8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver – 1999

Friction-dampers for seismic control of Justice Headquarters, Ottawa

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ABSTRACT

The East Memorial Building (EMB) is a heritage designated edifice in Ottawa. The earthquake resistance of the existing structure was significantly less than that of current building code requirements. Supplemental damping provided by Pall friction-dampers in steel bracing, offered an innovative solution for the seismic rehabilitation of this building. Since a major portion of the seismic energy is dissipated by the friction-dampers, the forces acting on the structure are considerably reduced. The structure was analyzed using a nonlinear time history dynamic analysis. The results of this analysis showed that the lateral deflections and floor accelerations were reduced significantly. This method of seismic rehabilitation offered both cost savings and reduction in the construction time when compared to traditional shearwall type methods.

INTRODUCTION

The EMB is an eight-storey building with plan dimensions of approximately 54 m x 91 m and a total area of 50,565 m^2. The exterior facade is stone cladding with sloped copper roofs. The EMB was constructed in 1955 as a memorial to the Canadians killed during the Second World War and has been designated as a heritage structure. A photograph of the building elevation is shown in Figure 1. A typical floor plan is shown in Figure 2.

The EMB structure is a concrete frame structure with cast in place concrete one-way slabs and nominally reinforced concrete walls around the elevator shafts. The lateral forces appear to have been resisted by the nominally reinforced concrete elevator shaft walls and the concrete frames some of which were infilled with brick and terra cotta.

The EMB is located in the Parliament Precinct on Wellington Street in Ottawa. As part of an overall rehabilitation program for the Parliament Hill buildings, the EMB was scheduled for extensive renovation work to become the new home for Canada's Department of Justice. Within the scope of these renovations a seismic evaluation of the existing structure was completed. The results of this evaluation demonstrated the need for strengthening the existing structure.

Consideration was initially given to conventional methods of reinforcing the structure. These included replacing the nominally reinforced concrete walls around the elevator with reinforced concrete shear walls detailed to current standards, reinforcing the existing concrete frames and inserting new concrete shear walls or rigid steel braced bays. All of these options required expensive foundation work and imposed significant restrictions on architectural design solutions and heritage conservation.

In addition to the conventional methods, non-conventional reinforcement methods were considered, including the addition of supplementary damping into the structure with Pall friction-dampers. Supplementary damping acts to dissipate the energy caused by a seismic event. The remaining energy that is not dissipated by the friction-dampers is then accommodated by elastic deformation of the existing lateral load system. In the case of the EMB structure, it was possible to insert sufficient damping into the structural matrix such that the existing structural elements would be adequate to accommodate the residual design earthquake loads. However, repairable cracks in the masonry may have to be accepted.

The Pall friction-dampers were introduced into the EMB structure in a series of either single or diagonal or chevron steel braces. Typical single diagonal and chevron braces during construction are shown in Figure 3. These were inserted into the concrete frames in both directions and were located along corridors, staircases and partitions. The slip loads were predetermined to suit the capacity of the existing concrete frame structure. When subjected to a seismic loading, the friction damped bracing behave elastically until a preset slip load is reached. When the magnitude of the load in the brace reaches the preset slip load, the friction-damper slips and begins to dissipate the seismic energy.

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The benefits of this solution were as follows:

1. The friction-dampers were installed in sufficient quantity and in such a manner such that the existing structure was no longer overloaded under seismic loads.
2. It was not necessary to align the friction-dampers vertically as with conventional shearwalls. This provided flexibility in space planning for the various floors and enabled superior preservation of the heritage character of the building.
3. Expensive foundation rehabilitation work was avoided.
4. The fast track construction schedule was enhanced in that braces with friction-dampers could be installed at any floor depending on vacancy, allowing flexibility in the scheduling of various trades.

This paper discusses a brief review of the development of Pall friction-dampers, the design criteria and design procedures used for the EMB structure and some of the details of construction used to install the braces containing friction-dampers.

PALL FRICTION-DAMPERS

Of all the methods available to extract kinetic energy from a moving body, the most widely adopted is undoubtedly the friction brake. It is the most effective, reliable and economical mean to dissipate energy. In late seventies, the principle of friction brake inspired the development of Pall friction-dampers (Pall 1979, Pall 1981a). Similar to automobiles, the motion of vibrating building can be slowed down by dissipating energy in friction. Several types of friction-dampers have been developed (Pall 1980, Pall 1981, Pall 1982, Pall 1989). For frame buildings, these are available for tension cross bracing, single diagonal bracing and chevron bracing.

