SEISMIC PROTECTION WITH FLUID VISCOUS DAMPERS FOR THE TORRE MAYOR, A 57-STORY OFFICE TOWER IN MEXICO CITY, MEXICO

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ABSTRACT

The 57-story Torre Mayor building is the new dominant structure in the Mexico City skyline. Completed in 2002, it is also the first tall building to utilize large Fluid Viscous Dampers as the primary means of seismic energy dissipation.

A total of ninety-eight dampers are used, including twenty-four large dampers, each rated at 570 tonnes of output force, located in the long walls of the building. The short walls utilize seventy-four smaller dampers, each rated at 280 tonnes of output force.

The damper design used on Torre Mayor is a U.S. technology originally developed for use on nuclear ballistic missile launchers and launch control facilities. This technology was declassified by the U.S. Department of Defense in 1990 and was commercialized through the efforts of the U.S. Multi-Disciplinary Center for Earthquake Engineering Research (MCEER) and the military damper manufacturer, Taylor Devices, Inc. Since the Torre Mayor building was completed, it has experienced numerous earthquakes. The most significant was a magnitude 7.6 event on January 21, 2003, that caused no damage of any type to the building.

The damping technology successfully implemented for Torre Mayor is now being used on more than ten other tall buildings, located in the USA, Japan, Taiwan, and China. A total of 240 building and bridge structures throughout the world now utilize Fluid Viscous Dampers from former U.S. military applications for earthquake, hurricane, and typhoon protection.

INTRODUCTION TO DAMPERS

In the classical mechanical engineering text "Vibration Theory and Applications," William Thomson [1] avoids a single, direct definition of damping by offering the following descriptions: "Vibrating systems are all more or less subject to *damping,* because energy is dissipated by friction and other resistances. Since no energy is supplied in free vibration, the motion in free vibration will diminish with time, and is said to be *damped."*

It follows from these descriptions that a *damper is* an element which can be added to a system to provide forces which are resistive to motion, thus providing a means of energy dissipation. Assuming that this working definition will suffice for general use, the next area of interest is to generally describe the functional output of a damper. As with the definition of damping, the functional output of a damper is somewhat controversial, since different output equations exist within the context of the various engineering disciplines.

GENERALIZED EFFECTS OF ADDED DAMPING

The concept of added-on dampers within a structure assumes that some of the energy input to the structure from a transient will be absorbed, not by the structure itself, but rather by supplemental damping elements. An idealized supplemental damper would be of a form such that the force being produced by the damper is of such a magnitude and occurs at such a time that the damper forces do not increase overall stress in the structure. Properly implemented, an ideal damper should be able to simultaneously reduce both stress and deflection in the structure.

Figure 1 depicts earthquake spectra capacity and demand curves for a sample building with 20%, 30%, and 40% damped demand curves. This Figure is reproduced from U.S. Government Publication FEMA 274 [2] and assumes linear or viscous damping elements are used.

The effects of added supplemental damping in a structure subjected to earthquake transients is depicted in the test results provided in Figures 2 and 3, from Constantinou and Symans [3]. The tested structure was a single story, steel building frame, using steel moment frame connections. Figure 2 shows the response of the test structure under a scaled input of 33% of the 1940 El Centro earthquake. Note that a small hysteresis loop is apparent in Figure 2, revealing that the test structure was at the onset of yield. Structural damping in the frame was in the 1-1/2 - 2% range. In comparison, Figure 3 is this same structure with 20% added damping, obtained by the addition of two small fluid dampers installed as diagonal brace elements. The large energy dissipation of added damping is readily apparent in the broad width damping curve superimposed over the structural spring rate curve. Not also that the input in Figure 3 is the full 100% El Centro earthquake, yet base shear and deflection of the frame are virtually unchanged from the undamped case of Figure 2. Thus, in this case, addition of 20% added fluid damping to the structure increased its earthquake resistance by a factor of 3, compared to that of the same structure without added damping. Most importantly, this threefold performance improvement was obtained without increasing the stress or deflection in the structure. In fact, it is this tremendous performance improvement that caused much of the interest in fluid dampers for structural engineering use.

