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Standard Test Procedures for Seismic Isolation Systems

by

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ABSTRACT

The Building and Fire Research Laboratory of the National Institute of Standards and Technology is currently engaged in an effort to develop guidelines for testing of seismic isolation systems. A comprehensive set of draft guidelines for testing has been developed and are available for use. The guidelines were developed to be independent of the type of superstructure, and generally independent of the type of isolation system. Three classes of tests are addressed in the guidelines: pre-qualification, prototype and quality control testing. The final guidelines for testing will be developed from the draft guidelines, based on industry feedback of the draft guidelines, and a test program to assess and evaluate the draft guidelines.

KEYWORDS: base isolation; building code; experimental; guidelines; seismic isolation; standard; testing.

1. INTRODUCTION

Seismic isolation is now generally accepted as a proven technology in earthquake hazard mitigation. A testimony to this fact is the increasing number of structures to be isolated in the United States and around the world (Kelly, 1993). One factor that has most certainly fostered confidence in the technology is the heavy reliance placed on testing to verify the performance and quality of manufacture of the isolation system.

Testing is currently required by the two major building codes that have adopted guidelines for design of isolated structures: for buildings, the 1991 *Uniform Building Code* (*Uniform*, 1991), and for bridges, the 1991 AASHTO *Guide Specifications for Seismic Isolation Design* (*Guide*, 1991). And although each requires an extensive series of tests, there currently do not exist standards for conducting these tests. As a result, test requirements are freely interpreted, leading to variability in the test procedures and subsequent test results from one supplier to the next. Furthermore, the lack of standard test procedures precludes an easy comparison of the performance of different isolation systems.

The Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) is currently engaged in an effort to develop guidelines (i.e., a pre-standard) for testing of seismic isolation systems. The first phase of this effort is complete, as signified by the publication of *draft guidelines* for testing of seismic isolation systems (Shenton, 1994a; Shenton, 1994b; Shenton, 1994c). The final guidelines for testing will be developed from the draft guidelines, based on industry feedback and a testing program. Presented in the paper is a brief summary and overview of the draft guidelines and a discussion of the plans for developing the final guidelines for testing.

2. OVERVIEW OF THE DRAFT GUIDELINES

2.1 Scope

Rather than focus on a particular isolation system and application, e.g., seismic isolation of bridges using elastomeric bearings, the guidelines were developed to be comprehensive and broad in scope. The guidelines were developed to be independent of the type of superstructure, and therefore, are applicable to a broad range of projects, e.g., buildings, bridges, water towers,

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etc. The guidelines are also generally independent of the type of isolation system, i.e., the test procedures are applicable to elastomeric, sliding, or hybrid isolation systems.

Three basic classes of tests are covered by the guidelines: pre-qualification, prototype and quality control testing. These are defined 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 are dependent on load and environmental factors.
>
> **Prototype tests** are project specific and are conducted to verify the design properties of the isolation system prior to construction.
>
> **Quality Control (QC) tests** are project specific and are conducted to verify the quality of manufacture and as-built properties of the isolation system prior to installation.

The guidelines are intended for *passive* systems that isolate in the *horizontal* plane only. Although some of the test procedures may be applicable to active systems, or systems that isolate in the vertical plane, the procedures were not developed with the latter in mind.

2.2 Rated Capacity

Fundamental to the guidelines is the concept of rated capacity. The onus is on the supplier of the isolation system to report certain fundamental properties of the isolation system, prior to testing. The properties to be reported include such things as seismic design displacement, thermal design displacement, effective horizontal stiffness at the design displacement, and energy dissipated per cycle at the design displacement. The complete list of properties to be rated is presented in Table 1.

Conditions under which the tests are conducted as outlined in the guidelines are based on the rated capacity of the system. For example, in a typical cyclic lateral load test, the vertical load and lateral displacement of the test are based on the suppliers rated capacity of the isolation system. In this way the test procedures are independent of the type of superstructure and autonomous of existing design guidelines and building codes for isolated structures. The standard list of rated properties should also facilitate the comparison of isolation systems from different suppliers and assist the designer in selecting the most appropriate system for the application.

2.3 General Requirements

The majority of the tests found in the guidelines are of a compression/shear type, i.e., a constant vertical load is maintained while the specimen is deformed laterally in shear. Many of the tests are, therefore, very similar in terms of the test set-up and test requirements. Consequently, general requirements are outlined in the guidelines for a typical compression/shear test, and exceptions or special requirements are noted in the test description.

General requirements address most of the issues related to test setup and instrumentation. Minimum requirements of the test facility, instrumentation, instrumentation calibration, data acquisition, and data analysis are discussed. This includes, for example, the number, type and positioning of displacement transducers; load capacity and calibration of the test facility, and a detailed description of the procedure for determining the effective stiffness and energy dissipation from a typical compression/shear test.

