MEGA BRACE SEISMIC DAMPERS FOR THE TORRE MAYOR PROJECT AT MEXICO CITY

by

Douglas P. Taylor, President
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748

MEGA BRACE SEISMIC DAMPERS FOR THE TORRE MAYOR PROJECT AT MEXICO CITY

Douglas P. Taylor
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748
716-694-0800

ABSTRACT

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

A total of 98 dampers are used, including 24 large dampers, each rated at 570 tonnes of output force, located in the long walls of the building. The short walls utilize 74 smaller dampers, each rated at 280 tonnes of output force. Dampers are installed in mega-brace elements, up to 20m in length, where a single damper spans up to six floors.

The damping technology successfully implemented for Torre Mayor is now being used on five other tall buildings, including three in the USA, and two in Japan. A total of one hundred and thirty structures throughout the world utilize Fluid Viscous Dampers for earthquake, hurricane, and typhoon protection.

INTRODUCTION

The completion of the Torre Mayor in 2003 marks the culmination of ten years of design efforts by a multinational architectural and engineering team. Not only is this new 57-story structure the tallest building in Mexico City, it is also the tallest in all of Latin America. Yet, the new building is sited in a severe seismic risk zone. Clearing of the construction site involved removing rubble still in place from the magnitude 8.1 Mexico City earthquake of 1985. No existing structures needed to be removed from the site, as the 1985 earthquake had leveled everything in the immediate area.

The building site is in the Reforma Centro District of Mexico City, a predominately soft soil area (Mexico City itself is situated in the bowl of an ancient volcano, now filled with rubble and silt generated over the centuries). Bedrock is located roughly 5,000 feet below the surface soil, making conventional foundation designs virtually useless.

The task given to the design team was straightforward, yet daunting; this being simply to “build a 50-plus story building in an area where building codes effectively limit the height of tall buildings to 30 floors or less.” The architectural group in the design team was perfectly willing to accept those requirements and promptly generated the required rendering as depicted in Figure 1. However, the engineering group, wishing to “test the waters,” asked the developer, “what happens if we end up with a 35-floor building due to the site limitations?” In reply, the developer, world-famous Reichmann International of Toronto, Ontario, emphatically stated that if the building was not 55 floors in height, then it would not be built.

FIGURE 1
TORRE MAYOR ~ ORIGINAL ARCHITECTURAL DRAWING

THE BUILDING DESIGN EFFORT

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.

As a last resort, 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.

The benefit of added fluid dampers and the associated stress reductions has been demonstrated by extensive analysis, followed by transient testing on shake tables using fractional and full-scale models. The results depicted in Figures 2 and 3 are typical and as reported by Constantinou and Symans [1]. In these tests, a single-story steel moment frame structure was tested on a shake table, the input being the 1940 El Centro, California earthquake. For the test frame with 2% structural damping, the frame is at the onset of yield, evidenced by the small, but readily apparent hysteresis loop in Figure 2. Figure 3 shows the response of the same frame with 20% added fluid damping. The earthquake has been increased to 100% of the El Centro event, yet peak stress and deflection in the frame remain virtually unchanged. The dampers generate the large hysteresis loop which is apparent in Figure 3. Yet, because the output of a viscous damper is inherently out of phase with structural bending and shear stresses, the overall stress and deflection are not increased by the presence of fluid damping.

