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FRICTION-DAMPERS FOR SEISMIC CONTROL OF BUILDINGS "A CANADIAN EXPERIENCE"

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ABSTRACT

Friction-dampers have been used in the aseismic design and construction of 15 new buildings and retrofit of existing buildings. Several others are under construction. By incorporating simple and inexpensive friction-dampers, the earthquake resistance and damage control potential of the structure is dramatically increased. During a major earthquake, the friction-dampers slip at a predetermined load before yielding occurs in members of a frame, and dissipate a major portion of the seismic energy. Three-dimensional nonlinear time-history dynamic analysis is employed for the analyses of buildings. The introduction of supplemental damping provided by the friction-dampers dramatically reduces the forces on the structure, amplitude of vibration and floor accelerations. While assuring added safety to occupants and contents of the building, the system offers the benefit of significant savings in the initial cost of construction. Shake table studies at the University of British Columbia in Vancouver and the University of California at Berkeley have confirmed the superior performance of this system. The friction-dampers possess a stable hysteretic behaviour and need no maintenance, repair or replacement after the earthquake. The building codes in Canada, the U.S. and several other countries recognize and allow the use of friction-dampers.

KEYWORDS

Aseismic design; damage control; earthquake resistant design; energy dissipation devices; friction-dampers; passive control of structural response; seismic retrofit; seismic rehabilitation; supplemental damping.

INTRODUCTION

During a major earthquake, a large amount of energy is fed into a structure. The manner in which this energy is consumed determines the level of damage. The design criteria stipulated in most building codes, including the National Building Code of Canada, are based on the philosophy of designing structures to resist moderate earthquakes without significant damage and to avoid structural collapse during a major earthquake. The primary emphasis is on life safety with an expectation of substantial structural damage. In general, reliance for survival is placed on the ductility of the structure to dissipate energy while undergoing large inelastic deformations causing bending, twisting and cracking. This assumes permanent damage, repair costs of which could be economically as significant as the collapse of the structure. Recent examples of these are the 1994 Northridge (California) and 1995 Kobe (Japan) earthquakes. In the devastating tragedy of Kobe, more than 5000 people were killed, 30,000 were seriously injured and over 300,000 were left homeless. The damage to the buildings and other associated costs were estimated to be more than US$150 billion. The cost of damage as a result of 1989 Loma Prieta and 1994 Northridge earthquakes is more than US$50 billion. These earthquakes have clearly shown that conventional construction in even technologically advanced industrialised countries is not immune to destruction.

While the minimum design provisions of the building codes were adequate in the past for most buildings, safer approaches are desirable for important buildings. In modern buildings, avoidance of structural collapse alone is not enough. The costs of finishes, contents, sensitive instrumentation and electronically stored records can be much higher than the cost of the structure itself and these must be protected. In view of huge financial losses and social suffering, highlighted by the recent earthquakes, the building officials, structural engineers, owners, bankers and insurers should carefully consider seismic response of the buildings in terms of damage control rather than life safety.

The problems created by the dependence on ductility of a structure can be reduced if a major portion of the seismic energy is dissipated mechanically, independent from the primary structure. With the emergence of friction-dampers, it has become economically feasible to significantly increase the earthquake resistance and damage control potential of a structure.

CONVENTIONAL CONSTRUCTION METHODS

Braced steel frames are known to be economical and effective in controlling lateral deflections due to wind or moderate earthquakes. During a major earthquake, these structures do not perform that well. Firstly, being stiffer, they tend to invite higher lateral inertial forces, and secondly, the energy dissipation capacity of the brace is very limited. A brace in tension stretches during severe shock and buckles in compression during reversal of load. On the next application of load in the same direction, this elongated brace is not effective even in tension until it is taut again and is stretched even further. As a result, the energy dissipation degrades very quickly and the structure may collapse. The 1995 Kobe earthquake demonstrated several failures of braced buildings.

