Courtesy of Brett Drury.

INNOVATION

THE MEANS TO THE END

By Jay Love, S.E.

In 2007, Sutter Health brought together its Integrated Project Delivery (IPD) team to produce its new San Francisco flagship hospital, California Pacific Medical Center (CPMC). At the first team meeting, Sutter challenged the IPD team, consisting of SmithGroupJJR, the design sub-consultants, the general contractor, HerreroBoldt and its major subcontractors, to bring innovation to the project to provide the best hospital possible within the Sutter-established budget. Specifically, Sutter challenged Degenkolb Engineers as the Structural Engineer of Record to examine the various seismic force resisting systems available to select the highest performing system that provided the greatest value to Sutter. Working as a team, Degenkolb defined value as providing improved seismic performance at a lower cost on the same schedule. For this project, improved seismic performance was defined as:

1) Reduced floor inertial accelerations at the same interstory displacement.
2) Decreased inelastic demand in the primary structural columns and girders.

The new CPMC hospital at the Van Ness and Geary Street campus is currently under construction. The hospital, when finished in Q1 of 2019, will consolidate the acute care services from two older CPMC campuses whose older buildings must be replaced in accordance with the California Senate Bill 1953 Regulations that followed the 1994 Northridge Earthquake. The new hospital will provide Women & Infants and Adult Care services in eleven stories of programmed space. Under the hospital, there will be two floors of parking. The central utilities plant is located on the top story, with HVAC equipment and emergency generators on the roof.

The primary lateral force resisting system above grade is a welded steel moment resisting frame with a supplemental damping system. Below grade, the perimeter concrete basement walls provide lateral resistance to the foundation. A total of 119 *viscous wall dampers*, or VWDs, provide the supplemental damping to the moment resisting system. Each floor above grade has a minimum of two dampers on two grid lines in each direction of the building. Additional dampers are installed on floors where the seismic response is greater, particularly at the mid-height stories of the building.

This system was jointly chosen by the IPD team after Degenkolb presented comparison designs for a conventional welded steel moment resisting system, a base-isolated system with a steel braced frame superstructure, and a damped steel moment resisting frame system. At this point in the process, the damped moment frame provided significant savings in steel material over both the conventional moment resisting frame and the based isolated system solution. In addition, the simplicity of the system was greatly preferred over the complexities of the moat system that would be necessary with the base-isolated solution. A third, but not inconsequential, consideration was that the viscous wall dampers could be strategically located between the windows

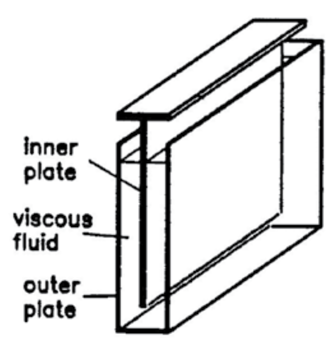

Figure 1. Schematic viscous wall damper.

on the exterior façade, providing unobstructed access to exterior light in the patient rooms.

Supplemental Viscous Damping

Structural engineers practicing in earthquake engineering are accustomed to providing strength and stiffness to structures to resist dynamic loading and limit displacement. The common assumption is that damping is a constant, typically 5% of critical damping (although in some structures, the damping may be on the order of 2% or less.) The standard equations of motion that govern the elastic analyses deal primarily with the interrelationship of first and third terms, mass and stiffness, to define the expected response of the structure, essentially ignoring the second, or damping, term.

$$ma(t) + cv(t) + kx(t) = -ma_g$$

Supplemental damping can increase the damping by a factor of four, and thereby decrease the required stiffness in order to achieve similar levels of interstory drift. This is especially significant when considering that the seismic design of steel moment resisting frames is frequently controlled by strict code-required interstory drift limitations, especially for Occupancy Category IV buildings such as hospitals. When designing a conventional moment frame structure with a 1% interstory drift limitation (*ASCE 7-05, Minimum Design Loads for Buildings and Other Structures*), the steel columns and girders are often much larger than required for strength in order to control the interstory drift. Supplemental damping can reduce the oversizing of the steel system yet still maintain strict drift limitations.

In the United States, supplemental damping has been used for seismic design, most commonly in conjunction with base isolation systems. The supplemental damping in such systems provides some control of the lateral displacements at the isolation plane. These damping systems are commonly cylindrical fluid dampers that look much like car shock absorbers.