Pall friction-dampers are simple and foolproof in construction and inexpensive in cost. They consist of series of steel plates specially treated to develop a most reliable friction. These plates are clamped together with high strength steel bolts. Friction-dampers are designed not to slip during wind. During severe seismic excitations, friction-dampers slip at a predetermined optimum slip load before overload occurs in other structural members. A major portion of the seismic energy is dissipated by the friction-dampers. This allows the building structure to remain elastic or at least yielding is delayed to be available during maximum credible earthquakes. Another feature of friction-damped buildings is that their natural period varies with the amplitude of vibration. Hence the phenomenon of resonance is avoided. After the earthquake, building returns to its near original alignment under the spring action of an elastic structure.

Pall friction-dampers have successfully gone through rigorous proof testing on shake tables in Canada and the United States. In 1985, a three-story frame equipped with friction-dampers was tested on a shake table at the University of British Columbia, Vancouver (Filiatrault, Cherry 1986). Even an earthquake record with a peak acceleration of 0.9g did not cause any damage to friction-damped braced frame, while the conventional frames were severely damaged at lower seismic levels. In 1987, a nine story 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, Kelly 1988). All members of the friction-damped frame remained elastic for 0.84g acceleration, while the moment-resisting frame would have yielded at about 0.3g acceleration.

Pall friction-dampers possess large rectangular hysteresis loops, similar to an ideal elasto-plastic behavior, with negligible fade over several cycles of reversals (Pall 1980, Filiatrault 1986). Unlike viscous or visco-elastic devices, the performance of Pall friction-dampers is independent of temperature and velocity. For a given force and displacement in a damper, the energy dissipation of Pall friction-damper is the largest compared to other damping devices (Figure 4). Therefore, fewer Pall friction-dampers are required to provide a given amount of supplemental damping. The maximum force in a friction-damper is well defined and remains constant for any future ground motion. Hence, the design of bracing and connections is economical. There is nothing to damage or leak. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. Pall friction-dampers are also very compact in design and can be easily hidden within drywall partitions. Architects often opt to expose these dampers to view as they add to the aesthetics of the structure.

Pall friction-dampers have found large practical application for both concrete and steel buildings in new construction and seismic retrofit of existing buildings (Pall 1987, Pall 1991, Vezina 1992, Pall 1993, Pasquin 1994, Godin 1995, Hale 1995, Savard 1995, Wagner 1995, Pall 1996, Deslaurier 1997, Pasquin 1998,1999). To date, more than three dozen buildings have already been fitted with Pall friction-dampers and several are under design or construction phase. Currently, the Boeing Commercial Airplane Factory at Everett – the world's largest building, is being upgraded with Pall friction-dampers.

DESIGN CRITERIA

The quasi-static design procedure given in the NBCC is ductility based and does not explicitly apply to friction-damped buildings. However, the Structural Commentary - J of the NBCC 1995, allows the use of friction-dampers for seismic control of buildings. It requires that the nonlinear analysis must demonstrate that the building so equipped will perform equally well in seismic events as the same building designed following the NBCC seismic requirements. 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 273 / 274. The provisions of the NBCC and above documents served as guidelines for the analysis and design of the above project.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

A three-dimensional nonlinear time-history dynamic analyzes was carried out using the computer program DRAIN-TABS, developed at the University of California, Berkeley. This program consists of a series of subroutines that carry out a step by step integration of the dynamic equilibrium equations using constant accelerations within any time step. Several other programs such as ETABS, SAP2000, SADSAP, DRAIN-2DX, DRAIN-3DX, are now available on which friction-dampers can be easily modeled. The modeling of Pall friction-damper is very simple. Since the hysteretic 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.

