8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver - 1999

Seismic Rehabilitation of Hotel Dieu Hospital, Sainte Hyacinthe, Quebec

Pasquin, Claude[1]., Leboeauf, Normand[1]., Pall, Rashmi[2]., Pall, Avtar[3]

ABSTRACT

The hospital building complex was built about 50 years ago. The earthquake resistance of the existing structure was significantly less than the requirements of current building code. Conventional methods of strengthening with concrete shearwalls or rigid steel bracing required expensive foundation work. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive alternative solution for the seismic rehabilitation of this building. This was achieved by introducing Pall friction-dampers in steel bracing. Since the dampers dissipate a major portion of the seismic energy, the forces acting on the structure are significantly reduced. Hence, expensive and time-consuming work on strengthening of members and pile foundations was not required. The results of three-dimensional nonlinear time-history dynamic analysis have shown that amplitude of vibrations and floor accelerations are significantly reduced. This method of seismic rehabilitation offered both cost savings and reduction in the construction time when compared to traditional method of strengthening with shearwalls or rigid steel bracing.

INTRODUCTION

This hospital is strategically located in Sainte Hyacinthe to serve the emergency needs of the community. The hospital building complex consists of 5-6 storeys, built in several phases over a period of more than 50 years. The existing structure of four blocks (B, D, E and F) consists of concrete frames with single-way concrete joist construction and the foundations are on piles. The other two blocks (A and C) which were in wood construction, were demolished and replaced with new as rehabilitation cost was not economically justifiable. The existing structure of four blocks derived its lateral rigidity from partial frame action and masonry infilling. The reinforcement detailing of columns and beams lacked ductility. Although masonry infilled frames have performed very well to resist wind, these have performed poorly in the event of a major earthquake. As with the majority of other buildings of this age, the earthquake resistance of the older structure was significantly less than that of current building code requirements. In 1998, it was decided to undertake the seismic rehabilitation work along with other major renovations, to protect the existing and new investments. Rehabilitation work started in August 1998 and is likely to be completed in 1999.

For seismic rehabilitation, conventional methods of strengthening with concrete shearwalls or rigid steel bracing were considered, however, these methods required expensive pile foundation work. Supplemental damping in conjunction with appropriate stiffness offered an innovative solution for the seismic rehabilitation of this hospital building. This was achieved by incorporating Pall friction-dampers in steel bracing. The friction-damped bracing were located along corridors, staircases and partitions. As soon as the structure undergoes small deformations, the friction-dampers go into action and start dissipating energy. However, repairable cracks in the masonry may have to be accepted. Since the dampers dissipate a major portion of the seismic energy, the forces acting on the structure are considerably reduced. By staggering the bracing at different story levels, overloading on columns and foundations was reduced. Hence, expensive and time-consuming work on strengthening of members and pile foundations was not required.

In contrast to shearwalls, the friction-damped bracing need not be vertically continuous. This aspect was particularly appealing to the architectural designers as it offered flexibility in space planning. This structural solution also facilitates construction scheduling since work could start at any floor level depending on vacancy or availability.

Front elevation of building and typical floor plan is shown in Figures 1 and 2, respectively.

This paper discusses the design procedure and results of analysis 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.

---

[1] Pasquin St-Jean & Associates Inc., 4222 St-Hubert, Montreal, Quebec, Canada
[2] Pall Dynamics Limited, 1604 – 811 Helmcken, Vancouver, BC. V6Z 1B1, Canada
[3] Pall Dynamics Limited, 100 Montevista, D.D.O., Montreal, QC, H9B 2Z9, Canada

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 the 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 slowed down by dissipating energy in friction.

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). Pall friction-dampers are available for: tension cross bracing; single diagonal bracing; chevron bracing; cladding connections; and friction base isolators. 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 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 service load and windstorms. 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. By selecting the proper 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. 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 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 possess large rectangular hysteresis loops, similar to an ideal elasto-plastic material, 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. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. Since they are not active during wind or service load conditions, there is no danger of failure due to fatigue. 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. Low cost of Pall friction-dampers suggests wide application.

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, Elliot 1999). To date, more than three dozen buildings have already been built and several are under design or construction phase. Currently, Boeing Commercial Airplane Factory at Everett – the world's largest building, is being retrofitted with Pall friction-dampers.

