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PERFORMANCE-BASED DESIGN USING PALL FRICTION DAMPERS - AN ECONOMICAL DESIGN SOLUTION.

Avtar PALL[1] and R. Tina PALL[1]

SUMMARY

Benefit-cost analysis approach suggests performance-based design for most modern buildings. The conventional structural systems are highly unlikely to provide adequate performance in the event of a major earthquake. With the emergence of Pall Friction Dampers, it has now become economically feasible to design high performance structures. Their low cost and maintenance free characteristics suggest wide application for new construction as well as for retrofit of existing buildings. Public sectors, private sectors, developers and developing countries are all benefiting from this technology. They have been used for the seismic protection of more than 80 major building projects, including the Boeing Commercial Airplane Factory at Everett, WA – the world's largest building in volume.

INTRODUCTION

During a major earthquake, a large amount of energy is pumped into the building. The manner in which this energy is consumed in a structure determines the level of damage. The building codes recognize that it is economically not feasible to reconcile this energy within the elastic capacity of materials. The criterion stipulated in conventional building codes is to design structures to resist moderate earthquakes without significant damage and avoid collapse during major earthquakes. The primary emphasis is on life safety. The reliance for survival is placed on ductility to dissipate energy during inelastic deformations causing bending, twisting and cracking. This assumes permanent damage, repair costs of which could be significant. Recent earthquakes have clearly demonstrated that conventional construction, even in technologically advanced countries, is not immune to destruction.

In modern buildings, avoidance of structural collapse alone is not enough. The cost of non-structural components and contents is much higher than the cost of the structure itself and must be protected. The buildings of post disaster importance such as hospitals, telecommunications, police stations etc. must remain operational. Benefit-cost analysis suggests performance-based design approach. Emphasis for performance based seismic design is being given in recent standards, e.g., Vision 2000, ATC-57 and FEMA-356/2000. While global deflections, story drifts, force and demand-capacity ratios are important to a structural engineer; these have no meaning to a developer. What are important to an owner is how much

[1] Pall Dynamics Limited, Montreal, Canada. www.palldynamics.com, E-mail: info@palldynamics.com

it will cost to build and how much it will cost to repair the damage, lost rental revenues from a future earthquake. Early on, the structural engineers should resolve these issues with the owner and develop performance-based design criteria consistent with the performance goals. In most cases, providing good seismic performance yields good return on the investment.

If the amount of energy getting into the structure can be controlled and a major portion of the energy can be dissipated mechanically independent of primary structure, the seismic response of the structure and damage control potential can be considerably improved. These objectives can be delivered by adopting new techniques of base isolation and energy dissipation devices. With the introduction of energy dissipation devices, supplemental damping of 20-30% of critical can be easily achieved (inherent damping is merely 1-5%). Thus forces exerted on the structure and the amplitudes of vibrations are considerably reduced. The drifts of the structure can be reduced by a factor of about two to three and by larger factors if the devices also add stiffness to the structure, refer Article C9.1 of FEMA-356 [27]. The energy dissipation systems should be considered in somewhat broader context than isolation systems (which are not feasible in taller buildings) as a design strategy when performance goals include damage control. Also, the construction cost is less with energy dissipation systems than base isolation systems.

Seismic isolation and energy dissipation systems are relatively new and sophisticated concepts that require more extensive design and detailed nonlinear time-history dynamic analysis than most conventional schemes. With the availability of several commercial programs and powerful desktop computers, the sophisticated analysis is no longer a daunting task and can be easily and quickly done in a small design office environment. However, the benefits accrued outweigh the extra design expense and resulting savings more than compensate the cost of dampers.

