FRICTION-DAMPERS FOR SEISMIC CONTROL OF LA GARDENIA TOWERS SOUTH CITY, GURGAON, INDIA

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SUMMARY

A novel structural system of friction-damped frames has been adopted for construction of eighteen-storey apartment building. By incorporating Pall friction-dampers in steel bracing, the earthquake resistance and damage control potential of the structure has dramatically increased. During a major earthquake, the friction-dampers slip at a predetermined load before yielding occurs in the members and dissipate a major portion of seismic energy. Hence total dependence on ductility is avoided and the structural elements generally remain elastic without damage. The results of three-dimensional nonlinear time-history dynamic analysis have shown superior performance of friction-damped frames compared to conventional construction. The introduction of supplemental damping provided by the friction-dampers significantly reduced the lateral inertial forces and amplitude of vibrations. The system offers savings in construction materials.

INTRODUCTION

La Gardenia housing complex consists of 7 towers of eighteen storeys with two levels of basements (Figure 1). Currently, one tower is under construction, which is likely to be completed in early 2000. The complex is spread over 11 acres of land in Southcity, Gurgaon, about 8 km from the international airport, New Delhi. The complex presents a new concept of good living that borrows in spirit from Gardenia - a very beautiful tropical flower. La Gardenia complex is developed and owned by Unitech Limited of New Delhi. To live up to the theme of La Gardenia, Unitech decided to use the latest construction materials for the comfort and safety of its occupants. The use of the state-of-the-art earthquake resistant design technology, is the first application in India.

In the chosen structural system, Pall friction-dampers are provided in steel bracing in concrete frames. The use of steel bracing eliminated the need of expensive concrete shearwalls and the use of friction-dampers eliminated the need of dependence on member ductility. Friction-damped bracing are located in partitions, around staircases or elevator shaft. Their use provided greater flexibility in space planning because unlike shearwalls they do not need to be located continuously one over the other. Since friction-damped bracing do not carry any gravity load, these do not need to 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 bracing is transferred through the rigid floor diaphragm to the perimeter retaining walls of the basement. The architects have exposed some friction-dampers to view as they add to the aesthetic appearance. A total of 66 friction-dampers were required to extract sufficient energy to safeguard the structure and its contents from damage.

A typical floor plan of a 3-bedroom apartment is shown in Figures 2. The area of each apartment is about 200 sq.m (2100 sq.ft). There are four apartments at each floor, giving nearly a symmetrical plan. Between ground and ninth floor, the two apartments in north are connected to the two apartments in south with only an elevator lobby slab. At upper levels, the two pairs of apartments are rigidly connected. This was a functional and an architectural requirement. The structure lacked torsional rigidity below ninth floor, when accidental eccentricity

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in mass and earthquake acting at an angle to the major axis are considered. It posed a unique structural challenge. Several alternatives were considered to overcome this deficiency. Finally, a mixed solution was chosen. The solution was to provide concrete shearwall around central elevator from foundation to ninth floor with thick lobby slab, in combination with friction-damped bracing from ground to fourteenth floor.

This paper describes the state-of-the-art, analysis, design and construction details of the project. A brief review on Pall friction-dampers has also been included so that the use of novel structural solution can be appreciated.

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 building codes, including Indian Standards, are based on the philosophy of designing structures to resist moderate earthquakes without significant damage and to avoid structural collapse during a major earthquake. In general, reliance for survival is placed on the ductility of the structure to dissipate energy while undergoing large inelastic deformations. This assumes permanent damage, repair costs of which could be economically as significant as the collapse of structure. Recent examples of these are the 1994 Northridge (California) and 1995 Kobe (Japan) earthquakes. The damage to the buildings and other associated costs for Northridge and Kobe are estimated to be more than US$ 50 billion and US$150 billion, respectively. These earthquakes have clearly shown that conventional construction, even in technologically advanced and industrialised countries, is not immune to destruction.

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. In view of huge financial losses and social suffering, highlighted by the recent earthquakes, the building officials, structural engineers, developers, bankers and insurers should carefully consider seismic response of the buildings in terms of damage control rather than life safety.

Conventional Construction

Braced steel frames are known to be economical and effective in controlling lateral deflections due to wind or moderate earthquakes. During a major earthquake, these structures do not perform that well. 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 even further. As a result, the energy dissipation degrades very quickly and the structure may collapse. The 1995 Kobe earthquake demonstrated several failures of braced buildings.