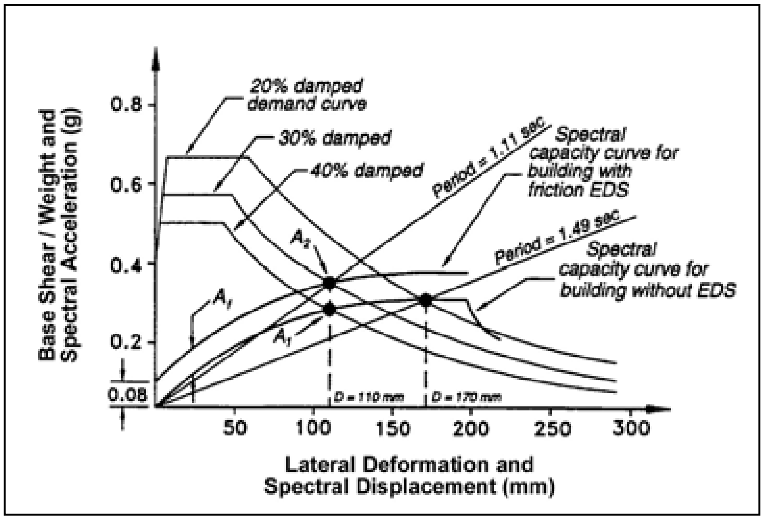

FIGURE 1
SPECTRAL CAPACITY DEMAND CURVES
FOR REHABILITATED ONE-STORY BUILDING

The most convenient and common functional output equation for a damper comes from classical systems theory, and is that of the so-called "*linear*" or "*viscous*" damping element:

$$F = C\dot{X}$$

where F = resistive force from the damping element

C = the damping constant

$\dot{X}$ = end-to-end velocity across the element

During the so-called Cold War between the USA and the former Soviet Union, extensive U.S. Government research was performed developing optimal output equations for fluid damping devices. These components were then implemented within military systems for the purpose of protecting strategic weapons and their base structures against nuclear attack. Much of this work was classified as military secrets, with virtually nothing being published.

When the Cold War ended in 1990, a restructuring period began for U.S. military and defense contractors. One of the outcomes was that the damping technology developed for military use during the Cold War was declassified and approved for sale to the general public. In civil engineering, high capacity dampers became available, virtually overnight, for use on buildings and bridges subjected to seismic or wind storm inputs.

It soon became evident that the former military dampers did not follow the old rules, where force is proportional to velocity. Instead, engineers were given entirely new rules for damper output, where:

$$F = C\dot{X}^{\alpha}$$

where α is an exponent of velocity, which can be specified by the engineer at virtually any value from 0.3 to 2.0, allowing a much broader range of applications.

The ability of damping functions to now be optimized and specified by the engineer was coupled with damper designs proven to be highly reliable through decades of military use. These dampers were readily available in large sizes, in the range of 50-1,000 tonnes output force. As a result, actual implementation began almost immediately on commercial structures in high seismic zones in the United States. Adding momentum to the use of dampers was the 1994 Northridge, California earthquake, which exhibited much higher shaking accelerations and velocities than had been predicted by the geotechnical community. The effects of the Northridge earthquake were reinforced by the 1995 Kobe, Japan earthquake, which damaged large numbers of structures thought to be highly resistant to seismic shaking.

When new post-Northridge and post-Kobe structures were designed, engineers quickly discovered that fluid dampers were an ideal solution to add substantial additional energy dissipation to a structure, accommodating the expected effects of ever-increasing seismic design requirements.

