Special Requirements: Test Facility: The facility shall be capable of testing with the lateral load plane or top plate of the specimen in a rotated position.

5.3.8 Test for dependence on bilateral load.

Test Designation: 1.8

Purpose: Establish dependence on bilateral loading.

Sequence: (a.) *Bilateral Load* - 3 fully reversed cycles to peak displacements of $\pm 0.8D$ in the x direction, while a displacement of $0.6D$ is maintained in the y direction.

(b.) *Unilateral Load* - 3 fully reversed cycles to peak displacements of $\pm 0.8D$ in the x direction.

Tests shall be conducted with a vertical load equal to P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Note - the compression-bilateral load test requires sophisticated test equipment; there are few facilities in existence today that can test under these conditions, and not at full scale and at the actual frequency of isolation. Consequently, limited research has been conducted to study the behavior of isolation systems under bilateral load. However, while the practicality of conducting such a test remains in question, the importance of establishing a dependence on bilateral loading is clear. The procedure outlined herein is a first attempt to develop a consistent test method for establishing bilateral load dependence. The methodology will be developed further as additional research is conducted and new, more sophisticated test facilities are built to conduct these types of tests.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Load the specimen in the y direction to a displacement of $0.6D$. Apply the cyclic lateral load in the x direction to a displacement of $\pm 0.8D$ for the required 3 fully reversed cycles. Remove the lateral load in the y direction. The test shall be run continuously without pause between cycles. Before conducting the unilateral load test, pause to allow the specimen sufficient time to dissipate any heat developed during the previous test. Apply the cyclic lateral load in the x direction to a maximum displacement of $\pm 0.8D$ for the required 3 fully reversed cycles. The vertical load shall be maintained between bilateral and unilateral load tests.

Criteria: The System, Unit or Component response is considered to be independent of bilateral loading if:

(1.) the Average Effective Stiffness measured in the x direction under bilateral loading is within $\pm\alpha\%$ of the Average Effective Stiffness measured in the x direction under unilateral load, i.e.,

$$\frac{\left| K_H^B - K_H \right|}{K_H} \leq 0.01\alpha \qquad (5.16)$$

where K_H is the reference Average Effective Stiffness measured under unilateral loading in the x direction and K_H^B denotes the Average Effective Stiffness measured in the x direction under bilateral loading.

(2.) the Average Energy Dissipation measured in the x direction under bilateral loading is within $\pm\beta\%$ of the Average Energy Dissipation measured in the x direction under unilateral load, i.e.,

$$\frac{\left| E_H^B - E_H \right|}{E_H} \leq 0.01\beta \qquad (5.17)$$

where E_H is the reference Average Energy Dissipation measured under unilateral loading in the x direction and E_H^B denotes the Average Energy Dissipation measured in the x direction under bilateral loading.

Special Requirements: Test Facility: Tests shall be conducted in a facility that is capable of applying simultaneously a static vertical load, a static lateral load and a cyclic lateral load that is orthogonal to the static lateral load. The test machine load capacities shall be at least 10% greater than the largest load expected in their respective directions. The static lateral load actuator shall have a stroke of at least $0.7D$, the cyclic lateral load actuator shall have a stroke of at least $2D$. The static lateral load may be under displacement control or load control, provided the static displacement can be maintained within ±5% of the specified displacement for the duration of the test.

Instrumentation: In addition to that specified in Section 4.3, transducers shall be in place to measure displacements at 2 points on opposite sides of the lateral load plane in the (y) direction.

Data Acquisition: In addition to that specified in Section 4.4, record the 2 static lateral displacements that are orthogonal to the cyclic lateral direction.

Data Analysis: In addition to that specified in Section 4.5, the time history of static lateral displacement in the y direction shall be computed as the average of the two measured lateral displacements, i.e.,

$$\Delta_y(t) = \frac{1}{2}(\Delta_{y_1}(t) + \Delta_{y_2}(t)) \qquad (5.18)$$

Construct hysteresis loops for loading in the x direction by plotting the lateral load (F_x) versus the lateral displacement (Δ_x) for the 3 cycles of the bilateral load test. Compute the Effective Stiffness, Average Effective Stiffness, Energy Dissipation and Average Energy Dissipation in the x direction for bilateral loading. Compute the Effective Stiffness, Average Effective Stiffness, Energy Dissipation and Average Energy Dissipation for the 3 cycles of test under unilateral loading using the standard procedure described in Chapter 4.

5.3.9 Test for dependence on temperature.

Test Designation: I.9

Purpose: Establish dependence on temperature.

Sequence: Three fully reversed cycles to peak displacements of $\pm D$. Tests shall be conducted for internal core temperatures at the start of cyclic loading corresponding to T_L, T_D and T_U. The maximum internal and external temperature differential of the specimen at the start of the test shall be not more than 22°C (40°F). Tests shall be conducted with a vertical load equal to P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Procedure: Bring the internal core of the specimen to the designated temperature; maintain the temperature to within ±5°C (±9°F) of that specified for a minimum of 1 hour. Place the specimen in the test machine and secure as necessary to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. The test shall be run continuously without pause between cycles. The test shall be conducted at the temperatures specified in the order T_L, T_D and T_U.

Criteria: The System, Unit or Component response is considered to be independent of temperature if:

(1.) the Average Effective Stiffnesses measured at temperatures T_L and T_U are within $\pm\alpha$% of the Average Effective Stiffness measured at a temperature of T_D, i.e.,

$$\frac{\left| K_H^T - K_H \right|}{K_H} \le 0.01\alpha \tag{5.19}$$

where K_H is the reference Average Effective Stiffness measured at a temperature of T_D and K_H^T denotes the Average Effective Stiffness measured at temperatures T_L and T_U.

(2.) the Average Energy Dissipation measured at temperatures T_L and T_U are within $\pm\beta$% of the Average Energy Dissipation measured at a temperature of T_D, i.e.,

$$\frac{\left| E_H^T - E_H \right|}{E_H} \le 0.01\beta \tag{5.20}$$

where E_H is the reference Average Energy Dissipation measured at a temperature of T_D and E_H^T denotes the Average Energy Dissipation measured at temperatures T_L and T_U.

Special Requirements: <u>Test Facility</u>: Tests shall be conducted in a facility that is capable of heating and cooling a specimen to the designated temperatures, and maintaining those temperatures so as to satisfy the core temperature and maximum differential temperature requirements.

Instrumentation: A thermocouple shall be installed or embedded near the core of the specimen to measure internal core temperature. A thermocouple shall be mounted to an external surface of the specimen that is exposed to ambient room temperature to measure surface temperature.

Data Acquisition: The internal and external temperature of the specimen shall be recorded along with the load and displacement data. Temperatures shall be recorded for a period of 30 sec immediately prior to the start of the test and for a period of 30 sec immediately following the end of the test.

Report of Results: Report the average internal core and external specimen temperatures at the start of each test. Report the average internal core and external specimen temperatures at the end of each test.

5.3.10 Test for dependence on creep.

Test Designation: I.10

Purpose: Establish dependence on creep.

Sequence: (a.) Three fully reversed cycles to peak displacements of $\pm D$. Tests shall be conducted with a vertical load of P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

(b.) Apply a vertical compressive load to the specimen equal to $1.5P_D$. The load shall be maintained for period of not less than 72 hours.

(c.) repeat test sequence (a).

Procedure: Sequence (a): Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. The test shall be run continuously without pause between cycles.

Sequence (b.): Place the specimen in the test machine and secure to the supports and loading plate. Apply the compressive load to the specimen. The total load shall be applied within a period of 10 minutes. The total load shall be maintained for period of not less than 72 hours, and within ±10% of that specified for the duration of the test.

Sequence (c.): Reduce the compressive load to P_D. Complete 3 fully reversed cycles to a peak displacement of $\pm D$. The frequency of loading shall be not less than f_L or 0.004 cyc/sec. The vertical load shall be maintained between test sequences (b) and (c).

Criteria: The System, Unit or Component response is considered to be independent of creep if:

(1.) the Average Effective Stiffness of the specimen measured in test sequence (c) is within $\pm\alpha$% of the Average Effective Stiffness measured in test sequence (a), i.e.,

$$\frac{\left| K_H^c - K_H^a \right|}{K_H^a} \leq 0.01\alpha \tag{5.21}$$

where K_H^a denotes the Average Effective Stiffness of the specimen prior to sustained compression and K_H^c denotes the Average Effective Stiffness after the sustained compression.

(2.) the Average Energy Dissipation of the specimen measured in test sequence (c) is within $\pm\beta$% of the Average Energy Dissipation measured in test sequence (a), i.e.,

$$\frac{\left| E_H^c - E_H^a \right|}{E_H^a} \leq 0.01\beta \tag{5.22}$$

where E_H^a denotes the Average Energy Dissipation of the specimen prior to the sustained compression and E_H^c denotes the Average Energy Dissipation after the sustained compression.

Special Requirements: Data Acquisition: Record the two vertical displacements (δ_1 and δ_2) of the lateral load plate a minimum of once an hour during test sequence (b).

Data Analysis: The net creep displacement (δ_c) shall be computed as follows

$$\delta_c = \delta_f - \delta_i \tag{5.23}$$

in which δ_i and δ_f denote the average vertical displacements of the lateral load plane at the beginning and end of the sustained compression sequence (b), respectively.

Report of Results: Report the net creep displacement of the Unit or Component.

5.3.11 Test for dependence on aging.

Test Designation: I.11

Purpose: Establish dependence on aging.

Sequence: Three fully reversed cycles to peak displacements of ±D, in an un-aged condition; three fully reversed cycles to peak displacements of ±D in a 50-year age accelerated condition. Tests shall be conducted with a vertical load equal to P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec.

Procedure: Place the un-aged specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. The test shall be run continuously without pause between cycles. Remove the specimen from the test machine and subject it to a suitable accelerated aging procedure. Place the aged specimen in the test machine and test as previously described.

Criteria: The System, Unit or Component response is considered to be independent of aging effects if:

(1.) the Average Effective Stiffness of the aged specimen is within ±α% of the Average Effective Stiffness of the un-aged specimen, i.e.,

$$\frac{\left| K_H^A - K_H \right|}{K_H} \leq 0.01\alpha \tag{5.24}$$

where K_H denotes the Average Effective Stiffness of the un-aged specimen and K_H^A denotes the Average Effective Stiffness of the aged specimen.

(2.) the Average Energy Dissipation of the aged specimen is within ±β% of the Average Energy Dissipation of the un-aged specimen, i.e.,

$$\frac{\left| E_H^A - E_H \right|}{E_H} \leq 0.01\beta \tag{5.25}$$

where E_H denotes the Average Energy Dissipation of the un-aged specimen and E_H^A denotes the Average Energy Dissipation of the aged specimen.

Special Requirements: Test Facility: Facilities shall be available for subjecting the specimens to a suitable age acceleration procedure.

Report of Results: Describe the age acceleration procedure. Provide references to relevant standards or materials on the procedure. Report pertinent observations or results of the age acceleration process.

5.4 Category II - Ultimate and Reserve Capacity

Note - Phase II tests should be supported, where possible, by a theory for calculating ultimate capacity of the Unit or Component, particularly if most or all of the tests are conducted on scale model specimens.

5.4.1 Ultimate Compression under Zero Lateral Load

Test Designation: II.1

Purpose: Establish the ultimate capacity in compression under zero lateral load.

Sequence: Apply a vertical compressive load to the specimen until failure is observed. The vertical load shall be applied at a constant rate.