DESIGN CRITERIA

The quasi-static design procedure given in the NBCC is ductility based and does 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 (BSE-1) is an event with 10% probability of exceedance in 50 years, while the MCE (BSE-2) 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 and that the structure does not collapse. 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 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. 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-3DX, are now available on which friction-dampers can be easily modelled. The modeling 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. 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 slipping of the friction-dampers is automatically taken into account by the computer program. P-Δ effects were 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. Analysis was carried out for earthquake motions in three directions, applied independently along the x-axis, y-axis and 45 degree direction. 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 110 friction-dampers of 400-500 kN slip load capacity were used.

Analyses were also conducted on frames with concentric rigid steel bracing. 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. The results compared are for the maximum response.

Discussion of Results

1. Time history of total energy input in the structure and that dissipated by the friction-dampers are shown in Figure 4. It is seen that about 75% of the seismic energy is dissipated by the friction-dampers.
2. Hysteretic loop of a typical friction-damper at third floor level is shown in Figure 5. The maximum amplitude of slippage is about 7 mm. Friction-dampers at all storeys participated in energy dissipation.
3. Time-histories of deflections at the top of building are shown in Figure 6. The peak amplitude of the FDF is about 65% of the BMF. After the earthquake, there was a permanent offset of 4 mm in the FDF and 16 mm for the BMF.
4. Maximum envelopes for storey shears are shown in Figures 7. The values of the FDF are about 50% of those for the BMF.
5. Maximum envelopes for axial forces in a column of a braced bay are shown in Figures 8. The values of the FDF are about 50% of those for the BMF.

CONCLUSION

The use of Pall friction-dampers has shown to provide a practical and economical solution for the seismic upgrade of the hospital building. 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.

REFERENCES

Aiken, I.D., Kelly, J.M., Pall, A.S., 1988, "Seismic Response of a Nine-Story Steel Frame with Friction- Damped Cross-Bracing", Report No. UCB / EERC-88/17. Earthquake Engineering Research Center, the University of California at Berkeley, pp. 1-7.

Deslaurier, F., Pall, A., Pall, R., 1997, "Seismic Rehabilitation of Federal Building, Sherbrooke", Proceedings, CSCE Annual Conference, Vol. 4, pp. 339-348.

Elliot, J., McCaffrey, G., Pall, R., Pall, A.S., 1999, "Friction-dampers for Seismic Control of Justice Headquarters, Ottawa", Proceedings, Eighth Canadian Conference on Earthquake Engineering, Vancouver.

Filiatrault, A., Cherry, S., 1986, "Seismic Tests of Friction-Damped Steel Frames", Proceedings Third Conference on Dynamic Response of Structures, ASCE, Los Angeles.

Godin, D., Poirer, R., Pall, R., Pall, A., 1995, "Reinforcement Sismique du Nouveau Campus de l'Ecole de Technologie Superieure de Montreal". Proceedings, Seventh Canadian Conference on Earthquake Engineering, Montreal, pp. 967-974.

Hale, T., Tokas, C., Pall, A., 1995, "Seismic Retrofit of Elevated Water Tanks at the University of California at Davis". Proceedings, Seventh Canadian Conference on Earthquake Engineering, Montreal, pp. 959-966.

Pall, A.S., Marsh, C., 1979, "Energy Dissipation in Large Panel Structures Using Limited Slip Bolted Joints", Proceedings, AICAP/CEB Seismic Conference, Rome, Italy, May, Vol. 3, pp. 27-34.

Pall, A.S., Marsh, C., Fazio, P., 1980, "Friction Joints for Seismic Control of Large Panel Structures", Proceedings, Journal of Prestressed Concrete Institute, Vol. 25, No. 6, pp. 38-61.

Pall, A.S., Marsh, C., 1981a, "Friction-Devices to Control Seismic Response", Proceedings, ASCE/EMD Speciality Conference on Dynamic Response of Structures, Atlanta, USA, January, pp. 809-818.

Pall, A.S., Marsh, C., 1981b, "Friction Damped Concrete Shearwalls", Journal of American Concrete Institute, No. 3, Proceedings, Vol. 78, pp. 187-193.

Pall, A.S., Marsh, C., 1982, "Seismic Response of Friction Damped Braced Frames", ASCE, Journal of Structural Division, Vol. 108, St. 9, June 1982, pp. 1313-1323. (ASCE "Raymond C. Reese Research Prize 1983").

Pall, A.S., 1984, "Response of Friction Damped Buildings", Proceedings, Eighth World Conference on Earthquake Engineering, San Francisco, Vol. V, pp. 1007-1014.

Pall, A.S., 1986, "Energy Dissipation Devices for Aseismic Design of Buildings", Proceedings, Seminar &Workshop on Base Isolation and Passive Energy Dissipation, ATC-17, San Francisco, March, pp. 241-250.