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

Concrete shearwalls or steel bracing is often used to add rigidity to the moment-resisting frames. Generally, stiffer structures attract higher ground accelerations thus exert higher forces on supporting members and foundations. Therefore, any advantage gained by added stiffness is negated by increased amount of energy input and place higher demand on strength and ductility. Ductility in a reinforced concrete wall is extremely sensitive to detailing and quality control and is often viewed with suspicion. Besides the high cost of construction, the use of shearwalls severely restricts the flexibility of space planning. Once located, they have to continue from top to foundation. Infilling the frames with unreinforced brick masonry are also quite popular. Although infilled frames have performed very well to resist wind, these have performed poorly in the event of a major earthquake.

The problems created by the dependence on ductility of structure can be reduced if a major portion of the seismic energy is dissipated mechanically, independent from the primary structure. With the emergence of Pall friction-dampers, it has become economically feasible to significantly increase the earthquake resistance and damage control potential of a structure.

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. For centuries, mechanical engineers have successfully used this concept to control the motion of machinery and automobiles. 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 a vibrating building can be controlled.

Friction-dampers suitable for different types of construction have been developed for 1) concrete shearwalls, precast (Pall 1980) and cast-in-place (Pall 1981b); 2) braced steel/concrete frames (Pall 1982); 3) low-rise buildings (Pall 1981a); and 4) clad-frame construction (Pall 1989). Patented Pall friction-dampers are available for: tension cross bracing; single diagonal bracing; chevron bracing; and cladding connections.

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. The slippage is without any stick-slip phenomenon. Friction-dampers are designed not to slip during service load and windstorms. During a major earthquake, friction-dampers slip at a predetermined optimum load before yielding occurs in other structural members and dissipate a major portion of the seismic energy. By properly selecting the slip load, it is possible to 'tune' the response of the structure to an optimum value. This allows the building to remain elastic or at least yielding is delayed to be available during maximum credible earthquakes. Parametric studies have shown that the optimum slip load is independent of earthquake record and is rather a structural property. Also, within a variation of ± 20% of slip load, the seismic response is not significantly affected. 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-storey 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 much lower seismic levels. In 1987, a nine-storey three-bay frame, equipped with friction-dampers, was tested on a shake table at Earthquake Engineering Research Centre 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 behaviour, 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 3). 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 straightforward and economical. There is nothing to damage or leak. Since they are not active during wind or service load conditions, there is no danger of failure due to fatigue. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. Architects like to expose these dampers to view as they add to the aesthetic appearance of structure. Pall friction-dampers are also very compact in design and can be easily hidden within drywall partitions. These 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 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, Hale 2000, Pall 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 Indian Standards and building codes in other countries are ductility based and do not explicitly apply to friction-damped buildings. However, the building codes in the U.S, Canada and some other countries allow 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. 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". These guidelines and provisions of Indian Standards IS: 1893 'Criteria for Earthquake Resistant Design of Structures', served as basis 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 a severe ground motion of probability of 2% in 50 years. 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. It is presumed that with proper ductile detailing, the structure will have sufficient reserve to resist any overstress conditions that occur during the MCE and collapse is avoided. 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.

NEHRP guidelines require that friction-dampers are designed for 130% MCE displacements and all bracing and connections are designed for 130% of damper slip load. Variation in slip load from design value should not be more that ±15%.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

The slippage of friction-damper in an elastic brace constitutes artificial 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 high-speed 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 carried out using the computer program ETABS. Several other programs such as, SAP2000, SADSAP, DRAIN-TABS, DRAIN-2DX, DRAIN-3DX, are now available on which friction-dampers can be easily modelled. The modelling 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.

Since different earthquake records, even of the same intensity, give widely varying structural responses, results obtained using a single record may not be conclusive. Therefore, three time-history records, suitable for the region, were used to ensure that possible coincidence of ground motions and building frequencies was not missed. To save in computation time, earthquake record of the first 20 seconds, which covers the peak ground accelerations of interest, was considered. Viscous damping of 5% 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 centre of mass was shifted by 10% of the building dimension in both axes. 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 66 friction-dampers of 700 kN slip load capacity were used. Figures 4 and 5 show friction-dampers for single diagonal bracing and cross bracing, respectively.

In order to compare the effectiveness of friction-damped frames (FDF), analyses were also conducted on braced-moment- frames (BMF) and frames with shearwalls (SWF). The BMF have concentric rigid steel bracing and 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. In case of SWF, the shearwalls are located at the same place as braced bays and are continuous from bottom to top. The results compared are for maximum responses.