Draft option

(a.) The specimen shall be free to deform laterally.

(b.) The specimen shall be restrained from deforming laterally.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the vertical compressive load to the specimen until failure is observed.

Criteria: Performance of the System, Unit or Component is adequate provided a minimum factor of safety of α is demonstrated under these test conditions, i.e.,

$$P_{ULT}^{C} \geq \alpha P_{D} \tag{5.26}$$

where P_{ULT}^{C} is the ultimate capacity in compression under zero lateral load and P_D is the rated capacity in compression under zero lateral load.

Draft option - α in the range 1.5 to 3.0

Special Requirements: Data Analysis: Plot the compression load (P) versus vertical displacement (δ). Plot the compression load (P) versus lateral displacement (Δ). The ultimate capacity P_{ULT}^{C} is the maximum compressive load reached during the test.

Report of Results: Report the velocity of loading, ultimate capacity in compression and compute the factor of safety. The report shall include the load-deformation plots, with P_{ULT}^{C} indicated. Provide a brief description of the observed mode(s) of failure.

Exception: The requirements of this test may be satisfied by demonstrating a load carrying capacity of αP_D in the undisplaced position, should the capacity of the specimen exceed that of the test facility, or the safety of personnel and equipment becomes in question during testing.

5.4.2 Compression in the Displaced Position

Test Designation:	II.2
Purpose:	Demonstrate capacity in compression in the displaced position.
Sequence:	Apply a vertical compressive load to the specimen while maintaining a static lateral displacement D. The vertical load shall be applied at a constant rate. The static lateral displacement shall be maintained within ±5% of D for the duration of the test.
Procedure:	Place the specimen in the test machine and secure to the supports and loading plate. Apply a vertical compressive load equal to $1.1 \times \alpha P_D$ and impose a lateral displacement D to the specimen. The order in which the load and displacement are imposed shall be chosen with due consideration of the capabilities of the test facility.
Criteria:	Performance of the System, Unit or Component is adequate provided the specimen can sustain a compressive load of αP_D in the displaced position, where P_D is the rated capacity of the Unit or Component under zero lateral load, and $F_{min} > 0 \qquad (5.27)$ where F_{min} is the minimum lateral load recorded (positive in the direction of displacement D). *Draft option - α in the range 1.1 to 3.0*
Special Requirements:	Data Analysis: Plot the compression load (P) versus vertical displacement (δ). Plot the compression load (P) versus time and the lateral load (F) versus time. Report of Results: Report the velocity of loading, displacement D, and maximum and minimum lateral loads (F_{max}, F_{min}). The report shall include the load-deformation and load-time plots. If failure is observed note the maximum compressive load applied and provide a brief description of the mode(s) of failure.

5.4.3 Ultimate Tension under Zero Lateral Load

Test Designation: II.3

Purpose: Establish the ultimate capacity in tension under zero lateral load.

Sequence: Apply a vertical tensile load to the specimen until failure is observed. The vertical load shall be applied at a constant rate

Draft option

(a.) The specimen shall be free to deform laterally.
(b.) The specimen shall be restrained from deforming laterally.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the vertical tensile load to the specimen until failure is observed.

Criteria: Performance of the System, Unit or Component is adequate provided a minimum factor of safety of α is demonstrated under these test conditions, i.e.,

$$P_{ULT}^{T} \geq \alpha P_{T} \tag{5.28}$$

where P_{ULT}^{T} is the ultimate capacity in tension under zero lateral load and P_T is the rated capacity in tension under zero lateral load.

Draft option

(a.) α in the range 1.5 to 3.0
(b.) factor of safety on the rated tensile displacement capacity
(c.) some combination of (a) and (b) that might depend on the type of Unit or Component, i.e., whether the tensile capacity is force limited or displacement limited.

Special Requirements: Data Analysis: Plot the tensile load (P) versus vertical displacement (δ). Plot the tensile load (P) versus lateral displacement (Δ). The ultimate capacity P_{ULT}^{T} is the maximum tensile load reached during the test.

Report of Results: Report the velocity of loading, ultimate capacity in tension and the displacement corresponding to the ultimate capacity in tension. The report shall include the load-deformation plots, with P_{ULT}^{T} indicated. Provide a brief description of the observed mode(s) of failure.

Exception: The requirements of this test may be satisfied by demonstrating a load carrying capacity of αP_T in the undisplaced position, should the capacity of the specimen exceed that of the test facility, or the safety of personnel and equipment becomes in question during testing.

This test may be waived for Units or Components that have been engineered and designed for zero tensile load capacity. This may be by means of an engineered mechanism or by the method of fastening the Unit or Component to the substructure and superstructure.

5.4.4 Tension in the Displaced Position

Test Designation: II.4

Purpose: Demonstrate capacity in tension in the displaced position.

Sequence: Apply a vertical tensile load to the specimen while maintaining a static lateral displacement *D*. The vertical load shall be applied at a constant rate. The static lateral displacement shall be maintained within ±5% of *D* for the duration of the test.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply a tensile load equal to $1.1\times\alpha P_T$ and impose a lateral displacement *D* to the specimen. The order in which the load and displacement are imposed shall be chosen with due consideration of the capabilities of the test facility.

Criteria:

Draft option

(a.) factor of safety on the rated tensile capacity;
(b.) factor of safety on the rated tensile displacement capacity;
(c.) some combination of (a) and (b), that might depend on whether the tensile capacity is force limited or displacement limited;
(d.) α in the range 1.1 to 3.0;
(e.) the minimum lateral load must be greater than zero.

Special Requirements: Data Analysis: Plot the tensile load (*P*) versus vertical displacement (δ). Plot the tensile load (*P*) versus time and the lateral load (*F*) versus time.

Report of Results: Report the velocity of loading, displacement *D*, and maximum and minimum lateral load (F_{max}, F_{min}). The report shall include the load-deformation and load-time plots. If failure is observed note the maximum tensile load applied and provide a brief description of the mode(s) of failure.

5.4.5 Lateral Load and Displacement Capacity under Design Vertical Load

Test Designation:	II.5
Purpose:	Demonstrate lateral load and displacement capacity under the rated vertical load capacity.
Sequence:	Apply a vertical compressive load corresponding to P_D. Impose a lateral load or displacement to the specimen until failure is observed. The vertical load shall be maintained within ±5% of P_D to the extent possible until failure or instability occurs.
Procedure:	Place the specimen in the test machine and secure to the supports and loading plate. Apply the vertical compressive load to the specimen and allow the load to stabilize. Impose the lateral load or displacement to the specimen.
Criteria:	***Draft option - criteria to be determined***
Special Requirements:	Test Facility: The lateral load system shall be under load or displacement control, or some combination thereof. Control will depend on whether the ultimate capacity of the Unit or Component is force or displacement limited. Data Analysis: Plot the lateral load (F) versus lateral displacement (Δ). Record the lateral load (F_D) corresponding to a lateral displacement of D. Plot the compression load (P) versus vertical displacement (δ). Report of Results: Report the velocity of lateral displacement, displacement D, lateral load F_D, the maximum lateral load achieved and the corresponding displacement, and the maximum lateral displacement achieved and the corresponding lateral load. The report shall include the load-deformation plots. If failure is observed note the maximum lateral displacement achieved and the corresponding lateral load and provide a brief description of the observed mode(s) of failure.

5.5 Commentary

C5.1 Introduction

C5.2 General Requirements for Pre-qualification Testing

C5.3 Category I - Preliminary Characterization

C5.3.1 Test for dependence on virgin loading

Tests have shown that Effective Stiffness and Energy Dissipation of an Isolation Unit or Component may vary considerably during the first few "virgin" cycles of loading, depending on the system. In most cases, as the system is "broken-in" and as joints and connections take full bearing the behavior stabilizes and is thereafter repeatable. Virgin loading effects are normally overcome by subjecting each Unit or Component to several cycles before installation. This is referred to as "scragging" or "running-in". In some instances the virgin loading response is recovered after a period of time.

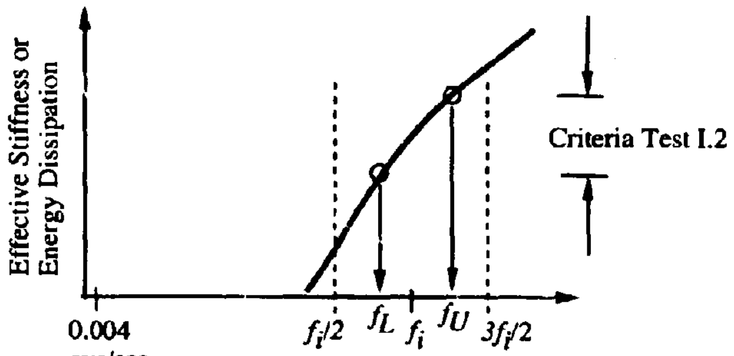
Test I.1 is designed to determine the effect of scragging or run-in on the system response. This is accomplished by comparing the Average Effective Stiffness and Average Energy Dissipation over a range of displacement increments, of a specimen that has been scragged (specimen A) to one that has not (specimen B). It is important that the specimens be new and never previously loaded in any manner for this test.

C5.3.2 Test for dependence on frequency of loading.

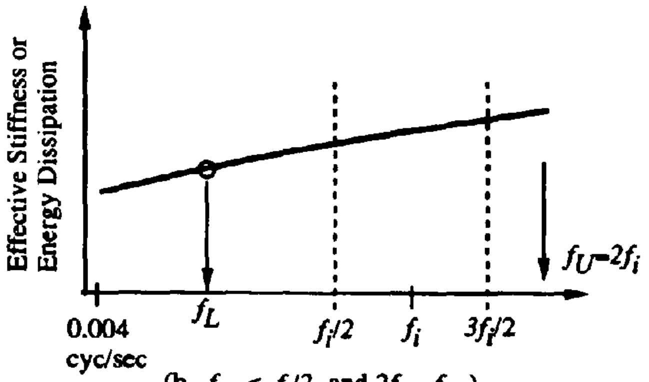
An isolated structure is designed to respond predominately at the isolation period, which is usually in the range 1.5 to 3 seconds. This corresponds to a frequency range of 0.67 to 0.33 cyc/sec. Because of the limitations of existing test equipment, however, it is usually impractical and in some cases impossible to test Isolation Units and Components at these rates. This is true in particular for full scale Units and Components. Nevertheless, the test frequency of loading must be such that the measured properties are comparable to the properties of the full scale Unit or Component at the expected frequency of response.

Test I.2 is designed to establish the effect of frequency of loading on the system response, and to determine the lower (f_L) and upper (f_U) threshold frequencies. Effective Stiffness and Energy Dissipation may or may not vary with frequency, a few different possible scenarios are illustrated in Figure 5.1. The lower and upper threshold frequencies bound the range of frequencies in which the measured response is within a certain percentage of the response measured at a frequency of f_i (the inverse of the isolated period T_i). Tests are conducted at a frequency corresponding to f_i to establish the reference properties. Tests are then conducted at frequencies lower than f_i to determine f_L, and at frequencies higher than f_i to establish f_U.

