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Cyclic Dynamic Testing of Fluid Viscous Dampers

by

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ABSTRACT

This paper provides an overview of an extensive dynamic testing program of fluid viscous dampers that was conducted as part of the seismic retrofit of the Golden Gate Bridge. The effort represents one of the most comprehensive testing programs performed to date of fluid viscous dampers for seismic applications.

Dampers from four manufacturers, two U.S. and two European, were included in the testing program. The test dampers were of a reduced scale compared to the full-size devices, having a maximum force output of approximately 100 kips at a peak velocity of 20 inches/second, and a displacement range of +/- 6 inches.

The main aspects of the testing program are described and some typical results are presented. Conclusions drawn from the test program and general observations on the testing of large dampers are also presented.

INTRODUCTION

Overview

The seismic retrofit design that has been developed for the suspension spans of the Golden Gate Bridge includes fluid viscous dampers. Detailed descriptions of the overall retrofit design and the basis for the selection of viscous dampers are provided by [Rodriguez and Ingham, 1995] and [Ingham et al., 1995]. The dampers address several vulnerabilities:

- They reduce the longitudinal relative displacements at the expansion joints and wind locks, thus eliminating the possibility of impact between the suspension spans and the towers,
- They also serve to reduce the tower stresses due to longitudinal displacements, and provide a reduction in stiffening truss demands, and
- They will be used to transversely isolate the south side span from the south pylon to avoid coupled vibration of the two systems.

In addition to their seismic benefits, the dampers also have the beneficial effect of controlling wind oscillations due to buffeting.

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Need For A Damper Testing Program

Fluid viscous dampers were identified as the type of energy dissipator that was most able to meet the demanding load and displacement requirements for the retrofit. In the design process, it was recognized that there is little precedent for the use of viscous damping devices in the seismic retrofit of bridges, at least in the United States, and that a comprehensive testing program would be required to verify that fluid viscous dampers could provided the desired performance.

The test program described in this paper was undertaken at the University of California at Berkeley Earthquake Engineering Research Center (EERC) specifically to validate the assumed mechanical characteristics of reduced-scale viscous dampers and ultimately to provide a basis for the technical pre-qualification of manufacturers to bid on the Golden Gate Bridge Seismic Retrofit Project.

On a broader level, the HITEC test program, sponsored by the Federal Highways Administration and Caltrans [Sultan and Sheng, 1995], has also been established to identify the characteristics of a range of energy dissipators and seismic isolation devices and attempt to address the rapid growth in the interest of energy dissipation and also seismic isolation, particularly for retrofit applications.

TEST DAMPERS

All four of the dampers in the testing program were uniaxial fluid viscous dampers. They were essentially cylindrically-shaped units, each with a piston and piston rod moving relative to the main body of the damper. End connections consisted of spherical bearings. The test dampers were reduced-scale with respect to the full-size units that will be used in the retrofit of the bridge. The dampers needed to be scaled down to achieve a reasonable size of device for the testing program.

Three of the four dampers tested were designed for a force-velocity relationship of

$$F = 22.4 \cdot v^{0.5} \text{ kips} \qquad \text{(Eq. 1)}$$

and one damper was designed with a three-stage force-velocity relationship, with

$$F = 77 \cdot v^{0.1} \text{ kips} \qquad \text{(Eq. 2)}$$

for velocities greater than about 1 in./sec. All of the test dampers were designed to produce approximately 100 kips at a velocity of 20 in./sec., and to have a displacement range of ±6 in These values represent scale factors of 1:6.5 for force, 1:4 for displacement, and 1:3.75 for velocity.

There are a number of important details of fluid viscous dampers that need to be considered when testing at a reduced scale. The most important factors are:

- Pressure, both ambient and operating
- Design of orifice(s)
- Design of sealing system(s)
- Type of viscous fluid

- Design quantities such as yield, ultimate and proof stress limits

The damper manufacturers were required to ensure that the basic functioning and characteristics of the reduced-scale and full-size dampers be as similar as possible, in terms of the above and any other important factors, so that the reduced-scale testing would be meaningful and give results indicative of the behavior of the full-size devices

TEST PROGRAM

The objectives of the test program and some description of the types of tests are provided in the following sections. The test program, and the results for all four of the dampers tested, are described in detail in [Aiken and Kelly, 1995].

