Application of Fluid Viscous Dampers to Earthquake Resistant Design

by Michael Constantinou

Abstract

Damping devices based on the operating principle of high velocity fluid flow through orifices have found numerous applications in the shock and vibration isolation of aerospace and defense systems. These previous uses include the attenuation of weapons grade shock, including airburst, water surface, and underwater detonations; with applications including individual weapons or electronic systems, ship decks, and command, control and communications equipment for all branches of the military. Other previous aerospace/defense uses include the attenuation of aircraft, spacecraft and ship vibration, plus wind and airblast isolation on large rocket launch gantries, such as the Space Shuttle.

In 1991, a cooperative effort between NCEER and Taylor Devices, Inc. of North Tonawanda, New York began to adapt this defense technology for hazard mitigation applications on buildings and bridges. After extensive technical interchange, a series of experiments was performed to demonstrate the benefits of fluid viscous damping devices as part of either a bracing arrangement or to augment existing design base isolation bearings. Steel moment frame and reinforced concrete building models and a steel bridge model were tested, and all exhibited improved resistance to a variety of seismic loads. For example, a three story steel building frame model without the dampers was found to be on the onset of yielding under an earthquake of only one-half the magnitude of the 1940 El Centro earthquake. With the bolt-on addition of six small fluid viscous dampers, the same structure withstood 150% of the El Centro earthquake, without any damage, for an overall three-fold enhancement of seismic capacity. The particular design of fluid viscous dampers used for this experiment was the same as that provided by Taylor Devices for use on the B-2 Stealth Bomber. Similar successful experiments on a reinforced concrete building model utilized damping devices used on the U.S. Navy's Tomahawk Cruise Missile.

A series of papers and reports published from October 1992 to August 1994 generated interest in the structural engineering community, many of whom had specific and immediate applications for this technology. In late 1993, Taylor Devices received a $4,900,000 contract from the County of San Bernardino, California, to provide large damping devices for five buildings of a new medical center located close to two major fault lines. This $680 million dollar project required a very high damping capacity isolation system, and the fluid viscous dampers were chosen as the most economical solution.

At this time, Taylor Devices has several other projects pending for this technology, is in the process of a $1.3 million facilities expansion in Western New York, and has created 25 new full time jobs.

Collaboration

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Andrei Reinhorn
University at Buffalo

Douglas P. Taylor
Taylor Devices

Shunji Fujii
Susumi Okamoto
Daisuku Ozaki
Taisei Corporation

Objectives and Approach

The research on the development of fluid viscous dampers for seismic applications was performed to accomplish three major objectives. The first was to demonstrate by analysis and experiment that fluid viscous dampers can improve the seismic capacity of a structure by reducing damage and displacements and without increasing stresses. The second was to develop mathematical models for these devices and demonstrate how these models can be incorporated in existing structural engineering software codes. Finally, the third was to thoroughly evaluate the reliability and environmental stability of the dampers for structural engineering applications.

The approach used to adapt fluid viscous dampers for hazard mitigation applications began with computer simulations of structures incorporating this technology to establish parametric baselines for a series of experiments. Experiments were performed at the component level to verify proper performance. Shake table tests were then performed with both steel moment frame and reinforced concrete building models and an isolated bridge model. Mathematical models were then developed to analytically predict the observed response and to assist in the interpretation of the experimental results.

This research task is part of NCEER's Building Project. Task numbers are 90-2101, 90-2102B and 91-5411B.

Accomplishments

Fluid damping devices are well proven by the test of time, with production of dampers in the 50 kip range dating to the mid-1890's. The earliest well documented use of large fluid dampers was by the military, to attenuate recoil transients on large caliber artillery pieces.