Viscous Wall Damper Development

Viscous wall dampers, shown schematically in *Figure 1*, were developed in Japan in the late 1980s by engineers at Sumitomo Construction Company, Ltd. (Arima, 1988). As part of the development, a four-story full scale prototype test frame was built on a shake table in the Building Research Institute in Tsukuba City in order to compare the viscous wall damper system with conventional braced frames structures, steel moment frame structures, and a lead-rubber bearing base-isolated system. The shake table tests showed a 50% reduction in floor accelerations at the roof when compared to the conventional systems. The tests also showed a 66% reduction in relative displacement compared to the conventional moment frame. (The displacements were similar between the viscous wall damped system and the braced frame system, as would be expected for stiff braced frames.)

In addition to shake table testing with scaled earthquake accelerations, the viscous wall damped prototype building experienced four real earthquakes between late 1987 and early 1988, with magnitudes varying from 4.5 to 6.7 at distances of 44 to 56 miles (70 to 90 km). The engineers used these real-world earthquakes to validate the results obtained from the shake table tests.

Figure 3. Production test rig in the DIS shop.

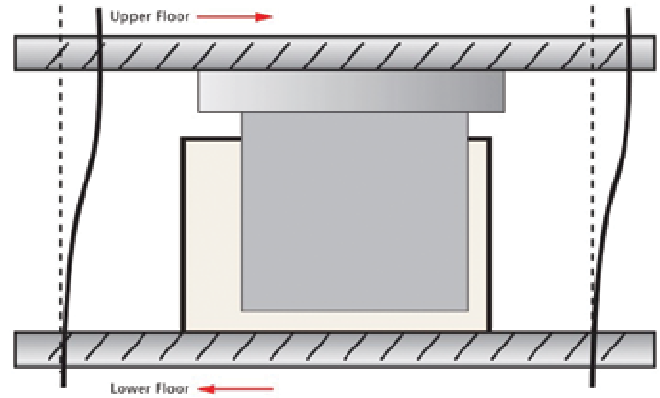

Figure 2. Viscous wall damper in a moment resisting frame.

In 1992, viscous wall dampers were installed in the Sato Building in Tokyo. Today, the wall damper system has been used on more than 100 projects.

Dynamic Isolation Systems, Inc., well-known for its development of lead-rubber base isolators in the United States, had teamed with Aseismic Device Corporation, Ltd., a subsidiary of Sumitomo, to bring this technology to the United States. ADC, Ltd. was formed in 1996 to bring the various seismic force reduction technologies to market.

A typical viscous wall damper is comprised of a simple steel tank, or wall section, connected to the floor girder below, with a vertical steel plate or vane(s) that is inserted into the steel box and connected to the floor girder above. The vane is free to translate horizontally (*Figure 2*) through a polymer viscous fluid in the tank.

The viscous fluid, polyisobutylene, a synthetic elastomer, provides the velocity-related damping when the vane pushes its way through the fluid as the floors displace horizontally from one another. The elastomer fluid is non-toxic, odorless, non-flammable material with a viscosity of about 95,000 poise at room temperature. The damper output force, F_d, is proportional to the damping coefficient, C_w, and the velocity, v(t) raised to an exponent, a. The damping coefficient and velocity exponent are both experimentally determined. The wall damper force depends on interstory velocity, displacement and, to a lesser degree, temperature. For buildings such as hospitals where the internal temperature is maintained by sophisticated HVAC systems with backup power, the temperature dependence is relatively small.

Analysis and Design

The analysis and design of the CPMC hospital were based on the 2007 Edition of the *California Building Code* (CBC). The CBC references ASCE 7-05 requirements for minimum design loads including gravity, seismic, and wind forces. In addition to the conventional requirements found in Chapter 12 – Seismic Design Requirements for Building Structures, the design had to also comply with Chapter 16 – Seismic Response History Procedures, Chapter 18 – Seismic Design Requirements for Structures with Damping Systems, and Chapter 21 – Site-Specific Ground Motions for Seismic Design.

Early analytic studies were based on performance data provided by Japanese engineers from ADC, Ltd. It was quickly apparent that additional full-scale test data would be

Figure 4. Shipping dampers from the DIS plant in Nevada.

required to extend the Japanese data to larger system velocities and displacements.