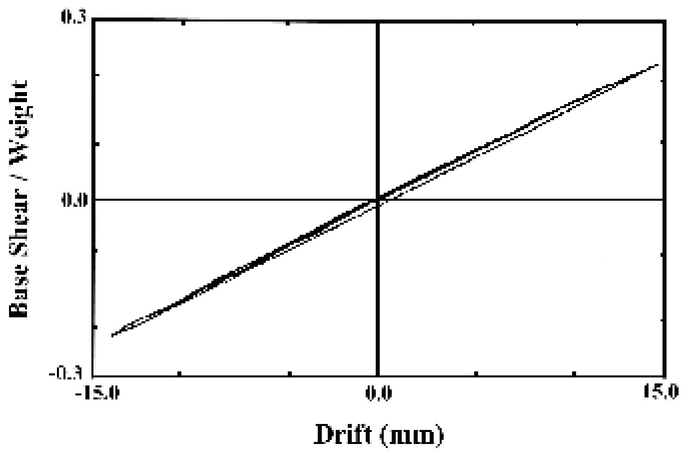

FIGURE 2
ONE-STORY STRUCTURE, NO DAMPERS
EL CENTRO 33.3%

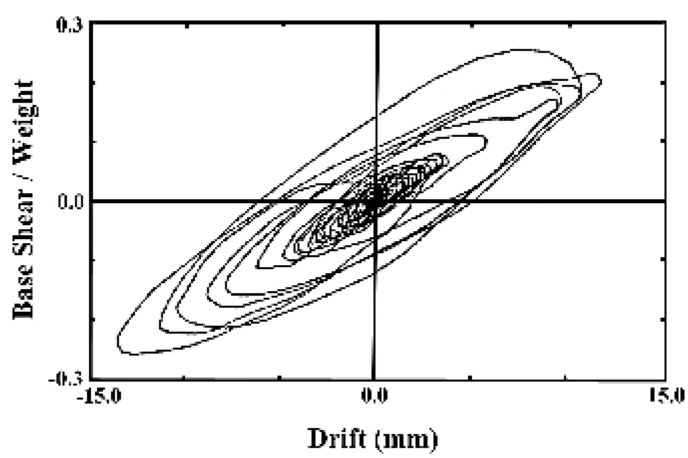

FIGURE 3
ONE-STORY STRUCTURE, TWO DAMPERS
EL CENTRO 100%

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.

DETAILED STRUCTURAL SYSTEM WITH FLUID DAMPERS

Once an overall damping level for the structure is selected, two additional levels of analysis are required. The first of these involves generating an implementation plan, since a given structure could use a large number of low force dampers or a small number of high force dampers. Input from the owner and the architectural team is also required since the combination of dampers can often be a driver in the interior layout of the structure.

A horizontal cut through the Torre Mayor reveals a cross section having two walls that are very long and two that are relatively short. The architects were strongly in favor of using as few dampers as possible in the long walls, since large open glass areas would be used and dampers are most effective when placed as closely as possible to the building perimeter. The reason for this is that seismic motions vary radically from event to event and placing dampers at the perimeter of the structure provides suppression of both in-plane and torsional responses. The dampers, however, will reduce viewing area through the window glass. The short walls did not have as many architectural restrictions. A simple cost optimization for the short wall dampers revealed that a total of 74 pieces of a device having approximately 300 tonnes of force would satisfy both mechanical and architectural constraints.

The long wall dampers proved to be a substantial problem in that the ideal number of devices from an appearance viewpoint would be 6-12 pieces on each long wall. The only way to do this in a structure of this size would be to use so-called "mega brace" elements, where a single damper, in a diagonal brace mounting, would span multiple floors of the building. Unfortunately, most mega brace concepts are not practical due to column loading limitations on the structure of the brace element itself. The mega elements for Torre Mayor were required to be up to 20m in length. With the limited number of elements specified, each element must accept bi-directional loads in the range of 500-700 tonnes, thus requiring an extremely large brace cross section. The brace element must also transmit structural loads to the dampers without significant internal strain, otherwise the building deformation during the earthquake would simply flex and strain the braces elastically without imparting proper deflection to the dampers.

The resulting solution was to use a structural steel system in the building which effectively placed the damper elements between widely spaced truss columns which impart maximum deflections to the mega brace elements. Each mega element is supported against bucking by the individual floors and floor trusses that the brace passes through in the area between the truss columns. This minimizes elastic buckling tendencies of the mega braces. The resulting structural system with mega brace damping elements is unique, with a U.S. Patent awarded in 2002 to Rahimian [2] for the basic design. The mega brace orientation and arrangement is shown in Figure 4, a photograph of the building frame under construction, looking at one of the long walls. The diagonal mega brace elements, forming a unique "diamond" pattern, can be easily seen.

