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

Friction-Dampers for Seismic Rehabilitation of "Casino de Montréal"

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ABSTRACT

The existing eight-storey steel structure, built in 1966, lacked lateral earthquake resistance and ductility requirements of the current building code. Introduction of friction-dampers in the existing bracings was the most effective and economical solution for the seismic rehabilitation of this building. Due to high damping provided by the friction-dampers, forces on the structure are considerably reduced. Hence, the provision of additional bracings, costly and time consuming strengthening of existing members and foundations, was not required. Friction-damped bracings have shown to be very effective to reduce distress caused by torsion due to high eccentricity. Three-dimensional nonlinear time-history dynamic analysis was used to determine the seismic performance of the structure. Compared to traditional retrofitting method, the use of friction-dampers resulted in a net saving of more than 50% in both construction cost and construction time.

INTRODUCTION

The former French Pavillion (Figure 1) was designed and built for EXPO'67. After the exposition, the French government donated it to the City of Montreal. It remained in temporary use to hold occasional exhibitions. The existing eight-storey structure was built of steel columns and beams with concrete floor topping on steel deck. The lateral resistance to wind was provided by four bays of steel K-bracing and a concrete core for stairs and elevators located at one end. Figures 2 and 3 show floor plans at gound floor and fifth floor, respectively. The floor configurations varied considerably at every storey. The rigidity of the structure was highly eccentric. The foundations are on piles.

In late 1992, Loto-Quebec decided to rehabilitate this building to house 'Le Casino de Montreal'. The seismic requirements of the building code have drastically changed over a period of twenty-six years. A preliminary analysis by the project structural engineers indicated that the lateral earthquake resistance of the existing structure was inadequate to meet the requirements of the National Building Code (NBC) of Canada 1990.

Two proposals for seismic strengthening were studied. These were: a) a conventional method of introducing additional steel bracings, and b) an innovative technique of introducing supplemental damping. The conventional method of strengthening with bracings required four additional braced bays at every floor and provision of extensive pile foundation work. This was very expensive and time consuming. Also, the additional braced bays interfered with the space planning of the casino. The innovative technique of introducing supplemental damping by installing friction-dampers in the existing steel bracings was considered to be the most effective, economical and practical solution for the seismic upgrading of this building. Due to the high damping provided by the friction-dampers, the forces on the structure are considerably reduced. Hence, provision of additional bracings, costly and

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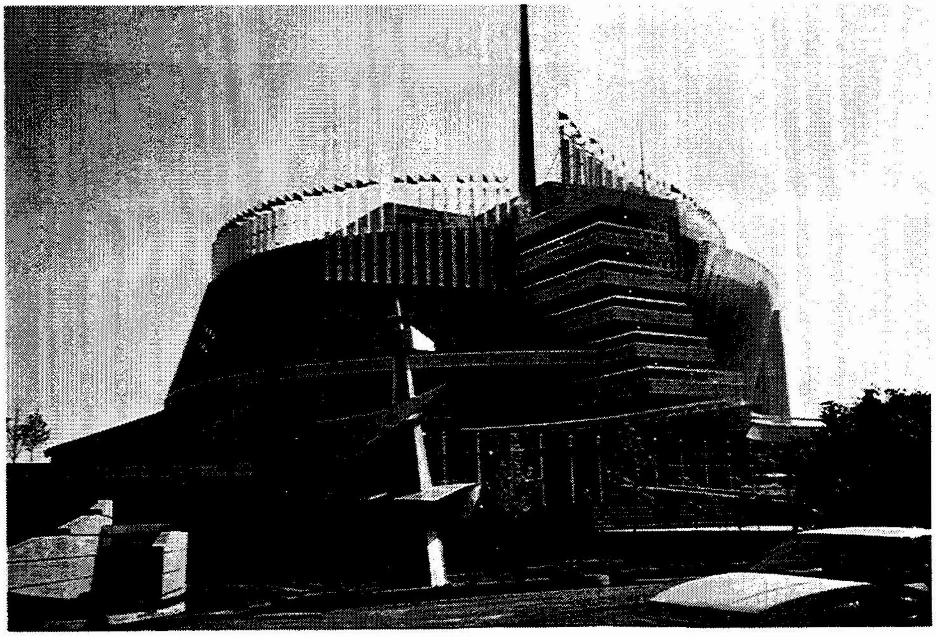


