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FRICTION-DAMPERS FOR SEISMIC UPGRADE OF QUEBEC POLICE HEADQUARTERS, MONTREAL

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SUMMARY

The existing sixteen-storey steel frame building was built in 1964. In 1998, it was to undergo major renovations to house the new headquarters of Quebec Provincial Police (Surete du Quebec). The seismic resistance of the existing structure was not adequate to meet the requirements of current building codes. Police stations of being of post-disaster importance, the seismic upgrading was undertaken along with other renovations and completed in 1999. Introduction of supplemental damping in conjunction with appropriate stiffness was the chosen solution. This was achieved by incorporating Pall friction-dampers in the existing and new bracing. The results of three-dimensional dynamic analysis have shown superior performance of friction-damped frames compared to conventional rehabilitation. The introduction of supplemental damping provided by friction-dampers significantly reduced the lateral inertial forces and amplitude of vibrations. The strengthening of expensive and time-consuming work on pile foundation was avoided. Besides superior seismic performance, the structural system offers savings in the upgrade cost compared to conventional stiffening methods.

INTRODUCTION

The existing sixteen-storey office building, with two levels of basement, was built in 1964. Front elevation of building is shown in Figure 1. Steel moment frames and some braced bays provided lateral resistance to the existing structure. The foundations are on piles. 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 capable of resisting only a small percentage of the seismic loads specified in the National Building Code of Canada (NBCC) 1995 and that the storey drifts were excessively high. Over a period of 35 years, the building codes had changed considerably, especially in terms of seismic provisions. Commentary K of the NBCC 1995, recommends a “triggering criterion” for the seismic upgrading of an existing building if its seismic resistance is less than 60% of the seismic loading for new buildings. In 1999, the work on seismic rehabilitation was undertaken along with major renovations to protect the original and new investment.

The conventional methods of stiffening consist of addition of concrete shearwalls or rigid steel bracing. During a major earthquake, these structures tend to attract higher ground accelerations causing higher inertial forces on the supporting structure. Therefore, any advantage gained with the added stiffness may be negated by the increased amount of energy input. In a conventional braced frame, the energy dissipation capacity of a 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 further. As a result, the energy dissipation degrades very quickly and the structure may collapse. Several rigid braced buildings have failed in Kobe earthquake. Both conventional methods require expensive and time-consuming work of strengthening the existing columns and foundations.

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For seismic rehabilitation, strengthening with rigid steel bracing were considered. However, the method required expensive and time-consuming work on pile foundation. Supplemental damping in conjunction with appropriate stiffness offered an innovative solution for the seismic rehabilitation of this building. This was achieved by incorporating Pall friction-dampers in existing cross bracing or new single diagonal steel bracing (Figures 2 and 3). As soon as the structure undergoes small deformations, the friction-dampers go into action and start dissipating energy. Since the dampers dissipate a major portion of the seismic energy, the forces acting on the structure and amplitude of vibration are considerably reduced. Hence, expensive and time-consuming work on strengthening of members and foundations was not required.

This paper discusses the design procedure, results of analysis and details of construction of the seismic rehabilitation. A brief review on the development of Pall friction-dampers has also been included so that the state-of-the-art structural solution can be appreciated.

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. Basically, these consist of series of steel plates specially treated to develop 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 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 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 possesses 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 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. The architects like to expose these dampers to view as they add to the aesthetic appearance.

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, Pasquin 1999, Balazic 2000, Chandra 2000, Hale 2000). To date, more than forty buildings have already been built and several are under design or construction. Currently, Boeing’s Commercial Aeroplane Factory - world’s largest building in volume, near Seattle, USA is being retrofitted with Pall friction-dampers.

DESIGN CRITERIA

The quasi-static design procedure given in the NBCC and building codes in other countries are ductility based and do not explicitly apply to friction-damped buildings. However, the Structural Commentary of the NBCC 1995, allows the use of friction-dampers for seismic control of buildings. It requires that 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, issued in October 1997". The provisions of the NBCC and above documents served as guidelines for the analysis and design of the above project.

