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Friction-dampers for aseismic design of Canadian Space Agency

S.Vezina & P.Proulx
LVLVA Inc., The SNC/Lavalin Group, Montreal, Que., Canada

R.Pall & A.Pall
Pall Dynamics Limited, DDO, Montreal, Que., Canada

ABSTRACT: An innovative structural system, which combines the strength and stiffness of a braced frame and the high energy dissipation capacity of friction-dampers, has been used to design the headquarters building of the Canadian Space Agency. Three-dimensional nonlinear time-history dynamic analysis was used to determine the seismic response of the structure. Comparison of seismic response with other structural systems demonstrated the superior performance of friction-damped structure. The introduction of supplemental damping provided by the friction-dampers eliminated the necessity for dependence on ductility while the structure remained elastic without damage. The chosen structural system provides an economical design solution and significantly increases its damage control potential to safeguard the building and its valuable contents against earthquakes.

1 INTRODUCTION

The design criteria stipulated in most building codes are based on the philosophy to design structures to resist moderate earthquakes without significant damage and to resist major earthquakes without structural collapse. 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, after repair costs of which could be economically as significant as the collapse of structure. While these minimum design provisions were adequate in the past for most buildings, safer approaches are desirable for important buildings, especially for those of post disaster importance. In modern buildings, avoidance of structural collapse alone is not enough. The cost of finishes, contents, sophisticated instrumentation and electronically stored records are much more expensive than the cost of structure itself and these must be protected.

The problems created by the dependance on ductility of the 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 possible to design damage free structures. The National Building Code of Canada 1990, Clause 83 of Commentary -J of the Supplement, allows the use of friction-dampers.

The headquarters of the Canadian Space Agency is a building of national importance. It houses very sensitive instrumentation and expensive equipment. Therefore, it is of vital importance to protect its valuable contents in the event of a major earthquake.

The innovative technique of introducing supplemental damping in conjunction with appropriate stiffness was considered to be the most economical, effective, practical and a smart hi-tech solution for the aseismic design of this building. Analytical studies have been made to compare the seismic response with traditional structural systems. This paper will discuss the results of these studies and provide design / construction details of the chosen structural system.

2 TRADITIONAL FRAMED BUILDINGS

Braced steel frames are known to be economical and are effective in controlling lateral deflections due to wind or moderate earthquakes. During major earthquakes, these structures do not perform well. Firstly, being stiffer, they tend to invite higher lateral inertial forces, and secondly, the energy dissipation capacity of the braces 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.

Moment-resisting frames are favoured for their earthquake resistance capability because they have stable ductile behaviour under repeated reversing loads. Their preference is reflected in various seismic codes by assigning lower seismic forces. However, these structures are very flexible and it is often economically difficult to develop enough stiffness to control storey drifts and deflections to prevent nonstructural damage.

Recent earthquakes have demonstrated the need for stiffer structures and strong interest has grown in the past few years to develop structural systems which combine the ductile behaviour of a moment-resisting frame and stiffness of a braced frame. Braced moment-resisting frames and eccentrically braced frames are some of the developments in this direction. Although the structure is saved from total collapse, but the braces or beams are sacrificed and may need extensive repairs or replacement after a major earthquake.

3 FRICTION-DAMPED BRACED FRAMES

In the proposed structural system (Pall 1982), each cross-bracing in the moment-resisting frame is provided with a friction-damper. The friction-dampers are designed not to slip during wind storms or moderate earthquakes. During severe seismic excitations, the 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 the yielding is delayed to be available during catastophic conditions. 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. Studies have shown that within a variation of ±20% of the optimum slip load, the response is not significantly affected.

Cyclic dynamic laboratory tests have been conducted on specimen devices (Pall 1980, Filiatrault 86). Their performance is reliable, repeatable and possesses 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 cracking of concrete. Unlike visco-elastic materials, their performance is not affected by temperature, velocity and stiffness degradation due to aging. Furthermore, these friction-damping devices need no maintenance or replacement over the life of building and are always ready to do their job regardless of how many times they have performed.