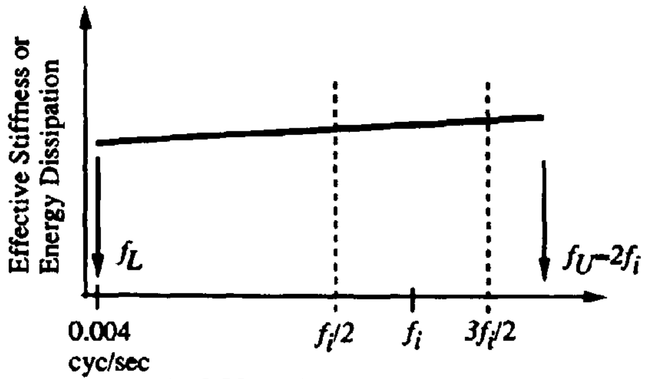
All subsequent tests outlined in the Guidelines must be conducted at a frequency of not less than f_L or 0.004 cyc/sec. If f_L and/or f_U falls within the range $f/2$ to $3f/2$ the system is said to be "dependent on frequency of load in the range of f_i". In that special case the principal test for



(a. $f_i/2 < f_L$ and $f_U < 3f_i/2$)



(b. $f_L < f_i/2$ and $2f_i = f_U$)



(c. $0.004 = f_L$ and $2f_i = f_U$)

Figure 5.1. Frequency Dependence and the Threshold Frequencies.

seismic performance (III.1, chapter 6) must be conducted at frequencies corresponding to *f/2*, *f*, and *3f/2*.

Few if any test facilities exist today that can test full size Isolation Units or Components at the actual frequency of isolation. In most cases the lower and upper bound frequencies will have to be determined using scale model specimens.

C5.3.3 Test for dependence on load cycle history

An isolated structure will undergo repeated cycles during an earthquake, cycles that will vary randomly in amplitude during the shaking. For example, a system may undergo several low amplitude cycles, followed by several high amplitude cycles, followed by several low amplitude cycles, or, visa-versa. The effect of load cycle history on the properties of the Isolation Unit or Component is to be established in Test I.3. This is addressed by comparing properties at equal increments of displacement, obtained as the displacement is increased from low to high (sequence (a)), to those obtained as the displacement is decreased from high to low (sequence (b)).

The effect of load cycle history is a complex problem; test I.3 is in no way designed to encompass the range of load cycle histories that a system is likely to be subjected. Further research is needed in order to establish the most appropriate test sequence for determining the effect of load cycle history.

C5.3.4 Test for dependence on load cycling (system degradation)

A reduction in Effective Stiffness or Energy Dissipation with load cycling is characteristic of some Isolation Units and Components. A system that behaves in this manner is commonly said to be "degrading". Although the term generally carries with it negative connotations, "degrading" systems can be safely implemented provided the extent of degradation is limiting and is fully established by test.

Test I.4 is designed to establish the extent of degradation with load cycling. Effective Stiffness and Energy Dissipation are measured at the Design Displacement and Design Vertical Load over fifty cycles. If stiffness and energy dissipation decrease or vary significantly the system is said to be dependent on load cycling.

C5.3.5 Test for dependence on vertical load

The vertical or axial load carried by an Isolation Unit or Component will vary during the life of the structure. The variation can take place relatively slowly, with changes in use and or with the redistribution of live load, or very rapidly, during strong earthquake ground shaking. The latter is particularly true for structures that are subject to large overturning moments and vertical accelerations. It is important to establish the effect or dependence of varying axial load on the system properties.

Test I.5 is designed to establish the dependence on vertical load by comparing the Average Effective Stiffness and Average Energy Dissipation for three vertical loads. The loads correspond to the rated low, design and high vertical load for the system. If the properties vary considerably the system is said to be dependent on vertical load.

C5.3.6 Test for dependence on load direction

Most Isolation Units and Components in use today are isotropic in the lateral plane, that is, the properties are the same regardless of the direction of loading. A system can be designed, however, to be non-isotropic, or, can be anisotropic not by design but as a result of the manufacturing process. Whether by design or by accident it is important to establish isotropy or anisotropy of the system. Test I.6 establishes the dependence on load direction by comparing the properties for loading in 3 directions: 0°, 45° and 90°.

C5.3.7 Test for dependence on load plane rotation

A diagram is presented in Figure 5.2 to illustrate load plane rotation. In some instances the load plane may be permanently rotated as a result of fabrication or construction error. The load plane may also rotate temporarily during an earthquake due to rotation of the column or beam-column connection to which the Unit or Component is connected. The extent to which the latter occurs will depend on the location of the Isolation System in the structure and other construction details. The system should perform as designed even with limited load plane rotation.

Test I.7 is designed to establish dependence on load plane rotation by comparing properties measured with the load plane parallel, to that obtained with the load plane rotated.

C5.3.8 Test for dependence on bilateral load

An Isolation System is subject to simultaneous lateral loading in two orthogonal directions during strong ground shaking. For the most part, however, Units and Components are tested under uni-lateral load, under the assumption that the system response is independent of bi-lateral load. It is important to establish the effect or dependence of bi-lateral loading on the system properties.

Test I.8 is designed to establish a dependence on bi-lateral loading by comparing the properties in the x direction measured under uni-lateral load, to the properties in the x direction measured under bi-lateral loading. The bi-lateral load consists of cyclic loading in the x direction while a static displacement is maintained in the y direction. The x and y displacements under bi-lateral load are such that the resultant displacement is equal to D, and the x displacement under uni-lateral loading is equal to that specified for bi-lateral loading.

This is a complex problem, and as with load cycle history, test I.8 is by no means designed to encompass the range of bilateral load cycles that a system is likely to be subjected to during its lifetime. Additional research is needed in order to establish the most appropriate test sequence for determining the effect of bi-lateral loading.

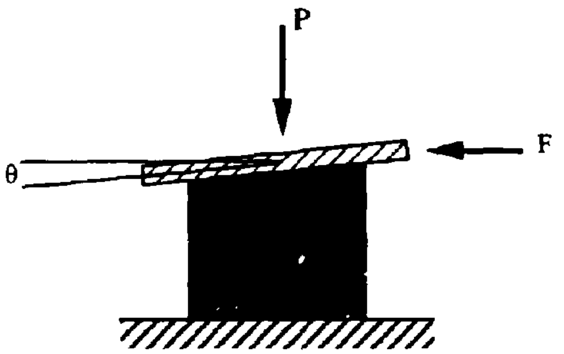


Figure 5.2. Load Plane Rotation.

C5.3.9 Test for dependence on temperature

In a typical application the Isolation System is installed near the foundation of the structure in an environment that is not temperature controlled. In the case of a bridge, the Isolation Units and Components are usually exposed directly to the weather and elements. A system can be subject to temperature variations during a typical day of up to 35° C (65° F), and equal or greater seasonal variations. There is also the potential for Isolation Systems to be installed in regions of widely varying temperature throughout the U.S. and world. In the U.S. this includes the extreme cold of Alaska to the extreme heat of southern California.

Test I.9 is designed to establish the dependence on variation in temperature by comparing the system properties at three different temperatures. The test temperatures correspond to the rated low, design and high operating temperatures for the system. Prior to testing the core of the specimen must be brought to the required temperature and held for one hour. The specimen is then installed in the test facility and tested. Note that it is not required to test the specimen in a temperature controlled chamber. The latter would be prohibitively expensive. However, core and differential temperature requirements must be satisfied at the start of lateral cycling.

C5.3.10 Test for dependence on creep

Vertical load carrying elements of an Isolation System may be prone to creep, depending on the materials used in fabrication of the Unit or Component. Creep may or may not adversely effect the seismic performance of the system. Test I.10 is designed to establish the dependence of the system response on sustained load and determine the extent of creep deformation. Effective Stiffness and Energy Dissipation are measured before and after a period (72 hours) of sustained load. Creep is the net deformation of the Unit or Component after 72 hours minus the initial elastic deformation.

If creep is found to have a significant effect on the response, or the creep deformation is significant, further testing may be needed with sustained loads of longer duration.

C5.3.11 Test for dependence on aging

An Isolation System is expected to perform as designed for the life of the structure, which is on the order of 50 years. During that time the system may be exposed to various environmental elements or factors such as:

- ozone
- oxidation
- moisture
- toxic fluids such as oil or gas
- fumes or gases
- fire
- flood

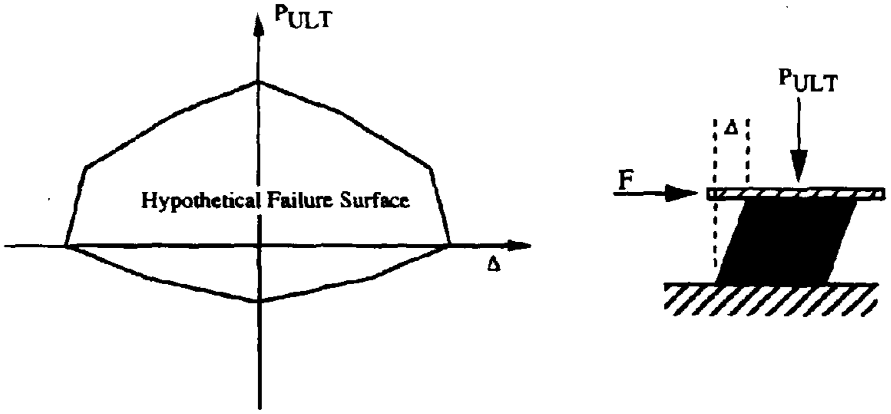
Each of these contributes to the natural process of aging of materials. In some cases steps can be taken to protect the Unit or Component from some or all of these elements. In other cases it is impossible or too expensive to provide protective systems. It is necessary, therefore, to establish how short or long term exposure to these elements effects the system response.

Test I.11 is designed to establish the dependence on aging by comparing Average Effective Stiffness and Average Energy Dissipation of an un-aged specimen, to that of a specimen that has an equivalent age of 50 years. Details of the aging process have not been specified: at the present time it does not appear as though a universal, widely applicable aging procedure exists that could be adopted for these Guidelines. It is the responsibility of the engineer to specify an appropriate procedure for the particular application. This is a complex issue that deserves research attention.

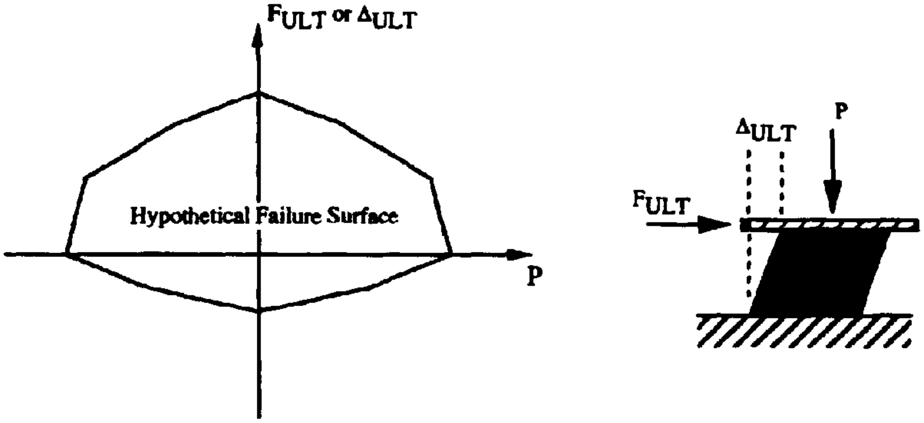
C5.4 Category II - Ultimate and Reserve Capacity

The elements of an Isolation System are structural members, just as the beams, columns and footings of a building or bridge are structural members. Failure of any member may lead to failure or collapse of the entire structure. To guard against catastrophic failure, ultimate or reserve capacity of the Unit or Component is to be established and checked against an accepted factor of safety for a given load condition.