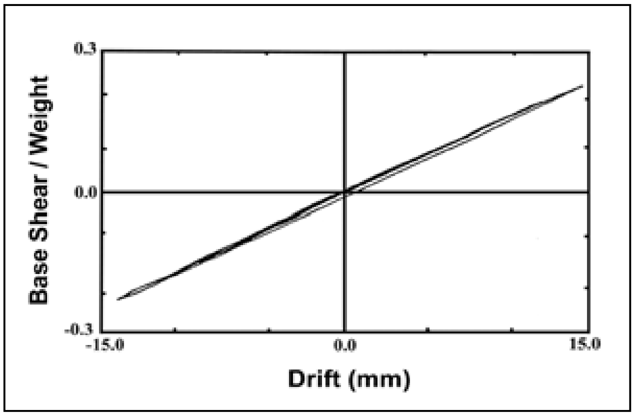

FIGURE 2
ONE-STORY STRUCTURE, NO DAMPERS
EL CENTRO 33.3%

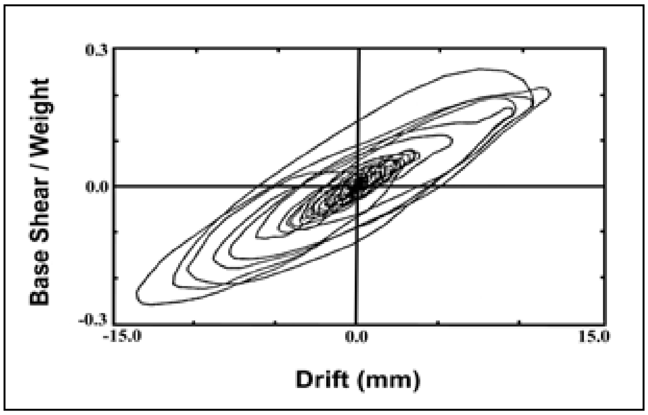

FIGURE 3
ONE-STORY STRUCTURE, TWO DAMPERS
EL CENTRO 100%

FLUID DAMPER DESIGN

The design elements of a fluid damper are relatively few. However, the detailing of these elements varies greatly and can, in some cases, become both difficult and complex. Figure 4 depicts a typical fluid damper and its parts. It can be seen that by simply moving the piston rod back and forth, fluid is orificed through the piston head orifices, generating damping force.

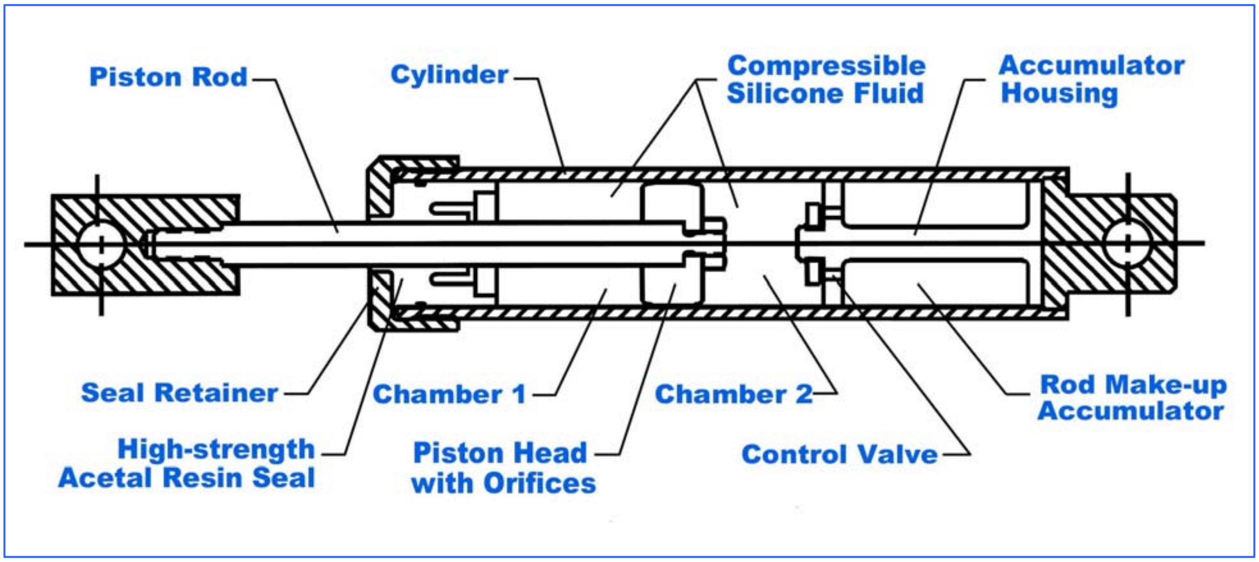

FIGURE 4
FLUID DAMPER

Major part descriptions are as follows, using Figure 4 as reference:

