7th Canadian Conference on Earthquake Engineering / Montreal / 1995
7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995

Hi-Tech Aseismic Design of "Maison 1 McGill"

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ABSTRACT

An innovative structural system of introducing supplemental damping has been used for the aseismic design of an eleven-storey concrete structure. The use of steel bracing has eliminated the need for expensive concrete shearwalls and the use of friction-dampers eliminated the dependence on ductility of structural elements. Also, the system provides greater flexibility in space planning because unlike shearwalls these need not be aligned vertically from bottom to top. The results of three-dimensional nonlinear time-history dynamic analysis have shown superior performance of the friction-damped frames compared to conventional construction. The introduction of supplemental damping provided by the friction-dampers dramatically reduced the forces, amplitude of vibration and floor accelerations. Beside offering significant savings in the initial cost of construction, the seismic resistance and damage control potential of the structure has considerably increased.

INTRODUCTION

All building codes, including the National Building Code of Canada 1990 (NBC), recognize that it is economically not feasible to reconcile the seismic energy within the elastic capacity of the materials. The code philosophy is to design structures to resist moderate earthquakes without significant damage, and to avoid collapse of the structure 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 earthquakes of Northridge-1994 of California and Kobe-1995 of Japan. Although the death tolls were relatively low, damage to the buildings and other associated costs were estimated to be more than US$ 20 billion and US$80 billion, respectively.

In modern buildings, avoidance of structural collapse alone is not enough. The costs of finishes, contents and sensitive equipment can be much higher than the cost of the structure itself and these must be protected. 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.

The innovative technique of introducing supplemental damping in conjunction with appropriate stiffness was considered to be the most economical, effective, practical and smart hi-tech solution for the aseismic design of this building. Analytical studies have been made to compare the seismic response of this building with friction-dampers to that with traditional concrete shearwalls. This paper will discuss the results of analyses and provide construction details of the chosen structural system. The construction of the structure was completed in February 1995 and building occupancy is expected in the summer of 1995.

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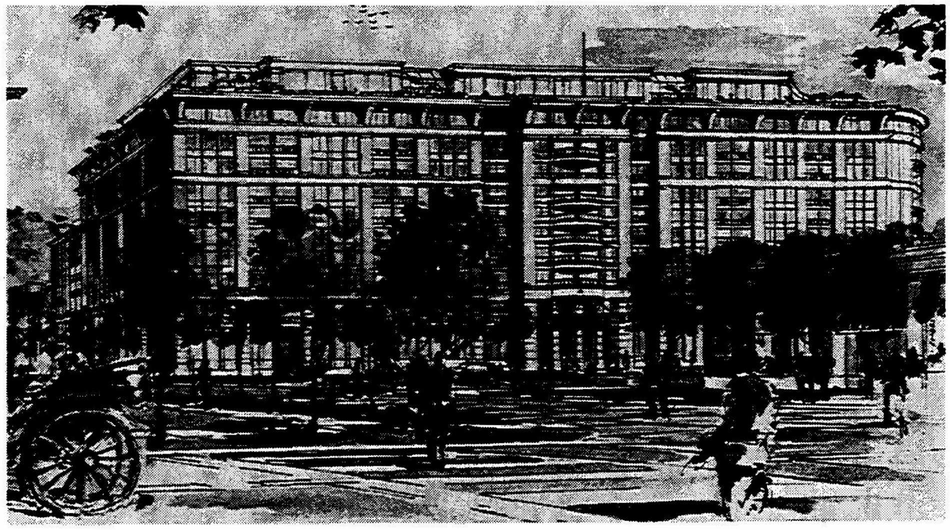