The ideal test program would establish a failure interaction diagram for the Unit or Component. The diagram would define ultimate vertical load carrying capacity as a function of lateral displacement. Another useful curve would define ultimate lateral load or displacement capacity versus vertical load. Hypothetical diagrams of this type are shown in Figure 5.3. An accepted procedure for testing to failure in the displaced position, however, apparently does not exist. The



(a. Ultimate Vertical Load versus Lateral Displacement)



(b. Ultimate Lateral Load or Displacement versus Vertical Load)

Figure 5.3. Hypothetical Failure Interaction Diagrams.

test is difficult to conduct because of the possible interaction between the specimen and test machine, i.e., while maintaining a fixed lateral displacement the test facility may force a mode of failure that is inconsistent with the failure mechanism of an isolation system installed in a building or bridge. Furthermore, the measured ultimate capacity may not be indicative of the true capacity when installed. For these reasons, tests outlined in the Guidelines are designed to establish ultimate capacity in the zero displaced position, but only demonstrate reserve capacity in the displaced position. The issue of testing to determine ultimate capacity in the displaced position deserves research attention.

Due to the limitations of existing test facilities, and the extreme load carrying capacity of many full size Units and Components, it may be only possible to conduct Category II tests using scale model specimens.

It is highly recommended that a theory for estimating ultimate capacity be developed and verified using the Category II tests, particularly if tests are conducted only on scale model specimens.

C5.4.1 Ultimate Compression under Zero Lateral Load

For the greater part of the life of the structure the Isolation System serves the purpose of simply transferring the dead load of the superstructure to the foundation. It is important, therefore, to establish the ultimate capacity in simple compression. This is accomplished in test II.1 by loading to failure in compression. The ultimate capacity is the peak axial load reached during the test and may not coincide with the failure load. Failure in this case is defined as a complete loss of vertical load carrying capacity and may be a result of overstress, buckling, rupture or other event.

In this test an exception is permitted under which only a specified reserve capacity need be demonstrated. This may be necessary if the capacity of the specimen exceeds that of the test facility, or the safety of personnel and equipment becomes in danger.

C5.4.2 Compression in the Displaced Position

During an earthquake the Isolation System is sheared laterally, to sometimes great displacements. At the same time, the system must maintain its vertical load carrying capacity. The vertical load on Units and Components will vary rapidly during an earthquake, and can deviate substantially from the nominal Design Vertical Load. It is this state of stress of the Unit or Component that is of greatest concern to the engineer. Test II.2 is designed to demonstrate a minimum level of reserve capacity in the design displaced position.

C5.4.3 Ultimate Tension under Zero Lateral Load

It is possible to develop tension in a vertical load carrying Unit or Component, particularly in structures that are subject to very large overturning moments. When the maximum overturning moment occurs the axial load at the extremes of the base of the structure reach their maximum and minimum values. The minimum load at the one extreme can be tensile if the conditions are correct. Practically speaking, tension in a zero displaced position is highly unlikely, except in the case of extreme vertical ground acceleration. Nevertheless, test II.3 can be conducted to failure in a ordinary universal test machine and provides fundamental information on the capacity of the specimen. Furthermore, the information can be used to validate a proposed theory for ultimate capacity, which in turn may help to estimate the capacity in the displaced position.

For Units and Components that are designed to be tension free members, this test is waived. This would be true for example for an elastomeric bearing with doweled connections or a sliding bearing that has no uplift restraint.

C5.4.4 Tension in the Displaced Position

Tension in the displaced position is another critical stress state. As with compression in the displaced position, this is a difficult test to conduct. Test II.4 is designed to demonstrate a minimum level of reserve tensile capacity in the design displaced position.

C5.4.5 Lateral Load and Displacement Capacity under Design Vertical Load

Test II.5 may be thought of as the companion to test III.3. The test is designed to demonstrate reserve lateral force or displacement capacity of a Unit or Component under the nominal design vertical load. This addresses the critical state of stress sustained during strong shaking.

6. PROTOTYPE TESTS

6.1 Introduction

A total of seven test procedures are outlined in this chapter. Tests are grouped into two categories: Seismic Loads (Category III) and Non-Seismic Loads (Category IV).

Category III tests (seismic loads) are defined to establish the properties and characteristics of the System, Unit or Component under seismic load conditions. Average Effective Stiffness and Average Energy Dissipation are evaluated for a range of displacements, under load and environmental conditions determined to be relevant from Category I tests (chapter 5). Stability of the system under extreme load conditions is also evaluated.

Category IV tests (non-seismic loads) are defined to demonstrate the System, Unit or Component capacity under non-seismic loads. This includes wind load, thermal displacement, thermal cycling and braking/centrifugal forces. Only those Category IV tests relevant to the project or application are required in prototype testing.

Once again, test procedures are outlined in a standard format. Draft options are preceded or enclosed in a "Draft Option" box, as seen previously in chapter 5.

The general requirements for prototype testing are discussed in Section 6.2. Guidelines for conducting Seismic Load tests (Category III) are presented in Section 6.3. Guidelines for conducting Non-Seismic Load tests (Category IV) tests are presented in Section 6.4. Limited commentary is presented in Section 6.5.

6.2 General Requirements of Prototype Tests

Unless otherwise specified Prototype tests shall be conducted in accordance with the following:

(a) Prototype tests shall include all test outlined in Category III and applicable tests in Category IV. The schedule of prototype tests is presented in Table 6.1. Prototype tests shall also include applicable quality control tests (not addressed here).

(b) Tests shall be performed separately on two full-scale specimens of each type and size of Isolation Unit or Component.

(c) For Systems that consist of two or more principal Components, prototype tests shall be conducted simultaneously on the combined components. The assembly and connection of the tested components shall be representative of the full System detail.

(d) For Systems with unidirectional Units or Components, the full sequence of tests shall be conducted in at least one direction that is orthogonal to the unidirectional device, and in at least one direction that is 45 degrees to the unidirectional device.

(e) The nominal capacity of the specimen to be tested must be "rated" by the supplier prior to testing. Properties to be rated are presented in chapter 3.

(f) Unless otherwise specified the frequency of isolation (f_i) (i.e., inverse of the isolated period $f_i = 1/T_i$) shall be determined from the rated Horizontal Stiffness (K_H) and the Design Vertical Load (P_D); the frequency for wind load tests (f_w) shall be determined from the rated Horizontal Stiffness under Wind (K_W) and the Design Vertical Load (P_D).

(g) Properly documented prototype tests previously conducted on a Unit or Component of similar size may be used to satisfy the requirements of this section, provided:

(1) the Unit or Component is of similar design, material and construction;
(2) the largest overall dimension of the Unit or Component to be tested is within ± 10% of the same dimension of the Unit or Component previously tested;
(3) most other critical dimensions are within ±15% of the size previously tested.

(h) Pre-qualification tests must have been conducted on a System, Unit or Component of similar design, material and construction prior to prototype testing.

Table 6.1. Schedule of Prototype Tests

Category	Test	Purpose
III	III.1	Effective Stiffness and Energy Dissipation
	III.2	Stability against degradation
	III.3	Stability at Maximum Lateral Displacement
IV	IV.1	Wind load
	IV.2	Thermal displacement
	IV.3	Stability with thermal cycling
	IV.4	Braking/Centrifugal force

6.3 Category III - Seismic Loads

6.3.1 Effective Stiffness and Energy Dissipation

Test Designation: III.1

Purpose: To measure Average Effective Stiffness and Average Energy Dissipation over a range of displacement amplitudes under load and environmental conditions relevant to the application.

Sequence: All Units and Components shall be tested in accordance with basic sequence (a) described below. Additional tests shall be conducted in accordance with applicable secondary sequences (b)-(e): relevant sequences are determined based on the results of Category I tests (chapter 5).

Unless otherwise specified tests shall be conducted with a vertical load corresponding to P_D and specimen internal core temperature of T_D. Tests shall be conducted at a frequency of loading of not less than f_L or 0.004 cyc/sec; for systems dependent on the frequency of load in the range of f_i, tests shall be conducted at a frequency f_i.

(a.) ***Basic sequence*** - three fully reversed cycles at each of the displacement increments $\pm0.25D$, $\pm0.5D$, $\pm0.75D$ and $\pm1.0D$.

(b.) *For vertical load dependent systems*[3] - three fully reversed cycles to $\pm D$ with vertical loads corresponding to P_L and P_U.

(c.) ***For bilateral load dependent systems***[4] - three fully reversed cycles to $0.8D$ in the x direction, while a static displacement of $0.6D$ is continuously maintained in the y direction.

(d.) ***For systems dependent on the frequency of load***[5] ***in the range of*** f_i - three fully reversed cycles to $\pm D$ at frequencies of corresponding to $f_i/2$ and $3f_i/2$.

(e.) ***For temperature dependent systems***[6] - three fully reversed cycles to $\pm D$, conducted at internal core temperatures corresponding to T_L and T_U at the start of cyclic loading. The maximum internal and external temperature differential of the specimen at the start of each test shall be not more than 22°C (40°F).

Procedure: Sequence (a): Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load

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[3] based on pre-qualification test I.5

[4] based on pre-qualification test I.8

[5] based on pre-qualification test I.2

[6] based on pre-qualification test I.9

to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test, in the order of incremental displacement, $\pm 0.25D$, $\pm 0.5D$, $\pm 0.75D$ and $\pm 1.0D$. The test shall be run continuously without pause between cycles at a given displacement, or without pause between changes in incremental displacement.

Sequence (b): For each test series apply the full vertical load and allow the load to stabilize. Apply the lateral load for the required number of fully reversed cycles, then remove the vertical load. Sufficient time shall be allowed between tests at different vertical loads to dissipate any heat developed during the previous test. Tests shall be conducted in the order of vertical load P_L, P_D and P_U.

Sequence (c): Draft

Sequence (d): Tests shall be conducted at the frequencies specified, in the order $f_i/2$, f_i and $3f_i/2$. Sufficient time shall be allowed between tests at the different rates to dissipate any heat developed during the previous test. The vertical load shall be maintained between tests at different rates.

Sequence (e): Bring the internal core of the specimen to the specified temperature; maintain the core temperature to within ±5°C (±9°F) of that specified for a minimum of 1 hour. Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test shall be conducted at the temperatures specified in the order T_L, T_D and T_U.

Criteria: Performance of the System, Unit or Component is considered to be satisfactory if:

(1.) for each specimen the Effective Stiffness of cycle i is within ±10% of the Average Effective Stiffness for the 3 cycles of each series of tests at a given displacement increment, i.e.,

$$\frac{\left| K_H^i - K_H \right|}{K_H} \leq 0.10 \qquad (6.1)$$

where K_H^i is the Effective Stiffness of cycle i and K_H is the Average Effective Stiffness for the 3 cycles at a given displacement increment.

(2.) for two specimens A and B of a common type and size, the Average Effective Stiffness of specimen A and the Average Effective Stiffness of specimen B are within 10% of each other for the 3 cycles of each series at a given displacement increment, i.e.,

$$\frac{\left| K_H^A - K_H^B \right|}{\min\left\{K_H^A, K_H^B\right\}} \leq 0.10 \qquad (6.2)$$

where K_H^A and K_H^B is the Average Effective Stiffness of specimen A and B, respectively, and $\min\{K_H^A$ and $K_H^B\}$ denotes the minimum of K_H^A and K_H^B.