2.4 Pre-qualification Tests

Pre-qualification tests are formally not required by the codes today; nevertheless, tests of this type are usually conducted in one form or another as a new isolation system is developed. The purpose of the test series is to establish the fundamental properties of the system and to characterize the response. The tests are designed to determine such things as the dependence on frequency of loading, vertical load, load direction and temperature, to name just a few. Tests are also outlined for establishing the ultimate or reserve capacity under load conditions likely to be encountered during an earthquake, and under normal operating conditions. The pre-qualification series is the most extensive and comprehensive of the three class of tests: pre-qualification tests are to be conducted only once, for any given system of a particular design, material and construction. Conceivably, in the future, a supplier may be required to submit the results of their pre-qualification test series as part of the bid package in order to be considered for a job.

Briefly, a complete series of pre-qualification tests is to include all tests listed in Table 2, a full series of prototype tests (Table 3) and applicable quality control tests (Table 4). Each pre-qualification test is to be performed separately on two specimens. Whenever possible, tests are to be conducted on full scale specimens; however, recognizing the limitations of existing test facilities, scale model specimens are acceptable, provided they are not less than 1/4 full scale and are representative of the full scale prototype.

Performance criteria, or a framework for specifying the criteria in the final guidelines, have been established for all test in the draft guidelines. Some of the criterion for the pre-qualification series are simply "benchmarks" for classifying the response of the isolation system. Others are measures of performance and the quality of manufacture: systems that do not meet or exceed these criteria may not perform adequately in service.

An example test description from the pre-qualification series is presented in Figure 1.

2.5 Prototype Tests

The prototype test series is intended to verify the principal design properties of the isolation system, namely, effective stiffness and energy dissipation. Other tests are included to verify reserve capacity or satisfactory performance under simulated seismic and non-seismic loads. The prototype series outlined in the guidelines is similar to, and in part based on, the test requirements given in the 1991 UBC (*Uniform*, 1991) and the 1991 AASHTO *Guide* (*Guide*, 1991).

A complete series of prototype tests is to include all tests listed in Table 3, and applicable quality control tests listed in Table 4. Each prototype test is to be performed on two full scale specimens. Properly documented prototype tests previously conducted on a unit of similar size may be used to satisfy the requirements of prototype testing, provided:

- the unit to be tested is similar in design, materials and construction;
- the largest dimension of the unit to be tested is within $\pm 10\%$ of the same dimension of the unit previously tested;
- most other critical dimensions are within $\pm 15\%$ of the size previously tested.

The latter is intended to provide relief from testing units that are identical in all respects, from one project to the next.

The most important test of the prototype series is the test to determine effective stiffness and energy dissipation. The basic test requires three fully reversed cycles at $\pm 0.25D$, $\pm 0.50D$, $\pm 0.75D$ and $\pm 1.0D$, at the design temperature and under the design vertical load, where D is the design lateral displacement. The full extent of testing, however, is in part based on the outcome of the pre-qualification test series: systems that are found to be dependent on vertical load, frequency of load, bilateral load or temperature are required to undergo additional tests, over and above the basic sequence described above.

2.6 Quality Control Tests

Quality control is an essential and integral element of any manufacturing process. It includes, among other things, proper documentation, material traceability, manufacturing instruction, inspection, part identification and testing. The quality control tests described in the guidelines are intended to be included *as part of* the supplier's overall quality control/quality assurance program, and are not to be construed as a comprehensive quality control program.

Two types of QC tests are discussed in the guidelines, production tests and completed unit tests. Production tests are conducted during fabrication, on the materials or parts that go into fabrication of a unit or device. Tests are then conducted on completed units, generally to verify the properties and manufacturing consistencies of the production units.

Pre-qualification and prototype tests can and should be independent of the type of isolation system; however, because of the nature of production tests and some of the completed unit tests, QC tests tend to be system specific. For this reason, the QC tests are contained in separate reports (Shenton, 1994b; Shenton, 1994c). Presented below is a brief overview of recommended QC tests for elastomeric and sliding isolation systems.

2.6.1 Elastomeric Systems

The guidelines outline a number of production tests for elastomeric systems. These tests are to be conducted on representative samples of the elastomer used in fabrication of the isolation unit. The recommended tests include hardness, tensile strength and elongation at break, bond strength, compression set, low temperature properties, high temperature aging and ozone resistance. A performance criterion is established for each production test that is based on a design specified value. Materials that do not meet or exceed these criteria should not be used in fabrication of isolation units.

Three completed unit tests are outlined for elastomeric systems: sustained compression, compression stiffness, and effective stiffness and energy dissipation (Table 4a). The sustained compression test was developed years ago as a means of testing the strength of the elastomer and steel bond. In this test the unit is subject to a vertical load equal to 1.5 times the nominal vertical load capacity, for a duration of not less than twelve hours. An exception is provided in the guidelines to reduce the time to three hours if a minimum number of consecutive tests have been conducted without failure.

It should be noted here that there is considerable debate within the community regarding the scope of quality control testing required. Since QC tests can be very expensive and time consuming, the debate centers around the number of completed unit tests to be conducted as part of the QC program. One position advocates testing every unit that comes out of the plant, while another would permit testing a percentage of the units produced, provided the results proved satisfactory based on a specified performance or acceptance criterion. Both options are communicated in the draft guidelines in a special "draft option" box. This is one example of an issue that must be, and will be resolved in the process of developing the final "Guidelines for Testing ...".

