TESTING OF SEISMIC ISOLATORS AND DAMPERS - CONSIDERATIONS AND LIMITATIONS

Ian D. Aiken

Seismic Isolation Engineering, Inc.
P.O. Box 11243, Oakland, CA 94611, USA

ABSTRACT

Building and bridge design codes for seismic isolation include specific requirements for the testing of isolation bearings. The testing is intended to serve a two-fold purpose; firstly, to confirm the physical properties of the isolation devices used in the design process and to demonstrate acceptable behavior under the maximum expected earthquake loading, and secondly, to provide a means for quality control over the properties of the isolation devices that will actually be used in the structure. For large structures, and structures in areas of high seismicity, the device testing requirements may impose severe demands on the capabilities of available testing equipment. This paper discusses the important characteristics of isolation devices and the influence of these characteristics on testing, in terms of such factors as displacement, force, rate of loading, and test temperature. The practical limitations of both institutional and manufacturers' testing facilities are discussed in terms of theoretical test force, displacement, and velocity requirements.

Various design code guideline documents also address energy dissipation devices and associated testing requirements. A growing interest in viscous and viscoelastic damping devices in particular, has highlighted the practical limitations of testing these types of devices. This paper also discusses the specific challenges related to testing highly rate-dependent devices, and factors to be considered in developing realistic test programs.

This paper is intended to provide engineers who are involved with or contemplating an isolation or energy dissipation project a context for defining a realistic and practical testing program for the devices that will be part of their project. By way of example, several recent testing programs are described, including the testing of isolation bearings for a new hospital building, the pre-qualification testing of viscous dampers for the retrofit of the Golden Gate Bridge, and the testing of viscoelastic dampers for a building retrofit.

INTRODUCTION

There are now a number of codes and guideline documents that include design provisions for seismic isolation and energy dissipation. Since 1991, the Uniform Building Code and AASHTO Guide Specification have both contained provisions for seismic isolation for new building and bridge structures that include requirements for testing, ICBO (1997), AASHTO (1997), and the recent *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* contain design and testing provisions for both seismic isolation and energy dissipation devices for retrofit, FEMA (1996). Other documents have been developed that directly address specific different types of device testing in significant detail, Shenton (1996), ASCE (1997).

The development of any isolation or damper test program should consider the following factors:

- Basic testing objectives: confirmation of design properties and QA/QC
- Code-mandated tests
- Project-specific needs for tests in addition to code-specified tests
- Acceptance criteria
- Cost of testing
- Time required for the test program

For designs involving very large devices, consideration should also be given to the practical question of whether or not the designed device can actually be tested, and tested in such a way that will provide meaningful results. The remainder of this paper presents a discussion of the main types of testing used for isolation and damping devices, the capabilities of various testing facilities, and examples of the types of testing undertaken for three specific projects.

METHODS OF TESTING

Reduced-Scale Dynamic Testing

Reduced-scale dynamic testing has been the mainstay of experimental research on isolation and energy dissipation devices. Without the need for additional massive equipment, particularly hydraulic pumps and accumulators, it has been possible to test devices of about 1/4- to 1/3-scale using existing hydraulic power systems associated with shake tables and large testing laboratories. For example, a test machine at the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley has been used for numerous research studies of isolation bearings subjected to generalized dynamic vertical and horizontal loading. The machine tests single bearings under vertical and one direction of horizontal loading, and is capable of vertical loads up to approximately 890 kN (200 kips), horizontal loads of 335 kN (75 kips), ±152 mm (±6 in.), and a maximum velocity of 635 mm/sec. (25 in./sec.). A machine with similar characteristics but slightly lower capacities exists at the State University of New York at Buffalo (SUNY). Some additional features of these machines are that they are capable of subjecting test specimens to axial tension loads, horizontal moments, and that they both measure bearing force directly via loadcells placed underneath the test specimen. This last feature is significant, since it allows direct measurement of bearing force characteristics without the need for dynamic and friction loss corrections to forces measured in-line with the horizontal actuator.

Both EERC and SUNY also have machines suitable for the dynamic testing of uniaxial energy dissipation devices. These machines, like the bearing test machines described above, are useful for testing reduced-scale and smaller full-size dampers. The EERC machine was originally designed for the viscous damper pre-qualification tests for the Golden Gate Bridge (described later in this paper), and is capable of cyclic testing of dampers up to 445 kN (100 kips) at a maximum sustained velocity of 508 mm/sec. (20 in./sec.) and with a maximum displacement of ±254 mm (±10 in.). The SUNY machine, originally configured for pre-prototype viscous damper tests for a hospital project, has a similar velocity capacity, but a maximum force output of about 222 kN (50 kips). Both machines have been used for temperature-varied tests, using either direct-contact heating and cooling or a temperature-controlled environmental enclosure.