Exception: Tests of scaled specimens may be used to quantify the properties of bilateral-load, frequency and temperature dependent systems, in lieu of tests on full-scale specimens. Tests on model specimens shall be conducted with the intent of determining multiplying factors; the factors can be used to adjust the full scale test results obtained in sequence (a), to reflect the expected variation with a change in frequency, temperature or bilateral load. The scaled specimens shall be representative of full-scale prototype specimens but in no case shall be less than 1/4 full scale.

Note - it is recognized that facilities do not yet exist to test full size Units or Components under the conditions outlined in sequences (c) and (d) of the test, due to the size and load carrying capacity of the specimen. In this case scale model specimens are acceptable. Efforts should be made to correlate the scale model results to full-scale, and also to determine adjusting or multiplying factors to reflect the variation in frequency and bilateral load.

6.3.2 System Degradation

Test Designation: III.2

Purpose: To demonstrate stability against degradation under cyclic loading.

Sequence: N_D but not less than 10 fully reversed cycles to a peak displacement of $\pm D$. Tests shall be conducted with a vertical load corresponding to P_D and at a frequency of loading of not less than f_L or 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test shall be run continuously without pause between cycles.

Criteria: Performance of the System, Unit or Component is considered to be satisfactory if:

(1.) for each specimen the Effective Stiffness of cycle i is within ±20% of the 1^{st} complete cycle Effective Stiffness, for the N_D (10) cycles of the test, i.e.,

$$\frac{\left| K_H^i - K_H^1 \right|}{K_H^1} \leq 0.20 \tag{6.3}$$

in which K_H^1 and K_H^i denote the 1^{st} cycle and i^{th} cycle Effective Stiffness, respectively;

(2.) for each specimen the Energy Dissipation of cycle i is at least 80% of the 1^{st} complete cycle Energy Dissipation for the N_D (10) cycles of the test, i.e.,

$$E_H^i \geq 0.8 E_H^1 \tag{6.4}$$

in which E_H^1 and E_H^i denote the 1^{st} cycle and i^{th} cycle Energy Dissipation, respectively.

6.3.3 Stability at Maximum Displacement

Test Designation: III.3

Purpose: Demonstrate stability at maximum and minimum vertical loads under extreme lateral displacement.

Draft option

Sequence: **Specimens shall be tested statically under vertical loads corresponding to P_L and P_U while maintaining a lateral displacement of D_{TM}. The full vertical load shall be maintained for a minimum of one minute. The rate of vertical loading shall be such that full load is reached within two minutes of the start of the test. The lateral displacement shall be maintained within ±5% of that specified for the duration of the test.**

Procedure: **Place the specimen in the test machine and secure to the supports and loading plate. Apply the vertical compressive load to the specimen. Apply a lateral load sufficient to produce a displacement of D_{TM}.**

or

Sequence: **One fully reversed cycle to a peak displacement of $\pm D_{TM}$, with vertical loads corresponding to P_L and P_U. The frequency of lateral loading shall be less than 0.004 cyc/sec.**

Procedure: **Place the specimen in the test machine and secure as necessary to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required one complete cycle.**

Criteria: Performance of the System, Unit or Component is adequate provided the full vertical load is maintained for the duration of the test and there is no observable damage to the specimen (e.g., cracking, fracture, rupture, debonding, or other such event).

Special Requirements: <u>Data Analysis</u>: Formal analysis of data as described in Chapter 4 is not required under this test.

<u>Report of Results:</u> Report the vertical loads P_L and P_U, and the lateral displacement. Describe observable damage or other indications of instability.

6.4 Category IV - Non-seismic Loads

6.4.1 Wind load

Test Designation: IV.1

Purpose: Demonstrate capacity under repeated loading to the design wind load.

Sequence: Twenty fully reversed cycles to a peak lateral force of $\pm F_W$. Tests shall be conducted with a vertical load corresponding to P_D and at a frequency of loading not less than f_w or 0.004 cyc/sec.

> **Draft option**
>
> ***For degrading systems* (based on pre-qualification test I.4) - two thousand cycles to a peak displacement of _____ with a vertical load corresponding to P_D and at a frequency of loading of not less than 0.004 cyc/sec. Repeat the standard test sequence for wind load.**

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required twenty fully reversed cycles of the test. The test shall be run continuously without pause between cycles.

Criteria: Performance of the System, Unit or Component is satisfactory provided vertical load carrying capacity is maintained for the duration of the test, the displacement corresponding to F_W is within acceptable limits and there is no visible damage to the specimen following the test.

Special Requirements: Data Analysis: Compute the Effective Stiffness for cycles 1, 2, 5, 10 and 20 corresponding to load F_w according to eq.(4.3).

Reporting of Results: Report the design wind load (F_w), vertical load and frequency of loading (f_w). Report Effective Stiffness for cycles 1, 2, 5, 10 and 20, listed by cycle number in increasing order. Report observable damage or other indications of instability.

6.4.2 Thermal Displacement

Test Designation: IV.2

Purpose: Demonstrate capacity under real-time thermal displacement and establish load corresponding to thermal displacement.

Sequence: Three fully reversed cycles to a peak displacement of ±D_r. Tests shall be conducted with a vertical load corresponding to P_D. The frequency of loading shall correspond to one cycle per twenty four hours.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. The test shall be run continuously without pause between cycles.

Criteria: Performance of the System, Unit or Component is satisfactory provided vertical load carrying capacity is maintained for the duration of the test, the force corresponding to D_t is within acceptable limits and there is no visible damage to the specimen following the test.

Special Requirements: Data Acquisition: Record the lateral load a minimum of once an hour during lateral cycling.

Data Analysis: Formal analysis as described in Chapter 4 is not required for this test.

Reporting of Results: Report the design thermal displacement (D_t), the load corresponding to the thermal displacement and vertical load. Plot the lateral load versus time, and the lateral load versus displacement for the duration of the test. Report observable damage or other indications of instability.

6.4.3 Stability with Thermal Cycling

Test Designation: IV.3

Purpose: Demonstrate capacity under repeated loading to the design thermal displacement.

Sequence: (a.) 3 fully reversed cycles to a peak displacement of $\pm D$. The test shall be conducted with a vertical load of P_D. The frequency of loading shall be not less than f_L or 0.004 cyc/sec;

(b.) 10,000 fully reversed cycles to a peak displacement of $\pm D_r$. Tests shall be conducted with a vertical load corresponding to P_D. The frequency of loading shall be sufficiently slow so as to not generate excessive heat. The environment (i.e., areas surrounding and including sliding interfaces, moving parts, critical fixtures, etc.) shall include dirt, debris, deicing salts and other realistic contaminants that are likely to occur over a 50 year time span for exposed systems;

(c.) repeat sequence (a).

Procedure: Sequences (a) and (c): Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required 3 fully reversed cycles of the test. Remove the vertical load. The test shall be run continuously without pause between cycles.

Sequence (b): Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test may be stopped temporarily as needed but vertical load shall be maintained at all times.

Criteria: Performance of the System, Unit or Component is satisfactory provided vertical load carrying capacity is maintained and there is no visible damage to the specimen following test sequence (b), and

(1.) the Average Effective Stiffness of the specimen measured in test sequence (c) is within $\pm\alpha$% of the Average Effective Stiffness measured in test sequence (a), i.e.,

$$\frac{\left| K_H^c - K_H^a \right|}{K_H^a} \le 0.01\alpha \qquad (6.5)$$

where K_H^a denotes the Average Effective Stiffness of the specimen prior to the 10,000 cycles and K_H^c denotes the Average Effective Stiffness after the 10,000 cycles.

(2.) the Average Energy Dissipation of the specimen measured in test sequence (c) is within $\pm\beta$% of the Average Energy Dissipation measured in test sequence (a), i.e.,

$$\frac{\left| E_H^c - E_H^a \right|}{E_H^a} \le 0.01\beta \qquad (6.6)$$

where E_H^a denotes the Average Energy Dissipation of the specimen prior to the 10,000 cycles and E_H^c denotes the Average Energy Dissipation after the 10,000 cycles.

Draft option - α and β in the range 10 to 30

Special Requirements: Data Analysis: For test sequence (b) compute the Effective Stiffness corresponding to displacement D_t according to eq.(4.3). Compute the stiffness a minimum of every two hundred cycles.

Reporting of Results: For test sequence (b) report the displacement D_t, vertical load and frequency of loading. Report Effective Stiffness for every two hundred cycles, listed by cycle number in increasing order. Report observable damage or other indications of instability.

Exception: Scale model specimens are acceptable provided they are not less than 1/4 full scale and are representative of the full scale prototype. Specimens cut from full size Units or Components are acceptable; the size and shape of the specimen is to be determined by the engineer of record.

6.4.4 Braking/Centrifugal

Test Designation: IV.4

Purpose: Demonstrate capacity under repeated loading to the design braking/centrifugal load.

Sequence: Two thousand fully reversed cycles to a peak lateral force of $\pm F_B$. Tests shall be conducted with a vertical load corresponding to P_D. The frequency of loading shall be sufficiently slow so as to not generate excessive heat, but in no case shall the frequency of loading be less than 0.004 cyc/sec.

Procedure: Place the specimen in the test machine and secure to the supports and loading plate. Apply the full vertical load to the specimen and allow the load to stabilize. Apply the cyclic lateral load to the specimen for the required number of fully reversed cycles of the test. The test may be stopped temporarily as needed but vertical load shall be maintained at all times.

Criteria: Performance of the System, Unit or Component is satisfactory provided vertical load carrying capacity is maintained for the duration of the test, the displacement corresponding to F_B is within acceptable limits and there is no visible damage to the specimen following the test.

Special Requirements: Data Analysis: Compute the Effective Stiffness corresponding to load F_B according to eq. (4.3). Compute the stiffness for the first ten cycles and every fortieth cycle thereafter.

Reporting of Results: Report the lateral load F_B, vertical load and frequency of loading. Report Effective Stiffness for the first ten cycles and every fortieth cycle thereafter, listed by cycle number in increasing order. Report observable damage or other indications of instability.

Exception: Scale model specimens are acceptable provided they are not less than 1/4 full scale and are representative of the full scale prototype.

6.5 Commentary

C6.3 Category III - Seismic Loads

Category III tests are similar to that outlined in the 1991 *Uniform Building Code* for prototype testing.

C6.3.1 Effective Stiffness and Energy Dissipation

The purpose of test III.1 is to evaluate the Average Effective Stiffness and Average Energy Dissipation of the System, Unit or Component over a range of displacements, under load and environmental conditions that were determined to be relevant for the System, based on the results of Category I testing. All specimens are tested under basic sequence (a) described in the guidelines. Relevant sequences (b) through (e) are added to the test procedure as necessary. Sample test procedures are described below.

Consider first a system that is dependent on vertical load, as established by test I.5. Testing would be required in accordance with sequences (a) and (b). Tests would be conducted at $\pm 0.25D$, $\pm 0.50D$, $\pm 0.75D$ and $\pm 1.0D$, with a vertical load of P_D, and additionally at $\pm 1.0D$ with vertical loads of P_L and P_U. A total of 18 cycles would be required.

Consider next a system that is dependent on frequency of load in the range of f_i and dependent on temperature, as determined in accordance with tests I.2 and I.9, respectively. Testing would be required in accordance with sequences (a), (d) and (e). Tests would be required at $\pm 0.25D$, $\pm 0.50D$, $\pm 0.75D$ and $\pm 1.0D$ at a frequency of f_i and temperature T_D. Additional tests would be required at $\pm 1.0D$ at frequencies of $f_i/2$ and $3f_i/2$ and temperature T_D, and at $\pm 1.0D$ at a frequency of f_i and at core temperatures of T_L and T_U. A total of 24 cycles would be required.

