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SEISMIC REHABILITATION OF JUSTICE HEADQUARTERS BUILDING OTTAWA, CANADA

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SUMMARY

The existing eight-story concrete frame building was built in 1955 and is of heritage importance. The earthquake resistance of the existing structure was significantly less than that of current building code requirements. Supplemental damping in conjunction with appropriate stiffness, provided by Pall friction-dampers in steel bracing, offered an innovative solution for the seismic rehabilitation of this prestigious building. Since the dampers dissipate a major portion of the seismic energy, the forces acting on the structure are significantly reduced. Expensive and time-consuming work on strengthening of columns and foundations was, therefore avoided. The results of three-dimensional nonlinear time-history dynamic analysis have shown that amplitude of lateral deflections and floor accelerations were significantly reduced. This method of seismic rehabilitation offered both cost savings and reduction in the construction schedule when compared to traditional shearwall type strengthening methods.

INTRODUCTION

The original East Memorial Building, an eight-story concrete frame structure (91 m x 54 m), was built in 1955 as a monument to those Canadians killed in Second World War. It is located on Wellington Street in nation’s parliamentary district. The building, clad with carved stone and copper roof, is a designated heritage structure. It has one basement below grade and the foundations are on spread footings. Front elevation of building and typical floor plan is shown in Figures 1 and 2, respectively.

The existing structure derived its lateral rigidity from nominally reinforced concrete shearwalls around elevators and concrete frames filled with unreinforced masonry. Although masonry infilled frames have performed very well to resist wind, these have performed poorly in the event of a major earthquake. The reinforcement detailing of columns and beams lacked ductility. Since its construction, the building codes have changed drastically in respect of provisions for earthquake resistant design.

The existing structure was capable of resisting only a small percentage of the seismic loads specified in the National Building Code of Canada (NBCC) 1995. Commentary K of the NBCC 1995, recommends a “triggering criterion” for the seismic upgrading of an existing building if its seismic resistance is less than 60% of the seismic loading for new buildings. In 1995, it was decided that the seismic rehabilitation work be undertaken along with major renovations, to protect the existing and new investment. These renovations were completed in 1997.

The conventional methods of stiffening consist of addition of concrete shearwalls or rigid steel bracing. 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. In a conventional braced frame, the energy dissipation capacity of a brace is very limited. A brace in tension stretches during severe shock and buckles in compression during reversal of

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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. Several rigid braced buildings have failed in Kobe earthquake. Both conventional methods require expensive and time-consuming work of strengthening the existing columns and foundations.

For seismic rehabilitation, conventional methods of strengthening with concrete shearwalls or rigid steel bracing were considered, however, these methods required expensive foundation work and were deemed to be too intrusive on the building heritage value. Supplemental damping in conjunction with appropriate stiffness offered an innovative solution for the seismic rehabilitation of this prestigious building. This was achieved by incorporating Pall friction-dampers in steel bracing. 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, the overloading on columns and foundations was reduced. Hence, expensive and time-consuming work on strengthening of members and foundations was not required. Higher energy dissipation capacity of friction-dampers compensates the lack of ductility and mitigates damage to other nonstructural components.

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.

This paper discusses the design procedure, results of analysis and details of construction 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.

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 late seventies, the principle of friction brake inspired the development of Pall friction-dampers (Pall 1979, Pall 1981a). Similar to automobiles, the motion of vibrating building can be slowed down by dissipating energy in friction. Several types of friction-dampers have been developed (Pall 1980, Pall 1981, Pall 1982, Pall 1989). For frame buildings, these are available for tension cross bracing, single diagonal bracing and chevron bracing.

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 wind. 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. This allows the building to remain elastic or at least yielding is delayed to be available during maximum credible earthquakes. 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-story 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 story 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, 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 behavior, 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 economical. There is nothing to damage or leak. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. Pall friction-dampers are also very compact in design and can be easily hidden within drywall partitions. The architects like to expose these dampers to view as they add to the aesthetic appearance.

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, Chandra 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 near Seattle - world's largest building in volume is being retrofitted with Pall friction-dampers.

Figures 4 and 5 show some Pall friction-dampers installed in bracing located in drywall partitions.