Piston Rod – Highly polished on its outside diameter, the piston rod slides through the seal and seal retainer. The external end of the piston rod is affixed to one of the two mounting clevises. The internal end of the piston rod attaches to the piston head. In general, the piston rod must react all damping forces, plus provide a sealing interface with the seal. Since the piston rod is relatively slender and must support column loading conditions, it is normally manufactured from high-strength steel material. Stainless steel is preferred as a piston rod material, since any type of rust or corrosion on the rod surface can cause catastrophic seal failure. In addition, the design of the piston rod should be strain based, rather than stress based, since elastic flexing of the piston rod during damper compression can cause binding or seal leakage.

Cylinder – The damper cylinder contains the fluid medium and must accept pressure vessel loading when the damper is operating. Cylinders are usually manufactured from seamless steel tubing. Welded or cast construction is not permissible for damper cylinders, due to concerns about fatigue life and stress cracking. Cylinders normally are designed for a minimum proof pressure loading equal to 1.25 times the internal pressure expected under a maximum credible seismic event. By definition, the proof pressure loading must be accommodated by the cylinder without yielding, damage, or leakage of any type.

Fluid - Dampers used in structural engineering applications require a fluid that is fire-resistant, non-toxic, thermally stable, and will not degrade with age. This fluid must be classified as both non-flammable and non-combustible, with a fluid flashpoint above 90° C. At present, the only fluids possessing all of these attributes are from the silicone family. Typical silicone fluids have a flashpoint in excess of 340° C, are cosmetically inert, completely non-toxic, and are thermally stable. The typical silicone fluid used in a damper is virtually identical to the silicone used in common hand and facial cream cosmetics.

Seal - The seals used in a fluid damper must be capable of a long service life; at least 25 years without requiring periodic replacement. The seal materials must be carefully chosen for this service life requirement and for compatibility with the damper=s fluid. Since dampers in structures are often subject to long periods of infrequent use, seals must not exhibit long-term sticking nor allow slow leakage of fluid. Most dampers use dynamic seals at the piston rod interface, and static seals where the end caps or seal retainers are attached to the cylinder. For static seals, conventional elastomer o-ring seals have proven to be acceptable. Dynamic seals for the piston rod should be manufactured from high-strength structural polymers, to eliminate sticking or compression set during long periods of inactivity. Typical dynamic seal materials include Teflon®, stabilized nylon, and members of the acetyl resin family. Dynamic seals manufactured from structural polymers do not age, degrade, or distort over time. In comparison, conventional elastomers will require periodic replacement if used as dynamic seals in a damper.

Piston Head - The piston head attaches to the piston rod, and effectively divides the cylinder into two pressure chambers. As such, the piston head serves to sweep fluid through orifices located inside it, thus generating damping pressure. The piston head is usually a very close fit to the cylinder bore; in some cases the piston head may even incorporate a seal to the cylinder bore. Piston heads are relatively simple in appearance. However, the orifice passages machined or built into the piston head usually have very complex shapes, depending on the damping output equation selected.

Seal Retainer - Used to close open ends of the cylinder, these are often referred to as end caps, end plates, or stuffing boxes. It is preferable to use large diameter threads turned on either the exterior or interior surface of the cylinder to engage the seal retainer. Alternate attachment means, such as multiple bolts, studs, or cylinder tie rods should be avoided as these can be excited to resonance by high frequency portions of either the earthquake transient or the building response spectra.