The performance criteria address two critical issues: stability of Effective Stiffness over three cycles and repeatability of Average Effective Stiffness between two specimens.

C6.3.2 System Degradation

Test III.2 is comparable to test I.4 with the exception of the number of required cycles. Some degradation is acceptable, provided the properties stabilize after a certain number of cycles. A system that continues to degrade in performance is not acceptable.

C6.3.3 Stability at Maximum Displacement

Test III.3 is similar in principle to test II.5 in Category II. During an earthquake the Isolation System will be required to sustain varying levels of axial load, simultaneously with large lateral displacements. The test is designed to demonstrate stability of the system in the displaced position.

C6.4 Category IV - Non-Seismic Loads

In this context, a non-seismic load may be defined as any live load that is not a result of earthquake ground shaking. The primary non-seismic load for buildings is wind. For bridges it includes wind, thermal displacement, thermal cycling and braking/centrifugal forces.

It was not the intention here to include all possible non-seismic loads. The four mentioned are the most important and address the non-seismic loads of the largest percentage of structures currently, or likely be isolated in the future. Obviously not all tests listed in this phase are applicable to all structures. The engineer is responsible for selecting those tests that are appropriate for the application.

C6.4.1 Wind Load

The characteristics of the response of an Isolation System under wind load can be quite different from the response under seismic load. The initial stiffness of the Isolation System is designed to be high to resist wind load, and under these relatively low magnitude loads the response may be nearly perfectly elastic. This is in contrast to the highly nonlinear behavior expected during an earthquake. Test IV.1 is designed to demonstrate the functionality of the system under multiple cycles at the design wind load. This requires that the displacement due to wind load be within acceptable limits and there be no significant residual displacement.

The wind load test is to be conducted at a frequency (f_w) corresponding to the expected frequency of response for wind loading. Frequency f_w is computed based on the effective stiffness under wind load K_w and the rated Design Vertical Load. A draft option is proposed to measure the stiffness under wind load before and after 2000 cycles for systems that degrade.

C6.4.2 Thermal Displacement

Thermal displacements can be significant in bridges because of long spans and their direct exposure to the sun. A bridge will experience daily, as well as seasonal variations in temperature. A bridge will experience thousands of thermal cycles throughout its life. Thermal cycling is not exclusive to bridges, however, and should be checked for any structure that is subject to daily or seasonal temperature variations and has relatively large span distances between supports.

Test IV.2 is designed to demonstrate capacity under real-time thermal displacement and establish the peak load corresponding to the rated thermal displacement. A very slow rate of loading is specified to simulate an actual 24 hour thermal cycle. Creep may have a significant affect on the peak load and therefore, it is important that the test be conducted at the very slow rate.

C6.4.3 Stability with Thermal Cycling

In bridge applications the Isolation System must be capable of withstanding thousands of thermal cycles without a significant degradation in seismic performance. Test IV.3 is designed to demonstrate adequate performance after thermal cycling. The test is modeled after the California Department of Transportation (CALTRANS), "Groaner" test, that is required of all Isolation

Systems installed in bridges in California. Effective Stiffness and Energy Dissipation are measured before and after 10,000 cycles to the rated Thermal Displacement. As it may adversely affect the performance of the system and promote degradation, the environment in and around the Unit or Component is to be contaminated with dirt and debris, to the extent that it would be expected to collect in the actual application.

It is important to monitor the temperature of the specimen during testing to ensure that excessive heat is not being generated. Excessive heat may be uncharacteristic of the behavior expected in the field and may result in poor performance. If excessive heat is being generated the frequency of loading should be reduced or the test should be temporarily stopped until the heat is dissipated.

C6.4.4 Braking/Centrifugal

Bridges are also subject to live loads due to traffic. Two effects that result in lateral loads at the pier or abutment include braking, and for curved or banked bridges, centrifugal forces. A bridge may be subject to thousands of cycles of these forces during its lifetime. Test IV.4 is designed to demonstrate capacity of the system under these lateral loads. It is sufficient to test only at a lateral load F_B that is the greater of the rated braking or rated centrifugal forces. Also, as with test IV.3, the temperature of the specimen should be monitored to ensure that excessive and uncharacteristic heat is not generated.

7. RESEARCH NEEDS IN TESTING OF SEISMIC ISOLATION SYSTEMS

7.1 Introduction

The concept of seismic isolation have been around since near the turn of the century (Buckle and Mayes, 1990), at least as reported or eluded to in the literature and patent records. However, the technology really began to emerge in the late 60's and early 70's as a result of advances in materials processing and computer analysis. Since then, tremendous progress has been made on both the experimental and analytical fronts, and the technology is now being used with confidence. Nevertheless, there are issues which remain to be resolved and require additional research effort. The issues which pertain specifically to testing of Isolation Units and Components are described in the sections to follow. These issues need to be resolved and the results incorporated into a revised set of guidelines.

7.2 Load Cycle History

The need for additional research or the effects of load cycle history was briefly mentioned in the commentary of test I.3. A structure supported on elastomeric isolation bearings is designed to response predominately at the isolation period, however, due to the random nature of earthquake ground motion the displacement amplitude of the isolation system varies with time. The amplitude *and* effective frequency of response can vary for structures supported on sliding or hybrid isolation systems. Nevertheless, the properties of the system should be stable or predictable even under varying load conditions. The manner and extent to which system properties vary for different load histories is of concern.

Work has been done recently on the effect of load history on elastomeric isolation bearings (Aiken, Clark and Kelly, 1992). Additional work is required along these lines and should be expanded to include a variety of systems. One or more standard load cycle histories should be developed that would establish history dependence. Standard load histories would also facilitate the direct comparison of different systems. Results of this research should be incorporated into Category I tests described in these Guidelines.

7.3 Bilateral Load

During an earthquake an Isolation System is subject to lateral loads in two orthogonal directions. The system responds by deforming simultaneously in two orthogonal directions, and in some cases in a torsion mode. The majority of tests conducted to date by researchers, however, have been uniaxial. The effect of bilateral load on stiffness, yield level and energy dissipation remains to be investigated for many systems. The results may prove to be insignificant, at least as related to the design process, but nevertheless should be examined.

Very limited data is available from bi-lateral load tests of Isolation Units and Components (Nagarajaiah, et al , 1989). Additional research is needed and should be expanded to include a variety of Isolation Systems. Research should focus on evaluating the force-deflection behavior and energy dissipation characteristics for a variety of bilateral load cases. Results should be interpreted with design and modeling in mind. As with load cycle history, a standard bilateral load history should be developed that would establish bilateral load dependence.

7.4 Aging

The life expectancy of a typical structure today is on the order of 50 years. This would be true for an isolated structure as well. The question of greatest concern to the owner, architect and engineer of an isolated structure is: Will the system perform as designed for an earthquake that occurs in the structure's 50th year? This is a question of aging of materials for most systems. For others there is additional concern over "dwell" time, i.e., the period between earthquakes during which there is no movement at all across the isolation interface.

To establish the effect of aging, one approach would be to build a complete prototype system, test, wait 50 years and then retest. This of course is impractical. The alternative is to use an accelerated aging technique that would reduce the time required by orders of magnitude and produce an equivalent aging effect. There are several ASTM standards for accelerated aging that are widely used by other industries. These standards, however, were not developed with seismic isolation in mind and for that reason their applicability remains in question. In addition, many of these standards use small samples or simply test materials and not complete components parts. Research should be undertaken to (1) critically review existing aging procedures and determine their applicability to isolation systems, (2) develop a new, or modify an existing standard aging test which would be applicable to all types of Isolation Units and Components, (3) develop guidelines and procedures for storing duplicate Units and Components near the installed isolation system, that can be tested at a later date in order to verify aging effects and the accelerated aging process. Results of this research should be incorporated into Category I tests described in these guidelines.

7.5 Viscous and Hysteretic Damping

Energy Dissipation of the Isolation System is often expressed in terms of percent equivalent viscous damping. One reason for this is because design and modeling of an isolated structure is usually based on a simple viscous damped single-degree-of-freedom oscillator. The Energy Dissipation in most systems, however, is judged to be best represented by some combination of viscous and hysteretic damping. Ideally, the two components of damping would be evaluated independently by experiment and then used in a more sophisticated model of the isolated structure. Research is needed to develop an appropriate test procedure for evaluating the viscous and hysteretic components of damping of an isolation system.

7.6 Delamination/Debonding in Elastomeric Isolation Bearings

Delamination or debonding of the steel and rubber layers in an elastomeric isolation bearing is a serious problem that can lead to failure. Delamination is an issue related to quality of manufacture and quality control testing and therefore is not specifically addressed in these guidelines. This issue is still of concern and raises the question: What effect does debonding have on the performance of the system and how can it best be detected before the Unit is installed?

Presently, quality control testing of laminated elastomeric bearings generally includes a 12 hour sustained compression test. The test has been shown to provide a reasonable check on debonding. The major drawback of the test is the time required. For example, for a large building which might require on the order of 200 bearings, QC testing would take 125 days, using a single test machine running 24 hours a day. Research is needed to develop a faster and more efficient technique for detecting delamination and debonding. One technique that has shown promise, based on the results of numerical studies, is a lateral load test under zero or small compressive load (personal communication, Buckle 1993). Although it is a difficult test to conduct with some systems, another possibility is a direct tension test. Research is needed to investigate these and other techniques experimentally, and to develop a nonintrusive/nondestructive technique.

7.7 Ultimate Capacity

Very few isolation units and components have been tested to complete failure, particularly full scale specimens. One reason for this is the extremely large load carrying capacity of most Units and Components and the limitations of existing test facilities. Consequently, the true factor of safety of many of these systems remains an unknown.

Research is needed to investigate the ultimate load carrying capacity of a variety of Isolation units and Components. The research should include tests on full scale and scale model specimens, and include both vertical and lateral ultimate capacity. Results of the full scale and scale model tests should be correlated so that future tests can be conducted on smaller, less expensive specimens. Failure load models should be refined or developed for these systems and the results verified using the experimental results. Results of this research should be incorporated into Category II tests described in these guidelines.

8. SUMMARY

Existing codes for seismic isolation require prototype and quality control tests of every isolation system designed and installed in the United States. At the present time, however, standards do not exist for conducting these tests. Consequently, test results are subject to unknown variability. This report represents the first step in the effort to develop standards for testing of seismic isolation systems.

Guidelines have been presented for conducting pre-qualification and prototype tests. Pre-qualification tests, although not required at this time by the codes, are generally conducted in some form during the development stage of a new system. The information obtained from these preliminary tests is essential for conducting all subsequent prototype tests. Therefore, guidelines have been included for these critical preliminary tests.

The guidelines (pre-standard) presented will ensure the systematic characterization of isolation system properties, allow for direct comparison of different systems, and prescribe a minimum level of acceptable performance of the system in service. The guidelines should also facilitate development of high quality systems and instill a certain level of confidence in the installed systems. These guidelines are considered draft and are subject to change, upon review by a larger group of experts involved in the design and construction of seismically isolated structures.