Figure 1. FRONT VIEW FROM McGILL STREET

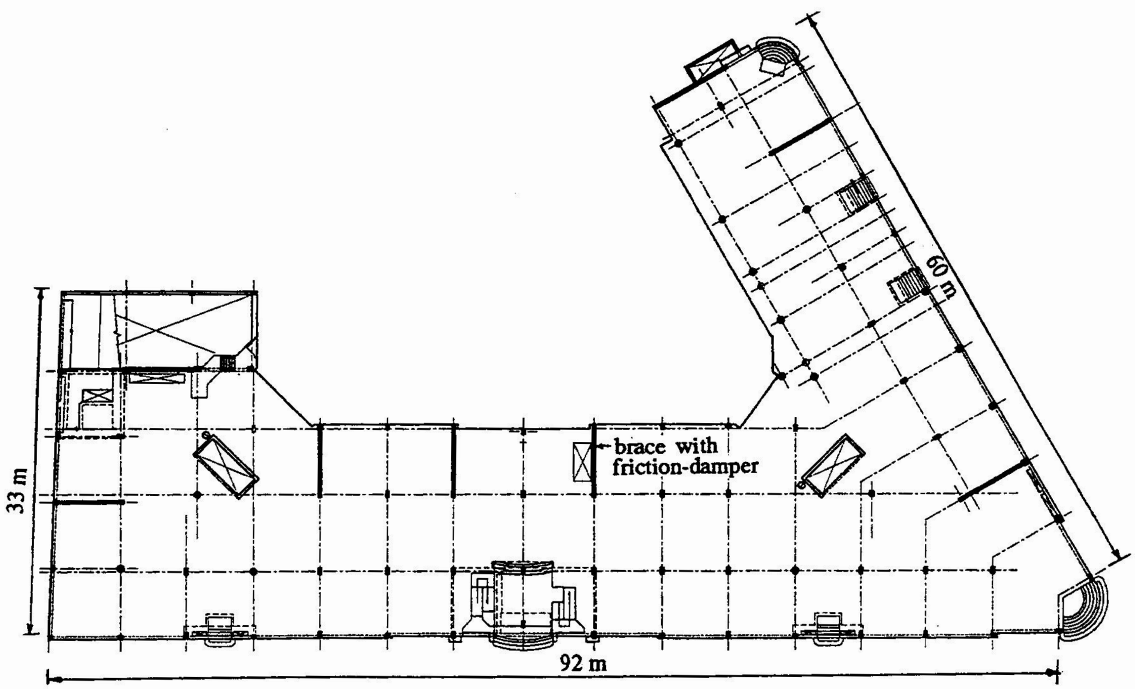

Figure 2. GROUND FLOOR PLAN

MAISON 1 McGILL

This magnificient condominium building facing the Saint Lawrence River is an eleven storey structure above ground and has two basements below for car parking. The total covered area of the building is about 35,500 m^2. Fire safety and restricted clear storey height considerations decided in favour of reinforced concrete structure and flat plate slab construction. The foundations are on spread footings. The exterior view and the ground floor plan of the building are shown in Figures 1 and 2, respectively.

Preliminary analysis indicated that the earthquake forces governed the structural design. Two structural systems were considered to provide lateral resistance for earthquake forces. These were: a). conventional reinforced concrete shearwalls; b). friction-damped braced frames.

Conventional Concrete Shearwalls

Concrete shearwalls are known to be effective in controlling lateral deflections due to wind and moderate earthquakes. 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, and thus place higher demand on strength and ductility.

The ductility in a reinforced concrete wall is extremely sensitive to detailing and quality control. The presence of construction joints and lapping of vertical reinforcement, all at floor level, are typical of the practical problems which often cause the ductility of concrete shearwalls to be viewed with suspicion. This is true even though suggestive detailing procedures for ductile shearwalls exists. In any event, it is desirable that less dependence be placed on the ductility of concrete shearwalls.

Besides the high cost of construction, the use of shearwalls severely restricts the flexibility in space planning. Once located, they have to continue from top to foundation.

Friction-Damped Braced Frames

In this structural system, each steel bracing in the frame is provided with a Pall friction-damper. The use of steel bracings eliminate the need for expensive concrete shearwalls and the use of friction-dampers eliminate the dependence on ductility of structural elements. The steel bracings may be in the form of tension-only K-bracings and single diagonal tension/compression bracings. Due to the use of flat slab construction, K-bracing was not adopted. As soon as the structure undergoes small deformations, the friction-dampers go into action and start dissipating seismic energy. Since a major portion of the seismic energy is dissipated by the dampers, the forces on the structure are considerably reduced.

