Development of Test Guidelines for Passive Energy Dissipation Devices

By

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ABSTRACT

Passive energy dissipation devices are effective for improving the dynamic response of structures by reducing their response to earthquake and wind excitations. Wide acceptance of these devices for structural applications depends on their performance being well documented, and on the availability of standards for their evaluation and testing. In response to this latter need, the Building and Fire Research Laboratory of the National Institute of Standards and Technology has initiated a research program to develop guidelines for testing supplemental damping devices.

The objective of the guidelines is to provide a standardized series of prototype and production tests for passive energy dissipation devices. The test guidelines are intended to be independent of both the device type and application. They are also meant to assist manufacturers, researchers, and practitioners in performing and interpreting the test results.

This paper provides an overview of the guidelines and describes their development.

KEYWORDS: passive dampers; passive energy dissipation; test guidelines; structural control; supplemental damping.

1 INTRODUCTION

Extensive research and initial implementations have shown that passive energy dissipation devices can significantly improve the dynamic response of structures (Hanson, et al., 1993; Soong and Constantinou, 1994; Sadek, et al., 1996; and Soong and Dargush, 1997). These devices, which are also known as passive control devices, supplemental dampers, or passive dampers, can reduce structural responses due to wind, earthquake, and other dynamic loads. Such devices can absorb part of the energy induced in the structure, minimizing the energy dissipation demand on the primary structural members, and thus reducing the inter-story drifts and nonstructural damage. In addition, they can be designed to provide additional stiffness to the structure and to be easily replaced if they are damaged.

Research and development have led to a variety of passive energy dissipation devices. They use a range of materials and mechanisms, which operate on principles such as sliding friction, yielding of metals,

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deformation of viscoelastic materials, and fluid flow through orifices.

These devices are now used in the design of new structures and the rehabilitation of existing ones in Canada, Japan, Mexico, New Zealand, Europe, and the United States. Nevertheless, most of these devices are still designed and manufactured on a per-project basis. Design and test standards are necessary for their widespread use. Although some design and test guidelines already exist (NEHRP, 1997; Taylor and Constantinou, 1994), most are specific to certain types of structures or have limited applications.

In response to this lack of test standards, the Building and Fire Research Laboratory of the National Institute of Standards and Technology has initiated a program to develop guidelines for testing supplemental damping devices. A draft version of these guidelines, titled "Guidelines for Testing Passive Energy Dissipation Devices" (Riley, et al., 1999), has been completed and is being reviewed. The guidelines recommend *prototype* and *quality control* tests for passive energy dissipation devices. In addition, they describe a series of *basic property* tests, which may be used as the basis for evaluating future devices as they are developed.

2 ENERGY DISSIPATION DEVICE TYPES

Some common types of passive energy dissipation devices are described below. These devices are currently available, and have been used in structures or laboratory experiments. This list of devices is not complete, due to the large number of existing devices. Moreover, the industry is rapidly evolving and, therefore, it is anticipated that many additional devices will be developed in the future. The test guidelines described in this paper are applicable to many other types of devices; not just those included below.

For the purpose of the test guidelines, these devices can be categorized according to their mechanical behavior as rate dependent, rate independent, or others. The following is a brief description of the properties and types of devices in each category.

2.1 Rate Independent Devices

Devices with force-displacement response characteristics that are primarily a function of the displacement amplitude are classified as rate independent devices. The behavior of these devices is generally independent of the relative velocity or the frequency of motion. They include friction and metallic devices.

2.1.1 Friction Devices

Friction devices use the friction between sliding surfaces to dissipate energy. They generally exhibit rigid-plastic behavior and their force response can be modeled by simple Coulomb friction, so the force-displacement curves of the devices are rectangular loops. These devices can be characterized by their displacement amplitude and slip-load.

Friction devices can dissipate large amounts of energy even at low velocities, while their peak forces are bounded even at large velocities. Unfortunately, their effective stiffness can be large when motions are small and their non-linear response complicates structural designs.

A variety of mechanisms can be used to create the friction forces, including sliding or twisting between simple metal surfaces. Performance of the devices may be enhanced by using friction pads or wedges. One type of friction device combines friction pads with a spring mechanism, which gives the device a re-centering capability and slip forces that are proportional to the displacement. Friction devices are typically located in braces or at the intersection of cross braces.