Early in the design, the team met with the Office of Statewide Health & Planning Development (OSHPD), the Authority Having Jurisdiction (AHJ) over the design of acute care hospitals in California, to present the basic design concepts for a damped moment resisting frame system. As this system had never been used on a hospital in California before, nor for that matter in the United States, OSHPD raised various concerns. However, by the end of the meeting, OSHPD made it clear that the team would have to thoroughly demonstrate through testing and analysis that the new hospital would perform as well or better than a conventional California hospital.

An independent panel of three design professionals, required by ASCE 7-05, Chapter 18, was convened to peer review the site-specific seismic criteria, the preliminary design of the damping system, and the final design of the entire lateral force resisting system. As part of the preliminary design process, a project-specific Structural Design Methodology and Criteria document was developed to more fully describe how the design would meet the requirements of ASCE 7-05. The Peer Review Panel reviewed and approved the Design Criteria development, providing valuable input during the process. In addition, the Peer Review Panel also reviewed test results from full-scale prototype testing programs described below.

In order to design the damped moment frame system, the team elected to use the nonlinear response history procedures, outlined in Chapter 18 of ASCE 7 and more fully developed in the *Design Criteria* document. The analysis was done with two 3-D nonlinear models using the PERFORM software package from Computers and Structure, Inc. The model included nonlinear elements to represent the Viscous Wall Dampers, girder connections and columns of the primary lateral system. Two models were used to bound the results of the analyses based on the expected properties of the wall dampers. The first model represented the upper bound damper properties, while the second model represented the lower bound properties of the dampers. The upper bound model generated more force in the dampers with less deformation in the girders and columns. The upper bound model results were used to check force-controlled elements such as collectors and columns subjected to high overturning forces. The lower bound model generated less force in the dampers, thus making the moment resisting frame more prominent in the force resisting system. The lower bound model was used to check the deformation-controlled girder elements.

For both upper and lower bound models, a suite of ten ground motion records selected by the owner's geotechnical consultant, Langan-Treadwell & Rollo (Langan) were used. Langan provided Maximum Considered Events (MCE) and Design Earthquake (DE) target spectra for both probabilistic and deterministic earthquakes. Given the proximity to the San Andreas Fault, 6.8 miles (11 km) away, the deterministic event controlled the seismic design for this site. Using these spectra, Langan provided ten ground motion records that were scaled to closely match the MCE and DE target spectra over the range of periods for the building. The Peer Review Panel, as well as the California Geologic Survey (CGS), reviewed and approve the target spectra, record selection, and scaling factors for Degenkolb's use.

Full Scale Prototype Testing

The first full scale testing of a 6-foot x 11-foot tall 'pre-prototype' damper took place at the UC San Diego Caltrans Seismic Response Modification Device (SRMD) Test Facility in May of 2008. This damper was put through a series of 26 tests, including in-plane sinusoidal tests and bi-directional earthquake response history tests. Twenty tests were in-plane sinusoidal tests of generally three to five cycles at displacements ranging from 0.5 inches to 3.4 inches, the estimated MCE interstory displacement. By varying the input frequency, velocities from 0.7 inches per second to 15.3 inches per second were achieved. The six bi-directional earthquake response history tests were based on both Design Earthquake and MCE level response history results taken from Degenkolb's nonlinear response history analyses for two different ground motions. The intent of these tests were to compare actual test results with the input motions developed from analysis models.

Using the results of the pre-prototype test program, the analytic damper model was evaluated and calibrated to continue with full analysis of the building. Given the varying floor-to-floor heights, three basic viscous damper sizes were selected, 7x9 feet, 7x10 feet, and 7x12 feet, to standardize the analysis as well as the fabrication processes. (The 7-foot width dimension was not an arbitrary selection; because many of the wall dampers would ultimately be located on the building exterior, the engineers worked with the architect to determine the available space between bedroom windows, approximately 8 feet. In doing so, the team successfully hid the dampers behind the solid portions of the exterior façade.)

Two additional sets of prototypes were tested at UC San Diego, including three 7- x 12-foot dampers and two 7- x 9-foot dampers. Testing protocols similar to the pre-prototype test program were followed with addition tests at 1 inch per second to provide calibration data for future production testing at the DIS fabrication plant. These prototype type tests established the Target Force, F_0 at 0 displacement and the Target Energy Dissipated per Cycle, or EDC. Both the Target Force and EDC values were calculated from the average of the last three cycles of a five cycle test sequence.