In 1985, a large scale 3-storey friction-damped braced frame 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 9-storey three bay frame, equipped with friction-dampers, was tested on a shake table at the Earthquake Engineering Research Center of the University of California at Berkeley (Aiken 1988). All members of friction-damped frame remained elastic for 0.84g acceleration - maximum capacity of the shake table, while the moment-resisting frame would have yielded at about 0.3g acceleration. In 1988, a single storey friction-damped frame was tested on a shake table at the Imperial college in London. Here again, the performance of the friction-damped braced frame was superior to the conventional moment-resisting frame. Other researchers have investigated the seismic response of friction-damped frames and reported on the superior performance of friction-damped frames (Austin 1985, Baktash 1986, Filiatrault 1986, 1988, Aiken 1988, Pekau 1991).

In Montreal, a 10-storey Concordia University library building has recently been completed (Pall 1987). The use of steel bracing in concrete frames eliminated the need for expensive shearwalls and the use of friction-dampers eliminated the need of dependence on the ductility of structural components. The use of this system has resulted in a net saving of 1.5% of the total building cost while its earthquake resistance and damage control potential has significantly increased. Friction-dampers have also been used in retofitting of Ecole Polyvalente at Sorel, damaged during 1988 Saguenay earthquake (Pall 1991). Their use has resulted in a net saving of 40% in retrofitting cost and 60% in construction time.

Friction-dampers for other construction methods are discussed elsewhere (Pall 80,81,84,89,91).

4 CANADIAN SPACE AGENCY

4.1 Description of Structure

The headquarters of the Canadian Space Agency is located in St.-Hubert, near Montreal. The building is about 130 m long, 43 m to 78 m wide and 15 m high. The ground floor plan and section of the structure are shown in Figures 1 and 2 respectively. The structure is made of structural steel frames and clad with prefabricated aluminum panels. All frames, except the braced bays, have semi-rigid connections of nominal moment capacity. The braced bays have rigid connections. The concrete floor slabs are supported on steel deck over open-web composite steel joists or beams. The composite action is ensured by using steel shear-studs. The building foundations are on piles and pile caps are interconnected by a grid of tie-beams.

The location of steel cross-bracings with friction-dampers in the lower storey is shown in Figure 1. Generally, the bracings at the upper level follow the same arrangement unless the space planning warranted it otherwise. There are a total of 58 braced bays with friction-dampers. Typical detail of a braced bay and a friction-damper are shown in Figures 3 and 4 respectively.

4.2 Non-linear Time-History Dynamic Analysis

Three-dimensional non-linear time-history dynamic analyses were carried out by using the computer program DRAIN-TABS, developed at University of California, Berkeley. This program consists of series of subroutines that carry out a step by step integration of the dynamic equilibrium equations using a constant acceleration within any time step. As future earthquakes may be erratic in nature, an artificial earthquake record generated to match the design spectrum of Newmark-Blume-Kapur, which is an average of many earthquake records and covers a wide range of frequency content, has been used. This earthquake record forms the basis of the NBC response spectrum. For St. Hubert, the peak ground accelerations of this earthquake record were scaled to 0.18g. The duration of the earthquake was 15 seconds and the integration time step was 0.005 second.

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 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 based on axial force under static loads.

Analyses were also conducted on alternative structural systems. The effectiveness of friction dampers in improving the seismic response is seen in comparison with results of other systems. Included in the comparative studies were: braced frames (BF), moment-resisting frames (MRF), moment-resisting braced frames (MRBF) and friction-damped braced frames (FDBF). All types of frames have the same member properties, except BF which has twice the area of brace than that used in other frames. For smaller and larger areas of brace, the responses of BF were higher. A total of 58 friction-dampers, each of 500 kN slip load capacity, were required to dissipate sufficient energy to safeguard the structure and its contents from damage.