With the emergence of Pall Friction Dampers[1-3,6], the performance-based design of buildings is now economically feasible. The first building with seismic dampers in North America was built with Pall Friction Dampers. Their low cost and maintenance free characteristics suggest wide application for new construction as well as for retrofit of existing buildings. Public sectors, private sectors and developers are using and benefiting this technology. They have been used for the seismic protection of more than 80 major building projects, including the Boeing Commercial Airplane Factory at Everett, WA – the world's largest building in volume. This technology is credited with for saving Boeing more than US$ 30 million. The City and County of San Francisco chose Pall Friction Dampers for the seismic control of Moscone West Convention Center and saved US$2.25 million, compared to alternate viscous dampers.

This paper describes the innovative structural system and several applications in the performance-based design of major projects including cost analysis.

PALL FRICTION DAMPERS

State-of-the-Art

Of all the methods so far available to extract kinetic energy from a moving body, the most widely adopted is undoubtedly the friction brake. Mechanical engineers have successfully used this concept for centuries to stop the motion of equipment, automobiles, railway trains, airplanes etc. No other mean has been able to replace the friction brake. Reason! It is the most effective, reliable and economical mean to dissipate kinetic energy. Similar to automobiles, the motion of vibrating building can be slowed down by dissipating seismic energy in friction.

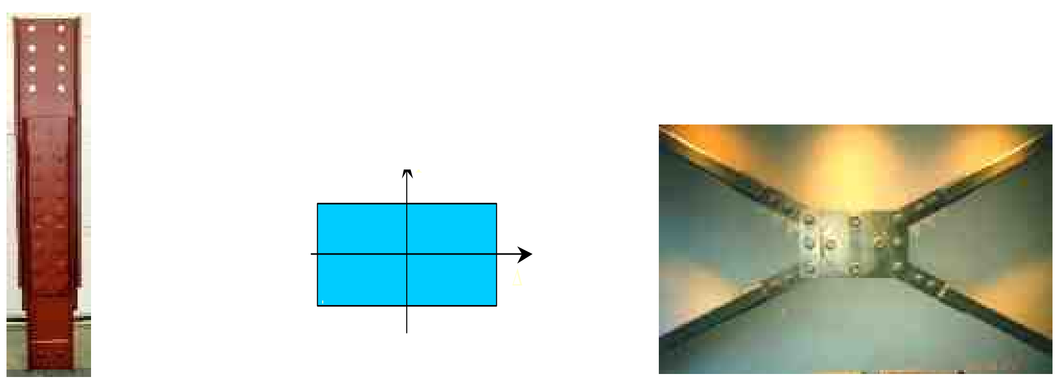
Inspired by the principle of friction brake in mid 1970's, Pall Friction Dampers were pioneered for the seismic control of buildings. Pall Friction Dampers significantly reduce the initial cost of construction while dramatically increasing the earthquake resistance against damage.

Friction dampers for a building must possess a reliable and stable performance over the life of building. Developing a reliable friction is very difficult and tricky. Over a period of more than a decade of research and development, the common problems in friction were successfully overcome by using specially treated surfaces and a unique manufacturing process. Over the years, Pall Dynamics has earned an international reputation for excellence and is a world leader in friction dampers for seismic control of buildings.

Pall Friction Dampers have successfully undergone rigorous proof testing in the U.S and Canada. In 1985, the National Research Council of Canada tested 3-story frame structures on a shaking table at the University of British Columbia, Vancouver [4]. In 1986-1987, the U.S. National Science Foundation tested a 9-story frame structure on a shaking table at the University of California at Berkeley [5]. The structures were subjected to more than 20 different major earthquake records. Even for an earthquake 5 times stronger than the 1985-Mexico earthquake, the frames equipped with friction dampers remained damage free. Pall Friction Dampers are well recognized and accepted by the building codes in Canada, the U.S and many other countries.