Pall, A.S., Verganelakis, V., Marsh, C., 1987, "Friction-Dampers for Seismic Control of Concordia University Library Building", Proceedings Fifth Canadian Conference on Earthquake Engineering, Ottawa, pp. 191-200.

Pall, A.S., 1989, "Friction Damped Connections for Precast Concrete Cladding", Proceedings, PCI- Architectural Precast Concrete Cladding - Its Contribution to Lateral Resistance of Buildings, pp. 300-309.

Pall, A.S., Ghorayeb, F., Pall, R., 1991a, "Friction-Dampers for Rehabilitation of Ecole Polyvalente at Sorel, Quebec", Proceedings, Sixth Canadian Conference on Earthquake Engineering, Toronto, pp. 389-396.

Pall, A.S., Pall, R., 1991b, "Friction Base-Isolated House in Montreal", Proceedings, Sixth Canadian Conference on Earthquake Engineering, Toronto, pp. 375-385.

Pall, A.S., Pall, R., 1993a, "Friction-Dampers Used for Seismic Control of New and Existing Buildings in Canada", Proceedings ATC 17-1, Seminar on Base Isolation, Passive Energy Dissipation and Active Control, San Francisco, Vol. 2, pp. 675-686.

Pall, A., Vezina, S., Proulx, Pall, R., 1993b, "Friction-Dampers for Seismic Control of Canadian Space Agency Headquarters", Journal Earthquake Spectra, Vol. 9, Number 3, pp. 547-557.

Pall, A., Pall, R., 1996, "Friction-Dampers for Seismic Control of Buildings – A Canadian Experience", Eleventh World Conference on Earthquake Engineering, Mexico, Paper No. 497.

Pasquin, C., Pall, A.S., Pall, R., 1994, "Hi-Tech Seismic Rehabilitation of Casino de Montreal", ASCE Structures Congress, Atlanta, pp. 1292-1297.

Pasquin, C., Charania, H., Steele, R., Pall, R., Pall, A.S., 1998, "Friction-dampers for Seismic Control of Selkirk Waterfront Offices, Victoria", Sixth U.S. National Conference on Earthquake Engg., Seattle.

Savard, G., Lalancette, J.R., Pall, R., Pall, A., 1995, "High Tech Seismic Design of Maison 1 McGill, Montreal", Proceedings, Seventh Canadian Conference on Earthquake Engineering, Montreal, pp. 935-942.

Vezina, S., Proulx, P., Pall, R., Pall, A., 1992, "Friction-Dampers for Aseismic Design of Canadian Space Agency", Proceedings, Tenth World Conference on Earthquake Engineering, Madrid, Spain, pp. 4123-4128.

Wagner, P., Vavak, L., Pall, R., Pall, A., 1995, "Seismic Rehabilitation of the New Hamilton Court House", Proceedings, Seventh Canadian Conference on Earthquake Engineering, Montreal, pp. 951-958.