Once the implementation plan for the dampers was finalized, the actual number of dampers and their approximate force levels were now established. At this point the final level of structural analysis began, which optimized the damper sizes and obtained specific output parameters.

Fluid damping devices follow a generalized output equation of the form:

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

Where F = Damping Force

$\dot{X}$ = Velocity Across the Damper Ends

C = The Damping Constant

a = The Damping Exponent

FIGURE 4
TORRE MAYOR BUILDING FRAME

An optimization analysis determines the exact "C" and "a" values needed for each damper. The value of C (the damping constant) can be practically any value and relates generally to the relative size of the internal damping orifices. The a value (the damping exponent) is usually considered as equal to 1.0 for a starting point, since this is the so-called classical linear damper where output force is proportional to velocity. Available a values for dampers change with the type and geometry of the specific internal orifices of the damper. The a values can be specified as fixed numbers within the range of a = 0.15 to a = 2.0 for present damping technology. For seismic protection of structures, a values usually fall within the range of 0.3 to 1.0 when the damper is set to absorb maximum energy with minimum force and deflection imparted to a specific structure.

The Torre Mayor project was optimized for damper size and cost with a total of six specific sets of damper parameters, three for the short wall dampers and three for the long wall dampers. Two of the three a values were a = 0.7 for both long and short wall dampers, with the remaining a values set at a = 1.0. The C values are different for each of the six parameter sets. These are used to adjust for discrete interstory velocities at specific positions and elevations within the building.

Finalized rated output was 280 tonnes for each of the short wall devices and 570 tonnes for each of the long wall devices. Figures 5 and 6 show the exterior configuration of each damper. One end of each damper has a mounting clevis with spherical bearing. The clevis attaches to the building frame with two tang plates and a closely fitted mounting pin. The pin is driven in place at installation and secured with simple 12mm diameter cotter retainers in cross-drilled holes through the pin. The opposite end of each damper has a bolt circle of threaded holes to allow for a bolted connection to the mega brace. The spherical bearing end connection on the damper is used to allow for potential out of plane motion without imposing bending loads on the damper itself.