Salient Features

Pall Friction Dampers are foolproof in construction. Basically, these consist of series of steel plates, which are specially treated to develop very reliable friction. These plates are clamped together and allowed to slip at a predetermined load. Decades of research and testing have led to perfecting the art of friction. Their performance is reliable, repeatable and they possess large rectangular hysteresis loops with negligible fade. Their performance is independent of velocity and hence exerts constant force for all future earthquakes, design-based earthquake (DBE) or maximum credible earthquake (MCE). A much greater quantity of energy can be dissipated in friction than any other method involving the yielding of steel plates, viscous or viscoelastic dampers. Therefore, fewer Pall Friction Dampers are required to provide the required amount of energy dissipation. Pall Friction Dampers are passive energy dissipation devices and, therefore, need no energy source other than earthquake to operate it. They do not require any repair or replacement after the earthquake and are always ready to do their job.



Friction Damper for Tension-Compression Brace

Hystersis Loop

Friction Damper in Tension-only Cross Brace

Figure 1. Pall Friction Dampers

In a typical undamped structure, the inherent damping is merely 1-5% of critical. With the introduction of Pall Friction Dampers, structural damping of 20-50% of critical can be easily achieved. As the dampers dissipate a major portion of the seismic energy, forces and deformations on the structure are significantly reduced. Pall Friction Dampers significantly reduce the initial cost of construction while dramatically increasing the earthquake resistance against damage.

Pall Friction Dampers are customized to suit site conditions and allow greater adaptability than is possible with other systems. These dampers can be bolted or welded into place.

Pall Friction Dampers are available for long slender tension-only cross bracing, single diagonal tension-compression bracing and chevron bracing (Figure 1). The damper for cross bracing is a unique mechanism. When one of the brace in tension forces the damper to slip, the damper mechanism forces the other brace to shorten and thus avoid buckling. In this manner, the other brace is immediately ready to slip the damper on reversal of cycle. These dampers have been used in 65 feet (22 m) long slender bracing.

To avoid pounding at the expansion joints, Pall Friction Connectors are custom made to accommodate bi-directional movements.

Slip Load of Friction Damper

The friction dampers are designed not to slip during wind. During a major earthquake, they slip prior to yielding of structural members. In general, the lower bound is about 130% of wind shear and the upper bound is 75% of the shear at which the members will yield. As seen in Figure 2, if the slip load is very low or very high, the response is very high. Several parametric studies have shown that the slip load of the friction damper is the principal variable with the appropriate selection of which it is possible to tune the response of structure to an optimum value. Optimum slip load gives minimum response. Selection of slip load should also ensure that after an earthquake, the building returns to its near original alignment under the spring action of an elastic structure. Studies have also shown that variations up to ±20% of the optimum slip load do not affect the response significantly. Therefore, small variations in slip load (8-10%) over life of the building do not warrant any adjustments or replacement of friction damper.

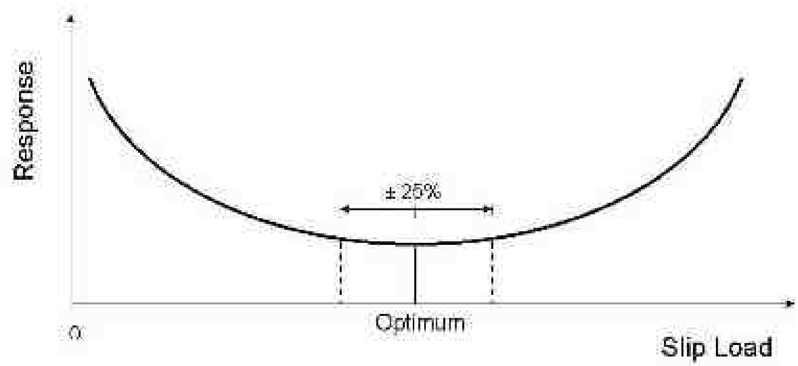


Figure 2. Response versus Slip Load

WHY PALL FRICTION DAMPERS ARE FAVORED?

- They are simple and foolproof in construction.
- Offer reliable and repeatable performance at low cost.
- Possess large rectangular hysteresis loops. Greater energy dissipation for a given force. Hence, fewer Pall Friction Dampers are needed. Conversely, exert lesser force for a given damping.
- Provide supplemental damping and stiffness for added stability.
- Performance is independent of velocity and temperature.
- Constant force for all future earthquakes (DBE/MCE). Therefore, design of connections and members is economical.