Taylor Devices, a small business employing 90 people in North Tonawanda, New York, began production of fluid viscous damping devices for military use in 1955. The company's first application within a structure was in 1959, on the Chance-Vought F-8 Crusader Fighter Aircraft. Taylor's dampers were installed into the tail section of this carrier based, supersonic jet, within the aircraft's arresting hook. When the aircraft lands, the arresting hook engages cables on the aircraft carrier deck, and the fluid damper is used to prevent shock loads from being transmitted to the aircraft. By 1990, Taylor Devices' damping devices were used in numerous aerospace structures in addition to applications in steel mills and power plants.

Comparatively, various energy dissipating devices have been proposed as add-on devices to buildings for improving seismic resistance. Most notable of these devices are mild steel dampers, frictional dampers and constrained-layer viscoelastic shear dampers. Experimental studies demonstrated that these dampers are effective in reducing drifts while maintaining shear forces at the same level or, under certain conditions, less than those of structures without dampers. However, due to their hysteretic or strong viscoelastic behavior, these devices introduce a substantial axial force component which is in phase with the maximum bending moment in columns.

Fluid viscous dampers may be designed to behave as linear viscous devices and, thus, they introduce damping forces which are out-of-phase with drifts and column bending moments. Accordingly, they can be very effective in reducing drifts and shear forces without introducing axial column forces which are in-phase with column bending moments. These significant properties of fluid viscous dampers have been confirmed in shake table testing of a series of one-story and three-story model structures. The experimental results demonstrated reductions of drifts and shear forces of the order of two to three in comparison to the response of the models without dampers for a wide range of earthquake input motions.

Furthermore, fluid dampers may be used as elements of seismic isolation systems for enhancing their energy dissipation capability. Tests have been conducted on a seismically isolated bridge model with and without fluid viscous dampers. The experimental results demonstrated a simultaneous reduction of isolation bearing displacement and force transmitted to the bridge superstructure. Moreover, the experiments showed that the isolated bridge with fluid dampers had a marked insensitivity to the frequency content of input motions.

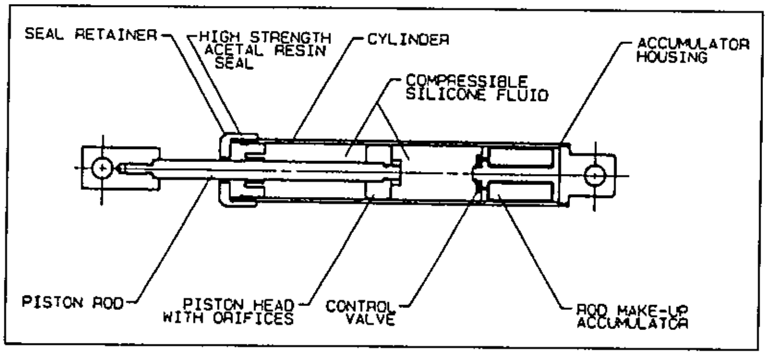


Figure 1
Construction of Fluid Damper

Construction and Properties of Fluid Dampers

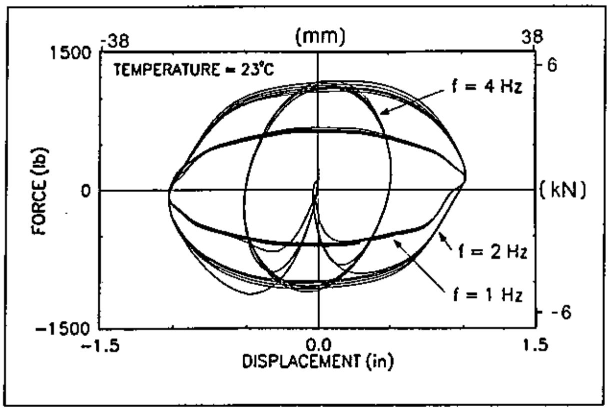
The construction of a fluid damper is shown in figure 1. It consists of a stainless steel piston with bronze orifice head and an accumulator. It is filled with silicon oil. The piston head utilizes specially shaped passages which alter the flow characteristics with fluid speed so that the force output is proportional to $|\dot{u}|^{\alpha}$, where $\dot{u}$ = piston rod velocity and α = predetermined coefficient in the range of 0.5 to 2. A design with α = 1 results in a linear viscous damper.