2.6.2 Sliding Systems

A series of production tests are outlined in the guidelines for a generic sliding device. The recommended tests include surface roughness, trueness of surface, interface material properties, backing material properties, bearing pad attachment and sliding interface attachment. Again, performance criteria are outlined that are based on a design specified value: materials that do not meet or exceed the minimum values should not be used in the fabrication of units or devices.

Two completed unit tests are included for sliding systems: sustained compression and effective stiffness and energy dissipation (Table 4b). The sustained compression test is similar to the sustained compression test for elastomeric systems, but is intended only for systems that are susceptible to creep.

3. PLANS FOR DEVELOPING THE FINAL GUIDELINES FOR TESTING

The draft guidelines are extremely comprehensive and fairly complete, nevertheless, they are still considered draft and are likely to undergo modest revision before the final "Guidelines for Testing..." are published. Over the next twelve to eighteen months efforts will be focused on developing the final guidelines for testing. The final guidelines are to be based on industry review of the draft guidelines, and a testing program. These steps will provide important feedback for developing the final guidelines.

The industry review of the draft guidelines will be carried out on several fronts. The draft guidelines are to be distributed to various individuals and organizations over the next several months. Individuals will be encouraged to provide written comments on the guidelines, and to provide reference to evidence or documentation that supports any suggested changes. The draft guidelines will also be submitted to various working groups or committees of selected code writing organizations for formal review and comment. Finally, a one day workshop is scheduled to be held that will provide a forum for review and discussion of the draft guidelines. The workshop will bring together individuals from private industry, research and government, with experience and interest in the design, fabrication and construction of seismic isolation systems and isolated structures. Participants will be charged with addressing some of the more important and unresolved issues related to testing. Feedback from these different avenues of review will be taken under consideration as the draft guidelines are revised and brought into final form.

A limited test program is to be undertaken at NIST over the next year, for the purpose of assessing and evaluating the procedures outlined in the draft guidelines. A selected number of isolation units will be tested that are representative of hardware available today. Tests will be conducted in strict accordance with the draft guidelines, with the objective of uncovering problems or inconsistencies in the procedures. Note that although different isolation systems will be tested, the purpose here is not to conduct a rigorous study to compare the relative performance of various isolation systems.

In a related effort, HITEC, the Highway Innovative Technology Evaluation Center of the Civil Engineering Research Foundation (CERF) is presently collaborating with the California Department of Transportation, and the Federal Highway Administration, to test and evaluate market ready seismic isolation systems for bridges. Organizers of the HITEC program are currently reviewing the NIST draft guidelines; in all probability the draft guidelines will be adopted for use in the HITEC test program. The results of the HITEC program should be extremely valuable, and will provide additional input in the effort to develop the final guidelines for testing.

4. SUMMARY

The Building and Fire Research Laboratory of the National Institute of Standards and Technology is presently engaged in an effort to develop guidelines for testing seismic isolation systems, i.e., a precursor to a standard for testing. The first phase of the effort is complete, as signified by the publishing of *draft* guidelines for testing.

The draft guidelines are extremely comprehensive and broad in scope. The guidelines are independent of the type of superstructure and generally independent of the type of isolation system. Therefore, the guidelines are applicable to seismic isolation of buildings, bridges, etc. Three classes of tests are covered by the guidelines, pre-qualification, prototype and quality control testing. The pre-qualification series is the first and most extensive of the three, but would only be required once for any system of a given design, material and construction.

The effort to develop the final guidelines will be carried out over the next year; however, the draft guidelines are sufficiently complete that they can be used effectively in their present form. The effort to develop the final guidelines is to be based on industry review of the draft guidelines and a testing program. The adoption of these guidelines for testing should facilitate and further promote the use of seismic isolation as a viable means for earthquake hazard mitigation.

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Table 1. Standard Rated Capacity List

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.
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.

Table 1. (cont'd) Standard Rated Capacity List

Parameter	Notation	Description
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 $\pm 15\%$ change in Effective Stiffness, or a $\pm 30\%$ 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 $\pm 15\%$ change in Effective Stiffness, or a $\pm 30\%$ 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.

Table 2. Schedule of Pre-Qualification Tests[1]

Category	Test	Title/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 (Table 3) and quality control tests (Table 4).

Table 3. Schedule of Prototype Tests[1]

Category	Test	Title/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

[1]Prototype shall also include a complete series of quality control tests (Table 4).

Table 4. Schedule of Quality Control Tests

(a.) QC Tests for Elastomeric Systems

Test	Title/Purpose
1	Sustained Compression
2	Compression Stiffness
3	Effective Stiffness and Energy Dissipation

(b.) QC Tests for Sliding Systems

Test	Title/Purpose
1	Sustained Compression
2	Effective Stiffness and Energy Dissipation

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.,

$$\frac{\left| K_H^P - K_H \right|}{K_H} \leq 0.01\alpha$$

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.,

$$\frac{\left| E_H^P - E_H \right|}{E_H} \leq 0.01\beta$$

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.

Figure 1. Example Test Description (Shenton, 1994a; see original reference for details and symbol definitions)