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 - J of the NBCC 1995, allows the use of friction-dampers for seismic control of buildings. It requires that the 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, October'1997". The provisions of the NBCC and above documents served as guidelines for the analysis and design of the above project.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

Three-dimensional nonlinear time-history dynamic analyses were carried out using the computer program DRAIN-TABS, developed at the University of California, Berkeley. This program consists of a series of subroutines that carry out a step by step integration of the dynamic equilibrium equations using constant accelerations within any time step. Several other programs such as ETABS, SAP2000, SADSAP, 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.

As different earthquake records even though of the same intensity, give widely varying structural response, the 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. A 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 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. 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 84 friction-dampers of 500-700 kN slip load were used in single diagonal and chevron bracing.

Analyses were also conducted on frames with concentric rigid 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, except that the BMF 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. The results compared are for the maximum response.

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 about 85% of the BMF. After the earthquake, there was a permanent offset of 4 mm in the FDF and 14 mm for the BMF.

2. Time history of slippage in a typical damper is shown in Figure 7. The slippage is about 6 mm. The permanent offset in the damper after the earthquake was 1 mm. Friction-dampers at all storeys participated in energy dissipation.

3. Maximum envelopes for shears in a column of a braced bay are shown in Figures 8. The values of the FDF are about 40% of those for the BMF.

4. Maximum envelopes for axial loads in a column of a braced bay are shown in Figures 9. The values of the FDF are about 60% of those for the BMF.

5. In the BMF, 60% of braces and 25% of columns had yielded. All members in the FDF remained elastic.

CONCLUSION

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

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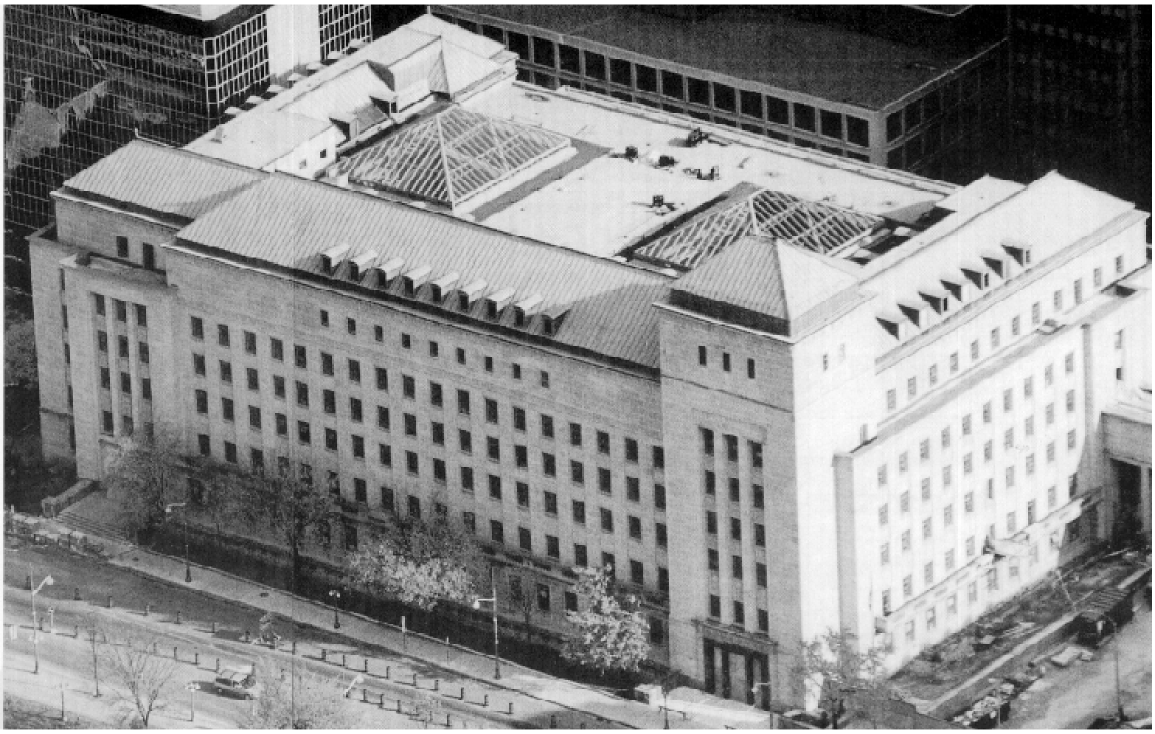