OBJECTIVES

The main objectives of the test program were to:

- Evaluate the performance of the dampers under a range of cyclic constant-velocity loading conditions to verify their constitutive relationships;
- Evaluate the damper constitutive relationships under a wide range of temperature, cyclic displacement amplitude, and frequency;
- Evaluate the energy dissipation capability of the dampers under sinusoidal displacement loading;
- Subject the dampers to a very large number of large-amplitude, low-velocity cycles to evaluate the wear characteristics of the seals; and
- Subject the dampers to a Maximum Credible Earthquake (MCE) displacement loading determined from design analyses.

DESCRIPTION

The test program developed to meet the above objectives consisted of about 50 tests and required about two weeks of testing for each damper. The test program consisted of four main parts:

1. Initial cyclic tests
2. Endurance/seal wear test
3. Cyclic tests
4. Seismic displacement input test

Other tests were also performed to identify the friction resistance of the dampers.

The main characteristics of these tests were as follows:

Initial Cyclic Tests and Cyclic Tests. Most of the testing program consisted of constant-velocity cyclic tests performed for a range of velocity, amplitude, and temperature. The applied velocity varied from 1 to 20 in./sec. (1, 2, 5, 10, 15 and 20 in./sec. nominal) with amplitudes of ±0.6 , 1, 3, and 6 in. and temperatures of 40 $^{\circ}$F, 70 $^{\circ}$F and 125 $^{\circ}$F. The very first tests of the dampers consisted of a series of initial cyclic tests, performed at 70 $^{\circ}$F, intended to provide a characterization of the dampers prior to the endurance test. The endurance test was then performed, followed by the same set of cyclic tests again. Thus, the two sets of cyclic tests could be compared to evaluate any change in damper behavior due to the large number of loading cycles in the endurance test. Some additional constant-velocity tests were performed at 70 °F, and then a selected series of tests was repeated at both 40 °F and 125 °F. All of the cyclic tests consisted of five cycles of loading. Because of the temperature chamber in place around the dampers for all of these tests, a lateral load to simulate gravity was not applied.

Endurance/Seal Wear Test. This test was intended to be an endurance/wear test of the dampers' sealing systems. The test consisted of 1800 cycles of loading at a constant velocity of 0.5 in./sec. and an amplitude of ±6 in. The test was performed without the temperature control chamber in place around the dampers, and with a lateral load applied to the dampers to simulate gravity loading. The endurance test had a total duration of 24 hours, and took 3-4 days to complete for each damper.

Sinusoidal/Energy Dissipation Tests. In addition to the constant-velocity cyclic tests, a number of sinusoidal tests were performed to evaluate the energy dissipation capacity of the dampers. The sinusoidal tests were at amplitudes of 2, 4 and 6 in., and peak velocities of 5, 10 and 20 in./sec. All of the sinusoidal tests but one consisted of five cycles of loading; the remaining test was a 10-cycle test of ±6 in. amplitude and a peak velocity of 20 in./sec. This test was the most severe of the entire test program, having an input energy-equivalent of approximately two MCEs.

Seismic Displacement Input Test. The final test of the dampers consisted of an MCE displacement input scaled from the global analysis of the Golden Gate Bridge. This analysis was performed for both of the types of dampers tested (i.e., both 0.5-power and 0.1-power dampers). A lateral load was applied to the dampers in this test.

Friction Test. A very-slow one-directional force-control test was performed to evaluate the friction resistance of the dampers. This test involved loading the damper very slowly until the damper piston rod began to move. The test was performed in both tension and compression directions of loading.

The entire test program (not including the endurance test) constituted a very large total energy input to the dampers - approximately 21 times the energy corresponding to the computed Maximum Credible Earthquake (MCE) response. As such, care was required in the execution of the test program to ensure that tests performed in close succession did not excessively over-heat the dampers. Tests were performed in groups, such that the total energy input to the damper in a group corresponded approximately to the MCE energy.

For the tests performed at a specific temperature, the dampers were pre-conditioned at that temperature for at least 12 hours before the start of testing. The dampers were permitted to cool between each group of tests, until the damper external temperature had stabilized close to the nominal test temperature. In some cases, the temperature chamber cooling system was used to accelerate the cooling of the dampers.

TEST MACHINE

A test machine was designed and fabricated specifically for the damper test program. The test machine was designed to utilize the full power output of the EERC hydraulic pumping system, and this in turn defined the maximum characteristics for the design of the test dampers. The machine tests dampers in the upright position, and consists of two 60-kip double-acting hydraulic actuators on either side of the test damper (Figure 1). Each actuator is driven by a 200 gpm servo-valve. A lateral load can be applied to the damper to simulate gravity, and for elevated or reduced temperature test conditions the damper is enclosed in a sealed and temperature-controlled chamber. Liquid nitrogen was used to reduce the chamber temperature, and industrial-grade heating tape with an output of about 2 kW was used to raise the temperature. Circulation fans were used to ensure a near uniform temperature distribution within the chamber. A uniaxial force transducer connected to the bottom end of the damper was used to measure the damper force, and the damper displacement was recorded by a wire potentiometer mounted directly on the side of the damper and connected to the top end of the damper piston rod.