- They are not active during service loads and wind. Hence, no possibility of failure due to fatigue before an earthquake.
- Need no repair or replacement before and after earthquake. There is nothing to damage or leak.
- Energy dissipation is through friction and not through the damaging process of yielding.
- After an earthquake, the building returns to its near original alignment due to spring action of an elastic structure.
- Compact and narrow enough to be hidden in partitions.
- They can accommodate foundation settlements.
- Available for all types of bracing, including tension cross bracing, and expansion joints.
- Custom made. Easily adaptable to any site condition. Can be welded or bolted

COMPARISON OF HYSTERESIS LOOPS OF DIFFERENT DAMPERS

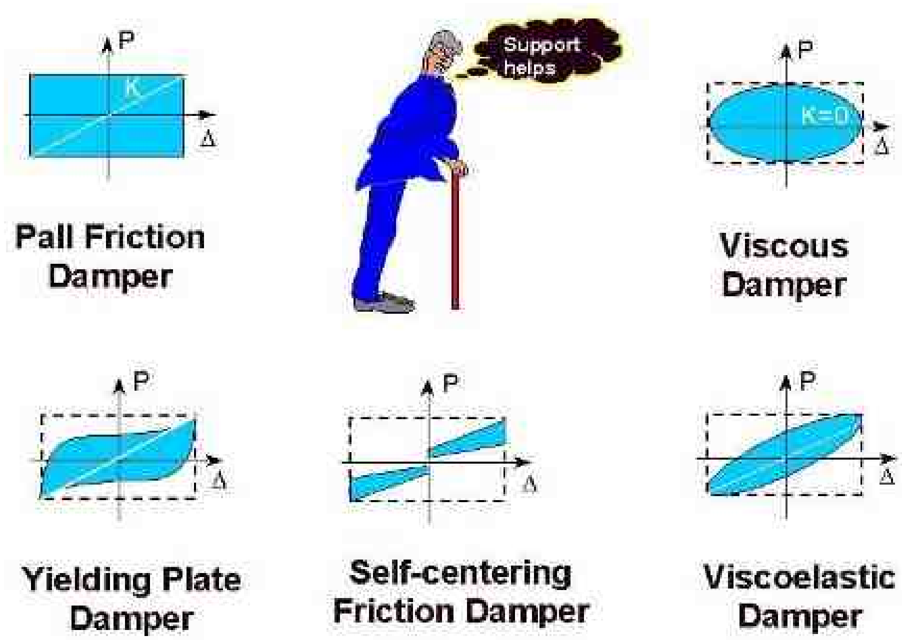


Figure 3. Comparison of Hysteresis Loops of Different Dampers

COMPARISON WITH OTHER DEVICES

Viscous Damper

Viscous dampers are velocity dependent. The forces exerted by the damper are, therefore, different for different earthquake records. Friction dampers are independent of velocity, therefore, exert constant force for all future earthquakes (DBE / MCE). A friction-damped structure is an engineered structure in which forces exerted are predetermined. This is a great technical and economic advantage over viscous dampers in which forces are much higher at MCE level.

The hysteresis loop of viscous damper is elliptical compared to rectangular for friction damper. For a given maximum force, the area of hysteresis loop (energy dissipation or damping) of viscous damper is about 70% of that for friction damper i.e. 70 friction dampers will achieve the same damping as 100 viscous dampers of a given force. Conversely, for a given number and damping value, the forces exerted by friction dampers are only 70% of those for viscous dampers. This leads to significant savings in cost of dampers, bracing, connections, columns and foundations.

While supplemental damping is beneficial in reducing the earthquake forces and amplitudes of vibration, added stiffness is beneficial for stability. A deflected building is similar to a stooped person. Similar to a cane support for stooped person, additional stiffness helps the deflected building against overturning. Pall Friction Dampers provide both added damping and added stiffness for stability - a complete structural solution. Viscous dampers provide only damping and no stiffness - the structure is on its own to struggle for stability.