4.3 Discussion of Results

1. The time-histories of deflections at the top of building are shown in Figure 5. The peak amplitudes are 192 mm, 158 mm, 128 mm and 47 mm for MRF, BF, MRBF and FDBF respectively. The maximum storey drifts were in the lower most storey. These were H/40, H/39, H/68 and H/200 for MRF, BF, MRBF and FDBF respectively. The maximum storey drifts allowed by the National Building Code of Canada (NBC) are H/50 for normal buildings and and H/100 for buildings of post disaster importance. Even these seem to be very high if damage to nonstructural components is to be avoided. The storey drift for FDBF is very small and well within acceptable limits.
2. The maximum floor accelerations experienced by the FDBF are only 22%, 30% and 40% of those for BF, MRF and MRBF respectively. Reduction in floor accelerations significantly increases the damage control potential.
3. The maximum envelopes for storey shears and column axial forces are shown in Figures 6 and 7 respectively. The values for FDBF are about 50% and 70% of those for BF and MRBF respectively.
4. The time-histories of slippage in a typical friction-damper in lower storey is shown in Figure 8. The maximum amplitude of slippage is about 17 mm. Friction-dampers at all storeys participated in energy dissipation.
5. The damage experienced by different types of frames after the earthquake is shown in Figure 9. In BF, all the braces yielded and had a permanent elongation of up to 85 mm. The permanent set at top of the frame was 120 mm. In MRF, about 66% beams yielded and the frame had a permanent set of 80 mm. In MRBF, all the braces yielded and had a permanent elongation of up to 37 mm, 33% of the beams yielded and the frame had a permanent set of 75 mm. In the case of FDBF, all members of the frame remained elastic without damage. The permanent set in friction-dampers and at the top of frame was about 1 mm.
6. No attempt was made to design the members of the alternative types of frames. However, it is estimated that a considerable increase in steel quantity, say 20-25% more, would have been necessary for other frames to achieve an acceptable level of seismic response. In spite of using more steel, their damage control potential will still not be the same as that of a FDBF.

5 CONCLUSIONS

The use of friction-dampers has shown to provide a practical, economical and effective new approach to design structures to resist major earthquakes. Besides savings in the initial cost of construction, the savings in life cycle cost are significant as damage to the building and its valuable contents is minimized.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the cooperation of Lemay & Associates / Webb Zerafa Menkes Housden, the project architects. The encouragement from Jean-Guy Rheault, project manager of Public Works Canada; Jean-Pierre Ruel, project director of the Canadian Space Agency; and Dr. Normand Morin, President of LVLVA Inc., is very much appreciated. Without their cooperation and encouragement, the use of this innovative system would not have been possible. Patented friction-dampers were designed and supplied by Pall Dynamics Limited.

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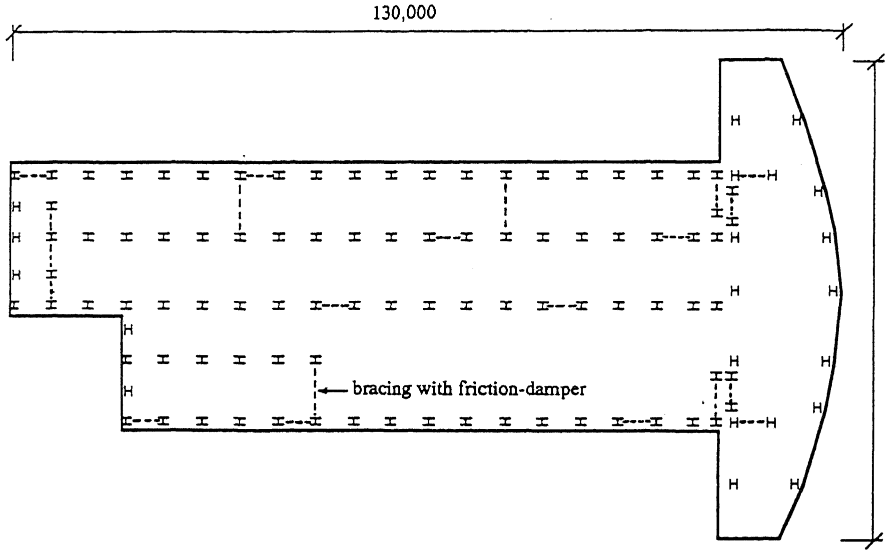