The use of friction-damped bracings provides greater flexibility in space planning because unlike shearwalls these need not be located continuously one over the other. Since bracings do not carry any gravity load, these need not 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 bracings is transferred through rigid floor diaphragm to the perimeter retaining walls of the basement.

The use of friction-dampers in steel bracings was considered to be the most economical, effective, and practical solution for the aseismic design of this building. The cost of the proposed structural system when compared to the cost of the structure with concrete shearwalls, resulted in a net saving of 6% in structural cost or 1.5% of the total building cost.

The location of steel braces with friction-dampers in the lower storey is shown in Figure 2. Architectural planning governed the location and type of bracings. Generally, the bracings at the upper level follow the same arrangement unless the space planning warranted it otherwise. Typical details of braced bays and friction-dampers are shown in Figures 3 and 4, respectively. Patented Pall friction dampers were designed and supplied by Pall Dynamics Limited.

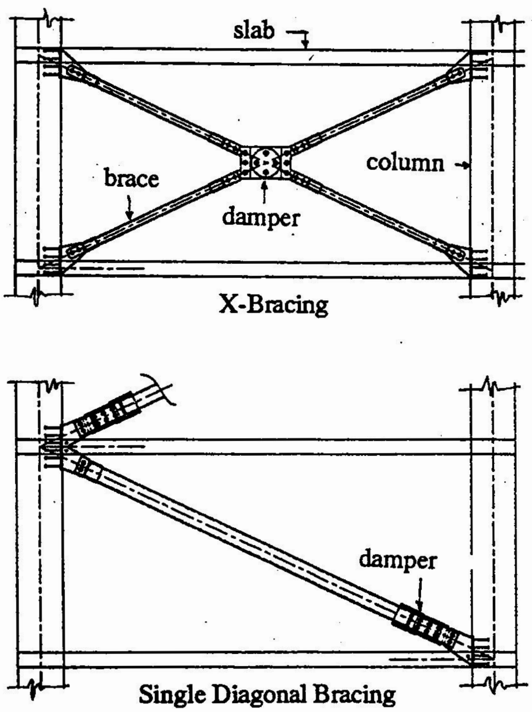

Figure 3. FRICTION-DAMPED BRACED BAYS

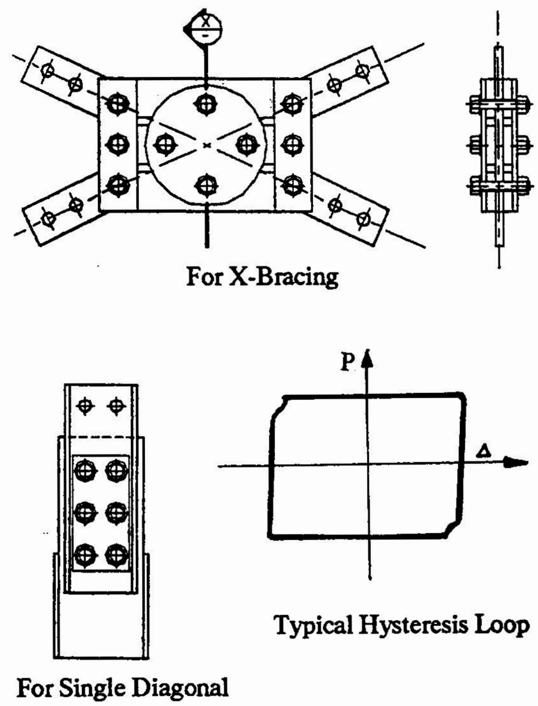

Figure 4. TYPICAL FRICTION-DAMPERS

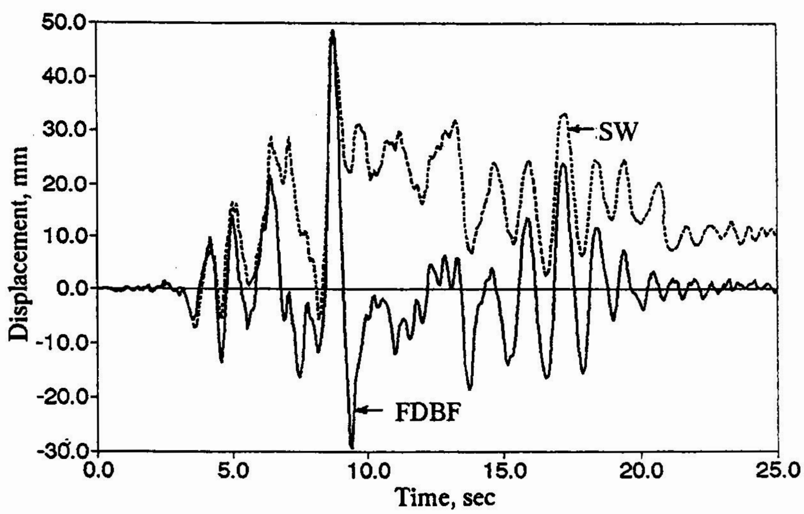

Figure 5. TIME-HISTORIES OF DEFLECTION AT TOP

PALL FRICTION-DAMPERS

Pall friction-dampers are simple and fool-proof in construction (Pall 1982). Basically, they consist of series of steel plates or sections with slotted holes, which are specially treated to develop most reliable friction. They are clamped together with high strength bolts and allowed to slip at pre-determined load. 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. A much greater quantity of energy can be dissipated in friction than any other method involving the yielding of steel plates or viscoelastic materials. Therefore, fewer damping devices are required to provide the required amount of energy dissipation. Their performance is not affected by temperature, velocity, stiffness degradation due to aging and they need no replacement after the earthquake. These friction-dampers do not require maintenance 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 a major earthquake they slip before yielding of structural members. After the earthquake, the strain energy of the structure brings the dampers back to their near original alignment.