Large-Scale Quasi-Static Testing

Quasi-static testing is obviously the most economical approach for testing of large devices, and is reasonable if the characteristics of the device in question are not much effected by rate of loading or thermodynamic effects. It is the most common type of testing performed on elastomeric isolation bearings. Typical rates of loading are slow - of the order of 200-300 mm/min. (8-12 in./min.) - which mean that only modest hydraulic pump or accumulator systems are required. (Large friction isolation bearings, such as the Friction Pendulum System, are typically tested at velocities of about 25-100 mm/sec. (1-4 in./sec.)). Various types of dampers, for example, yielding steel devices, are also amenable to this type of testing.

Manufacturers' Facilities

Most manufacturers of elastomeric isolation bearings test bearings two at a time, stacked one on top of the other (or side by side) by applying shear load to a platen between the two bearings. This is a particularly economical configuration, since the large vertical loads required can be applied to a fixed - as opposed to a moving - platen. The implication of this configuration is that test results are average results for a pair of specimens. One manufacturer tests bearings individually, in a configuration that applies simultaneous shear loads in opposite directions to the upper and lower platens. Depending on manufacturer, the machines also have varying degrees of tension force/uplift deformation capability. The larger machines are currently capable of horizontal/shear loading of about 4450 kN (1000 kips) and ±760 mm (±30 in.) displacement, and about 17,800 kN (4000 kips) maximum vertical load. Test machine platens range in size up to about 1830 mm (72 in.) square and can accept specimens up to about 915 mm (36 in.) maximum height. Maximum vertical tension forces of about 1780 kN (400 kips) are possible. In all cases, manufacturers' test machines subject bearings to one direction of horizontal loading only.

Large-Scale Dynamic Testing

To date, dynamic testing of full-scale devices has primarily been used for viscous dampers, and as such, the greatest capability in the U.S. for doing this type of testing currently exists with the viscous damper manufacturers, Enidine, Inc., and Taylor Devices, Inc. An independent test facility in Southern California (ETEC) has a machine capable of testing large isolators and dampers (although not the largest devices used), and a new test system being developed by Caltrans will have even greater capabilities. Both of these test facilities are described in subsequent sections, along with mention of some manufacturers' testing capabilities.

A type of testing originally used for shock and impact applications, called drop testing, has been extended for the testing of seismic viscous dampers. The test method involves dropping a known weight onto the test specimen, causing a high impact force at a measured velocity. The test method is suitable for determining force-velocity relationships for viscous dampers. Its most significant limitation, however, is that because the test is of extremely short duration, no significant energy is input to the damper, and therefore any transient temperature effects are not revealed. A strategy used for several damper projects has involved calibration of drop testing and dynamic cyclic testing of reduced-scale dampers, and then drop testing only for full-scale dampers. The other test method, dynamic cyclic testing, involves subjecting a test specimen to a loading generated by a servo-hydraulic test system. While more comprehensive, this type of testing can be very demanding in terms of hydraulic power requirements.

So far, dynamic testing of full-size isolators has not been widely used. Slow-speed dynamic testing of friction isolators is performed, but at rates of loading significantly slower than actual earthquake loading conditions. As for dampers, there are very large hydraulic power requirements for dynamic testing of full-size isolators, and the test arrangement for isolators is additionally complicated over that for uniaxial viscous dampers by the very large orthogonal forces required to represent the vertical load on the bearings.

Energy Technology Engineering Center (ETEC) Facility

The test machine at ETEC in Canoga Park, California, was originally designed and constructed to perform dynamic tests of large isolation bearings for research on seismic isolation for nuclear power plants. The machine can test isolation bearings under vertical and one direction of horizontal loading, and uniaxial energy dissipation devices. It was recently enhanced as part of a testing program for HITEC, to evaluate seismic isolation and energy dissipation devices for bridges, HITEC (1996). The HITEC program involved rigorous testing of both isolation and damping devices, from about ten different manufacturers, under a pre-defined testing program to evaluate performance under a range of service and earthquake loading conditions, Sultan and Sheng (1995). While not originally intended as such, successful participation in the HITEC program has come to be viewed by many as a pre-qualification for bridge isolation and energy dissipation manufacturers. The formal intent of the program was to provide a standardized means for evaluating different types of devices, and to establish dynamic performance information about devices for use in the design process. The ETEC test machine capabilities are shown in Table 1.