Unbonded Brace

Unbonded brace is often called by other names like 'Yielding brace' or 'Buckling-Restrained brace'. It consists of a slender steel brace (core steel), surrounded by a steel tube or pipe, which is then filled with concrete or grout. The core steel is wrapped with plastic like material to separate it from the concrete around. The concrete in steel tube prevents buckling of the steel brace.

Unbonded brace dissipates energy through the process of yielding. Yielding involves damage. No damage, no energy dissipation or damping. After an earthquake, the brace may be damaged and needs to be replaced. Replacement of brace after an earthquake is expensive and time consuming. It is too difficult to replace before imminent aftershocks. Another problem is that the brace is enclosed in concrete and is not visible for inspection to verify if it is broken or otherwise.

The cost of supply of core steel and wrapping material may appear to be small, but the overall cost of an installed unbonded brace, including filling of outer tube with concrete and connections, is higher than the installed friction damper. As friction dampers dissipate a large amount of energy mechanically, the forces exerted are far less than those exerted by the unbonded braces. Besides, the structure with friction damper is economical to design and always ready to resist earthquakes one after another without replacement.

DESIGN CRITERIA

The quasi-static design procedure given in most building codes are ductility based and do not explicitly apply to buildings with supplemental damping. In the past few years, several guidelines on the analysis and design procedure of passive energy dissipation devices have been developed in the U.S. The latest and most comprehensive document is the "NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 356 / 357, issued in 2000" [27]. This equally applies to new buildings.

The Guidelines require that the structure be evaluated for response to two levels of ground shaking, a design basis earthquake (DBE) and a maximum considered earthquake (MCE). The DBE is an event with 10% probability of exceedance in 50 years, while the MCE represents a severe ground motion of probability of 2% in 50 years. Under the DBE, the structure is evaluated to ensure that the strength demands on structural elements do not exceed their capacities and that the drift in the structure is within the acceptable limits. For the MCE, the structure is evaluated to determine the maximum displacement and overstress. It is presumed that if proper ductile detailing has been followed, the structure will have sufficient reserve to avoid collapse during MCE.

Since different earthquake records, even of the same intensity, give widely varying structural responses, results obtained using a single record may not be conclusive. Therefore, three time-history records, suitable for the region should be used; one of which should be preferably site specific. The maximum response is used for the design.

NEHRP guidelines require that friction dampers are designed for 130% MCE displacements and all bracing and connections are designed for 130% of damper slip load. Variation in slip load from design value should not be more that ± 15%.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

The slippage of friction damper in an elastic brace constitutes nonlinearity. Also, the amount of energy dissipation or equivalent structural damping is proportional to the displacement. Therefore, the design of friction-damped buildings requires the use of nonlinear time-history dynamic analysis. With these analyses, the time-history response of the structure during and after an earthquake can be accurately understood. Several nonlinear computer programs are now capable of modeling friction dampers. Some of these programs are ETABS, SAP2000, DRAIN-TABS, DRAIN-2DX, DRAIN-3DX, ANSYS etc. With the availability of powerful personal computers, the sophisticated nonlinear time history analysis can be easily and quickly done in a small design office environment.

The modeling of friction dampers is very simple. Since the hysteresis loop of the damper is similar to the rectangular loop of an ideal elasto-plastic material, the slip load of the friction damper can be considered as a fictitious yield force.

PRACTICAL APPLICATIONS

The first building built with seismic dampers in North America was with Pall Friction Dampers (1987). Pall Friction Dampers are finding increasing application worldwide for new construction as well as for retrofit of existing buildings, including overhead water tanks. They have been used for the seismic protection of more than 80 major buildings in Canada, the U.S., China and India. These are hospitals, telecommunication buildings, educational institutions, police headquarters, defense installations, convention centers, courthouses, office and residential buildings. Some projects are discussed below:

Seismic Upgrade of Boeing Commercial Airplane Factory, Everrett, WA, USA.