Figure 1: Ariel view of Justice Headquarter Building

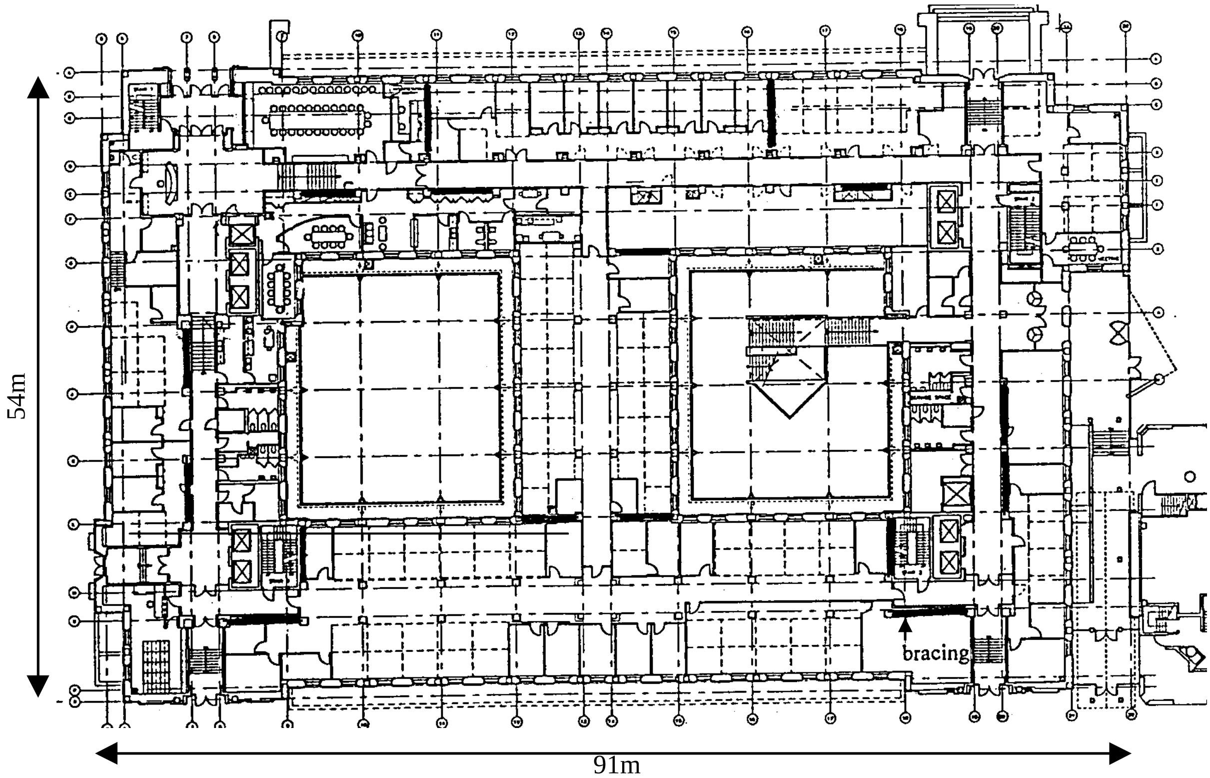

Figure 2: Typical floor plan showing location of bracing with Pall Friction-Dampers