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APPENDIX A. SYMBOLS AND NOTATION

The symbols and notation below apply to the guidelines outlined in this document:

D - Design Displacement;

D_c - Creep displacement;

D_{TM} - Total maximum displacement;

D_t - Thermal displacement;

D_V - Vertical displacement;

E_H - Average Energy Dissipation over *n* cycles;

$E_H^{(\ )}$ - Average Energy Dissipation over *n* cycles for different specimens or for varied conditions as outlined in the test, ( ) - A,B,a,b,O,P,R or T;

E_{H_i} - Energy Dissipation for cycle *i*, e.g., E_{H_1} is the 1st cycle Energy Dissipation;

f_i - isolation frequency and the inverse of the isolation period (T_i);

f_L, f_U - threshold frequencies that define the range of frequencies in which the measured response is within a certain percent of the response at a frequency of f_i;

f_W - frequency for wind load test;

F - lateral load;

F^+, F^- - maximum lateral load ($max\{F\}$) for a single cycle, minimum lateral load ($min\{F\}$) for a single cycle;

F_B - lateral load due to braking or centrifugal forces;

F_W - wind load;

F_x - lateral load in the x direction;

F_x^+, F_x^- - maximum lateral load in the x direction for a single cycle, minimum lateral load in the x direction for a single cycle;

F_y - lateral load in the y direction;

K_H - Average Effective Stiffness over *n* cycles;

$K_H^{(\ )}$ - Average Effective Stiffness over *n* cycles for different specimens or for varied conditions as outlined in the test, ( ) - A,B,a,b,O,P,R or T;

K_{H_i} - Effective Stiffness for cycle *i*, e.g., K_{H_1} is the 1st cycle Effective Stiffness;

K_V - Effective Vertical Stiffness at the Design Vertical Load;

K_W - Effective Stiffness at the Design Wind Load;

N_D - degradation cycle limit;
N_t - thermal cycle limit;
P - vertical load;
P_L - low vertical load;
P_D - design vertical load;
P_T - tensile load;
P_U - high vertical load;
P_{ULT}^{C} - ultimate capacity in compression under zero lateral load;
P_{ULT}^{T} - ultimate capacity in tension under zero lateral load;
T_i - isolation period;
T_L - low temperature;
T_D - design temperature;
T_U - high temperature;
Δ - lateral displacement;
Δ^+,Δ^- - maximum lateral displacement ($max\{\Delta\}$) for a single cycle, minimum lateral displacement ($min\{\Delta\}$) for a single cycle;
Δ_1,Δ_2 - measured lateral displacements;
Δ_x - lateral displacement in the x direction;
Δ_{x1},Δ_{x2} - measured lateral displacement in the x direction;
Δ_x^+,Δ_x^- - maximum lateral displacement in the x direction for a single cycle, minimum lateral displacement in the x direction for a single cycle;
Δ_y - lateral displacement in the y direction;
Δ_{y1},Δ_{y2} - measured lateral displacement in the y direction;
δ - vertical displacement;
δ_1, δ_2 - measured vertical displacements.
θ^+, θ^- - lateral load plane rotation;

APPENDIX B. GLOSSARY OF TERMS

The definitions below apply to the guidelines outlined in this document:

Accuracy	A "generic concept of exactness related to the closeness of agreement between the average of one or more test results and an accepted reference value" (ASTM E177-90a).
Average Effective Stiffness	The average of the Effective Stiffnesses over a number of cycles for a specified set of test conditions.
Average Energy Dissipation	The average of the Energy Dissipation over a prescribed number of cycles for a specified set of test conditions.
Design Displacement	The minimum lateral seismic displacement at the center of rigidity required for design of Isolation System, exclussive of additional displacement due to torsion.
Effective Stiffness	Lateral force in the Isolation System, Unit or Component, divided by the lateral displacement.
Energy Dissipation	The area enclosed by a single hysteresis loop.
Hysteresis Loop	A curve generated by plotting force versus displacement, which under cyclic loading generally forms a loop.
Hysteretic Damping	A damping mechanism which is proportional to displacement and in-phase with velocity, but is independent of the frequency of response.
Isolation System	The collection of structural elements that includes all individual Isolation Units, Components, other structural members and connections that transfer force between the substructure and superstructure and form the isolation interface. The Isolation System also includes any other lateral restraint system that is utilized to resist non-seismic loads, or serves as an ultimate restraint device.
Isolation Unit	A flexible structural element of the Isolation System which permits large lateral deformations under seismic excitation. An Isolation Unit provides all restoring force and damping attributes in a single integrated structural element. An Isolation Unit may also be used as a structural member for non-seismic loads.
Isolation Component	A flexible structural element of the Isolation System which permits large lateral deformations under seismic excitation. An Isolation Component provides primarily a restoring force or damping attribute in a single structural element. An Isolation Component may also be used as a structural member for non-seismic loads. An Isolation Component in and of itself cannot fulfill the restoring force and energy dissipation properties required of the System.

Isolation Interface	The boundary between the upper portion of the structure (superstructure) which is isolated, and the lower portion of the structure (substructure) which is not isolated.
Precision	A "generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated" (ASTM E177-90a).
Rate of Load	The velocity of the actuator or load fixture expressed as distance per unit time.
Frequency of Load	The number of full cycles of loading completed per unit time, usually expressed as cycles/sec.
Viscous Damping	A damping mechanism which is proportional to velocity and is dependent on the frequency of response.
Uncertainty	A statistical estimate of the error limits of a quantity obtained from a calibration equation (ASTM E74-91).

APPENDIX C. TEST FACILITIES

Schematic drawings of five test facilities are presented in this Appendix. This includes facilities owned and/or operated by:

Earthquake Engineering Research Center, University of California at Berkeley, Richmond, California.

Dynamic Isolation Systems, Inc., Berkeley, Califonia.

Earthquake Protective Systems, Inc., San Francisco, California.

Bridgestone Corporation, Yokohama, Japan.

Oiles Corporation, Fujisawa, Japan.

The facilities range in capacity and capability and all except one were built to test a single Isolation Unit. The facility owned by Dynamic Isolation Systems, Inc. was built to test Isolation Units in a dual configuration. The drawings are presented simply for reference and to illustrate the diversity of test facilities in use today.

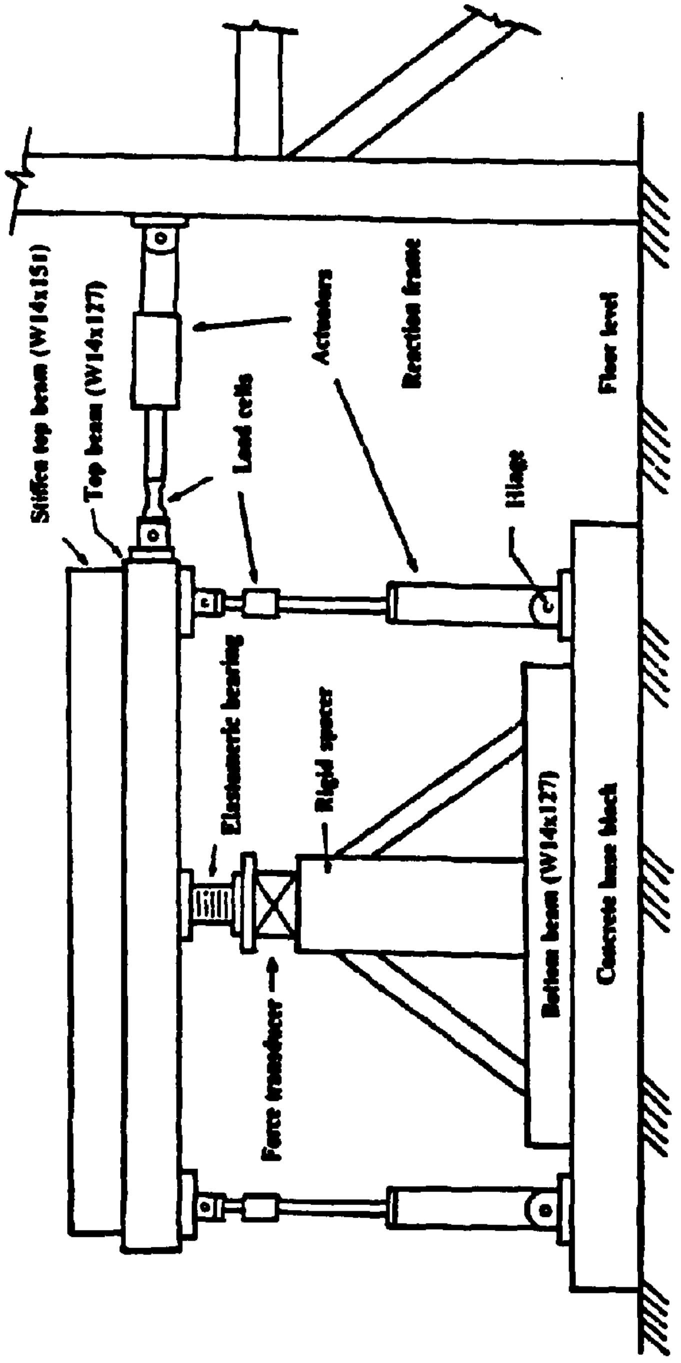

Figure C.1 Isolation Unit Test Facility, Earthquake Engineering Research Center, University of California at Berkeley, Richmond, California

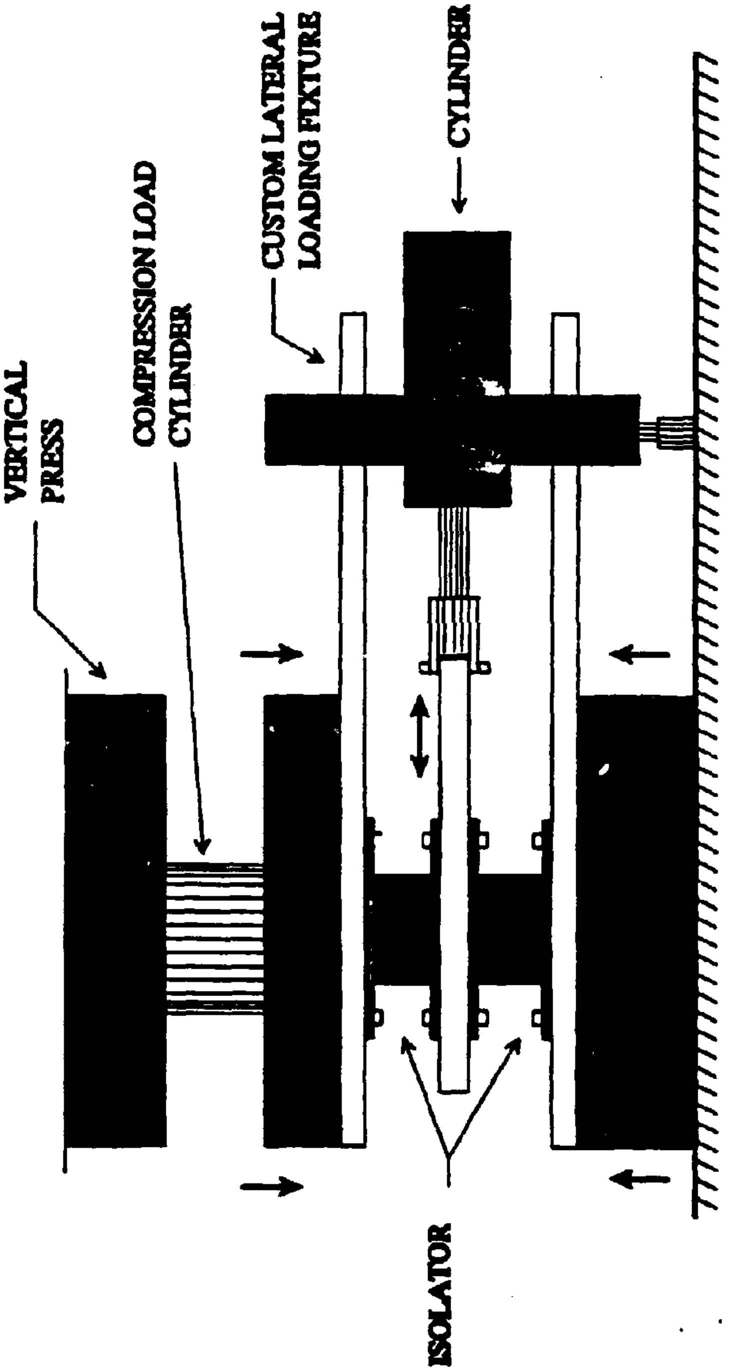

Figure C.2 Isolation Unit Test Facility, Dynamic Isolation Systems, Inc., Berkeley, California