Figure 4. (a). Inside View of Boeing Factory. (b). Pall Friction Dampers

The mammoth Boeing plant, which could contain Disneyland under one roof, is the world's largest building in volume [25]. It was built in phases from 1968-1991, for the assembly of wide-bodied 747 jetliners - world's largest commercial airplane. The steel frame building is 120 feet (37 m) high with clear spans of 350 feet (107 m) and covers more than 98 acres.

In 1996, the Boeing engineers considered several seismic upgrade schemes for this structure. They chose Pall Friction Dampers as they are foolproof in construction and offer reliable maintenance free performance at low cost. Also, they possess stiffness for added stability. The performance of friction dampers is independent of velocity, therefore, the forces on the connections remain constant for any future earthquake. This is an engineered solution. Economy in the design of connections and easy installation of dampers provided significant savings in construction cost and time.

Several types of Pall Friction Dampers, suitably modified to adapt to the site conditions, were incorporated in different types of existing bracing. Friction dampers of capacity up to 200,000 lb. (900 KN) and stroke up to 15 inch (380 mm) have been used. Pall Friction Dampers met or exceeded Boeing's stringent specifications. Work on seismic upgrade was undertaken in 1998 and completed in 2002.

Cost of Retrofit: US$65 million. Savings: US$30 million compared to conventional construction.

Moscone West Convention Center, San Francisco, USA

Figure 5. (a). View of Moscone West (b). Pall Friction Damper

The Moscone West Convention Center is located in downtown San Francisco, between San Andrea's and Hayward faults, which are about 19 kM in each direction. The four-story steel frame building is 112 feet (34 m) high with clear spans of 45 to 90 feet (14-28 m) [26]. The US$186 million expansion of the 1.2 million sq. feet (111,700 m^2) convention center was California's largest project of 2001.

Bids were invited on two alternate designs, one with viscous dampers and another with Pall Friction Dampers. The scheme with friction dampers offered a saving of US$2.25 million compared to viscous dampers. On the recommendations of peer reviewers and two specialist consultants from the University of California at Berkeley, the City and County of San Francisco chose Pall Friction Dampers for seismic control of this prestigious building. The construction of the convention center was completed in 2003. Pall Friction Dampers up to 500,000 lb. (2250 kN) capacity and 9 inch (230 mm) stroke have been used.

The use of friction dampers reduced the story drifts from 2% without dampers to 1% with dampers. About 80% of the earthquake energy has been dissipated by the friction dampers leaving the building with little damage. According to the project architects and engineers, the use of technology saved a couple of million dollars in the initial construction costs and will save tens of millions of dollars in lowered repair costs in the event of an earthquake.

Seismic Retrofit of Boeing Development Center, Cafeteria and Auditorium Buildings, Boeing Field, Seattle, WA, USA

Figure 6. (a). View of Cafeteria, Auditorium and Fitness Building (b). Pall Friction Damper

There are three 2-story Boeing Development buildings and a 4-story Boeing Cafeteria, Auditorium and Fitness Center building. These are steel frame buildings, built in 1980's. The foundations are on 70-80 feet deep friction piles. Some of these buildings were damaged during February 28, 2001 Nisqually Earthquake of magnitude 6.8. The epicenter was about 20 miles from the building site. Due to liquefaction of soil, the differential settlements in pile foundations were 4-5 inches. This resulted in substantial non-structural and structural damage to the Cafeteria and Auditorium building. The structural damage was primarily to rigid steel bracing. Several bracing in the Cafeteria and Auditorium building buckled or broke.

Several structural schemes were considered for the seismic retrofit of these buildings. Friction dampers were considered to be an ideal solution as they provide both damping and stiffness. Besides, they can be easily modified to suit site conditions and designed to accommodate any future foundation settlements.