Moment-resisting frames are favoured for their earthquake resistance capability because properly detailed frames have stable ductile behavior under repeated reversing loads. This preference is reflected in various seismic codes by assigning lower seismic forces to them. However, these structures are very flexible and it is often economically difficult to develop enough stiffness to control storey drifts and deflections to prevent non-structural damage. The 1995 Northridge earthquake has highlighted that the welded beam-column connection of moment-resisting frames are much more susceptible to damage than previously thought.

The use of concrete shearwalls, concentric or eccentric bracing are some methods to add rigidity to the moment-resisting frames. Generally, stiffer structures attract higher ground accelerations thus exert higher forces on supporting members and foundations. Therefore any advantage gained by added stiffness is negated by the increased amount of energy input, and thus place higher demand on strength and ductility. The ductility in a reinforced concrete wall is extremely sensitive to detailing and quality control and is viewed with suspicion. Besides the high cost of construction, the use of shearwalls severely restricts the flexibility of space planning. Once located, they have to continue from top to foundation. In eccentric braced frames, energy is dissipated by shear distortions in beams. After the earthquake, these beams would need major repairs or replacement.

FRICTION-DAMPED BUILDING

The friction brake is widely used to extract kinetic energy from a moving body as it is the most effective, reliable and economical mean to dissipate energy. For centuries, mechanical engineers have successfully used this concept to control the motion of machinery and automobiles. The principle of friction brake inspired the development of Pall friction-dampers.

The development of friction-damping devices was pioneered in the late seventies (Pall 1979, Pall 1981a). Friction-dampers suitable for different types of construction have been developed for: 1) concrete shearwalls, both precast and cast-in-place (Pall 1980, Pall 1981b); 2) braced steel/concrete frames (Pall 1982); 3) low-rise buildings (Pall 1981a); and 4) clad-frame construction (Pall 1989). Patented Pall friction-dampers are available for: tension cross-bracing; single diagonal bracing; chevron bracing; cladding connections; and friction base isolators. These friction-dampers meet a high standard of quality control. Every damper is load tested to ensure proper slip load before it is shipped to site.

Pall friction-dampers are simple and fool-proof in construction and inexpensive in cost. Basically, these consist of series of steel plates which are specially treated to develop most reliable friction. These plates are clamped together with high strength steel bolts and allowed to slip at a predetermined load. Cyclic dynamic laboratory tests have been conducted on specimen friction-damping devices (Pall 1980, Filiatrault 1986). Their performance is reliable, repeatable and possess large rectangular hysteresis loops with negligible fade over several cycles of reversals that can be encountered in successive earthquakes. Much greater quantity of energy can be disposed of in friction than any other method involving the damaging process of yielding of steel or viscoelastic materials. Therefore, fewer Pall friction-dampers are needed to provide the required energy dissipation. Unlike viscoelastic materials, their performance is not affected by temperature, velocity and stiffness degradation due to ageing. The maximum earthquake force with friction-dampers is well defined when compared to viscous or viscoelastic dampers in which it varies with the velocity and displacement across the device. Unlike devices that dissipate energy by the damaging process of yielding of steel plates, these do not need repair or replacement after the earthquake. Also, yielding devices may develop premature fracture due to fatigue caused by frequent occurrence of wind loadings and hence require regular inspection. Pall friction-dampers need no maintenance over the life of the building and are always ready to do their job regardless of how many times they have performed.

Friction-dampers are designed not to slip during wind storms or moderate earthquakes. During severe seismic excitations, friction-dampers slip at a predetermined optimum load before yielding occurs in other structural members and dissipate a major portion of the seismic energy. This allows the building to remain elastic or at least yielding is delayed to be available during catastrophic conditions. By selecting the proper slip load, it is possible to 'tune' the response of the structure to an optimum value. Parametric dynamic studies have shown that the optimum slip load is independent of the time-history of the earthquake motion and is rather a structural property. Also, within a variation of $\pm$ 20% of slip load, the seismic response is not significantly affected. Another interesting feature of friction-damped buildings is that their natural period varies with the amplitude of vibration, i.e. the severity of earthquake. Hence the phenomenon of resonance or quasi-resonance for future earthquakes is avoided.