Figure 1. Ground Floor Plan

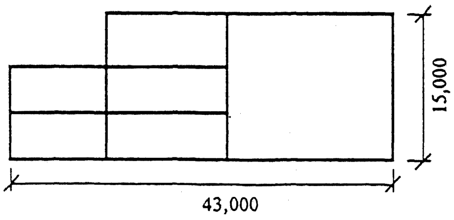

Figure 2. Cross-Section

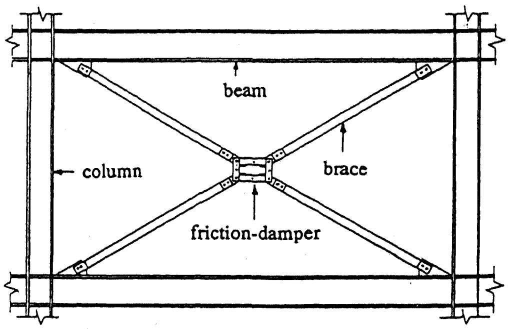

Figure 3. Typical Braced Bay

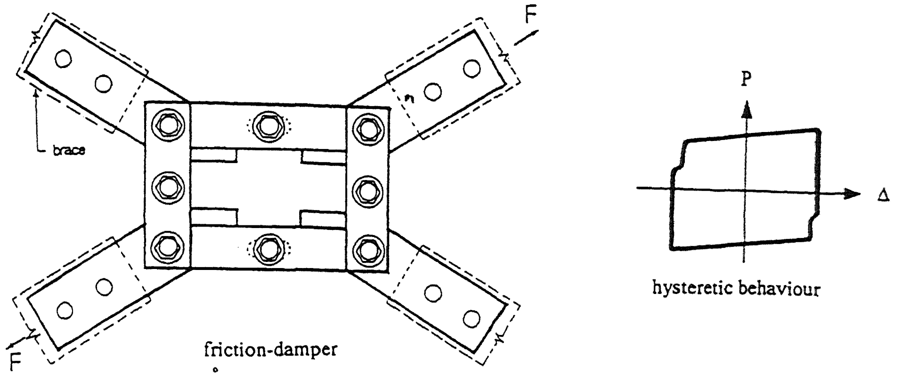

Figure 4. Typical Friction Damper

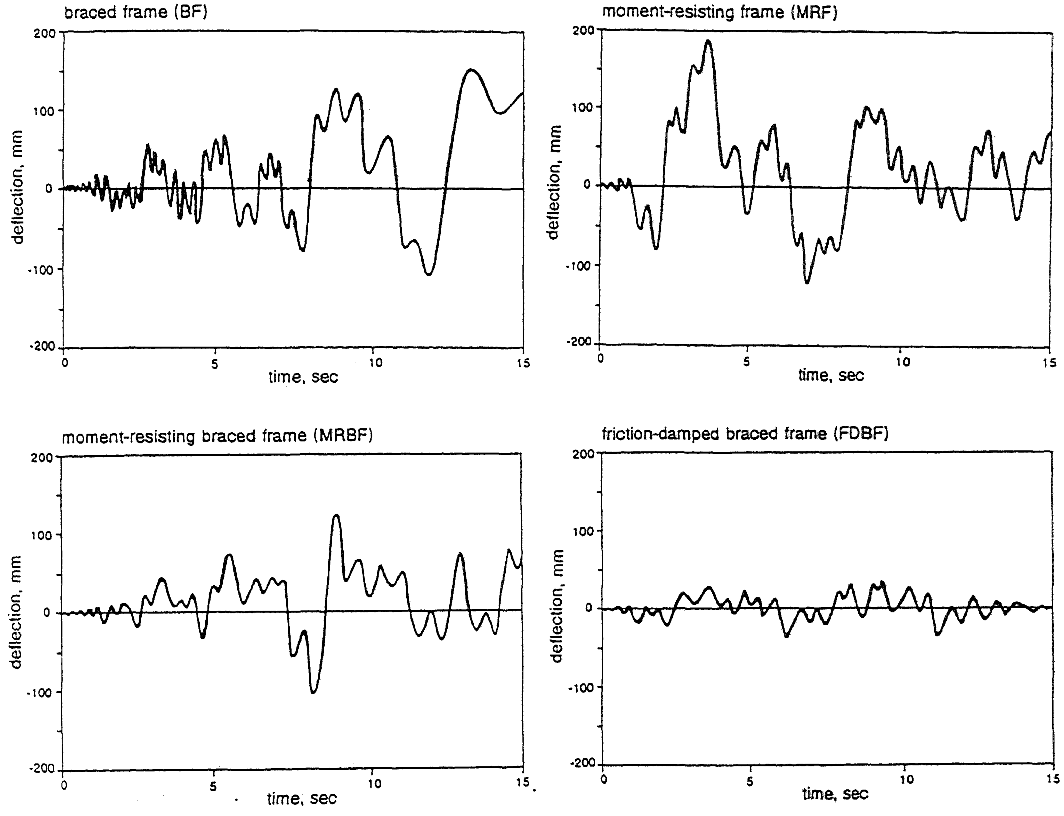

Figure 5. Time-Histories of Deflection at Top