Accumulator - The simple damper depicted in Figure 4 utilizes an internal, in-line rod make-up accumulator. The accumulator consists of either a block of closed cell plastic foam, a moveable (and gas pressurized) accumulator piston, or a rubber bladder. The purpose of the accumulator is to allow for the volumetric displacement of the piston rod as it enters or exits the damper during excitation. A second purpose is to compensate for thermal expansion and contraction of the fluid. The damper in Figure 4 uses a control valve to meter the amount of fluid displaced into the accumulator when the damper is being compressed. When the damper extends, the control valve opens to allow fluid from the accumulator to freely enter the damper pressure chambers.

Some types of dampers use a so-called "through rod," where the piston rod goes entirely through the damper cylinder. These dampers do not require accumulators at all, but do require two sets of seals.

Orifices - The pressurized flow of the fluid through the piston head is controlled by orifices. These can consist of complex modular machined passageways, or alternately, can use drilled holes, spring-loaded balls, poppets, or spools. Relatively complex orifices are needed if the damper is to produce output with a damping exponent of less than two. Indeed, a simple drilled hole orifice will follow Bernoulli's equation, and damper output will be limited to varying force with the square of the damper velocity. Since "velocity squared" damping is of limited use in seismic energy dissipation, more robust and sophisticated orifice methods are usually required. Depending on the damping output equation desired, orifice passages may utilize converging or diverging flows, vortexes may be induced to form at specific areas, or flow passages may bend or twist radically.

DESIGN AND IMPLEMENTATION OF FLUID DAMPERS AT TORRE MAYOR

A combination caisson/mat system was selected for the foundation of the tower. The reinforced concrete mat system connects a series of caissons of up to 1.2m diameter, reaching down only 40m into a rubble layer below the soft surface soil. The concrete mat thickness varies from 1m-2m in thickness and ties together the caissons and the 0.8m thick foundation walls.

The seismic code requirements for Mexico City involve the use of shock response spectra, with the associated site transients. This is combined with a limitation on allowable soil-bearing stress. The design team evaluated more than 25 different structural systems, but was unable to find a structural configuration allowing a 55-floor building to be constructed at the site. The best configurations yielded a design with 35-38 floors maximum. The engineers noted that it was probably no coincidence that the tallest existing structures in Mexico City are roughly this height.

The potential of adding viscous damping to the structure was evaluated as a means to reduce structural stress during seismic loadings. The underlying design concept was to use the dampers to reduce stress, then lighten the building frame by removing steel until the stress crept up to the code allowables. Conceptually, the steel that had been "removed" by this process could then be used to add additional floors.

For the Torre Mayor, inherent structural damping in the frame was assumed to be 1% of critical. Multiple computer runs were made with added fluid damping in 2% increments. The approach used was to add damping until a lightweight 55-plus story building would result or until damping reached a value of 30% critical, at which point Constantinou and Symans' research indicated that peak stresses would begin to increase.

When the added damping in the structure reached 10% critical the resulting maximum height structure was calculated to be 57 floors. The structural detailing of the new tower could begin, having achieved the goals of the building's owner for a 55-plus story structure. Figure 5 is the architectural drawing of the building.

FIGURE 5
TORRE MAYOR ~ ORIGINAL
ARCHITECTURAL DRAWING

The first step in the design process of damper implementation involves an extensive structural analysis to determine the desired overall damping level. The number of dampers and damper sizes are roughly estimated at this point to balance the cost of the dampers vs. the overall performance and cost of the structure. After the desired level of performance has been achieved, the second step in the design process begins. This second step adjusts the number of dampers and damper sizes against the available mounting locations in the structure and the desired architectural configuration. For example, if a total of 10,000 tonnes of fluid damping force was desired, one can obtain this output with various numbers of dampers, such as:

10 pieces of 1000 tonnes force damper
20 pieces of 500 tonnes force damper
100 pieces of 100 tonnes force damper, etc.

The third step in the design and implementation process optimizes the performance of the individual dampers within the structure by varying the damping coefficients and exponents. For the case of the Torre Mayor Project, it was decided to use twenty-four large dampers of 570 tonnes rated force in the long walls of the structure. Each damper spans multiple floors, using a so-called “mega brace” element, installed in a diamond pattern. In the short walls of the structure, seventy-four pieces of a smaller 280 tonnes rated force damper are used. Figures 6 and 7 show the dimensions and configuration of the dampers themselves, without the bracing elements. Figure 8 is a photo of the building frame taken during construction. This photo shows the diamond arrangement of the installed large dampers in their mega brace elements.