Figure 1. VIEW OF CASINO DE MONTREAL

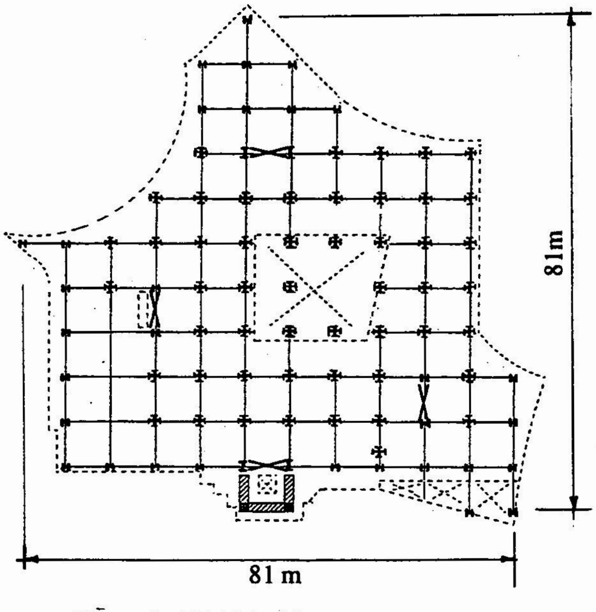


Figure 2. PLAN - GROUND FLOOR

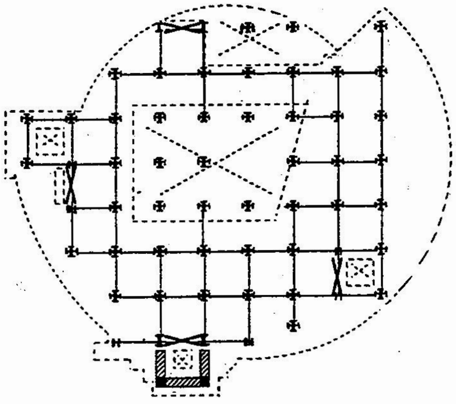


Figure 3. PLAN - FIFTH FLOOR

time consuming work on pile foundation was not required. A saving in construction time to meet the tight schedule of completion overwhelmingly decided in favour of this technique.

This paper will discuss the analysis, design and construction details of the chosen retrofit method. All rehabilitation work including seismic retrofit was completed in record time and the Casino was opened to public in October 1993.

STATE-OF-THE-ART

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 1990 (NBC), are based on the philosophy of designing structures to resist moderate earthquakes without significant damage and to resist major earthquakes without structural collapse. 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 in California and Kobe-1995 in 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.

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. 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 Retrofit Methods

Conventional methods of stiffening with concrete shearwalls or steel bracings 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 inertial forces on the supporting elements. Therefore, any advantage gained with the added stiffness may be negated by the increased amount of energy input. Moreover, the construction work for shearwalls and its foundations in an existing building is very difficult and expensive. In a conventional braced frame, the energy dissipation capacity of a brace is 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. Both conventional methods require an expensive and time consuming work of strengthening existing columns and foundations, apart from severely restricting the flexibility of space planning.

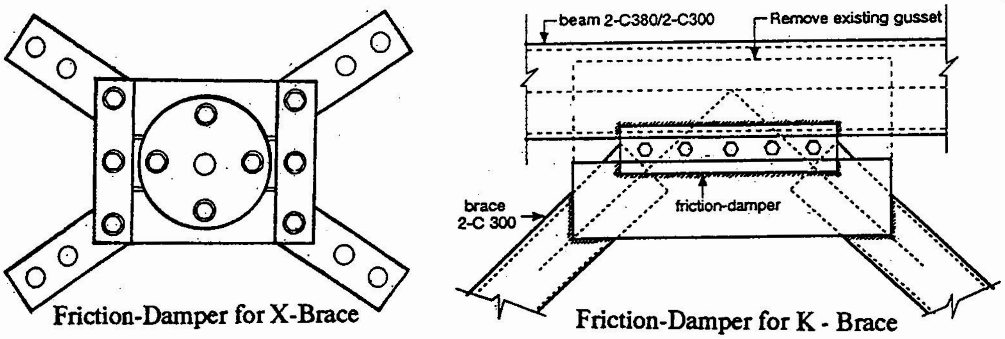
Pall Friction-Dampers

The Pall friction-damping devices were pioneered in the late seventies. Friction-damping devices suitable for different types of construction have been developed for: 1) concrete shearwalls, both precast and cast-in-place (Pall 1980, Pall 1981a); 2) braced steel / concrete frames (Pall 1982); 3) low-rise buildings (Pall 1981b); and 4) clad-frame construction (Pall 1989).