2.1.2 Metallic Devices

Metallic yielding devices take advantage of the stable hysteretic force-displacement behavior of metals to absorb energy. These devices use flexural, shear, or extensional deformations in the metal's plastic range to provide the structure with increased stiffness and energy dissipation capacity. They typically exhibit hysteretic force-displacement behavior, which can be approximated as bilinear or trilinear.

These devices tend to be inexpensive to produce and their properties will remain stable over the long lives of buildings and bridges. Unfortunately, they often have a limited number of working cycles, which may require them to be replaced after large seismic events. Like friction devices, their non-linear response can complicate structural designs.

These devices can be installed in the bracing systems of building frames, or used between the structure and foundation of seismically isolated structures to increase the damping in the isolation system.

2.2 Rate Dependent Devices

Rate dependent devices have force-displacement response characteristics that are a function of either the relative velocity between the ends of the device or the frequency of the motion. The response of the devices in this category, however, may be a function of the relative displacement as well. These devices include solid viscoelastic, fluid viscoelastic, and viscous fluid devices.

2.2.1 Solid Viscoelastic Devices

Solid viscoelastic devices are constructed from constrained layers of acrylic polymers and designed such that they produce damping forces through shear deformations in the polymers. When deformed, the viscoelastic materials exhibit the combined features of an elastic solid and viscous liquid. The resulting response can be modeled using a Kelvin model, which consists of a spring and dashpot in parallel.

These devices have proven to be efficient and cost effective for reducing wind induced vibrations. Unfortunately, their effective stiffness and the damping forces are generally dependent on the excitation frequency and the operating temperature, including the temperature rise due to excitation. Because of this temperature dependence, these devices may not be useful in structures where the climate is not continuously controlled.

These devices are typically used in moment resisting frames, where they are installed in cross braces or in connections between floor trusses and columns.

2.2.2 Fluid Viscoelastic Devices

Fluid viscoelastic devices, such as viscous shear walls, operate by shearing viscoelastic fluids. Their behavior and response characteristics are similar to solid viscoelastic devices, except that the fluid viscoelastic dampers do not exhibit stiffness when static loads are applied. These devices can be modeled with Maxwell model, which consists of a spring and dashpot in series.

2.2.3 Fluid Viscous Devices

Fluid viscous devices are used extensively in a variety of structural and mechanical systems, to reduce responses to vibrations and shock. These devices operate on the

Table 1. Test Categories

Type of Test	Test Category	Notes
Quality Control Tests	Material Properties	Tests of materials and components.
	Production Unit	Tests of completed devices.
Prototype Tests	System Properties	Determination of response properties.
	Applied Loads	Validation of response to realistic loads.
	Reserve Capacities	Validation of response to extreme loads.
Basic Property Tests	Basic Properties	Tests for device development only.

principle of fluid flow through orifices. They tend to act as ideal viscous dampers, generating only damping forces, but they may exhibit some stiffness at high frequencies.

Fluid viscous devices can dissipate large amounts of energy, over a wide range of excitation frequencies. Their force response is proportional to velocity, so designing structures that use these devices is generally straightforward. The life span of these devices tends to be limited only by wear of their seals.

The devices are typically installed in the bracing systems of buildings or used in conjunction with the isolators in seismically isolated structures. They can be used effectively for buildings, bridges, and other structural systems.

2.3 Other Types of Dampers

Other energy dissipation devices have been developed that cannot be classified as either rate dependent or independent. One such device type is shape memory alloys, which undergo a reversible phase transformation and exhibit superelastic behavior when deformed.

3 OVERVIEW OF THE GUIDELINES

The guidelines include a series of test procedures and requirements for how the tests should be performed. The test procedures are grouped into five categories in two series, according to the nature and purpose of the tests. The test series are *quality control* tests and *prototype* tests. In addition, the guidelines describe a series of *basic property* test, which are not required, but are intended as guidance for how to test newly developed device types. The test types and categories are listed in Table 1.

All of the tests in these guidelines are presented in a standard format, which includes the procedure and any applicable performance criteria. Systems that fail to meet the performance criteria may not perform adequately in service.