Table 1: ETEC Test Machine Capabilities

Parameter		Capacity
Horizontal	Force Displacement Velocity	±1180 kN (±265 kips) ±380 mm (±15 in.) ± mm/sec. (± in./sec.)
Vertical	Force Displacement Velocity	3,560 kN (800 kips) ±102 mm (±4 in.) ±254 mm/sec. (±10 in./sec.)

The HITEC program was funded primarily by the Federal Highways Administration with a grant of approximately $2.4M, and the California Department of Transportation (Caltrans) contributed project management and coordination. The device manufacturers paid a small participation fee and provided test specimens at no cost.

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

Several of the major toll bridge retrofits being undertaken by Caltrans will incorporate seismic isolation or energy dissipation devices as part of the overall retrofit strategy. Six major toll bridge retrofits are planned, utilizing isolation bearings with vertical load and horizontal displacement capacities up to 22,250 kN (5000 kips) and ±1370 mm (54 in.), and energy dissipation devices with force, velocity and displacement capacities up to 3,560 kN (800 kips), ±1780 mm/sec. (70 in./sec.), and ±914 mm (36 in.), respectively. The size of some of these devices, and their use in such large and long structures, is unprecedented. Also, the fact that they play such a key role in the dynamic response characteristics of the bridge structures raises concerns about their seismic performance, as well as their longevity and wear characteristics. With these concerns in mind, Caltrans has embarked on the development of a dedicated testing facility, to be located at the University of California, San Diego (UCSD), called the Seismic Response Modification Device (SRMD) Test System, to support the design and application of SRMDs in the Toll Bridge Retrofit Program, Mellon, (1997). The Test System will be capable of large capacity bi-directional horizontal plus vertical loading of isolation devices in real time, and large capacity uni-axial loading of damping devices. A summary of capabilities is presented in Table 2.

The hydraulic power supply will be via an accumulator bank providing 5,680 l (1500 gal.) of displaced oil volume, and the system will be capable of delivering an average power of 6,000 kW (8040 hp) during a 20-second test, with a peak output of several times that level. This power capacity satisfies the testing requirements for actual earthquake signals and the largest isolation devices envisaged in the Toll Bridge Retrofit Program.

Table 2: SRMD Test System Capabilities

Parameter	Capacity
Vertical force	44,500 kN (10,000 kips)
Horiz. force: longit. / trans.	±8900 kN / ±4450 kN (±2, 000 kips/ ±1, 000 kips)
Vertical displ.	254 mm (10 inches)
Horiz. displ.: longit. / trans.	±1220 mm / ±610 mm (±48 inches / ±24 inches)
Vertical velocity	±254 mm/sec. (±10 inch/sec.)
Horiz. velocity: longit. / trans.	±1780 mm/sec. / ±760 mm/sec. (±70 inch/sec. / ±30 inch/sec.)
Maximum specimen size	3.66 m x 3.66 m in plan x 1.52 m high (12 ft. x 12 ft. in plan x 5 ft. high)

The size of the SRMD Test System and the complexities associated with its design, construction and implementation, along with the testing needs for specific projects, have resulted in a three-phase testing program for the first testing project, isolators for the Benicia-Martinez retrofit. Phase 1 testing will consist of uni-directional, slow-speed testing with constant vertical load; Phase 2 testing will involve real-time, multi-directional motions (six degrees of freedom) and actual earthquake time-history inputs; Phase 3 will consist of long-term testing of devices, including actual devices removed from structures after 5-10 periods of service.

The SRMD Test System is being jointly designed by MTS Corporation and UCSD. The new building infrastructure is currently under construction at UCSD, and the Test System is scheduled to be available for Phase 1 testing of isolation devices for the Benicia-Martinez Bridge retrofit in the middle of 1998. Phase 2 testing is anticipated for late 1998. The cost of the Test System, including the Benicia-Martinez tests, is $14.8M. While the machine will be available subsequently for other testing, it is expected that its large size relative to average project testing requirements, as well as expected high testing costs and overheads, will result in rather limited use.

Manufacturers' Facilities

Because the basic properties of viscous damping devices are dependent on the rate of applied loading, viscous damper manufacturers have, by necessity, established dynamic testing capabilities for testing their dampers. The two main methods used to test viscous dampers are drop testing and cyclic dynamic testing. Drop testing capabilities exist for applied impact loads of up to 8,900 kN (2000 kips) at a maximum velocity of 11.43 m/sec. (450 in./sec.). Drop tests can be performed so that the damper is loaded in both its extension and retraction directions, and with the piston in different starting positions. Cyclic dynamic testing is performed using high-performance servo-hydraulic systems. The largest test machine can currently achieve a maximum output of 2225 kN (500 kips) at 1525 mm/sec. (60 in./sec.). The machine is capable of higher velocities at lower peak forces, and has been used to test 890 kN (200 kip) dampers at 2540 mm/sec. (100 in./sec.).

