



SEISMIC RETROFIT OF MUCTC BUILDING USING FRICTION DAMPERS, PALAIS DES CONGRES, MONTREAL

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SUMMARY

The ten-storey MUCTC Building, built in 1928, is designated as a structure of heritage importance. In 2000, it was decided to expand the adjoining convention centre 'Palais des Congres'. The new expansion is built around and integrated with the MUCTC Building. The expansion prompted the seismic upgrade of the MUCTC Building. Conventional methods of seismic rehabilitation, with concrete shearwalls or rigid steel bracing, were not suitable for the MUCTC Building. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of this prestigious building. This was achieved by introducing Pall friction dampers in steel bracing.

INTRODUCTION

The MUCTC Building (Figure 1) is located in the heart of Montreal - close to historic Old Montreal and in the area slated to be the most prestigious in town, the International District. This ten-storey concrete frame office building was built in 1928. The floor slabs are one-way joist system and the foundations are spread footings. As with the majority of buildings of this age, the earthquake resistance of the existing structure was significantly less than that of current building code requirements. In 2000, it was decided to expand the nearby Palais des Congres (Convention Centre). The new extension is built around and integrated with the MUCTC Building, which had to be preserved as it is of historic significance (Figure 2). The expansion prompted the seismic upgrade of the MUCTC Building.

Conventional methods of seismic rehabilitation, with concrete shearwalls or rigid steel bracing, were not considered suitable for the MUCTC Building as upgrade with these methods would have required expensive and time consuming foundation work. Also, the shearwalls would have interfered with the heritage character of the structure. The tight budget and schedule made these conventional options unfeasible. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of this prestigious building. This was achieved by introducing friction dampers in steel bracing. In contrast to shearwalls, friction-damped bracing need not be vertically continuous. This aspect was particularly appealing to the architectural designers as it offered flexibility in space planning. Since friction-damped bracing do not carry any gravity load, these do not

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Figure 1. MUCTC Building



Figure 2. Palais des Congrès extension integrating MUCTC Building

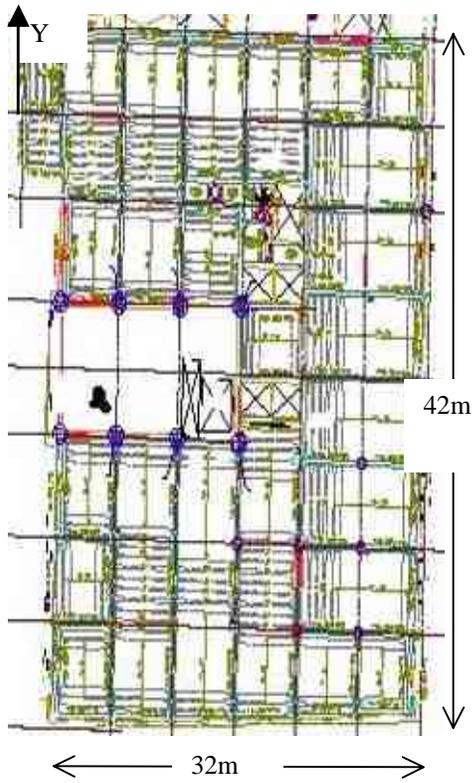


Figure 3. Typical floor



Figure 4. Friction damper at bottom of single diagonal brace



Figure 5. Typical detail of connections

need to go down through the basement to the foundation. 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. A typical floor plan is shown in Figure 3.

A total of 88 friction dampers were required to extract sufficient energy to safeguard the structure and its contents from damage. A typical friction damper in steel bracing and connection details is shown in Figures 4 and 5, respectively.

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

CONVENTIONAL CONSTRUCTION

The design criteria stipulated in all building codes, including the National Building Code of Canada (NBCC 1995), is 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 causing bending, twisting and cracking. This results in permanent damage. Repair costs can often be as significant as the costs of collapse of the structure. Recent earthquakes have clearly shown that conventional construction even in technologically advanced and industrialized countries is not immune to destruction.

While the minimum design provisions of the building codes were adequate in the past, in modern buildings, avoidance of structural collapse alone is not enough. The cost 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 the massive financial losses and social sufferings, highlighted by recent earthquakes, building officials, structural engineers, developers, owners, bankers and insurers have started giving due consideration to performance based design rather than life safety alone.

Braced steel frames are known to be economical and effective in controlling lateral deflections due to wind and 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.