Different earthquake records, even though of the same intensity, give widely varying structural response and hence the results obtained using a single record may not be conclusive. Therefore, three time-history records, suitable for the Ottawa region, were used to ensure that possible coincidence of ground motions and building frequencies was not missed. A viscous damping of 5% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements. Hysteretic 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 were taken into account by including geometric stiffness. To account for any accidental eccentricity due to uncertainty in the distribution of mass or possible variation in relative stiffness, the centre of mass was shifted by 10% of the building dimension in both axes. Analysis was carried out for earthquake motions in three directions, applied independently along the x-axis, y-axis and 45 degree direction. The analysis that provided maximum response was used for the design. A series of analyses were made to determine the optimum slip load of friction-dampers to achieve minimum response. A total of 84 friction-dampers of 500-700 kN slip load were used in single diagonal and chevron bracing.

Analyses were also conducted on frames with concentric rigid bracing. The effectiveness of friction-dampers in improving the seismic response is seen in comparison of the results of two types of frames. The friction damped frames (FDF) and the concentrically braced moment frames (BMF) have the same member properties, except that the BMF has twice the area of brace than that in the FDF. For smaller or larger areas of brace, the response of the BMF was higher. The results compared are for the maximum response.

Discussion of Results

1. Time-histories of deflections at the top of building are shown in Figure 5. The peak amplitude of the FDF is about 85% of the BMF. After the earthquake, there was a permanent offset of 4 mm in the FDF and 14 mm for the BMF.
2. Time history of slippage in a typical damper is shown in Figure 6. The maximum amplitude of slippage is about 6 mm. The permanent offset in the damper after the earthquake was 1 mm. Friction-dampers at all storeys participated in energy dissipation.
3. Maximum envelopes for shears in a column of a braced bay are shown in Figures 7. The values of the FDF are about 40% of those for the BMF.
4. Maximum envelopes for axial in a column of a braced bay are shown in Figures 8. The values of the FDF are about 60% of those for the BMF.
5. In the BMF, 60% of braces and 25% of columns had yielded. All members in the FDF remained elastic.

CONCLUSION

The use of Pall friction-dampers has shown to provide a practical and economical solution for the seismic upgrade of the Justice Headquarters Building. The analytical studies have shown that the rehabilitated structure should perform satisfactorily in a major seismic event with possibly reduced damage to building and its contents.

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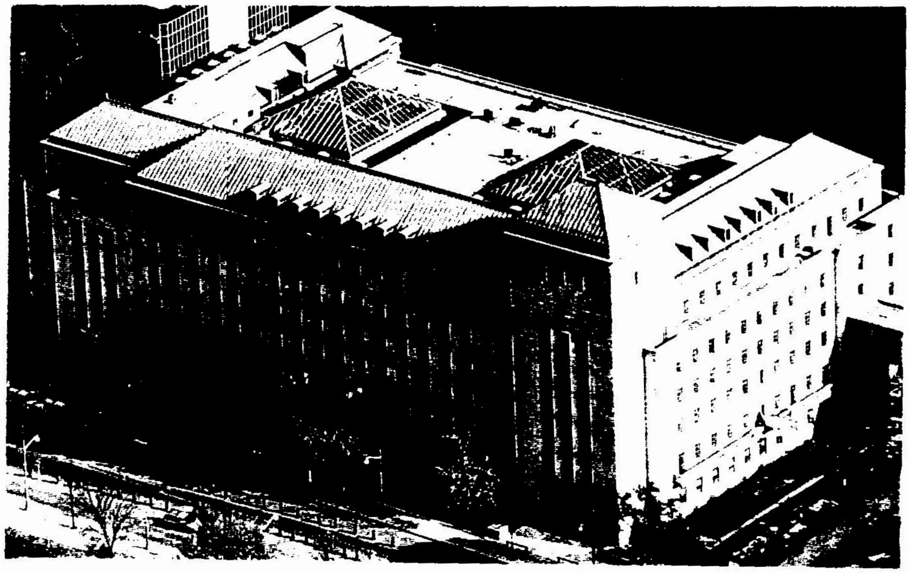