While drop test machines are limited to short-duration impact loading, cyclic dynamic test machines can be used to subject devices to multiple cycles of loading and thus to input significant amounts of energy. The type of loading is also flexible, from sinusoidal displacement to constant velocity (sawtooth displacement) to generalized transients such as earthquake-type motions.

PROJECT EXAMPLES

By way of example, testing programs conducted for three recent projects (one using seismic isolation and two using energy dissipation) are briefly presented. These describe the types of tests that are actually performed and illustrate how test programs are defined to meet code requirements and satisfy various project-specific objectives.

LAC+USC Medical Center Replacement Project - Isolation Bearings

This project is an example of the additional testing that is sometimes necessary for hospital isolation projects in California. The basic testing requirements for the high-damping rubber bearing isolation system were defined to be those of the 1994 UBC. Because the design involved uplift at some column locations, which was accommodated by a loose-bolt arrangement between the bearing flange plates and the superstructure, additional tests were specified to verify this connection detail and its influence on bearing behavior. The comprehensive prototype test program undertaken involved the testing of bearings with loose-bolted flange plates, fully-bolted flange plates (both connection arrangements for bearings tested in pairs), and also some tests of single bearings with loose-bolt connection details and no applied vertical load. The bearings were tested in pairs, and two prototype pairs were tested for each different bearing type. The test loads and displacements were very demanding, with maximum vertical loads of nearly 17,800 kN (4000 kips) combined with horizontal shear displacements up to 508 mm (20 in.).

For more routine projects, the additional cost and time associated with undertaking such extensive testing should be carefully weighed against the specific needs of each particular project.

Golden Gate Bridge Seismic Retrofit - Viscous Dampers

Viscous dampers are an integral part of the seismic retrofit of the suspension spans of the Golden Gate Bridge, included to control the motions of the deck spans relative to the main tower legs. The importance of the dampers to the overall retrofit, and the large size of the devices, led to a thorough damper pre-qualification testing program. The full-size dampers were too large to be suitable for a comprehensive dynamic testing program, so reduced-scale dampers were designed. A comparison of the reduced-scale and full-size dampers is given in Table 3. The full-size dampers under design loading will produce an average power of 261 kW and a peak power of 5.41 MW.

Table 3: Reduced-Scale and Full-Size Viscous Dampers for the Golden Gate Bridge

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

Test dampers were obtained from prospective manufacturers, and satisfactory performance in the pre-qualification program was defined as a necessary requirement for their subsequent bid for the project.

The test program consisted of an 1800-cycle endurance test (to simulate wind-induced high-cycle wear on the dampers seals and moving parts), sinusoidal and constant velocity tests over a range of displacement amplitude, velocity and loading frequencies, and MCE earthquake input motions derived from the retrofit design analyses, Aiken (1996). The cyclic tests were performed at temperatures of 4.4, 21, and 52^{o}C (40, 70 and 125 ^{o}F). The primary evaluation approach was to compare the experimentally determined damper force-velocity relationship with the design target constitutive relationship. In most cases, an acceptable range of behavior was defined as ±15 % from the design target value. Dampers from four manufacturers were tested, and each damper took about 2-3 weeks to test (the endurance test alone typically required 4-5 days). The cost of the test program was about $150,000, the major component of which was the fabrication of a test machine for the program; the test dampers were provided by the manufacturers at no cost.

An extensive series of dynamic cyclic tests were performed in the pre-qualification phase. Depending on practical test capabilities, the production phase testing will consist of either drop tests or a limited set of dynamic cyclic tests of full-size dampers.

LAPD Recruit Training Center Retrofit - Viscoelastic Dampers

This project involved the viscoelastic (VE) damper retrofit of a four-story steel moment-resisting frame in west Los Angeles, that was damaged in the 1994 Northridge Earthquake. FEMA-273 was used to define the basic retrofit performance objectives and damper testing requirements, along with some project-specific objectives, FEMA (1996). Extensive linear and nonlinear analyses were performed as part of the design. These analyses included nonlinear fractional derivative modeling of the deformation-frequency-temperature properties of the VE dampers using an enhanced version of the finite-element program, ANSYS. Instead of using the default FEMA-273 acceptance criteria of for determining suitability of the test dampers, which have as their basis single values of stiffness and equivalent damping determined from multiple-cycle tests, it was decided to take advantage of the fact that sophisticated analysis methods were used in the design process. Damper acceptance was determined by comparing blind computer model predictions of the test damper response (i.e., made prior to the tests) with the actual measured results. Tests at a range of temperatures were waived on the basis that the analytical model was shown to be capable of accurately predicting temperature effects during the prototype tests.