Discussion of Results

1. Time-histories of deflections at the top of building are shown in Figure 6. The peak amplitude of the FDF is 63% and 64 % of those for BMF and SWF, respectively.

2. Envelope of seismic energy input and energy dissipated by friction-dampers is shown in Figure 7. It is seen that about 40% of seismic energy is dissipated by friction-dampers. Total energy input for FDF is 80% and 69% of those for BMF and SWF, respectively.

3. Hysteretic loop of a typical damper in bracing is shown in Figure 8. The slippage in the damper was about ±8 mm. The permanent offset in the damper after the earthquake was less than 1 mm. Friction-dampers at all storeys participated in energy dissipation.

4. Maximum envelopes of storey shears in FDF, BMF and SWF are shown in Figure 9. The values of the FDF are 62% and 53% of those for the BMF and SWF, respectively.

5. Maximum envelopes for axial load in a column of a braced bay are shown in Figures 10. The values of the FDF are 27% of those for the BMF.

6. In the BMF, all braces and 25% of columns had yielded. All members in the FDF remained elastic. Shearwalls at the base were also overstressed by 40%.

CONCLUSION

The use of Pall friction-dampers has shown to provide a practical and economical solution for the seismic control of structures. As the seismic forces exerted on the structure are significantly reduced, the system offers saving in construction materials. The analytical studies have shown that the friction-damped structure should perform satisfactorily in the event of a major earthquake, with possibly reduced damage to building and its contents.

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Figure 1. La Gardenia Complex