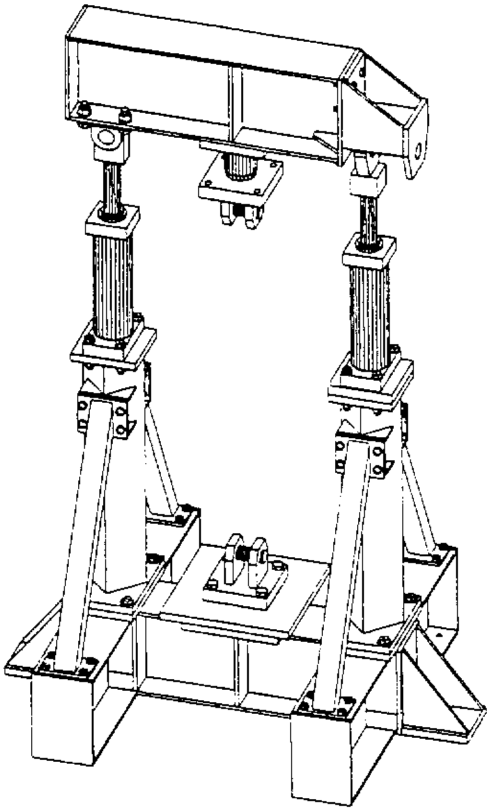

Figure 1. Damper Test Machine

TEST RESULTS

In total, about 200 tests were performed on the four dampers. Some results for one of the dampers are presented and discussed here; the complete set of results for all four dampers are presented in detail in [Aiken and Kelly, 1995].

A typical damper force-displacement plot for a constant-velocity test is shown in Figure 2. The plot is for a five-cycle test with a target constant velocity of 10 in./sec. It can be seen that the damper force output was very stable and repeatable in this test. Note that because the damper force is a function of velocity and that the applied velocity was approximately constant, the damper force is therefore also approximately constant across the test displacement range. This obviously would not be the case for a sinusoidal displacement loading. For each of the constant-velocity tests, an "average" value of damper force as a function of velocity was determined, and then compared against the target force-velocity relationship. Figure 4 summarizes all of the 70 °F constant-velocity tests before and immediately after the endurance test. The solid line shown in the figure is the target force-velocity law (Eq. 1). It can be seen that the endurance test apparently had little effect on the force-velocity behavior of the damper. None of the four dampers showed any identifiable change in behavior as a result of the 1800-cycle endurance/seal wear test. Figure 5 summarizes the results for all of the constant-velocity tests performed on the damper, at 40, 70 and 125 °F. Again, the solid line shown in the figure is the target force-velocity law (Eq. 1). It can be seen, that in general, there is good agreement between the actual and target damper behavior.

Other damper characteristics that were evaluated in the test program included: the change in damper force output over the duration of a significant energy input; the predictability of the damper behavior under severe seismic loading; and the frictional resistance of the dampers.