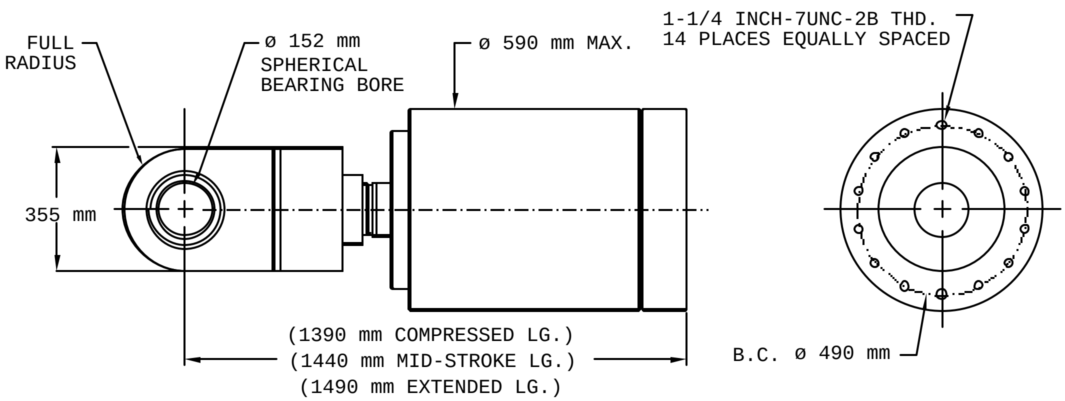

FIGURE 5
570 TONNES FORCE FLUID VISCOUS DAMPER

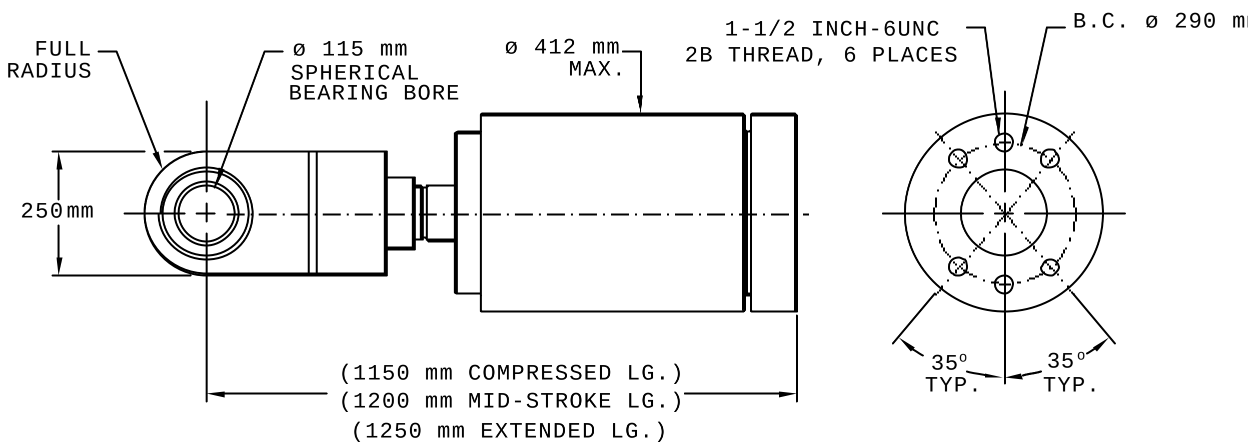

FIGURE 6
280 TONNES FORCE FLUID VISCOUS DAMPER

MANUFACTURING AND INSTALLATION OF THE TORRE MAYOR DAMPERS

All dampers for the Torre Mayor were manufactured by Taylor Devices of North Tonawanda, New York. The damper design is based upon products built for use by the U.S. military during the Cold War period and used for hardening structures against weapons detonation. The brace elements were fabricated in Mexico with final assembly of the dampers to the bracing elements taking place at the construction site. Because of the high seismic risk associated with the project, liability insurance regulations were such that each damper required specific acceptance tests. These included both a proof pressure test and a full load performance test.

The proof load tests involved internally pressurizing the damper to a pressure of 1.25 times the pressure resulting inside the damper at peak output force. When the maximum pressure was achieved, it was held for a minimum of two minutes, the damper being inspected for any sign of leakage or parts failure both during and after the test.

Following proof testing, the first damper of each part number was subjected to load tests. These verified proper damping output force and damping exponents over a wide range of testing speeds up to the maximum damper force and velocity specified for the project. Figure 7 shows Taylor Devices' large hydraulic seismic test machine, which can test to 750 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 production damper was cycled in the test machine at maximum rated force and velocity. These tests verified both performance and traceability to the first article units. Figure 8 shows a group of completed large and small dampers ready for shipment to the job site.