Figure 1. East View of the Hospital

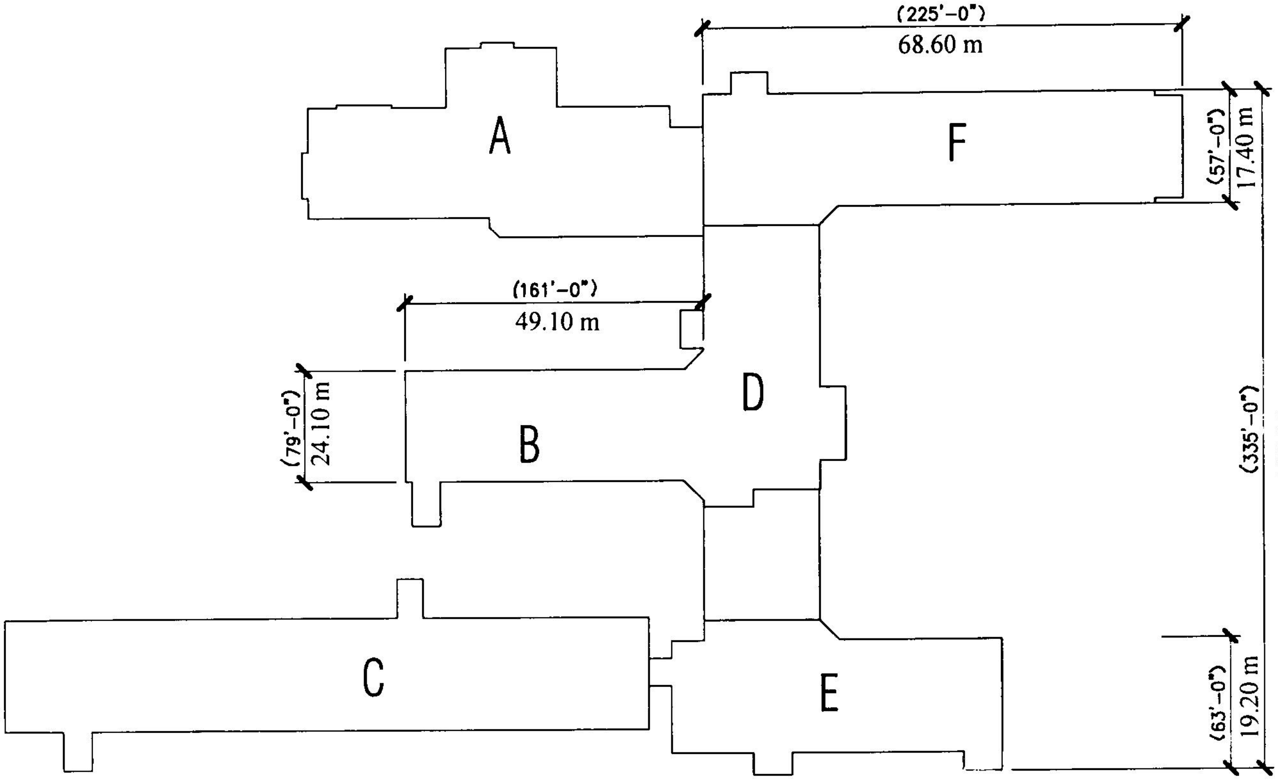
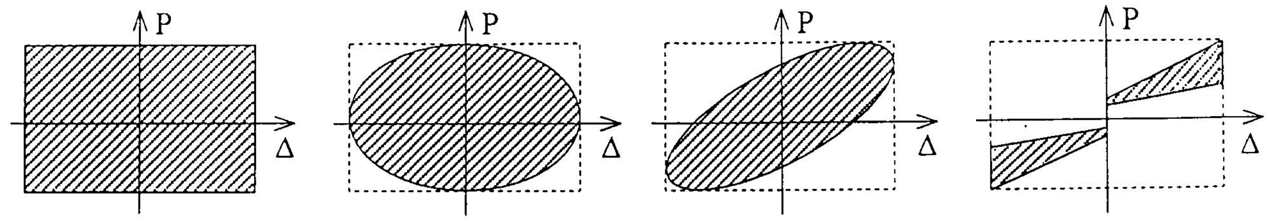


Figure 2. Key Plan



Pall Friction-Damper Viscous Damper Viscoelastic Damper Self-centring Friction-Damper