Figure 1. Front View from Wellington Street

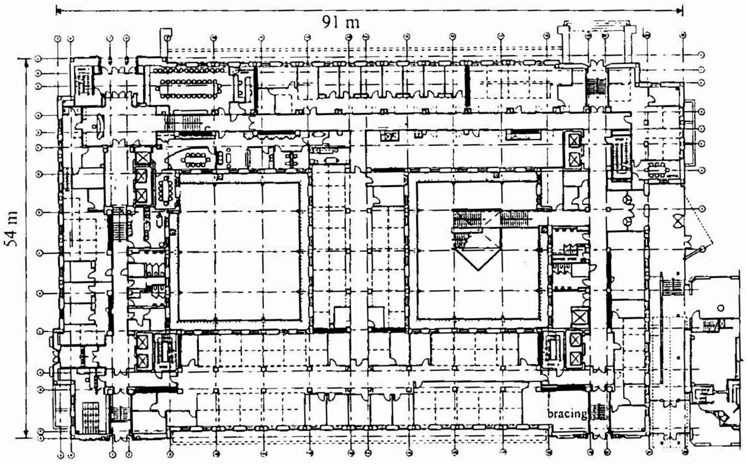
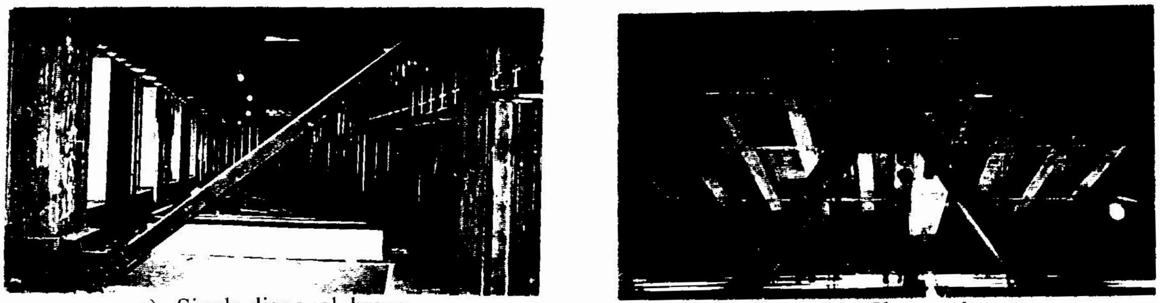


Figure 2. Typical Floor Plan. Bracing with Friction-Dampers shown in thick lines.