This behavior dominates for frequencies of motion below a predetermined cutoff frequency (related to the characteristics of the accumulator valves). Beyond this frequency, the fluid dampers exhibit strong stiffness in addition to substantial ability to dissipate energy. The existence of the cutoff frequency is desirable, since the lower modes of vibration are only damped while the higher ones are both damped and stiffened so that their contribution is completely suppressed.

The orifice flow may be compensated by a passive bi-metallic thermostat which allows operation of the device over a temperature range of -40°C to 70°C. The performance characteristics of the device are considered state-of-the-art. The described device with fluidic control orifices, bi-metallic thermostat and special silicon oil originated within products used in classified applications of the U.S. Air Force. Over 30,000 of these devices are currently in service in the United States.

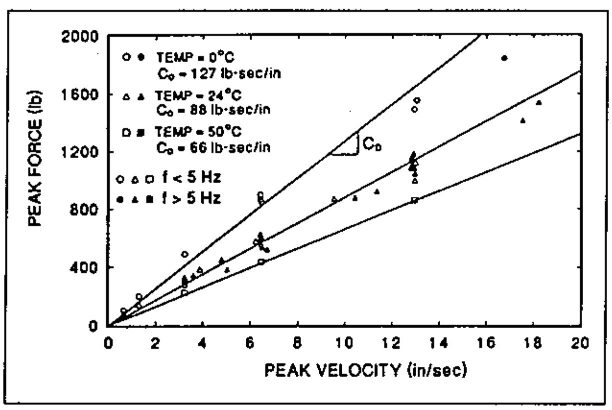
The fluid dampers tested initially had all of the aforementioned characteristics and they were designed to behave as linear viscous dampers. Each had stroke of ± 51 mm, length of 280 mm and weighed 10 N. They were used in the tested building model described in the sequel and a bridge model.

Figure 2 shows recorded loops of force vs. displacement of one damper at a temperature of 23°C. The purely viscous nature of the device is apparent. For frequencies above about 4 Hz, the dampers exhibited stiffness. Figure 3 shows recorded data on the peak output force vs. peak velocity of input at temperatures of 0°, 25°, and 50°C. It may seem that the experimental results may be fitted with straight lines of slope C_o which



■ **Figure 2**
Loops of Force vs. Displacement of Fluid Damper.

represents the damping constant. The behavior of the device was completely unaffected by the amplitude of motion. The values of C_0 in figure 3 demonstrate the small dependency of the characteristics of the device on temperature.

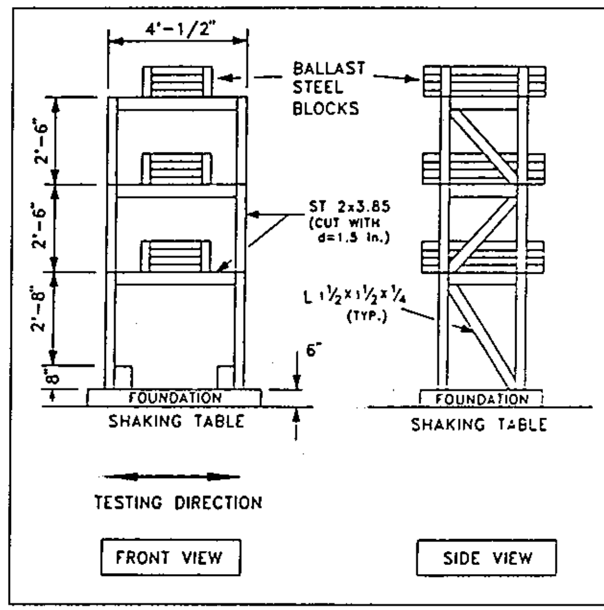


■ **Figure 3**
Mechanical Properties of Tested Fluid Dampers.