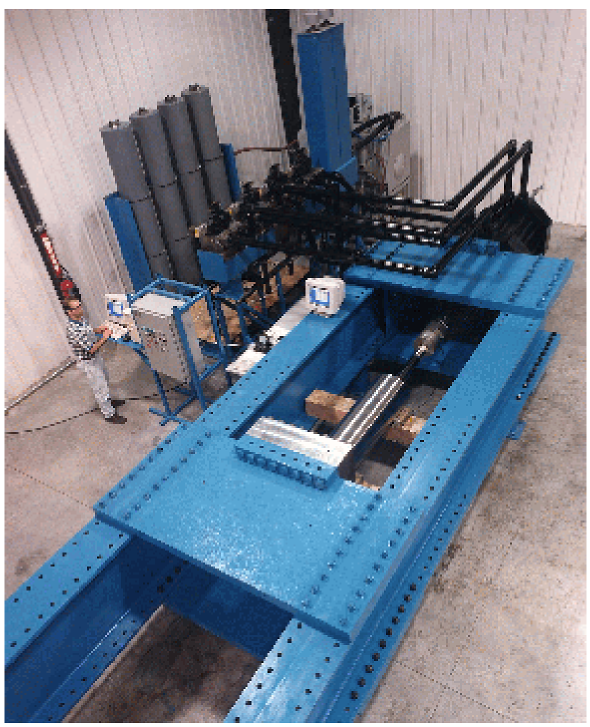

FIGURE 7
TAYLOR DEVICES' LARGE
HYDRAULIC SEISMIC TEST MACHINE

FIGURE 8
DAMPERS READY FOR SHIPMENT

The production scheduling for the building used "just in time" delivery, with individual shipping lots of dampers timed to arrive at the site simultaneously with their respective brace elements. Delivery at the site was timed to be just prior to a given floor location being readied to accept dampers. Dampers and brace elements for the short walls were completely assembled at ground level and hoisted via crane to the proper floors for installation.

The long wall dampers were assembled at ground level to the first section of the mega brace element. The partly complete brace element with attached damper was then lifted to the proper floor. Other sections of the mega braces were hoisted to the floor areas where they were to be located. As they were installed, the ends of each brace section were then connected to each other to complete the installation.

After this, final insertion of the damper clevis pins took place and the installation was complete. Figure 9 shows a completed installation of two long wall dampers. Figures 10 and 11 show completely installed short wall dampers.

FIGURE 9
DAMPER INSTALLATION, LONG WALLS

FIGURE 10
DAMPER INSTALLATION, SHORT WALLS

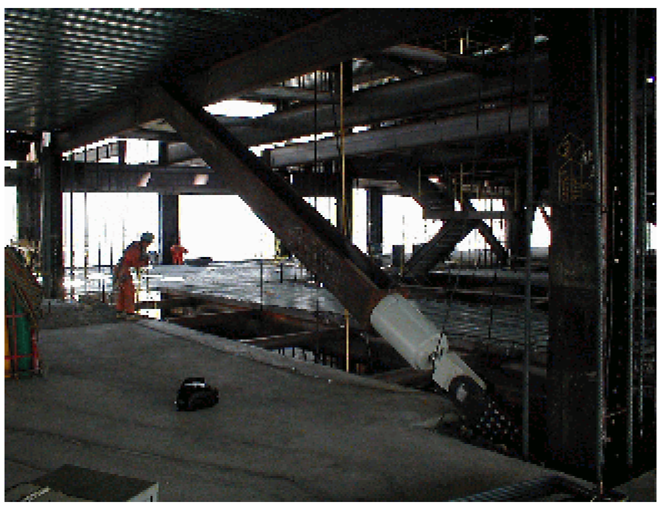

FIGURE 11
DAMPER INSTALLATION, SHORT WALLS

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 this newest and tallest building in Latin America 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 the Cold War 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 and was one of four finalists for the U.S. Civil Engineering Research Foundation's 2003 Charles J. Pankow Award for Innovation. Figure 12 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 12
COMPLETED TORRE MAYOR BUILDING

REFERENCES

[1] Constantinou, M., Symans, M., 1992, "Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers," Technical Report NCEER-92-0032, National Center for Earthquake Engineering Research, Buffalo, NY

[2] Rahimian, A, 2002, "Coupled Truss Systems with Damping for Seismic Protection of Buildings," U.S. Patent 6,397,527, Assigned to the Cantor Seinuk Group, P.C., New York, NY

ACKNOWLEDGMENTS

The author would like to acknowledge Lorrie Battaglia and Alan Klembczyk of Taylor Devices, Inc. for their assistance with this paper.