a). Single diagonal brace

b). Chevron brace

Figure 3. Typical Friction-Dampers

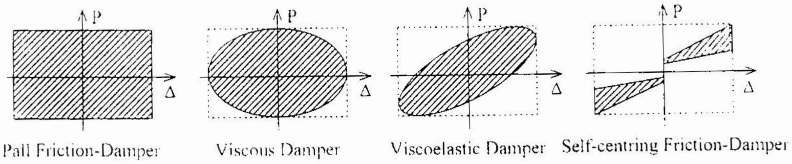


Figure 4. Hysteretic Loops of Different Dampers

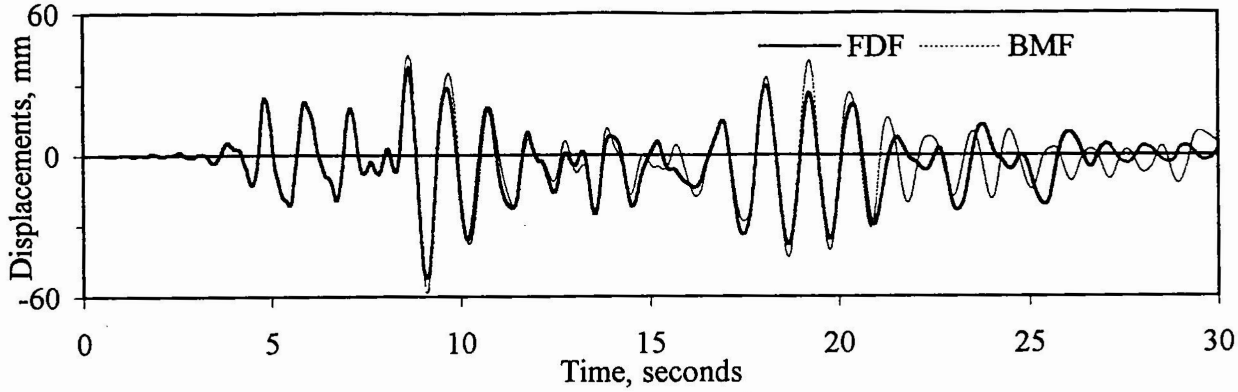


Figure 5 . Time-Histories of Deflection at Top

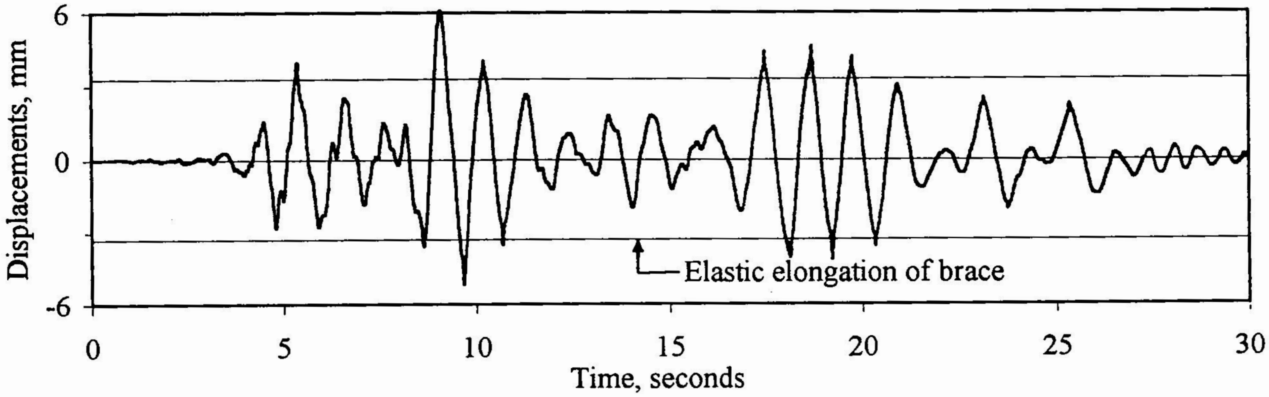


Figure 6 . Time-Histories of Slippage in Friction-Damper

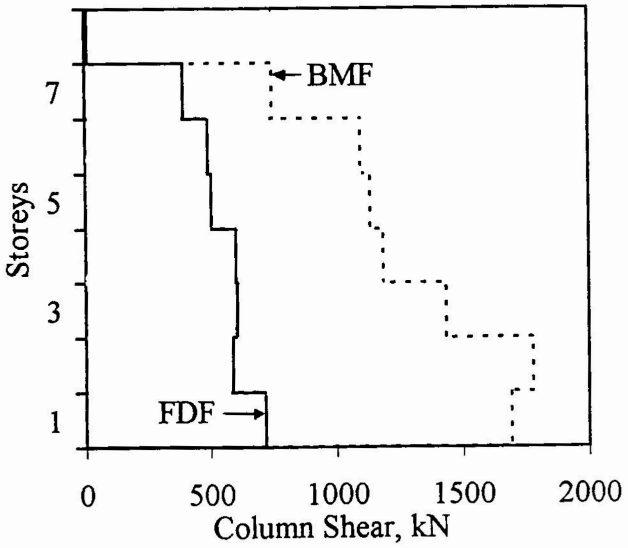


Figure 7. Envelope of Column Shear

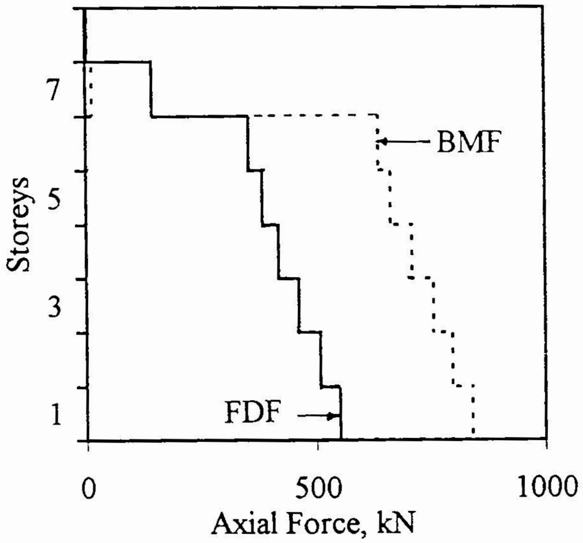


Figure 8. Envelope of Column Axial Force