A total of 350 Pall friction Damper of 100-500 kip slip load and up to 10 inches stroke, were used in the existing steel bracing. The seismic retrofit was completed in 2002. Savings are estimated to be more than 60% compared to conventional retrofit.

Ambulatory Care Center, Sharp Memorial Hospital, San Diego, California, USA

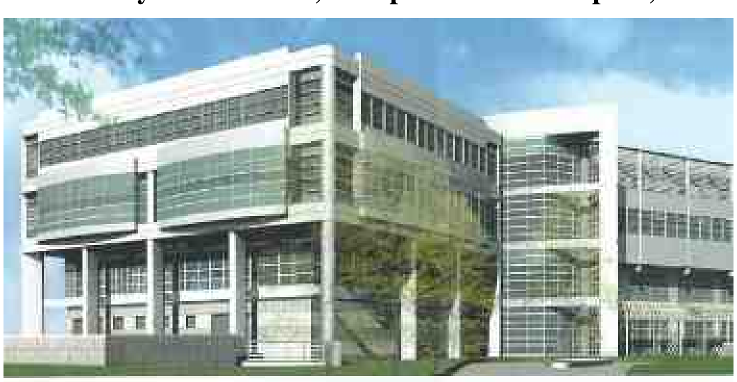


Figure 7. View of New Ambulatory Care Center Pall Friction Dampers in Chevron Brace

The Ambulatory Care Center complex consists of two buildings of four and five floors, connected in two places by a pedestrian bridge and an elevator lobby. This facility will provide extensive medical services to the community including surgery.

The project engineers selected steel-frame design for the cost efficiency, design flexibility and speedy construction. Moment-resisting frames, in combination with Pall Friction Dampers in steel bracing, were selected to resist lateral seismic forces. The structure was designed to meet 1997UBC and 1998 California Code requirements for Seismic Zone 4. In this performance-based design, the Pall Friction Dampers reduced building drift from 2% to 1%. The savings in construction cost due to reduced forces, more than offset the cost of dampers. In case of a major seismic event, the dampers reduce building content damage and increase safety of occupants. This resulted in long-term savings to the client through lower seismic insurance premiums.

Seismic Retrofit of 3-Million Gallon Reservoir, Sacramento, California, USA

The Freeport water tower, a distinctive landmark visible from Interstate-5, was built in 1956 [22]. The steel reservoir stands about 120 feet high. The supporting structure consists of 27 steel columns with two levels of 60 feet long tension cross bracing. Of the several seismic retrofit options, the scheme with Pall Friction Dampers in tension cross bracing was chosen. When tension in one of the brace forces the damper to slip, the damper's mechanism shortens the other brace, thus preventing buckling.

Due to high damping provided by the Pall Friction Dampers, the strengthening of columns and foundations was not necessary. Friction dampers up to 150 kip slip capacity were used. Seismic retrofit was completed in 1999.

Savings: More than 60% compared to conventional.

Figure 8. 3-Million Gallon Water Tank.

Concordia University Library Building, Montreal, Canada

Figure 9. (a). View of Concordia Library Building

(b). Pall Friction Damper in Cross Bracing

The ten-story McConnell Library Building is a masterpiece in innovative structural design [7]. The building was designed in 1987 and construction was completed in 1991. Pall Friction Dampers are installed at the junction of steel cross bracing in rigid concrete frames. The use of steel bracing eliminated the need of expensive concrete shearwalls and the introduction of supplemental damping provided by friction dampers eliminated the need of dependence on ductility of structural members.

Unlike concrete shearwalls, the bracing were generally not continuous one over the other and thus provided greater flexibility in space planning. Since the bracing do not carry any gravity load, they do not go through the basement to the foundations. Therefore, they allow more space for parking. The architects have boldly exposed several bracing with dampers as these add to the aesthetic appearance.

The innovative structural system provided an economical design solution to safeguard the building and its valuable contents from earthquake damage.