3.1 Scope

The guidelines are intended to be comprehensive and to apply to all passive energy dissipators, all structural systems, and many types of dynamic loads. Therefore, the need to develop standards for a particular damper type or application is minimized. Although many of the proposed tests may be applicable to components of active, semi-active, or hybrid systems, these guidelines are not being developed for such devices.

The guidelines are not intended to recommend one energy dissipation system over another. They are intended only to validate that a particular device will perform properly in a given application; therefore, they are expected to encourage competition between various systems.

3.2 Test Requirements

The guidelines include a set of general requirements that apply to all prototype and quality control tests. All tests should be conducted in accordance with these requirements; however, certain requirements may be waived if they are deemed unnecessary for a particular device or design. When necessary, additional special requirements are presented with the individual test specifications.

The general requirements define the necessary facilities and reported information. The necessary test apparatus, instrumentation, and data acquisition are described. The data that should be recorded, analyzed, and reported are also defined.

The requirements also describe how to define the device classification and capacity. To properly test a device, the required force, amplitude, and stroke capacities of the device need to be known. The design response must also be defined, to allow comparison between the actual and required response of the device.

Finally, the devices need to be categorized according to how their response varies to external influences. The devices should be categorized according to whether or not their response depends on the excitation frequency, the loading rate, stroke position, or device temperature. The devices should also be categorized according to how their response degrades with continued use.

3.3 Test Series

As listed in Table 1, above, the guidelines contain three test series and six test categories. A graphical description of how the test series are related, and when each test series should be performed, is shown in Figure 1. The three test series - *quality control* tests, *prototype* tests, and *basic property* tests - are described in detail below.

3.3.1 Quality Control Tests

The quality control tests are intended to verify the as-built characteristics of the completed devices and should be performed on all units before installation. This test series includes two test categories, the *material property tests* and *production unit tests*.

The material property test category includes tests of the materials used in the device and tests of each unit's sub-components. These tests are conducted to monitor the quality and consistency of the manufacturing process. They should be performed during fabrication of the devices and should meet the appropriate test standards. The details of these tests are not described in the guidelines; instead, appropriate tests should be performed for each type of device, as necessary.

The production unit test category consists of four tests, which are intended to verify the as-built properties of the devices. In general, only one of the four tests will need to be performed on a particular device, although in some cases a second test will be needed. All four tests investigate the stiffness and energy dissipation properties of the devices.

The response of the devices during the production unit tests is considered acceptable if the properties fall within a defined range of acceptable values.

3.3.2 Prototype Tests

The prototype tests are intended to verify the design properties of a specific device. This test series includes three test categories, the *system property tests, applied load tests,* and *reserve capacity tests.* These tests should be performed on two specimens for each design and unique application.

The system property test category consists of four tests. The first test in this category is designed to determine the response properties of the device. This test is identical to the first production unit test, and needs to be performed only if the first production unit test was not performed. The remaining three tests are designed to determine how the properties change with changes in the loading conditions. These tests need to be performed only on devices whose response is dependent on the loading frequency, stroke offsets, or device temperature.

The applied loads test category consists of three tests that are intended to validate the device's ability to withstand realistic loading. The first test verifies that the device can survive a lifetime of the expected loads. The second and third tests verify the device's ability to withstand seismic and wind loads. Only those tests that are applicable to a particular device and application need to be performed.

The reserve capacity test category consists of two tests that are intended to verify that the device can withstand loads that exceed the design values. The first test verifies that the device will perform properly when