The Guidelines require that the structure with energy dissipating devices 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 the most severe ground motion the structure is ever likely to experience. 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 tolerable limits. For the MCE, the structure is evaluated to determine the maximum displacement requirement of the damping device. It is presumed that if proper ductile detailing have been followed, the structure will have sufficient reserve to resist any overstress conditions that occur during the MCE. Nonlinear time-history analysis is required both for the DBE and the MCE. The maximum response of at least three earthquake records should be used for design.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

The slippage of a friction-damper in an elastic brace constitutes nonlinearity. Also, the amount of energy dissipation or equivalent structural damping is proportional to the displacement. 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 an earthquake can be accurately understood. With the availability of fast personal computers, the use of sophisticated nonlinear time-history dynamic analysis can be easily and quickly done in a small design office environment. Three-dimensional nonlinear time-history dynamic analyses were made using computer program ETABS (Figure 5). Several nonlinear programs such as SAP2000, DRAIN-TABS, DRAIN-2DX, DRAIN-3DX and ANSYS are now capable of modelling friction-dampers.

It is known that different earthquake records even though of the same intensity, give widely varying structural response, so the results obtained using a single record may not be conclusive. Three time-history records, suitable for this region, were used to ensure that possible coincidence of ground motions and building frequencies was not missed. A viscous damping of 2% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements. P-Δ effect was taken into account. To account for any accidental eccentricity due to uncertainty in the distribution of mass or possible variation in relative stiffness, the center 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 modelling of friction-damper is very simple. Since the hysteretic loop of the friction-damper is similar to the rectangular loop of an ideal elasto-plastic material, the slip load of friction-damper can be considered as a fictitious yield force. A series of analyses were made to determine the optimum slip load of friction-dampers to achieve minimum response. In case of dampers in existing bracing, the capacity of existing bracing governed the slip load. In total there are 62 friction-dampers with slip loads varying from 225 to 670 kN (50 to 150 kip).

Analyses were also conducted on frames with concentric rigid bracing in moment frames. 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. Almost all existing bracing needed to be replaced with new. The results compared are for the maximum response of the DBE record.

Discussion of Results

1. The total energy input in the structure and the energy dissipated by friction-dampers is shown in Figure 6. It is seen that 50 % of the energy is dissipated by the friction-damper

2. The deflection at the top of building was 180 mm and 210 mm for FDF and BMF, respectively. After the earthquake, there was a permanent offset of 5 mm in the FDF and 45 mm for the BMF.

3. Hysteretic loop of a single diagonal friction-damper and brace of 450 kN slip load is shown in Figure 7. The maximum amplitude of slippage is about 12 mm. The permanent offset in the damper after the earthquake was 1 mm. Friction-dampers at all storeys participated in energy dissipation.

4. Maximum envelopes for story shears are shown in Figures 8. The values of the FDF are about 75% of those for the BMF.

5. Maximum envelopes for axial load in a column of a braced bay are shown in Figures 9. The values of the FDF are about 30% of those for the BMF.

6. In the BMF, 75% of braces 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 rehabilitation of Police headquarters. 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. Elevation view of Quebec police headquarters