These friction-dampers have successfully gone through rigorous proof-testing on shake tables in Canada and the United States. In 1985, a large scale three-storey frame equipped with friction-dampers was tested on a shake table at the University of British Columbia, Vancouver (Filiatrault 1986). The response of friction-damped braced frame was much superior to that of moment-resisting frame and moment-resisting braced frame. Even an earthquake record with a peak acceleration of 0.9g did not cause any damage to friction-damped braced frame, while the other two frames suffered large permanent deformations. In 1987, a nine-storey three bay frame, equipped with friction-dampers, was tested on a shake table at Earthquake Engineering Research Center of the University of California at Berkeley (Aiken 1988). All members of the friction-damped frame remained elastic for 0.84g acceleration - the maximum capacity of shake table, while the moment-resisting frame would have yielded at about 0.3g acceleration.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

During a major earthquake, the slippage of friction-damper in an elastic brace constitutes artificial nonlinearity which is similar to an elasto-plastic behaviour of steel. Also, the amount of energy dissipation or equivalent structural damping is proportional to the amplitude. Hence, 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 the earthquake, can be accurately understood. With the availability of high speed personal computers, the use of sophisticated nonlinear time-history dynamic analysis is no longer limited to university research projects. Such analysis can be easily and quickly done in a small design office environment.

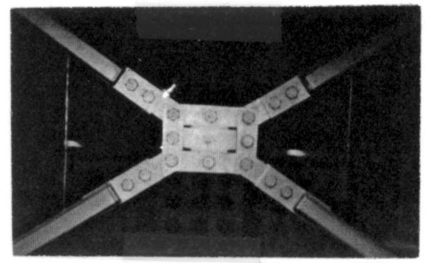
Three-dimensional nonlinear time-history dynamic analyses are carried out using the computer program DRAIN-TABS (Guendelman-Isreal and Powell 1977), developed at the University of California, Berkeley. The original program is developed for main frame, and can be modified for use on personal computers. This program consists of a series of subroutines that carry out a step by step integration of the dynamic equilibrium equations using a constant accelerations within any time step. It is known that different earthquake records, even though of the same intensity, give widely varying structural response and results obtained using a single record may not be conclusive. Therefore, it is necessary to use at least three pairs of earthquake time-histories suitable for the region. Hysteritic damping due to inelastic action of structural elements and slipping of the friction-dampers is automatically taken into account by the computer program. Interaction between axial forces and moments for columns and P-Δ effect are taken into account by including geometric stiffness based on axial loads under static loads.

The modelling of friction-damper is very simple. Since the hysteretic loop of the friction-damper is similar to the rectangular loop of a perfectly elasto-plastic material, the slip load of friction-damper may be considered as a fictitious yield force. An elastic brace with a friction-damper can be considered as a brace yielding at slip load.

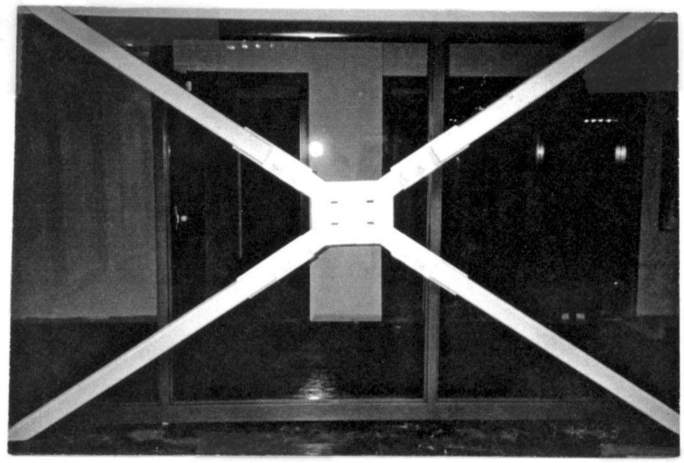
PRACTICAL APPLICATIONS

Pall friction-dampers have found several applications for both steel and concrete buildings in new construction and retrofit of existing buildings (Table 1). Several others are under construction. Some of these are briefly discussed below. Detailed information is available in the cited references.