Covered Area: 52,000 m^2. Cost: $65 million. Savings: 6.5% of structural or 1.5% of building cost.

Seismic Rehabilitation of Justice Headquarters, Ottawa, Canada.

Figure 10. (a). View of Justice Headquarters (b). Pall Friction Damper

This eight-story concrete frame building is located in the nation's parliamentary district [21]. It was built in 1955 as a memorial to the Canadians killed during the Second World War. The stone clad building, with sloping copper roof, has been designated a heritage structure. The existing structure was not capable of resisting seismic forces specified in the Building Code. In 1997, seismic rehabilitation was undertaken along with major renovations to protect the original and new investment.

Pall Friction Dampers offered the best solution for the seismic upgrade. Since the dampers dissipate a major portion of the seismic energy, forces acting on the structure are considerably reduced. By staggering the bracing at different story levels, overloading of columns and foundations was avoided. Hence, expensive and time-consuming work of strengthening existing members and foundations was not required.

Unlike shearwalls, the friction-damped bracing need not be vertically continuous. This aspect was particularly appealing to the architects as it offered flexibility in space planning. This structural solution also facilitated construction scheduling as work could start at any floor level, depending on vacancy or availability.
Covered Area: 50,565 m^2**.** Savings: More than 40% in construction cost and time.

Canadian Space Agency Headquarters, St-Hubert, Canada

Figure 11. View of Canadian Space Agency Headquarters

The headquarters of the Canadian Space Agency is a building of national importance [11]. It contains extremely sensitive and costly equipment / instrumentation. Therefore, it is of vital importance to protect its valuable contents and electronically stored data in the event of a major earthquake.

The use of Pall Friction Dampers significantly increased the damage control potential of the building while offering savings in the initial cost of construction. Construction was completed in 1992.

Covered Area: 50,000 m2. Cost $60,000,000. Savings: 1.25% of total cost.

Seismic Rehabilitation of Casino de Montreal, Canada

Figure 12. Casino de Montreal

In 1993, Casino de Montreal was housed in the existing French Pavilion built for EXPO'1967 [12]. The lateral earthquake resistance of the existing eight-story braced steel structure was not adequate to meet the requirements of the National Building Code of Canada.

Introduction of supplemental damping provided by Pall Friction Dampers was the most effective, economical and hi-tech solution for the seismic rehabilitation of this building. The use of Pall Friction Dampers in the existing steel bracing considerably reduced the forces on the structure. Hence, the provision of additional bracing, strengthening of existing members and pile foundation was not required.

Covered Area: 38,000 m2. Savings: 50% in construction cost & time.

Quebec Provincial Police Headquarters, Montreal, Canada

Figure 13. (a). View of Police Headquarters　　**(b). Pall Friction Dampers in Bracing**

The existing sixteen-story office building, with two levels of basement, was built in 1964 [23]. Steel moment frames and some braced bays provided lateral resistance to the existing structure. A change of occupancy was planned in 1997 to house the provincial police (Surete du Quebec) headquarters. The project structural engineers evaluated that the existing structure was not capable of resisting seismic forces and the story drifts were excessively high, especially at the lover level due to soft story effect.

In 1999, the work on seismic rehabilitation was undertaken along with major renovations to protect the original and new investment. Pall Friction Dampers offered the best solution for the seismic upgrade. Since the dampers dissipate a major portion of the seismic energy, the story drifts and forces acting on the structure are considerably reduced. Hence, expensive and time-consuming work of strengthening existing member and pile foundations was not required. Pall Friction Dampers were incorporated in existing and new bracing. The innovative structural scheme offered savings of more than 50% over conventional retrofit scheme.

CONCLUSION

The use of Pall Friction Dampers has shown to provide a practical, economical and effective approach for the performance-based design of new and retrofit of existing structures to resist major earthquakes. The low cost and maintenance free characteristics of Pall Friction Dampers suggest wide application. Public sector, private sector and developers, including developing countries, are using and benefiting from Pall Friction Damper technology.

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