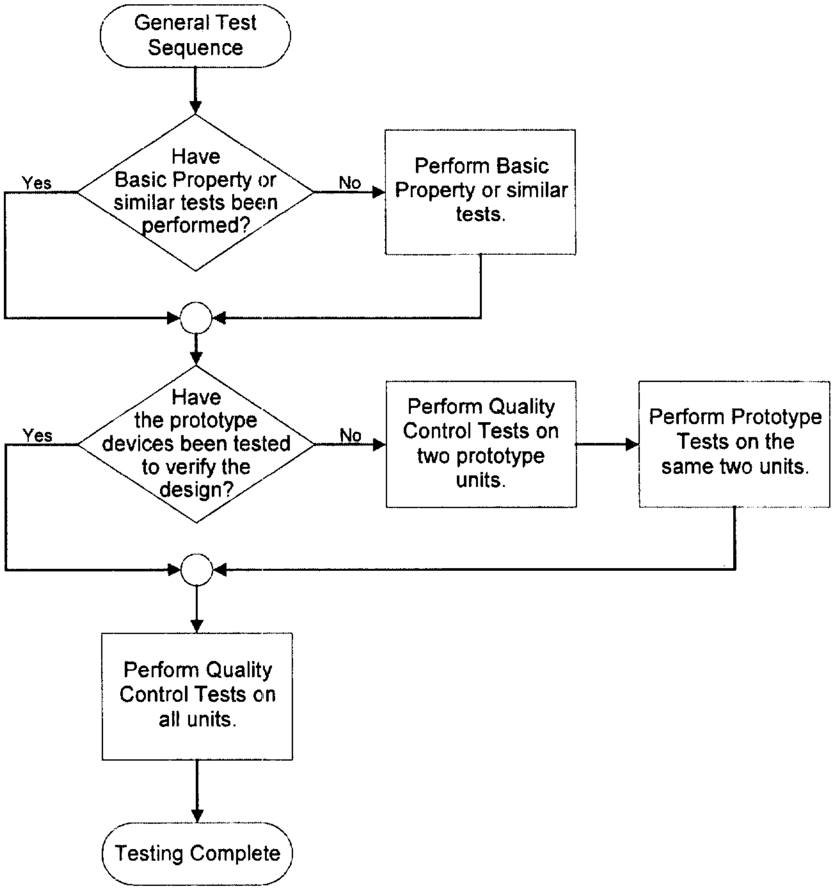

Figure 1. Test Sequence for Passive Energy Dissipation Devices.

subjected to the maximum expected loading velocity. The second test verifies that the device has a reserve capacity for withstanding displacements and forces beyond the design values.

The device's response during the prototype tests is considered acceptable if the properties fall within a defined range of acceptable values or if the variation of the properties is accurately predicted by mathematical models of the device. In addition, the device should not be permanently damaged by the tests.

3.3.3 Basic Property Tests

The basic property tests are included in an appendix to the guidelines. These tests are not required, but may be used to determine the characteristics of new devices or existing ones that are substantially modified. These test guidelines provide only guidance on how to perform these types of tests. The basic property tests consist of three subcategories: preliminary characterization tests, device durability tests, and realistic load tests.

The preliminary characterization tests are intended to determine how the device will respond to a variety of loading conditions. These tests characterize the device properties and determine how the properties will vary with changes in loading frequency, load amplitude, temperature, and load history. These tests are intended to provide results that can be used to develop mathematical models of the device response.

The device durability tests are intended to determine the device's usable life and resistance to damage. These tests characterize how the device will respond to extended cycling, extreme loads, extreme temperatures, impact, and aging. The results of these tests can be used to develop practical guides for how long the devices will last and under what circumstances they will need to be replaced.

The realistic load tests are intended to verify that the devices and structure will perform properly when used as a complete system. These tests include realistic seismic, wind, and service loads. Preferably, these tests should be performed with the devices installed in realistic, scale-model structures.

There are no acceptance criteria for the basic property tests, since these tests are intended only to determine how the device will perform in various conditions. The tests are not intended to verify how a device will perform in a particular application.

4 DEVELOPMENT PROCEDURE

The proposed test guidelines are being developed with the assistance of an advisory committee, feedback from experts working in the area of passive energy dissipation, and a workshop to be sponsored by NIST before the guidelines are finalized. To develop confidence in the guidelines and to foster adoption of the proposed test procedures, the guidelines will be evaluated by conducting selected tests on typical supplemental damping devices. These tests will expose any inconsistencies, omissions of important data, or other unforeseen problems with the procedures, in addition to investigating the applicability of the test procedures.

Through this process, we expect to develop guidelines that will be valuable to the civil engineering community, and will facilitate the use of these devices.

5 SUMMARY

The development of these guidelines is intended to lead to more systematic evaluations of passive energy dissipation devices. Properly used, these guidelines will ensure the quality of the installed devices and should expedite the development of new systems, by allowing direct comparisons between devices. Since they will be independent of the application and applicable to all passive energy dissipation devices, these guidelines should assist in the design and construction of structures with supplemental dampers and enhance the use of this promising technology.

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