1 (b). Exposed Friction-Damper in Library Office



2 (c). Exposed Friction-Damper along Partitions



2 (b). Exposed Friction-Damper in Control Room

1 (a). Partial View

Figure 1. Concordia University Library Building

2 (a). Partial View

Figure 2. Canadian Space Agency Headquarters

Concordia University Library Building, Montreal

Concordia University's new library complex consists of a ten-storey and a six-storey building which are interconnected with an atrium. The total floor area of the building is approximately 50,000 sq.m. Fig. 1 shows part view of the building. In the chosen structural system (Pall 1987), friction-dampers are provided at the junction of each steel cross-bracing in the concrete frame. The use of steel bracing eliminated the need of expensive concrete shearwalls and the use of friction-dampers eliminated the need of dependence on member ductility The use of friction-damped bracing provides greater flexibility in space planning because unlike shearwalls these do not need to be located continuously one over the other. Since bracing do not carry any gravity load, these do not need to go down through the basements to the foundation. This allows more open space for car parking in the basement. At the ground floor level, the lateral shear from the bracing is transferred through the rigid floor diaphragm to the perimeter retaining walls of the basement. A total of 143 friction-dampers of 600-700 kN slip load were required to extract sufficient energy to safeguard the structure and its contents from damage. The architects have exposed several friction-dampers to view as they add to the aesthetic appearance. The use of friction-dampers in steel cross-bracing has resulted in a net saving of 6.5% of the structural cost or 1.5% of the total building cost of $65 million. Higher savings are expected in regions more severely affected by earthquakes.

Canadian Space Agency Headquarters, St-Hubert

The headquarters of the Canadian Space Agency (Fig. 2) is a building of national importance (Vezina 1992). It houses very sensitive instrumentation and expensive equipment. Therefore, it was of vital importance to protect its valuable contents in the event of a major earthquake. The structure is made of structural steel frames. The innovative technique of introducing supplemental damping through friction-dampers was considered to be the most economical, effective and practical solution for the aseismic design of this building. A total of 58 friction-dampers were required to dissipate sufficient energy to safeguard the structure and its contents from damage. The optimum slip load of the friction-dampers was 500 kN. Analyses were also conducted on alternative structural systems. It was seen that the savings in structural steel for friction-damped frame was 20-25%, while its earthquake response was much superior to other frames.

Seismic Retrofit of Ecole Polyvalente, Sorel

The school complex, built in1967, consists of three precast concrete buildings of 40,000 sq.m. covered area (Pall, 1991a). These buildings suffered some structural damage during the 1988 Saguenay (Quebec) earthquake. The existing structure lacked in lateral resistance and ductility requirements of the current building code. The conventional methods of retrofitting with concrete shearwalls or rigid steel bracing were time consuming and expensive. The innovative technique with friction-dampers in steel bracing was the most effective, practical and economical design solution for the seismic upgrading of the three buildings. The introduction of supplemental damping provided by the friction-dampers reduced the seismic forces, therefore, strengthening of the structural members and foundations was not necessary. The retrofit was completed in record time during the school's summer vacation of 1990. Net saving was 40% in construction cost and 60% in construction time.

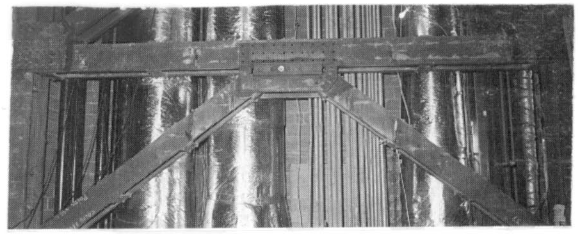
Seismic Rehabilitation of Casino de Montreal

In 1993, Casino de Montreal (Fig. 3) was housed in the existing French Pavillion built for EXPO'1967 (Pasquin, 1994). The lateral earthquake resistance of the existing eight-storey braced steel structure was not adequate to meet the requirements of the new National Building Code of Canada. Introduction of supplemental damping provided by friction-dampers was the most effective, economical and hi-tech solution for the seismic rehabilitation of this building. The use of 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 foundations was not required. Net savings were more than 50% in construction cost and construction time.