These friction-dampers have successfully gone through rigorous proof-testing on shake tables in Canada and the United States (Filiatrault 1986, Aiken 1988). Patented Pall friction-dampers are available for tension-only X-bracings, single diagonal in tension/compression and K-bracing systems (Pall 1982). The 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 have found several applications for both steel and concrete buildings in new construction and retrofit of existing buildings (Hale 1995, Godin 1995, Pall 1987, Pall 1991, Pall 1993, Pasquin 1993, Vezina 1992, Wagner 1995) and several others are under construction.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

Three-dimensional nonlinear time-history dynamic analyses were carried out using the computer program DRAIN-TABS (Guendelman-Israel and Powell 1977), developed at the 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. It is known that different earthquake records, even though of the same intensity, give widely varying structural responses and results obtained using a single record may not be conclusive. Two pairs of time-histories of earthquake records, which have peak horizontal velocities (0.08-0.11m/sec) and peak ground accelerations (0.16-0.23g), falling within the ranges prescribed by NBC for Montreal seismic zone were selected (Filiatrault 1994). These were: Imperial Valley aftershock 1979 (Anderson Road El Centro, 230); and Whittier 1987 (Hollywood storage, Los Angeles, 360). In addition, a third pair of time-histories record for a Quebec region earthquake of Saguenay 1988 (Baie St-Paul, longitudinal), was chosen. The peak ground accelerations of these records were scaled to 0.18g for Montreal region. Analyses were carried out for earthquake excitations applied along the x-axis, the y-axis and in 60 degree direction. Of the three earthquake records, the Whittier earthquake record gave the higher response.

Viscous damping of 3% of critical was assumed in the initial elastic stage to account for the presence of nonstructural 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 based on axial force under static loads. To account for any accidental eccentricity due to uncertainty in the distribution of mass or possible variation in relative stiffness, etc., the center of mass was shifted by 10% of the building dimension in both axes.

A series of analyses were made to determine the optimum slip load of the friction-dampers. A slip load of 700 kN was provided for friction-dampers in lower five storeys and 600 kN for upper five