Viscous Wall Damper Production

DIS manufactured and production-tested the viscous wall dampers at its Nevada facility. DIS designed and constructed a test rig (*Figure 3, page 51*) to expedite the final production testing approval process. To facilitate the cutting and welding, DIS constructed fabrication jigs in its shop that assure each damper met the precise tolerances necessary to obtain consistent performance.

The Production Testing Program was defined in the *Design Criteria* document to test a proportion of the total number of fabricated dampers. For each size damper, the first five production devices were tested at 1 inch per second to a displacement of 2 inches for five cycles to

Courtesy of Brett Drury.

compare against the Target Values established in the Prototype Test Program. The allowable tolerance for production testing was +/-10% on the entire group of dampers and +/-15% on any individual damper. If all five dampers met the target values within +/-15%, then only 50% of the next ten devices would be tested. If those devices met the target values, then only 40% of the next ten devices were tested and so on. Overall, with all tested production dampers meeting the Target Force and Target EDC values, 49 of the 119 (approximately 40%) production dampers were tested. On average, the production dampers were less than 5% below the Target Force, F_0, and were less than 5% above the Target EDC as established in the Prototype testing. The production testing was witnessed by an independent testing laboratory in the DIS shop.

After successful production testing, DIS shipped the wall dampers to the project steel fabricator/erector, The Herrick Corporation, in Stockton, California. While the fluid is very viscous, it is necessary to ship the dampers in the upright position (*Figure 4*), a practical shipping limitation to the maximum vertical height that can be fabricated and delivered on a project. Herrick took on responsibility for scheduling and shipping the dampers to the site in close coordination with the steel girders that connect to the dampers.

Site Erection

Due to tight site conditions (See STRUCTURE magazine, December 2015 issue – *Working at a Congested Urban Site*.), Herrick shipped the dampers to the site "just in time" to coordinate with the primary frame erection. The tower crane lifted each damper, approximately 10,000 pounds apiece, to its final location on the frame, setting and connecting the damper to the bottom girder with high-strength bolts.

Conclusions

Sutter originally challenged the team to bring value to its new hospital by finding innovative solutions. Given that the viscous wall damper system was developed over 25 years ago and used extensively in Japan, one might argue the team was not that innovative. However, the team needed a great deal of perseverance, technical excellence, attention to detail, and ultimately, support from the client to bring this system to the United States for the first time in a California hospital.

Was the team successful on this project? In a word, yes. Viscous wall dampers substantially decreased the floor inertial accelerations, especially the upper floors of the structure where seismic accelerations are typically greatest in conventional buildings. The viscous wall dampers saved a substantial amount of steel framing by controlling interstory drift. Based on the nonlinear analyses, the viscous wall dampers are expected to absorb nearly 90% of the earthquake energy at the Design Earthquake level. Without viscous wall dampers, a steel moment resisting frame would have required 50% to 60% more steel in terms of tonnage, and more moment frames on more column lines in the building. Factoring in the cost of the viscous wall damper with the structural steel, the owner saved 25% of the cost of the structural steel system. And lastly, including the damper testing program, the review and approval process, and damper fabrication, the construction schedule was not compromised by the use of the dampers.

Is there a viable future for viscous wall damper systems in the United States? In several words, a qualified yes. Throughout this project, many people asked, "Why has it taken so long to bring this technology to the United States?" We can look at the slow implementation of base isolation in the United States for some similar impediments to implementation (Arendt, 2010). In order for this technology to gain greater acceptance in the U.S.:

1) Building owners, the decision makers, must place greater value on the seismic performance of their structures,
2) Engineers must understand the technology and its benefits to effectively demonstrate that value to the owner,
3) Relevant codes must be reviewed for improvements that would ease the use without reducing safeguards, and
4) Professional associations must promote dissemination of information for higher performance levels.

Accomplishing a first in the U.S. was not an easy path, but the results have made the journey worthwhile.▪

Jay Love, S.E., is the Structural Engineer of Record at Degenkolb Engineers. He can be reached at ***rjlove@degenkolb.com****.*