Friction Base -Isolated House, Montreal

In low-rise structures, where overturning moments are not significant, friction base isolators are located horizontally between the foundation and the superstructure to partly isolate the superstructure from the forcing ground motion (Pall 1981b). Ideally, friction-less joints will allow the foundation to move without exerting any force on the building, but the displacements of the building relative to the ground will be very large. A sufficient friction force is required to react to the wind. During a severe earthquake the magnitude of lateral force that the building can experience is limited to the slip load. The slip load is so selected that the stresses in the materials do

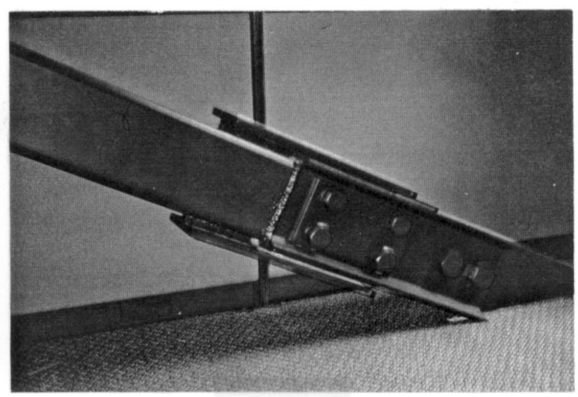
3 (a). Front View



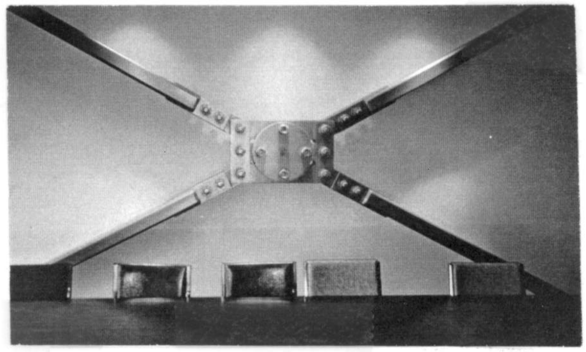
3 (b). Friction-Damper in Chevron Bracing in Partitions