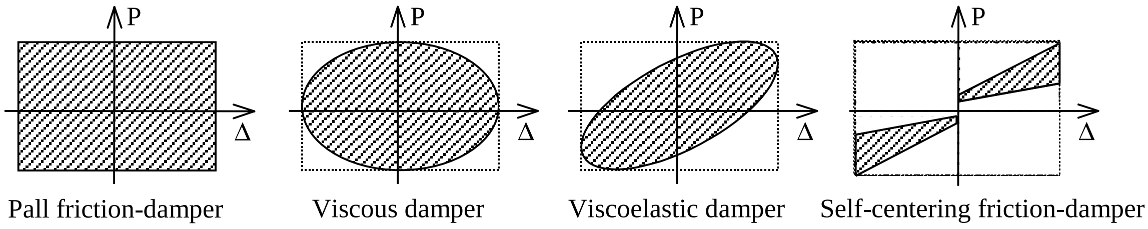

Figure 3: Hysteretic loops of different dampers

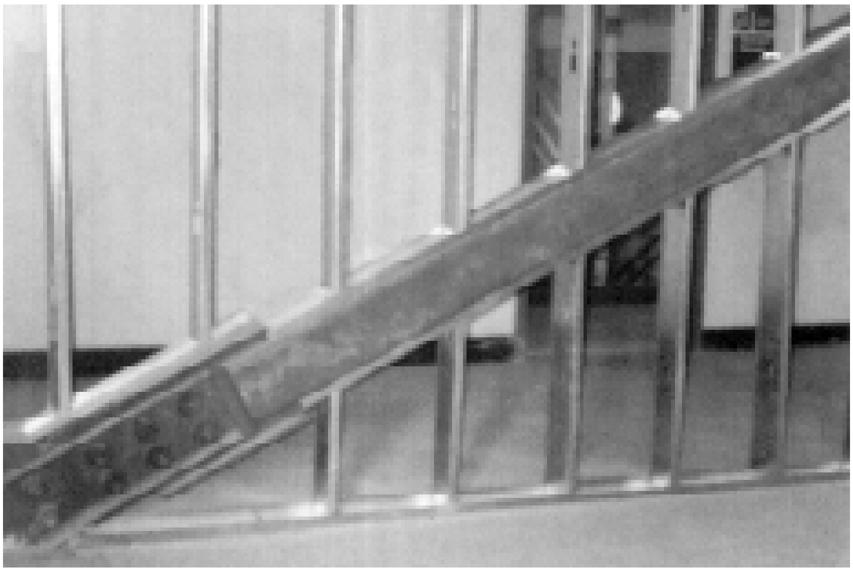

Figure 4: Pall friction-damper at bottom of single diagonal brace

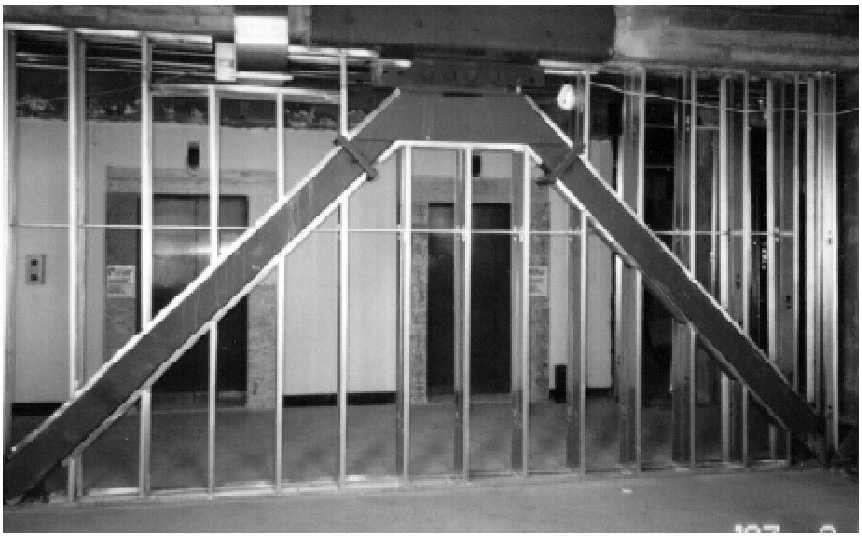

Figure 5: Pall friction-damper at top of chevron brace

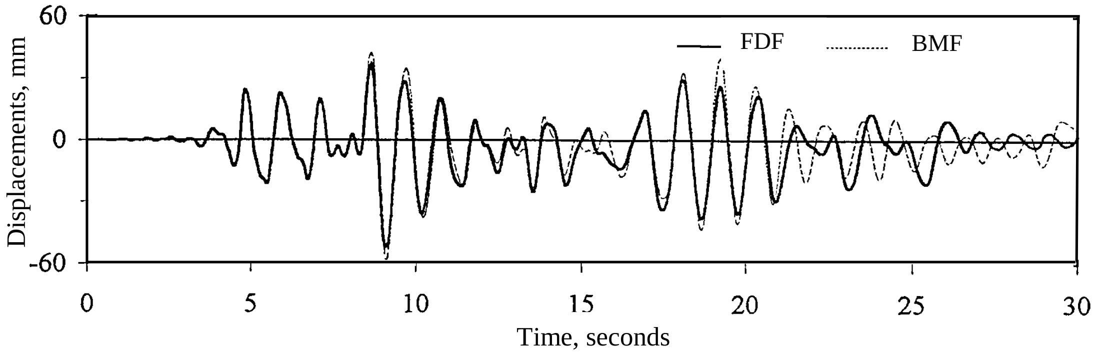