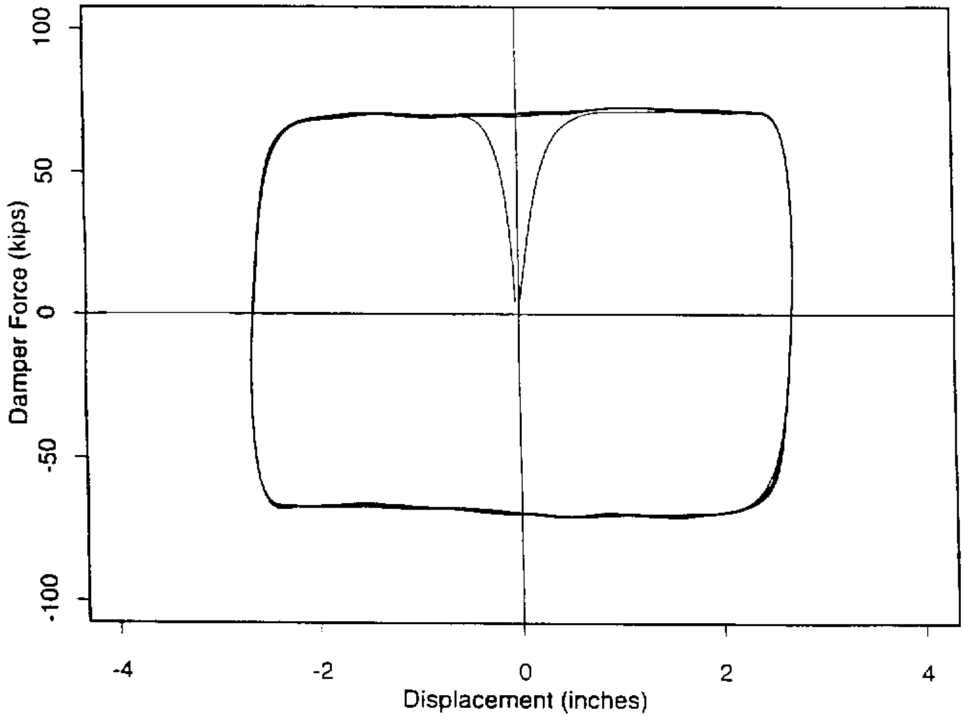

Figure 2. Typical Damper Force versus Displacement Plot for a Cyclic Constant-Velocity Test (5 cycles, 10 in./sec., +/- 3 in., 70 °F)

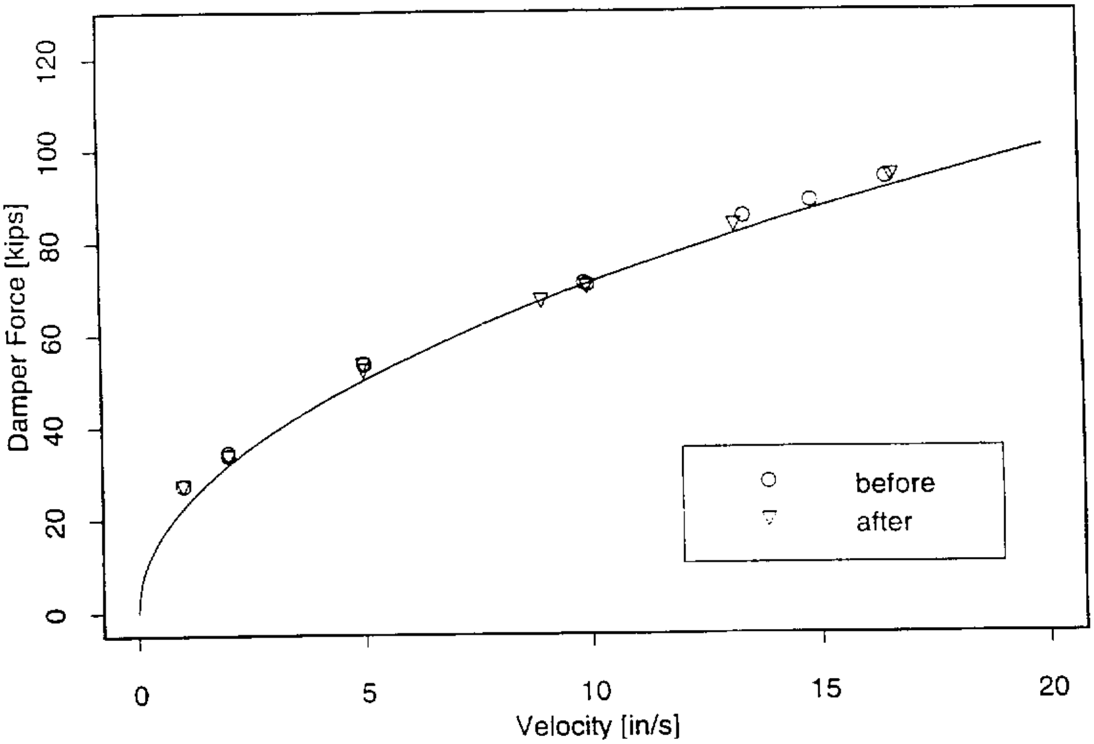

Figure 3. Damper Force versus Velocity from 70 °F Cyclic Constant-Velocity Tests Before and After the Endurance Test