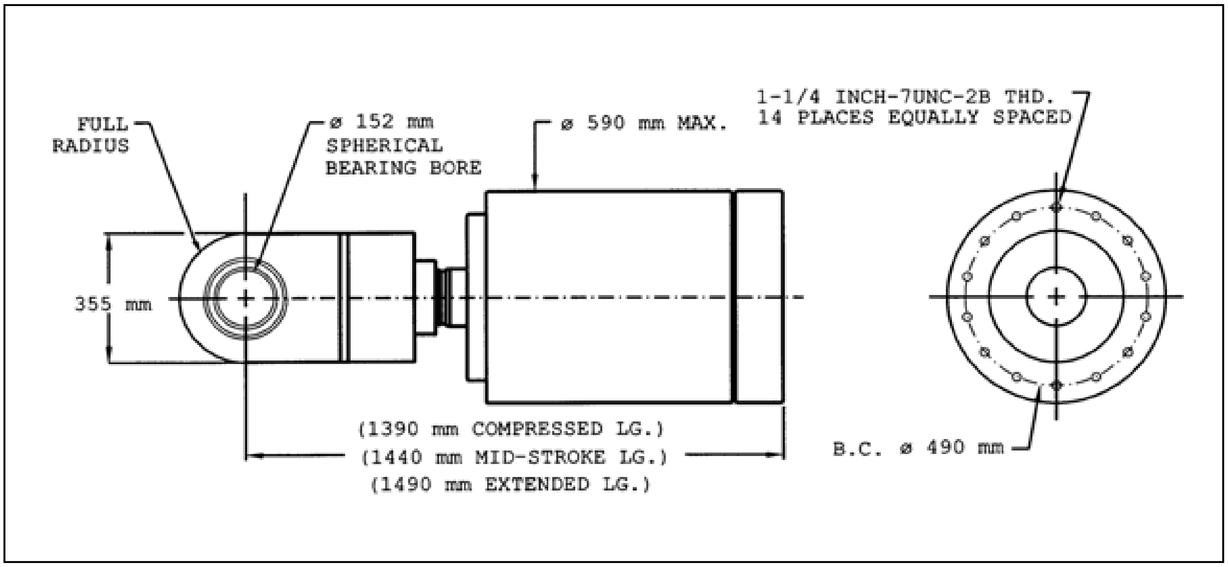

FIGURE 6
570 TONNES FORCE FLUID VISCOUS DAMPER

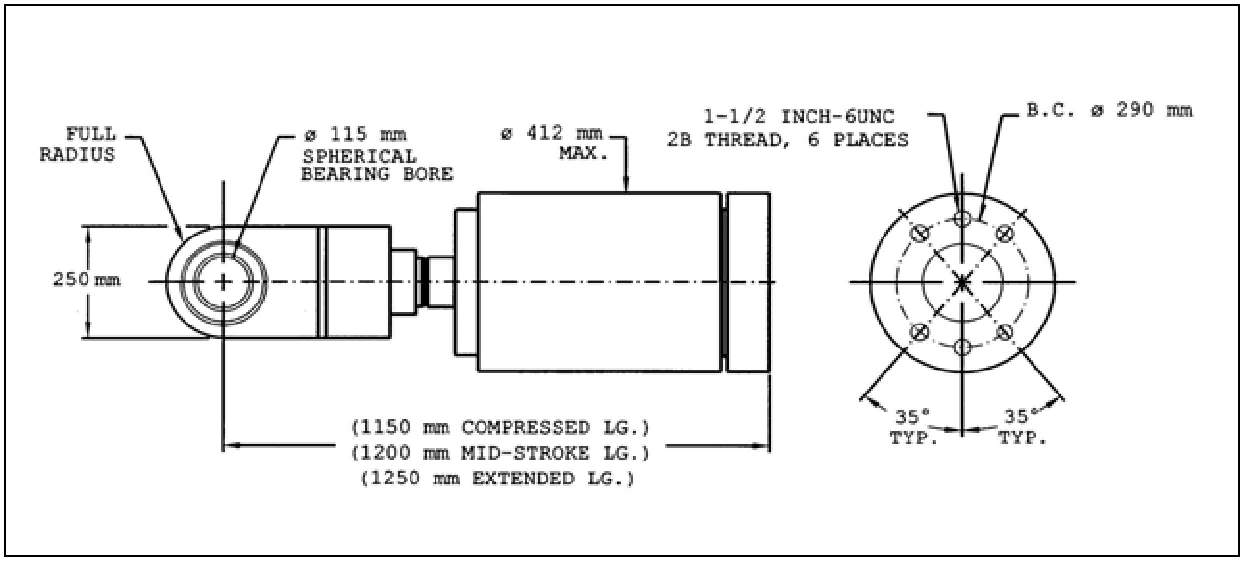

FIGURE 7
280 TONNES FORCE FLUID VISCOUS DAMPER

The end use of the dampers was to reduce deflection and shear stresses in the building frame. To construct a building of this size in Mexico City involves meeting the latest Mexico City seismic code requirements, plus meeting soil bearing stress limitations specific to the Reforma Centro district of the city. Since the building was to be the tallest building in Mexico City, and indeed all of Latin America, it was important to use the dampers=energy dissipation to reduce ductility demands on the building=s frame.

FIGURE 8
TORRE MAYOR BUILDING FRAME

Optimization analyses were performed to develop the best performing damping exponents. The end result is that a total of six separate damper part numbers are used, three for the large dampers, and three for the small dampers. Each part number defines a specific damping coefficient "C," and damping exponent "α," with a damping equation:

$$F = C\dot{X}^{\alpha}$$

The α values selected are 0.7 for two of the three part numbers, and 1.0 for the third part number, for both large and small dampers. The C values are also different for each part number, and set the damper output for the interstory velocities expected at specific positions and elevations within the building.

MANUFACTURING OF THE TORRE MAYOR DAMPERS

The basic design and force ratings of the Torre Mayor dampers were the same as used previously in other projects of Taylor Devices, so no research activity was required. Design drawings were generated and subjected to external independent peer review for both internal and external parts. After review, fabrication of parts commenced at Taylor Devices' facilities located in North Tonawanda, NY. All operations at the facility are in compliance with ISO 9001 Quality Standards, plus U.S. Military Standards MIL-I-45208 and MIL-Q-9858.