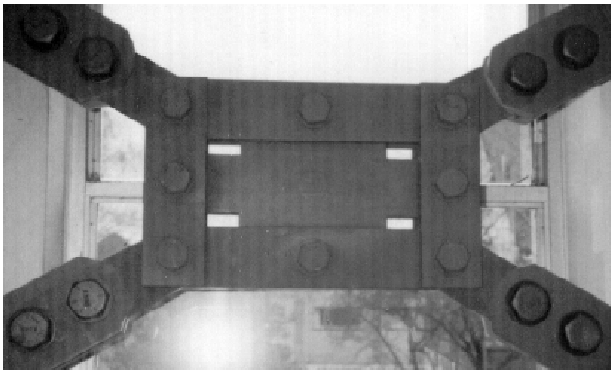


Figure 2. Pall friction-damper in existing cross bracing

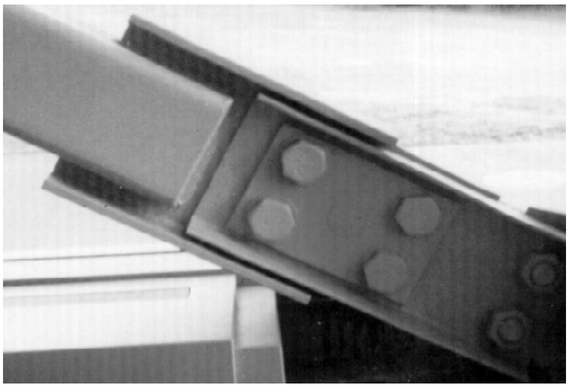
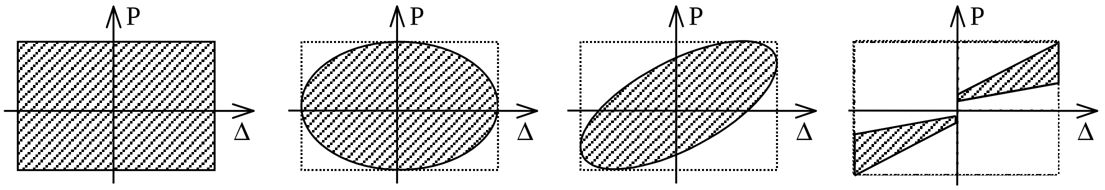


Figure 3. Pall friction-damper in single diagonal bracing



Pall friction-damper Viscous damper Viscoelastic damper Self-centering friction-damper