Figure 3. Hysteretic Loops of Different Dampers

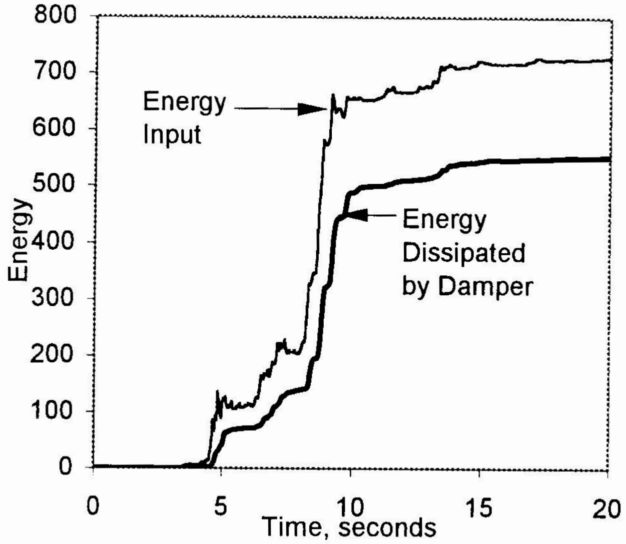


Figure 4. Time-History of Energy Input/Dissipated

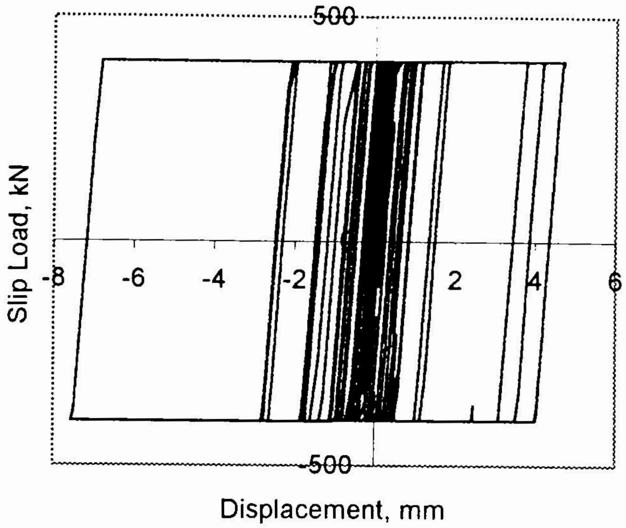


Figure 5. Hysteretic Loop of Friction-Damper at 3rd Level

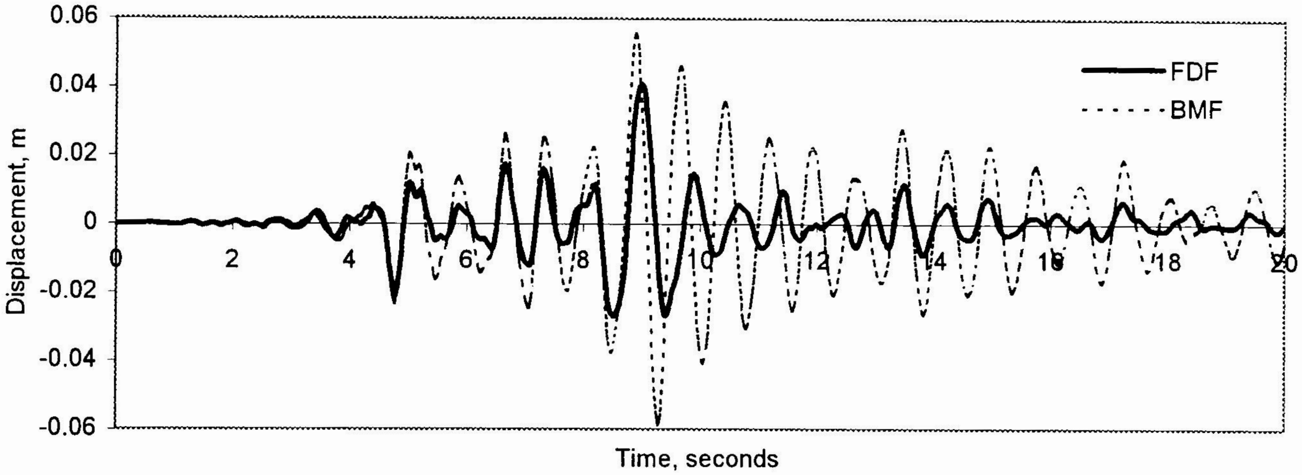


Figure 6. Time-Histories of Deflection at Top

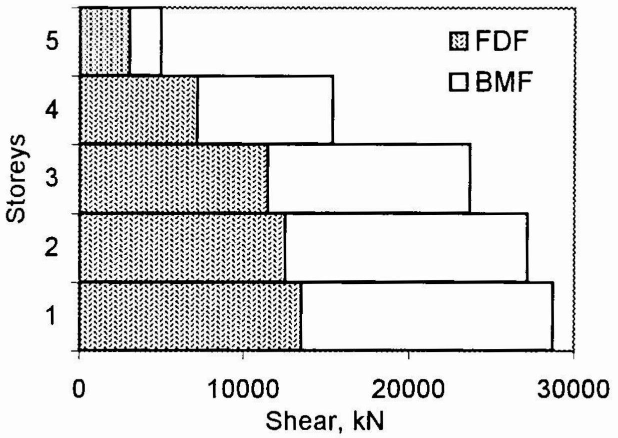


Figure 7. Envelope of Storey Shears

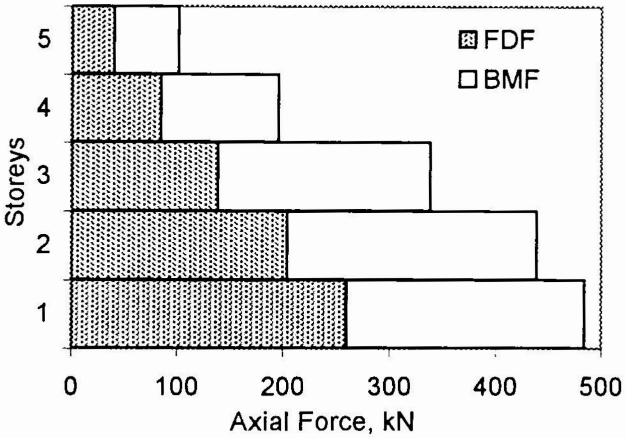


Figure 8. Envelope of Column Axial Force