The Torre Mayor dampers use a through rod design with no accumulators. Orifices in the damper piston head are modular machined passages with no control valves. Seals are machined from solid billets of a proprietary rigid acetyl resin material.

The main cylinders for the dampers were constructed from custom tubes made from aircraft quality AISI Type 4140 steel. The manufacture of large diameter heavy walled steel pressure vessels must be closely quality controlled to insure proper chemical and physical properties. In addition, Taylor Devices imposed additional steel requirements for the cylinders mandating specific grain flow orientation relative to the cylinder centerline. To provide this high level of quality control, purchase orders were placed directly with the steel mill for a dedicated melt of material, forged into short billets. These billets of solid steel were then sent to a finishing mill to be reheated and pierced into rough tubes. The rough tubes were then heat treated, and precision machined into their finished configuration.

Other parts of the dampers were machined from wrought steel bar stock, with the piston rods being machined from stainless steel bar. The piston rods use an extreme high strength aircraft quality material, alloy 17-4 PH stainless steel, being specified to U.S. Aerospace Material Standard AMS5643. The piston rods are heat treated to 1240 MPa yield strength after machining. Final piston rod finishing is performed by hand after heat treating, to a mirror-like surface of 0.1 micron average surface roughness.

The cylinder and piston rod are the two most critical parts of the damper, and the material and manufacturing must be controlled, certified, and inspected on a special basis. All other damper parts utilize materials certified to appropriate U.S. Federal or ISO Standards. Most machining processes utilized multiple axis computer numeric controlled (CNC) machines.