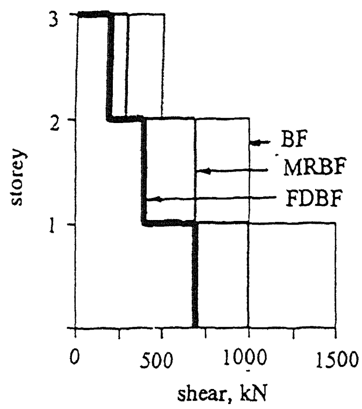

Figure 6. Envelope of Storey Shear

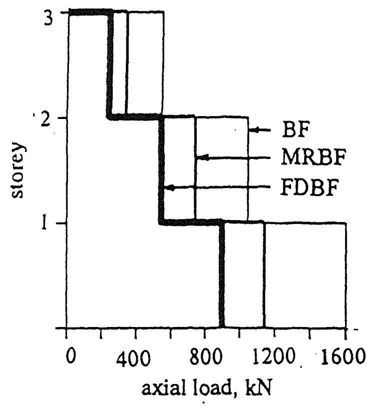

Figure 7. Envelope of Axial Loads in Columns

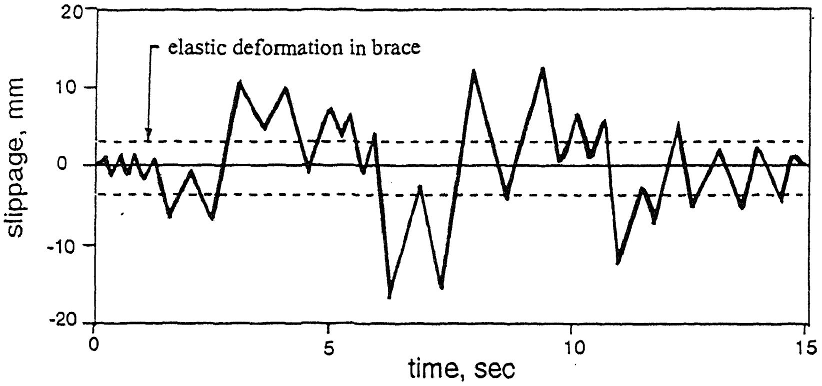

Figure 8. Time-Histories of Slippage in Friction-Damper

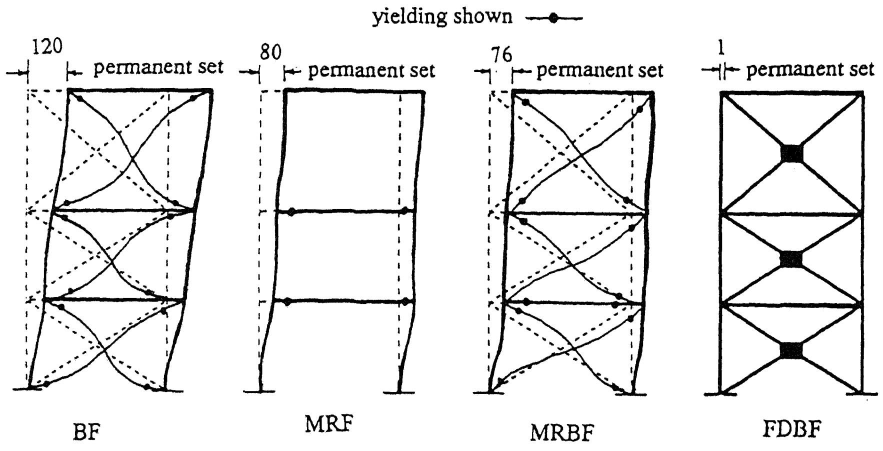

Figure 9. Damage Experienced after Earthquake