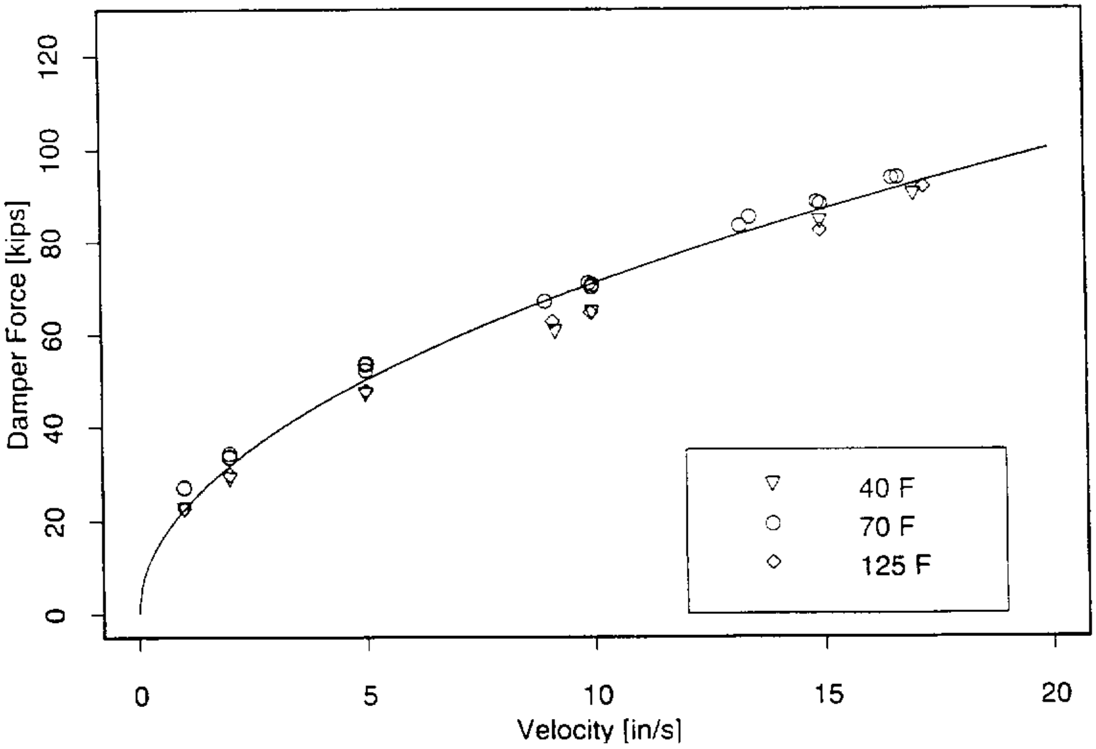

Figure 4. Damper Force versus Velocity for all Cyclic Constant-Velocity Tests

CONCLUSIONS

Summary

The test program described represents one of the most comprehensive efforts to date to evaluate fluid viscous dampers for seismic applications. Dampers from four different manufacturers were subjected to an extensive testing program to evaluate their dynamic characteristics. Cyclic dynamic testing, with constant-velocity and sinusoidal displacement inputs, and performed at different temperatures, allowed the behavior of the dampers to be investigated over a wide range of loading conditions. In general, the dampers all performed well. As a result of the test program, all four manufacturers were pre-qualified to bid to supply dampers for the Golden Gate Bridge Seismic Retrofit.

Other Comments

The power demands associated with the cyclic dynamic testing of large viscous dampers may be very large, particularly for large displacement conditions. Unlike dampers with displacement-based force output characteristics (where it may be reasonable to test at a relatively slow rate of loading), the velocity-based force output characteristic of viscous dampers requires that the loading rate be properly simulated to achieve the correct damper force response. In the case of the Golden Gate Bridge, the peak and average power outputs of the full-size dampers, for the MCE earthquake excitation, are about 7250 horsepower and 350 horsepower (5.41MW and 0.26 MW), respectively. Such requirements are well in excess of the capabilities of existing testing facilities.

The ETEC facility, where the HITEC test program is currently being conducted, and a damper manufacturer's new test machine both make extensive use of accumulators to meet the transient hydraulic power demands. Even with this approach, it is unlikely that any practical test facility will ever be capable of subjecting dampers of the size envisaged for the Golden Gate Bridge to loadings as severe as those anticipated for the MCE. This means that rigorous and reliable alternative testing methods must be utilized. One such method, drop or impact testing, is already used in some cases, and has been compared against cyclic dynamic testing (Taylor and Constantinou, 1994). Cyclic dynamic testing of full-size dampers may be possible if the cyclic displacement amplitudes are kept small. The suitability of a particular test method for specific types of dampers should also be carefully assessed; for example, impact versus cyclic testing for dampers that incorporate relief valves. Importantly, additional work is required to establish the consistency of results obtained using different types of test methods.

ACKNOWLEDGEMENTS

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