Figure 3. Casino de Montreal

4 (a). Front View

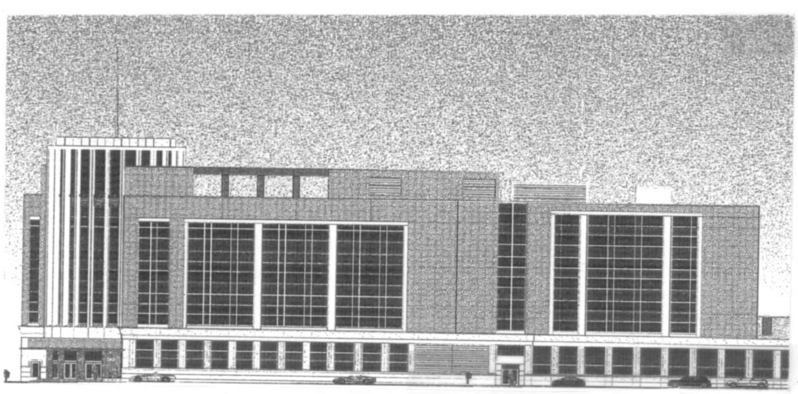


4 (b). Friction-Damper in Single Diagonal

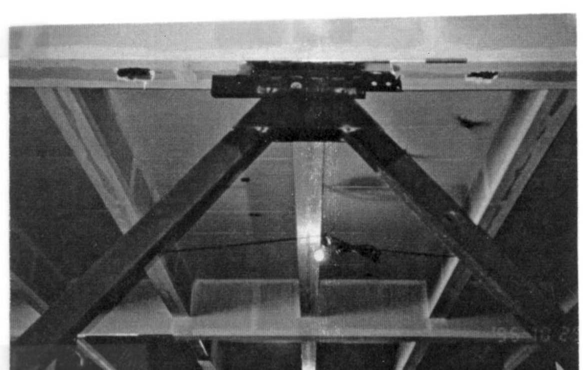


4 (c). Friction-Damper in X-Bracing

Figure 4. Maison 1 McGill



5 (a). Front View



5 (b). Friction-Damper in Chevron Bracing

Figure 5. Ecole de Technologie Superieure

not exceed the permissible elastic value of the materials and that the relative displacements are limited to an acceptable limit. In order to provide restraint on the total movement, increasing resistance to sliding is provided by the ramp shape in steel plates or by providing an elastic pad at the end of travel.

Friction base isolators have been used in a two-storey residential house in Montreal. The house was incorporated with 15 friction base isolators between the foundation and the superstructure (Pall 1991). The low cost of the friction base isolators suggest wide application in low-rise construction including residential houses.

Table 1. Buildings with Pall Friction-Dampers

NAME OF STRUTURE	TYPE OF STRUCTURE	NEW OR EXISTING	QUANTITY (SLIP LOAD)	REFERENCE
1.Concordia University Library, Montreal	Ten-storey concrete frame building	New, 1987-1991	143 (600-700kN)	Pall, 1987
2. Ecole Polyvalente, Sorel	3 three-storey precast concrete buildings	Built in 1967, retrofitted in 1990	64 (225-335kN)	Pall, 1991a
3. Canadian Space Agency Headquarters	Four-storey steel frame building	New, 1992	58 (500kN)	Vezina, 1992
4. CCRIT, Laval	Four-storey steel frame building	New, 1992	(350kN)	
5. Casino de Montreal, Montreal	Eight-storey steel frame building	Built in 1967, rehabilitated in 1993	32 (700-1800kN)	Pasquin, 1994
6. Deptt. of National Defence of Canada, Ottawa	Three-storey concrete frame building	New, 1992	(500kN)	
7. Maison 1 McGill, Montreal	Eleven-storey concrete frame building	New, 1995	65 (600-700kN)	Savard, 1995
8. Hamilton Courthouse, Hamilton	Eight-storey steel frame building	Built in 1934, rehabilitated in 1996	73 (500-700kN)	Wagner, 1995
9. Ecole Technologie Superieure, Montreal	2 steel frame buildings	Built in 1949 & 1977, rehabilitated in 1995	74 (700kN)	Godin, 1995
10. Federal Building, Sherbrooke	Four-storey concrete frame building	Built in 1950, rehabilitated in 1995	30 (350kN)	
11. Desjardin Life Insurance Building, Quebec	Six-storey concrete frame building	New, 1995	30 (600-700kN)	
12. Residence Maison-Neuve, Montreal	Six-storey steel frame building	Built in 1972, rehabilitated in 1996	42 (500kN)	
13. Water Tank, Beaux Arts, WA, USA	Overhead steel tower	Built in 1950, rehabilitated in1995	12 (75kN)	
14. Residential House, Montreal	Two-storey and basement, wood stud, brick veneer	New, 1988	15 friction base-isolators	Pall, 1991b
15. Water Tanks, University of California at Davis, USA	Overhead steel tower	Built in 1958, rehabilitated to be completed in March 1996	48 (135-160kN)	Hale, 1995

CONCLUSION

The use of Pall friction-dampers has shown to provide a practical, economical and effective new approach to design buildings to resist earthquakes. Also, these can be conveniently incorporated in existing frame buildings to upgrade their seismic resistance. Some of the technical and economic advantages of Pall friction-dampers are:

1. Offer savings in the initial cost of new construction or retrofit of existing buildings.
2. Simple and fool-proof in construction, and inexpensive in cost.
3. Possess large rectangular hysteretic loops with negligible fade over many cycles of reversals.
4. Very high energy dissipation capacity. Hence, fewer Pall friction-dampers are required.
5. Reliable and maintenance free performance. No repair or replacement needed after an earthquake.

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