The 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 the

X - Braced Bay

K - Braced Bay



Friction-Damper for X-Brace

Friction-Damper for K - Brace

Figure 4. TYPICAL BRACED BAYS AND FRICTION-DAMPERS

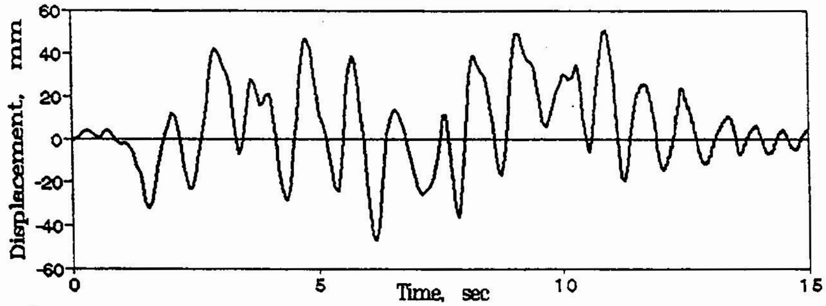


Figure 5. TIME-HISTORY OF DEFLECTION AT TOP (Artificial Earthquake)

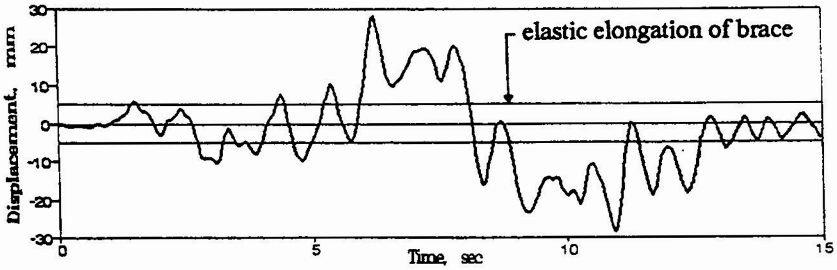


Figure 6. TIME-HISTORY OF SLIPPAGE IN A FRICTION-DAMPER

most reliable friction. They are clamped together with high strength 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, Aiken 1988). Their performance is reliable, repeatable and have 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 maximum wind loads or moderate earthquakes. During a major earthquake they slip before the 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, Savard 1995, Vezina 1992, Wagner 1995) and several others are under construction.

Typical details of braced bays and friction-dampers for the retrofitting of the Casino are shown in Figure 4. Friction-dampers were designed and supplied by Pall Dynamics Limited.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

Three-dimensional nonlinear time-history dynamic analyses were carried out by using the computer program DRAIN-TABS (Guendelman-Israel and Powell 1977), developed at the University of California, Berkeley. 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. As future earthquakes may be erratic in nature, an artificially generated time-history, which includes nine earthquake records, was used (Newmark, Blume, Kapur 1973).

Subsequently, analyses were conducted for three 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 (Filiatrault 1994). These were: Imperial Valley aftershock 1979 (Anderson Road El Centro, 230); Adak, Alaska 1971 (Naval Base West); and Whittier 1987 (Hollywood storage, Los Angeles, 360). In addition, a verification analysis was also conducted using time-histories record for the Quebec region Saguenay earthquake of 1988 (Baie St-Paul, longitudinal). To save computation time, the duration for earthquake records was limited to fifteen seconds. This duration included all peaking ground acceleration values.

The peak ground accelerations of all the earthquake records were scaled to 0.18g for Montreal region. Viscous damping of 5% of critical was assumed in the initial elastic stage to account for the presence of nonstructural elements. Nominal moment capacity of the existing beam-column connections was taken into account. 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, the center of mass was shifted 10% of the building dimension in both axes.

A series of analyses were made to determine the optimum slip load of the friction dampers. The optimization was governed by the safe load carrying capacity of the existing braces, beam / column