Each damper was assembled, and subjected to a proof test at 1.25 times the internal pressure calculated at maximum rated output force. This test is performed by using a high pressure pump to generate the required pressure. When maximum pressure is reached, the pressure is held for a minimum of two minutes. No leakage of any type from any part is permitted. This type of proof test originated hundreds of years ago for military testing of cannons except that with a firearm, the pressure is applied only for a very short period with the weapon being fired with an extra large propellant charge.

Following proof testing, the first damper of each part number was subjected to a load test, verifying proper damping output force and damping exponent over a wide range of testing speeds, up to the maximum specified for the project. Figure 9 shows Taylor Devices' large hydraulic seismic test machine, which can test to 1000 tonnes force at up to 1 meter per second velocity. This machine was used to test the Torre Mayor dampers. After first piece testing was complete, each subsequent damper was cycled in the test machine at the maximum rated force and velocity.

After testing, the completed dampers were shipped to the job site, where the brace extenders were attached. Figure 10 shows a group of large and small dampers ready for shipment to the job site.

Actual installation involved lifting the completed dampers, with their extender braces attached, to their final locations within the building. Figures 11, 12 and 13 show the finished damper installation.

FIGURE 9
TAYLOR DEVICES' LARGE
HYDRAULIC SEISMIC TEST MACHINE

FIGURE 10
DAMPERS READY FOR SHIPMENT

FIGURE 11
DAMPER INSTALLATION

FIGURE 12
DAMPER INSTALLATION

FIGURE 13
DAMPER INSTALLATION

THE EARTHQUAKE OF JANUARY 21, 2003 ~ TORRE MAYOR SURVIVES A "BIG ONE"

The problem with earthquakes is that one designs for transient events large enough to occur only once in 500 years or so, yet this still leaves a statistical probability that a significant event can occur in the near term.

On January 21, 2003, the coastal region of the State of Colima, Mexico experienced a 7.6 magnitude earthquake. This particular earthquake affected a very large land area, including the nearby Mexican States of Jalisco and Michoacan, including the entire Mexico City area. Even though the epicenter of the quake was in an area of low population, damage was extensive. More than 13,000 residential structures and 600 commercial structures reported damage. Of these, more than 2,700 structures were totally destroyed.

When the quake reached Mexico City it was amplified by the soft soils in the area. This resulted in a relatively strong response with some 30 seconds of shaking. Meanwhile, the occupants of Torre Mayor became aware that a quake was occurring when hanging light fixtures began to sway. One person reported that he heard a slight noise, then turned toward the noise and saw that the large damper outside his office was stroking. This, of course, signified that an earthquake was occurring. At the time of the quake, 31 floors of the recently opened Torre Mayor were occupied, the balance still undergoing final interior finishing. A Government required post-earthquake inspection was performed with no damage of any kind noted. Building occupants reported that from inside the building the quake felt far less severe than it actually was. This may well be due to the extensive use of fluid dampers as a primary element of the building's earthquake resistance capability. Since Torre Mayor is now the dominant structure in all of Latin America, its earthquake performance will continue to be watched very closely by the world's engineering community as a precursor to the design of future urban office towers.

CONCLUSION

The use of fluid dampers on the Torre Mayor Project allowed a 57-story building to be sited in an area historically limited to smaller structures of conventional design. The dampers utilize proven technology from U.S. Military structures of the Cold War era to produce a robust, yet elegant solution to the seismic protection requirements of a modern tall building. Torre Mayor is the first tall building to use mega brace damping elements, where a single damper spans multiple floors. This allows the interior of the building to have maximum floor space with minimal obstructions to the architectural theme.

The Torre Mayor has received several American Construction Industry awards, including the U.S. Civil Engineering Research Foundation's 2005 Charles J. Pankow Award for Innovation. Figure 14 shows the completed Torre Mayor and provides visual evidence of the building's dominance of the city's skyline. The dampers are plainly visible through the window glass.

FIGURE 14
COMPLETED TORRE MAYOR BUILDING

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ACKNOWLEDGMENTS

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