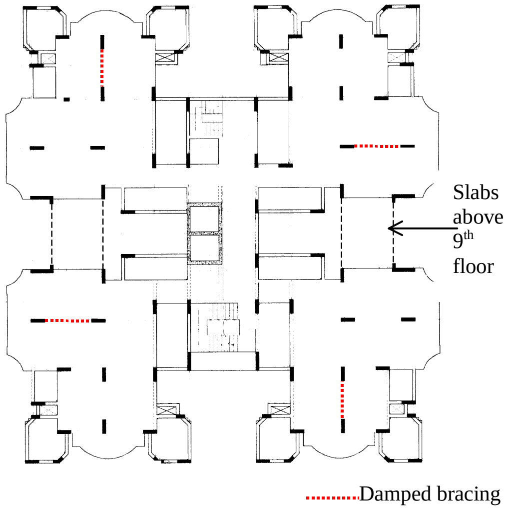

Figure 2.Typical plan of 3-bedroom apartment

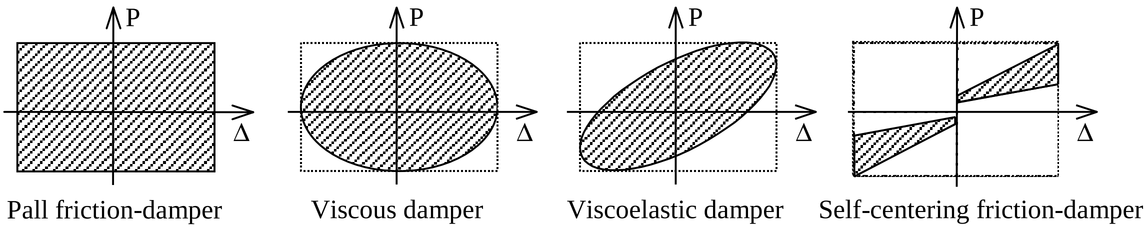

Figure 3. Hysteretic loops of different dampers

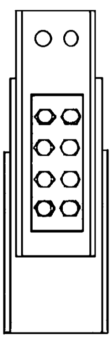

Figure 4. Single diagonal brace friction-damper

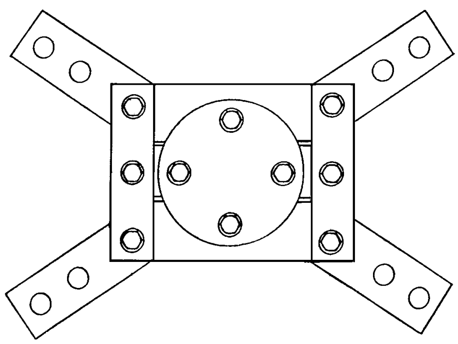

Figure 5. Cross brace friction-damper

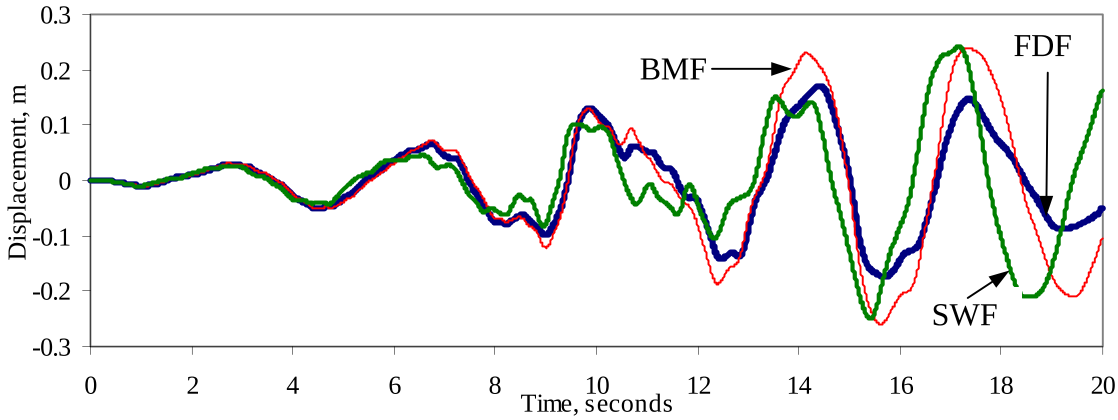

Figure 6. Time histories of displacements at roof

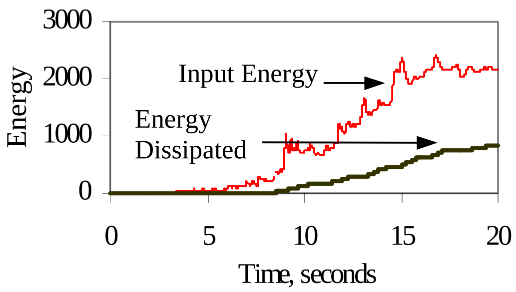

Figure 7. Energy input and energy dissipated by friction-dampers

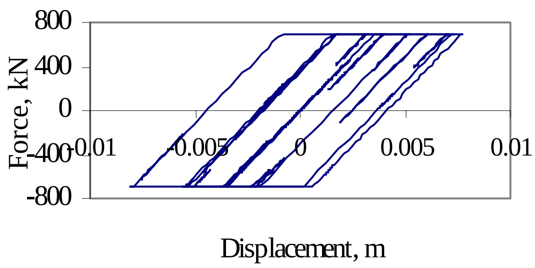

Figure 8. Hysteretic loop of friction-damper and brace

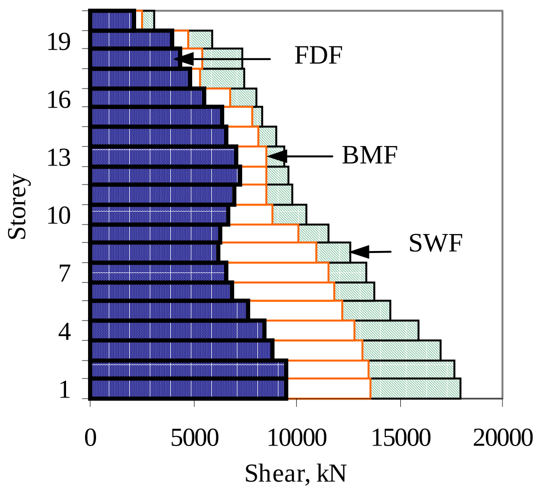

Figure 9. Envelope of storey shear

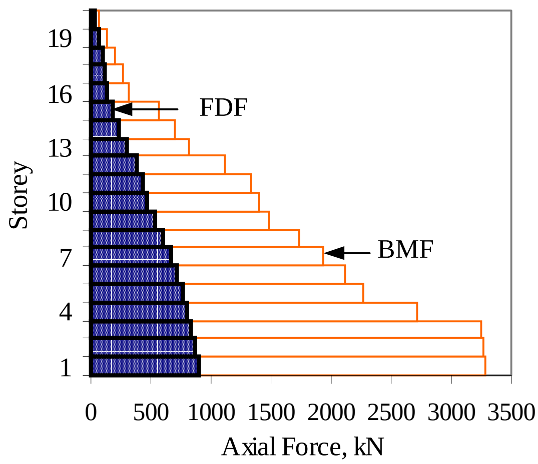

Figure 10. Envelope of column axial force