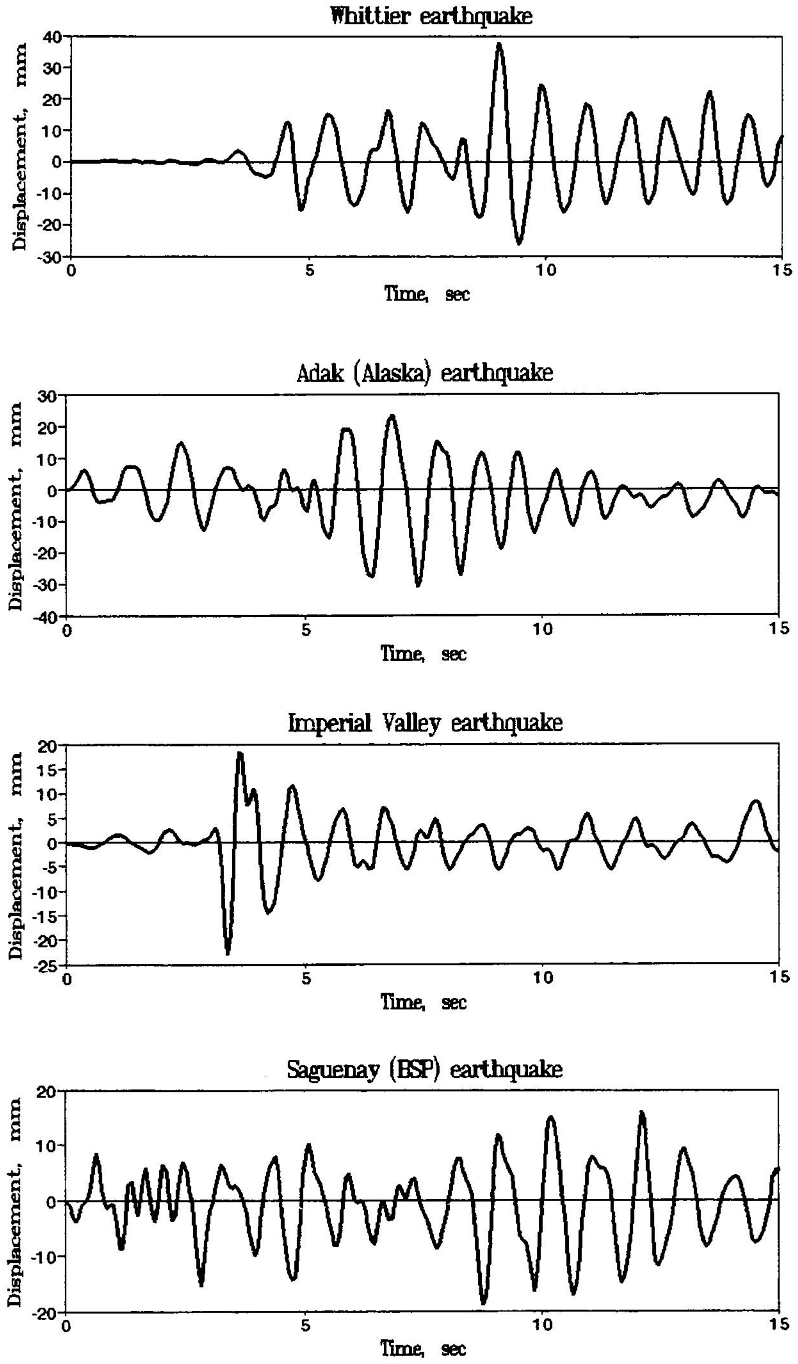


Figure 7. TIME-HISTORIES OF DEFLECTION AT TOP FOR VARIOUS RECORDS

connections, columns and foundations. Analyses were carried out for earthquake excitations applied independently along the x-axis, the y-axis and in 45 degree direction. Of all the earthquake records, the artificial earthquake record gave the highest response.

RESULTS OF ANALYSIS

The results presented below, unless indicated otherwise, are are for responses obtained with the artificial earthquake record.

1. The existing structure, without any retrofit, was not able to survive even 30% of the code specified earthquake forces.
2. A total of 32 friction-dampers, including one in the new bracing, were needed to dissipate sufficient energy to safeguard the structure from damage. The slip load of friction-dampers varied from 1800 kN in the bottom storey to 700 kN in the top storey.
3. Time-histories of deflection at top is shown in Figure 5. The peak amplitude at top is 57 mm, which is about H/500. The maximum storey drift was H/200, which is only 25% of that permitted by the building code. After the earthquake, the permanent offset at the top was 6 mm.
4. Time-histories of slippage in a friction-damper in x-bracing is shown in Figure 6. Maximum slippage was 22 mm. After the earthquake, the damper returned to its near original alignment.
5. Time-histories of deflection at top for Whittier, Adak, Imperial Valley and Saguenay earthquake records are shown in Figure 7. The response for these earthquake records is lower than that for the artificial earthquake shown in Figure 6.
6. The introduction of supplemental damping provided by the friction-dampers significantly reduced the forces on the structure. Except for the strengthening of beam-column connections of the braced bays, the strengthening of structural members or foundations was not necessary.

CONCLUSIONS

The use of friction-dampers has shown to provide a practical, economical and effective new approach to upgrade the seismic resistance of structures. Besides savings in the initial cost of retrofit, the savings in life cycle cost could be significant as damage to the building and its contents is minimized.

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