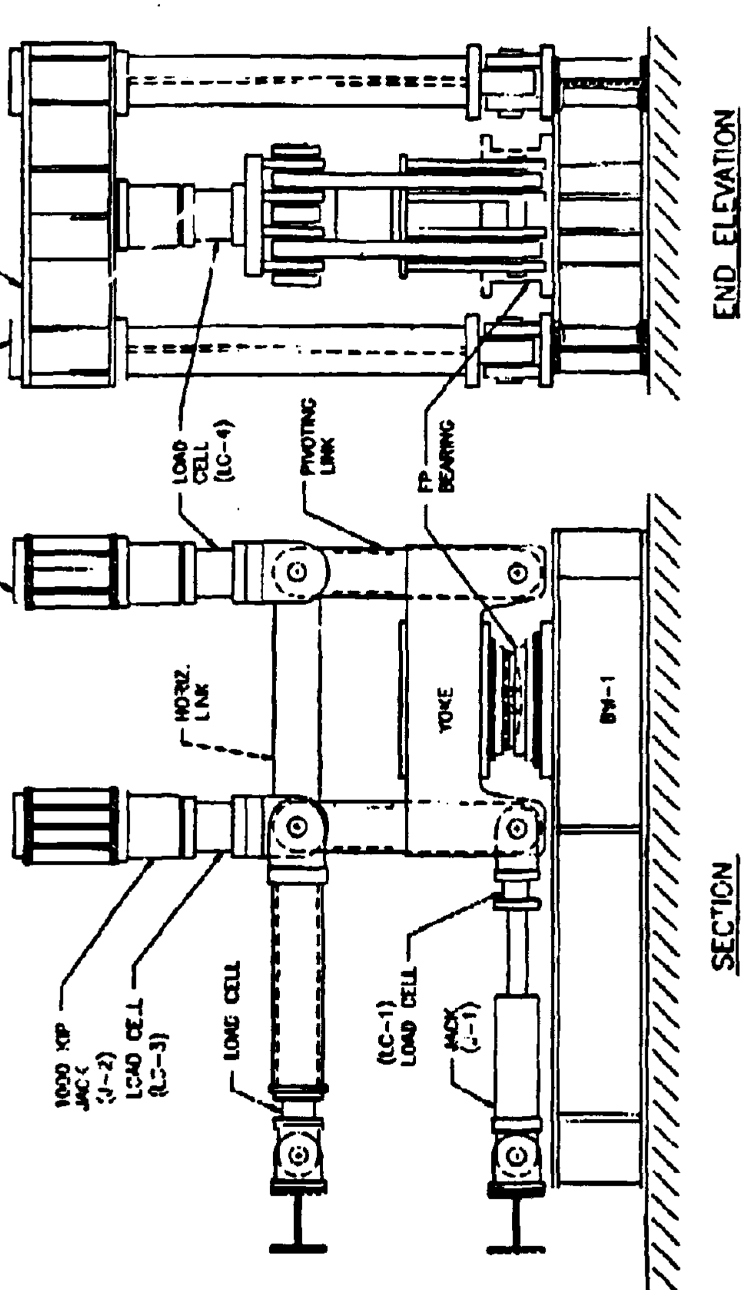

Figure C.3 Isolation Unit Test Facility, Earthquake Protective Systems, Inc., San Francisco, California

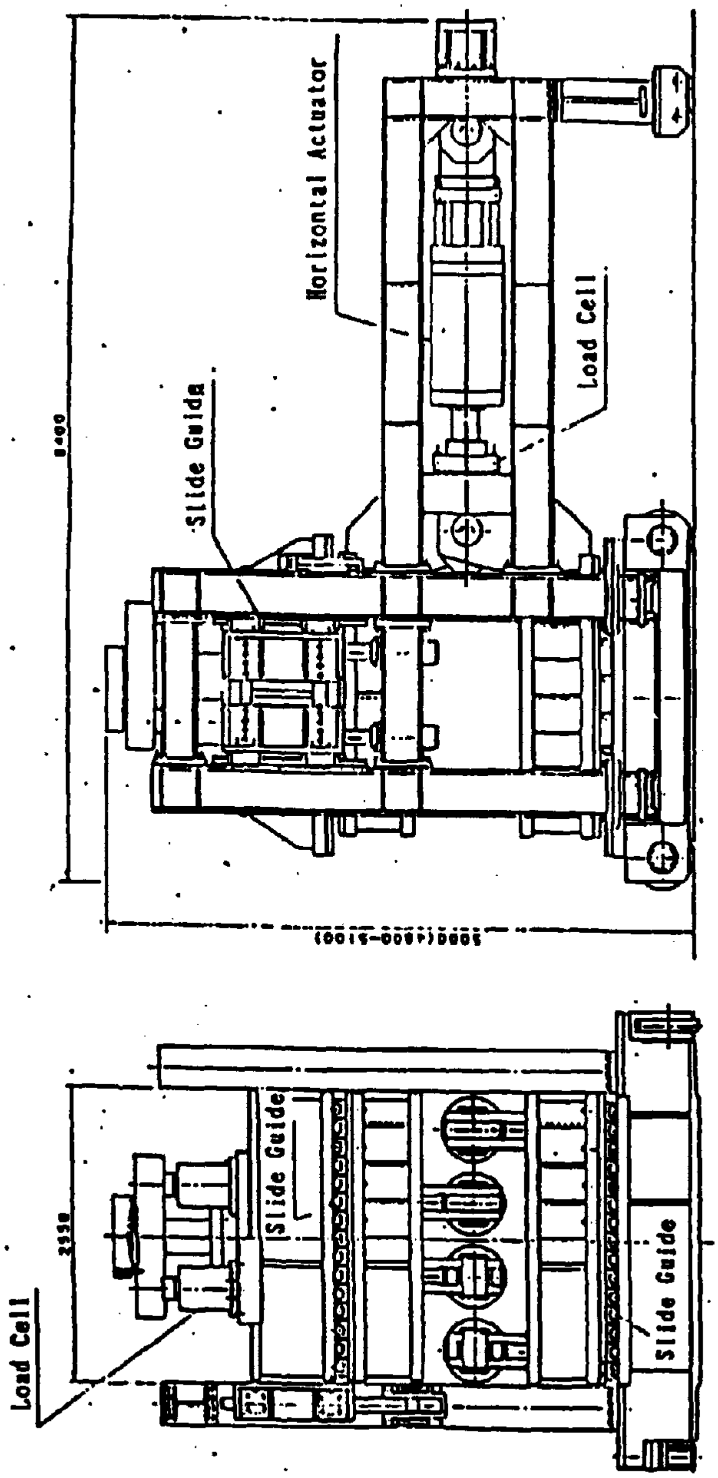

Figure C.4 Isolation Unit Test Facility, Bridgestone Corporation, Yokohama, Japan

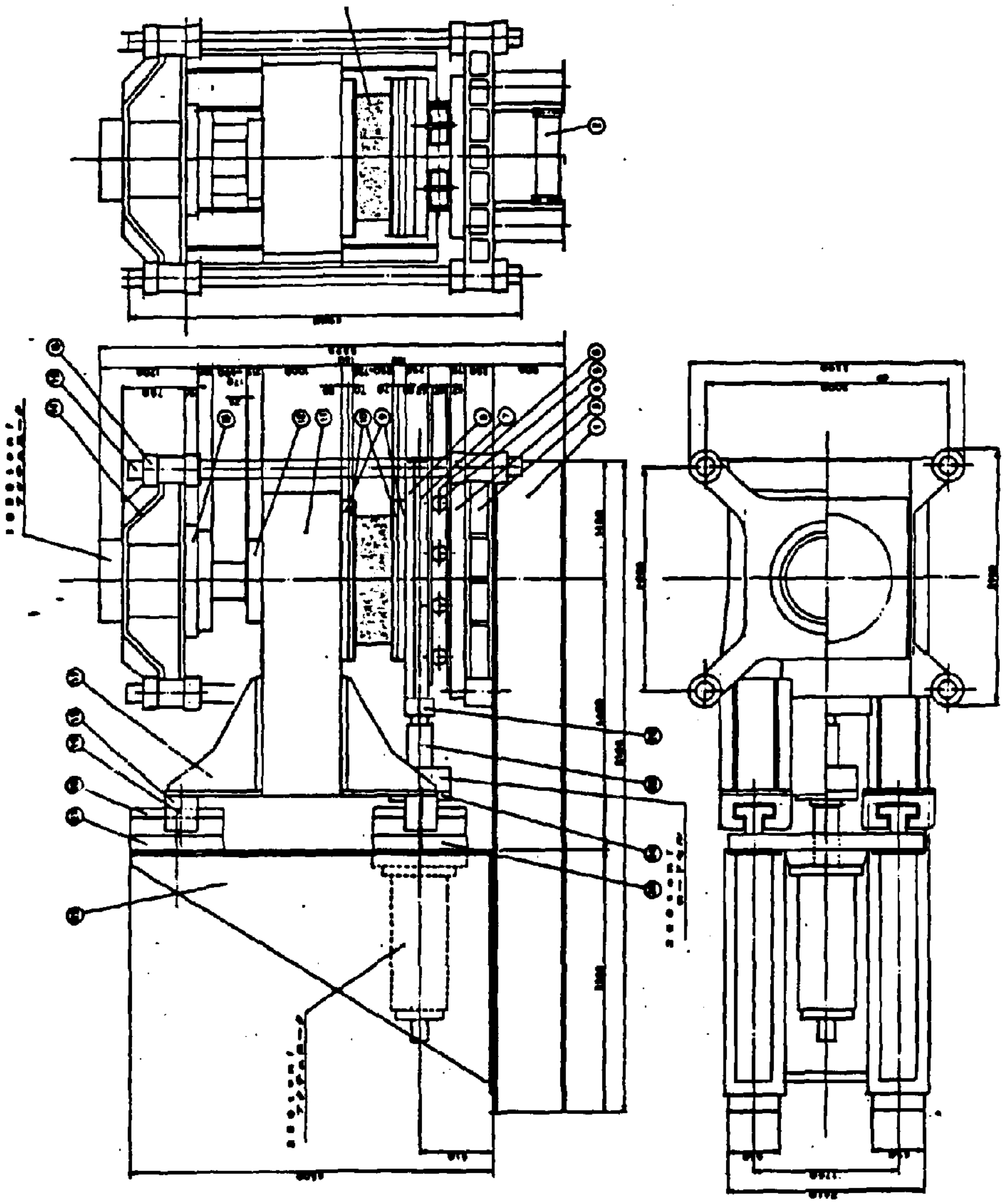

Figure C.5 Isolation Unit Test Facility, Oiles Corporation, Fujisawa, Japan