Figure 6: Time-histories of deflections at top

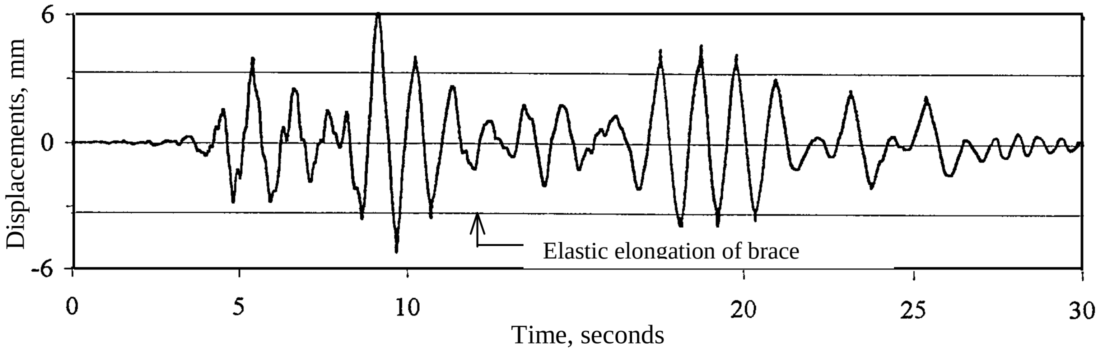

Figure 7: Time-histories of slippage in friction-damper

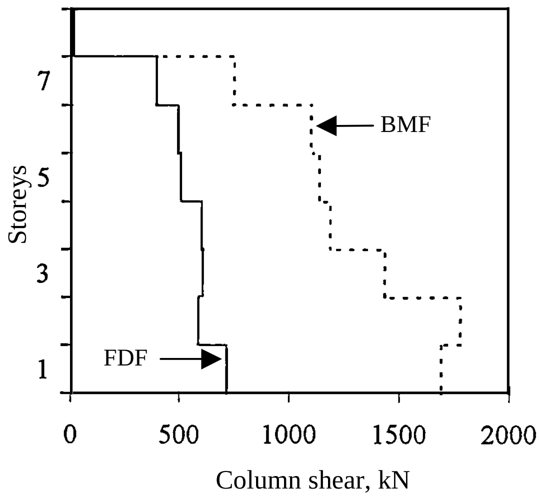

Figure 8: Envelope of column shear

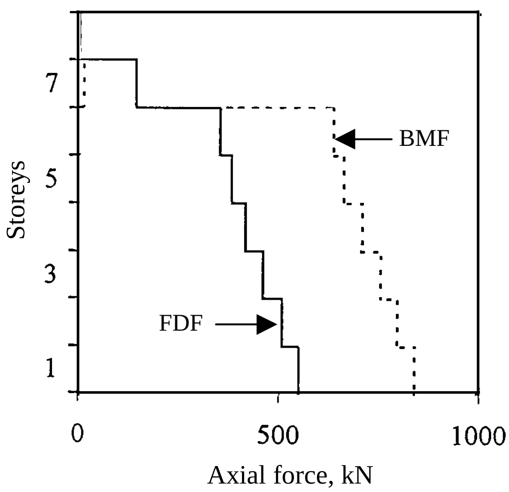

Figure 9: Envelope of column axial force