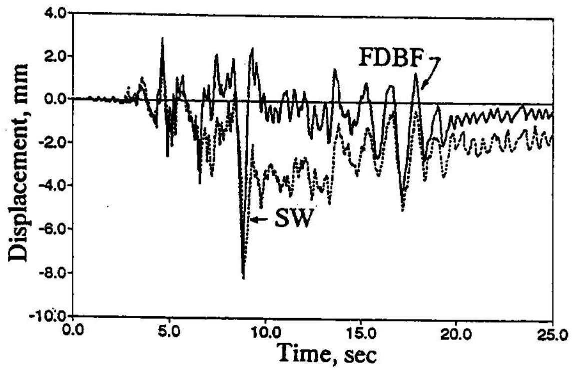

Figure 6. TIME-HISTORIES OF STOREY DRIFT IN FIRST STOREY

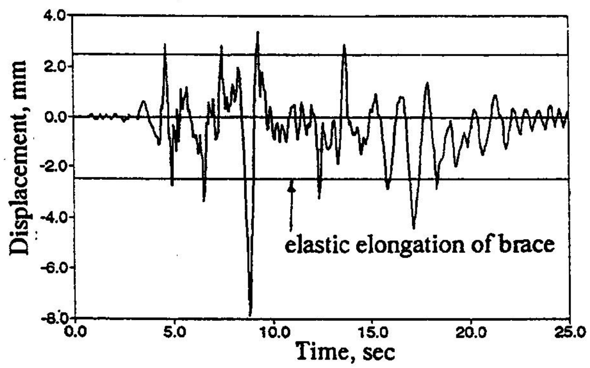

Figure 7. TIME-HISTORIES OF SLIPPAGE IN FRICTION-DAMPER

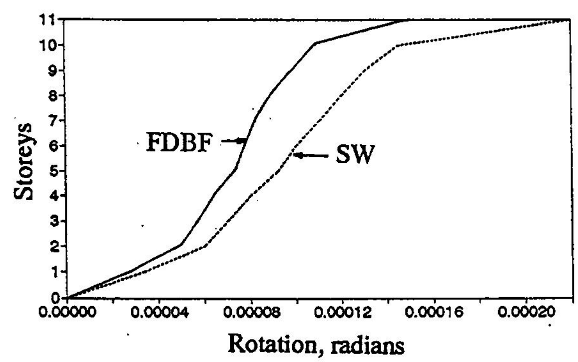

Figure 8. TORSIONAL ROTATION OF BUILDING

storeys. A total of 65 friction-dampers were required to extract sufficient seismic energy to safeguard the structure from damage.

The effectiveness of friction-dampers in improving the seismic response is seen when the results of the traditional shearwall (SW) structure is compared with those of the friction-damped braced frame (FDBF). Of the three earthquake records used, the Whittier earthquake gave the higher response. The results presented are for responses obtained with the Whittier earthquake record.

RESULTS OF ANALYSIS

1. The time-histories of deflections at the top of the building are shown in Figure 5. The peak amplitudes are 53 mm (H/580) and 54 mm (H/570) for FDBF and SW, respectively. The permanent offset after the earthquake was 2 mm for FDBF and 9 mm for SW.

2. The maximum storey drift was in the first storey. Time-histories of drift is shown in Figure 6. These were H/400 for both FDBF and SW. Permanent offset after the earthquake was 0.5 mm and 1.5 mm for FDBF and SW, respectively. Shear walls developed cracks at the base of first storey.

3. The maximum floor accelerations experienced by the FDBF are only 60% of those for SW. Reduction in floor accelerations can significantly reduce the damage to the nonstructural components, finishes and contents of the building.

4. The time-histories of slippage in a typical friction-damper in the first storey is shown in Figure 7. The maximum slippage was 8 mm. After the earthquake, the friction-dampers returned to their near original alignment.

5. The use of friction-damped braces have significantly improved the torsional response of the structure. The torsional rotation of two types of structures is shown in Figure 8. The rotation for FDBF is 64% of that for SW.

CONCLUSIONS

The use of friction-dampers, in lieu of conventional shearwalls, has shown to provide a practical, economical and effective new approach for the design of concrete structures to resist major earthquakes. The savings in the initial cost of construction were about 6% of the structural cost or 1.5% of the total building cost. Besides savings in the initial cost of construction, the savings in life cycle cost could be significant as damage to the building and its contents is minimized.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the cooperation of the project architects Cardinal Hardy et Desmarais, Pilon Cousineau Yaghijian St-Jean Rogers; and the construction managers FORMCO Inc. The encouragement from Jacques Dufresne, President of Immeuble de la Commune McGill Inc., and management of Tecsult Inc. is very much appreciated. Claude Duquette was very helpful in preparing the diagrams for this paper.

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