The complete damper assemblies designed for the retrofit each consisted of four individual VE damper modules of varying sizes. Because of the test machine force and velocity limitations, two modules were tested as representative of an entire damper. Two pairs of modules were tested for each different size of damper. The test modules, while having the same layer arrangement and total thickness of VE material, had a smaller shear area than the dampers for installation. This meant that full-scale displacements could be applied to the test specimens, but with corresponding lower forces.

The test program, while in general accordance with FEMA-273, also included MCE earthquake input motions that were determined from the design analyses. The production damper test program was established using ASTM-defined statistical sampling techniques, which permit only a portion of a production lot to be tested, depending on the accuracy of agreement between test results for different specimens. The prototype damper tests were successfully performed in April 1997 using the EERC damper test machine (described earlier), and the retrofit construction will be completed by early 1998.

OTHER TESTING ISSUES

With the move toward more dynamic testing, particularly for viscous and viscoelastic damping devices, energy issues become very important. The definition of any test consisting of multiple cycles of dynamic loading for a device should include an assessment of the test input energy in comparison with the energy associated with the design earthquake. In many cases, it is possible to specify a sinusoidal displacement or constant velocity test of about 6-10 cycles that would subject the device to a much larger input energy than the design earthquake input energy. The reasonableness or otherwise of such a test, and the ability of the device to adequately sustain such an input, should be carefully considered. A secondary input energy consideration is the cumulative energy input to a device by a series of tests in quick succession. Temperature build-up in a device due to multiple tests may necessitate cooling between tests or periodically throughout the test program. The time associated with cooling may actually dominate the total time required to perform the test program.

SUMMARY

The primary objective of any prototype isolator or damper testing program should be to confirm the device properties used in the design. If the as-tested properties are appropriately accounted for in the design process then a rigorous and reasonable design will result. Production tests should serve a specific and clearly-defined QA/QC purpose.

The costs of testing are substantial, and should not be overlooked. Design codes that address testing of isolation and damping devices generally permit some interpretation in establishing a test program for a given project. Careful consideration should be given to the code-mandated tests and additional project-specific needs, if any. Acceptance criteria can often be defined in more than one way, and these should be carefully prescribed on the basis of the design assumptions and actual device behavior characteristics.

With the commissioning of Caltrans' SRMD Test System in 1998, it is fair to say that the physical capability to test full-size isolation and damping devices in real-time exists, at least in the near future. The challenges for engineers will remain, however, to define reasonable, thorough and cost-realistic test programs that address the specific needs of individual projects.

ACKNOWLEDGEMENTS

The County of Los Angeles, the Golden Gate Highway and Transportation District and the City of Los Angeles are acknowledged for the use of information pertaining to their projects.

REFERENCES

AASHTO, Revision to the Guide Specifications for Seismic Isolation Design, *Ballot Version*, T3 Committee, May, 1997.

ASCE Standards Committee on Testing of Base Isolation Systems, ASCE Standard for Testing Seismic Isolation Systems, Units and Components. *Draft D Ballot Version*, January, 1997.

Aiken, I.D. and Kelly, J.M., Cyclic Dynamic Testing of Fluid Viscous Dampers. *Proceedings, Caltrans Fourth Seismic Research Workshop*, Sacramento, California, July, 1996.

FEMA, NEHRP Guidelines for the Seismic Rehabilitation of Buildings. *FEMA-273 Ballot Version*, Federal Emergency Management Agency, Washington, D.C., September, 1996.

HITEC (Highway Innovative Technology Evaluation Center), Guidelines for the Testing of Seismic Isolation and Energy Dissipation Devices. *CERF Report HITEC 96-02*, March, 1996.

ICBO, Uniform Building Code. International Conference of Building Officials, Whittier, California, April, 1997.

Mellon, D., Caltrans' Proposed Testing of the Seismic Response Modification Devices for the Toll Bridge Retrofit Program. *Proceedings, Second National Seismic Bridge Conference,* Sacramento, California, July, 1997.

Shenton, H.W., Guidelines for Pre-Qualification, Prototype, and Quality Control Testing of Seismic Isolation Systems. *NISTIR 5800*, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, January, 1996.

Sultan, M. and Sheng, L.-H., Caltrans/FHWA Program for the Performance Testing of Seismic Isolation and Energy Dissipation Systems. *Proceedings, National Seismic Conference on Highways and Bridges*, Federal Highway Administration, San Diego, California, December, 1995.