Concrete shearwalls or steel bracing is often used to add rigidity to 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. 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.

The problems created by the dependence on ductility of the structure can be reduced if a major portion of the seismic energy is dissipated mechanically, independent of 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 buildings.

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 the late 1970's, the principle of friction brake inspired the development of friction dampers, Pall [1,2]. Similar to automobiles, the motion of a vibrating building can be controlled.

Friction dampers suitable for use in different types of bracing have been developed, Pall [3]. They 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. The plates are clamped together with high strength steel bolts. Slippage is without any stick-slip phenomenon. Friction dampers are designed not to slip during service load and windstorms. During a major earthquake, they 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 $\pm 20\%$ of slip load, the seismic response is not significantly affected. After the earthquake, building returns to its near original alignment under the spring action of an elastic structure.

These particular 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, Cherry [4]. Even an earthquake record with a peak acceleration of 0.9g did not cause any damage to the 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, Kelly [5]. All members of the friction damped frame remained elastic for 0.84g acceleration, while the moment-resisting frame would have yielded.

These friction dampers possess large rectangular hysteresis loops, similar to an ideal elasto-plastic behaviour, with negligible fade over several cycles of reversals, Pall [6], Filiatrault [4]. Unlike viscous or visco-elastic devices, the performance of friction dampers is independent of temperature and velocity. For

a given force and displacement in a damper, the energy dissipation of a friction damper is the largest compared to other damping devices (Figure 6). Therefore, fewer friction dampers are required to provide a given amount of supplemental damping.

Unlike systems that dissipate energy through the process of yielding – causing permanent damage, friction dampers dissipate seismic energy in friction. 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. Since they are not active during wind or service load conditions, there is no danger of failure due to fatigue. There is nothing to leak or damage. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. 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.

These friction dampers have found many applications. They have been used in both new construction and seismic retrofit of existing buildings, Pall [7-11,17,23], Pasquin [12,19,20], Vezina [9,11], Godin [13], Hale [14,22], Savard [15], Wagner [16], Deslaurier [18], Balazic [21], Chandra [24]. Boeing Commercial Airplane Factory at Everett – the world’s largest building in volume and Boeing Development Center Buildings at Seattle have been retrofitted with these friction dampers, Vail [25]. Compared to conventional retrofit, Boeing saved more than US\$30 million. The City and County of San Francisco chose Pall friction dampers for seismic control of Moscone Convention Center as it saved US\$2.25 million compared to alternate viscous dampers, Sahai [26]. To date, more than eighty buildings have already been built and several are under design or construction. For more details refer: www.palldynamics.com.

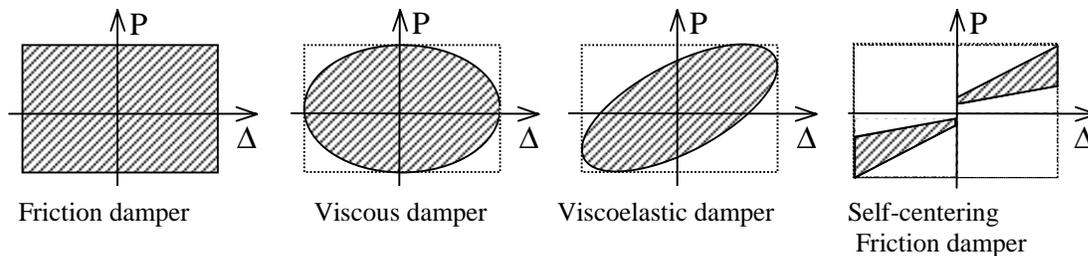


Figure 6. Comparison of hysteresis loops of different dampers

DESIGN CRITERIA

The quasi-static design procedure given in the NBCC is ductility based and does not explicitly apply to friction-damped buildings. However, structural commentary - J of the NBCC, allows the use of friction dampers for seismic control of buildings. It requires that nonlinear analysis must demonstrate that a 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 356 / 357, issued in 2000. These guidelines and provisions of NBCC, served as basis for the analysis and design of the MUCTC Building.

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 is within the tolerable limits. For the MCE, the structure is evaluated to determine the maximum displacement requirement of the damping device. It is presumed that if proper ductile detailing has been followed, the structure will have sufficient reserve to resist any overstress conditions that occur during MCE.

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 than $\pm 15\%$.