Experimental Models

The experimental models included a three-story steel structure shown in figure 4. At quarter length scale, the model weighs 28.5 kN, (equally distributed to the three floors). The model was tested without dampers and with dampers installed as braces at an angel of about 35°. Tests were conducted with four dampers installed at the first story and with six dampers installed in pairs at each story.

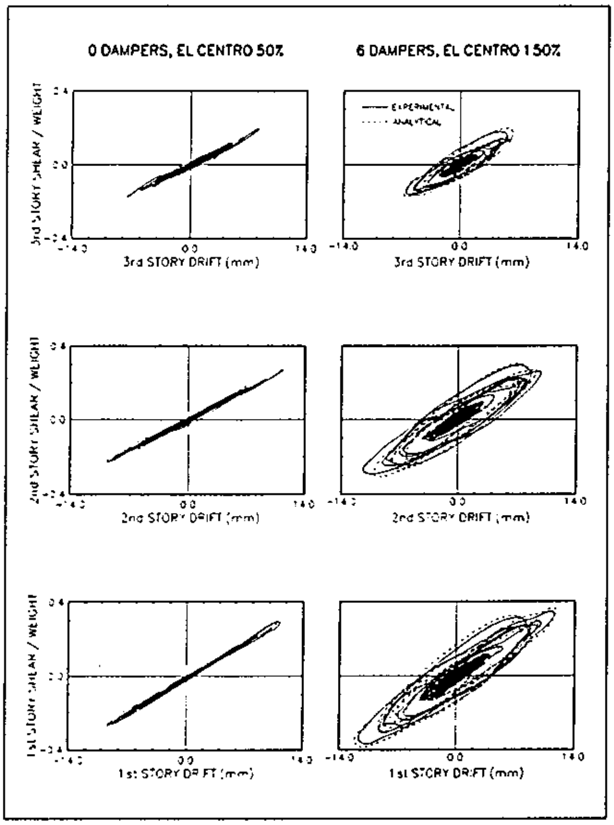
Typical test results are shown in figure 5, where the addition of six dampers to the model allows the earthquake magnitude to be increased by 300%, without causing any significant increase in either stress or deflection.



■ **Figure 4**
Tested Three-story Model Structure.

The San Bernardino County Medical Center

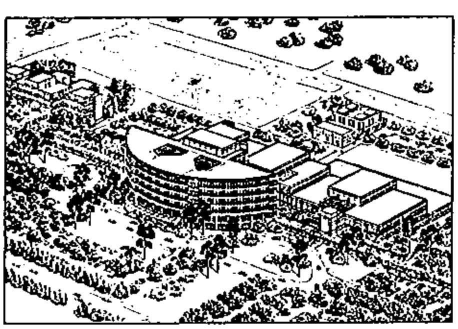
The five buildings of the San Bernadino County Medical Center are shown in figure 6 and require a total of 233 fluid viscous dampers, each having an output of 320,000 lbs. with an available displacement of 48 inches. Each damper is 14 feet in length and weighs nearly 3,000 lbs. The damper design is illustrated in figure 7. No seismic test facility in the U.S. can test this device, each of which generates an energy dissipation level of 3,000 horsepower at a speed of 60 inches



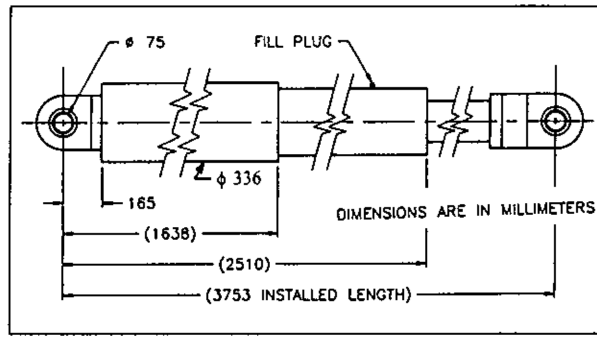
■ **Figure 5**
Response of Three-story Model With and Without Fluid Dampers.

per second. The 60 in/sec. speed can be compared to the 51 in/sec. maximum peak ground velocity for the damaging Northridge earthquake of 1994, and shows the tremendous seismic capacity desired for the medical center.