Figure 4. Hysteretic loops of different dampers

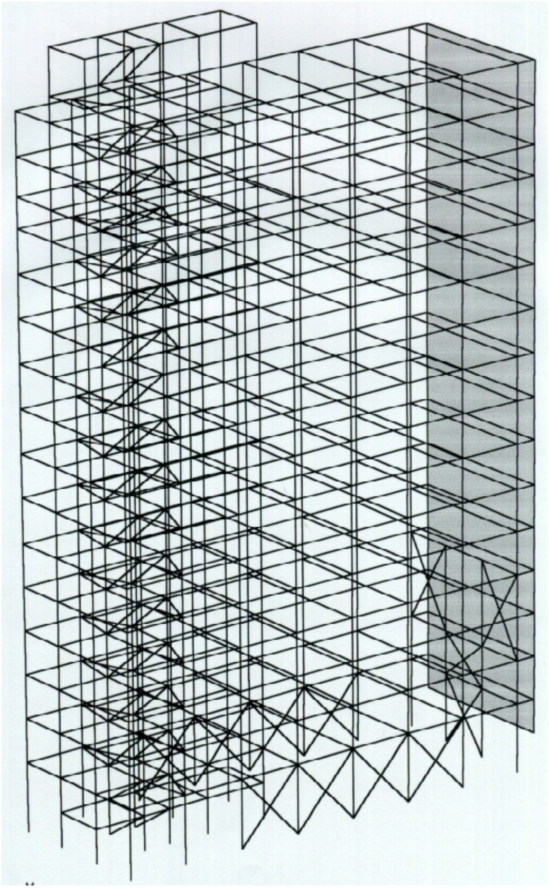


Figure 5. Computer model of building structure

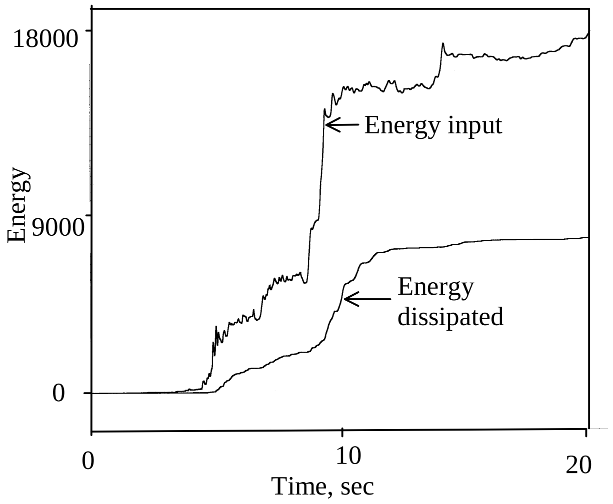


Figure 6. Energy input and energy dissipated by brace, friction-dampers

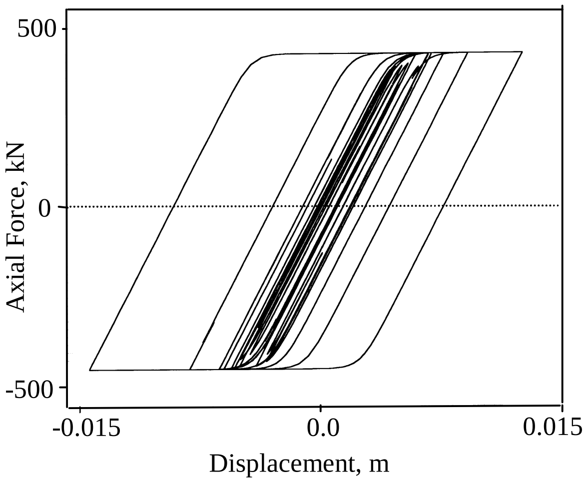


Figure 7. Hysteretic loop of friction-damper and 445 kN slip load

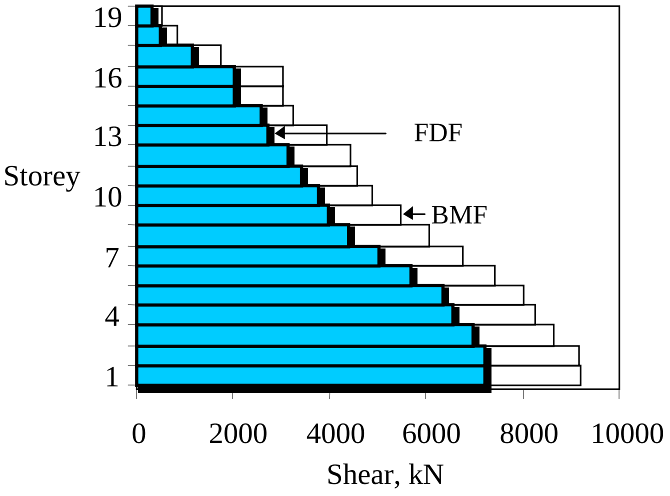


Figure 8. Envelope of storey shear

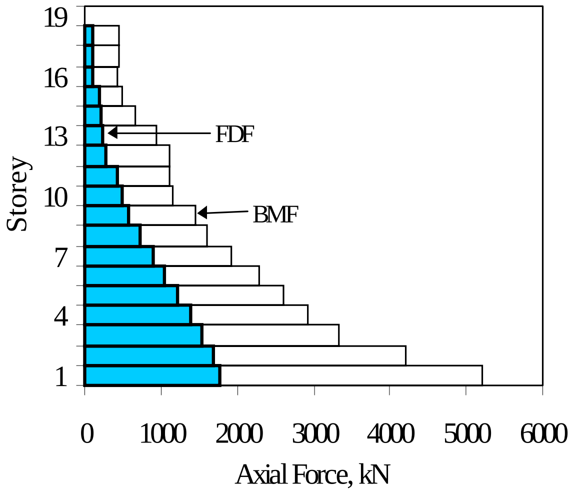


Figure 9. Envelope of Column Axial Force