Professor Constantinou and Douglas Taylor worked closely with the building owner, the Architect-Engineer, and the California Office of State Hospital Planning and Development to formulate an accept-

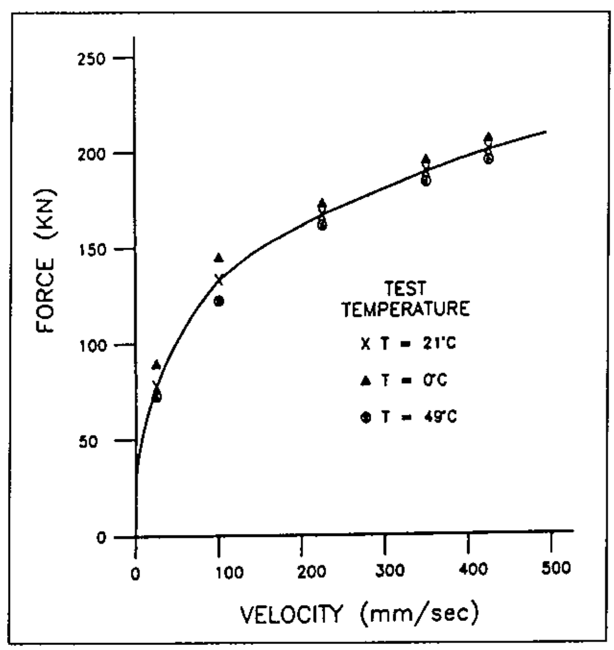


■ **Figure 6**
Artist's View of San Bernardino County Medical Center.



■ **Figure 7**
Construction of Fluid Viscous Damper for San Bernardino County Medical Center.

able testing program for this project. The program which evolved required both the facilities of the University at Buffalo and Taylor Devices. The method accepted by the owner involved cyclic testing of a 50,000 lb. output force scaled damper at the University at Buffalo, followed by heavy weight drop testing of the same device at Taylor Devices. Once test machine correlation was established, it would then be possible to test the full-sized device using the maximum falling weight capacity of Taylor Devices' test machine,



■ **Figure 8**
Force-Velocity Relation of Tested Scaled Fluid Viscous Damper for San Bernardino County Medical Center.

normally used to simulate nuclear weapons detonations for the military. Test results for the 50,000 lb. output force device are presented in figure 8. The figure shows the peak force-velocity relation of the device, determined in cyclic testing at temperatures of 0°, 21°, and 49°C. The device exhibits nonlinear viscous behavior and remarkable insensitivity to temperature.

Conclusion

Fluid viscous damping devices have been proven to be a reliable and affordable solution to seismic design problems, and have been tested on both steel and reinforced concrete building models. The successful relationship between NCEER and Taylor Devices has allowed technology from major defense programs of the Cold War years to find new uses towards enhancing public safety as the next century approaches.

Personnel and Institutions

Professor Michael C. Constantinou of the University at Buffalo was the primary collaborator for NCEER. Douglas P. Taylor of Taylor Devices was in charge of Taylor Devices' project effort.

Other collaborators from NCEER included Professor Andrei Reinhorn, and graduate students M.D. Symans and P. Tsopelas. Moreover, Dr. S. Fujii, S. Okamoto and D. Ozaki of Taisei Corporation, Japan collaborated on the bridge testing. On the San Bernardino Medical Center Project, tests were performed at the University at Buffalo. For these tests, collaboration was additionally provided by the County of San Bernardino, and Engineers-Architects KPFF, Bobrow-Thomas and Associates, and Peck-Jones.

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