NONLINEAR TIME-HISTORY DYNAMIC ANALYSIS

The slippage of friction damper in an elastic brace constitutes 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 (Nonlinear version), developed by Computers and Structures Inc. Analytical computer model is shown in Figure 7. Several other programs are also available on which friction dampers can be easily modeled. The modeling of friction dampers 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. The earthquake record based on the Whittier earthquake of 1987 provided maximum response and was used for the design. Analyses were carried out for ground motions simultaneously 100% along x-direction and 30% along y-direction, and also for ground motions 100% along y-direction and 30% along x-direction. Viscous damping of 2% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements. Several iterations were made to determine the optimum slip load to achieve minimum response. A total of 88 friction dampers of 500-600 kN slip load were used in diagonal and chevron bracing (Figure 8).

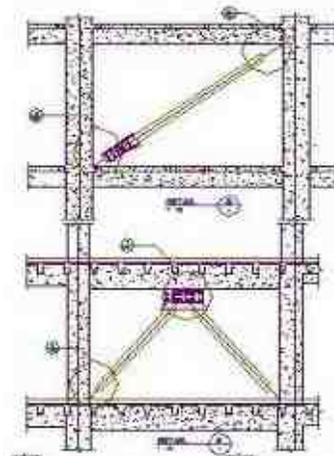
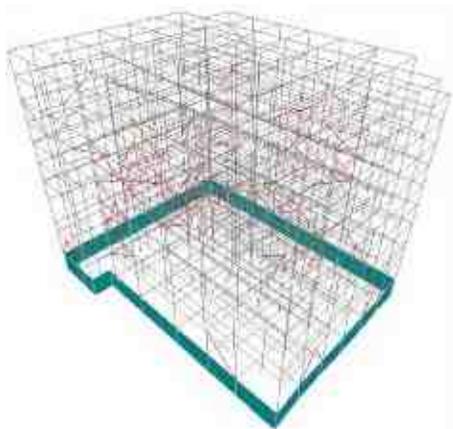


Figure 7. Analytical computer model

Figure 8. Friction dampers in diagonal and chevron bracing

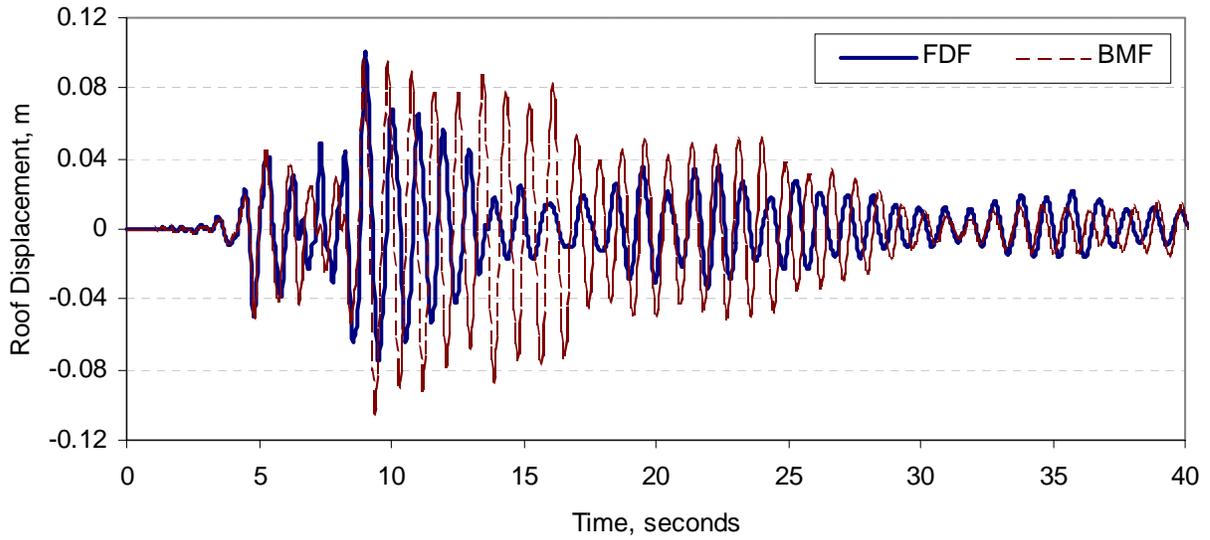


Figure 9. Time histories of displacements at roof

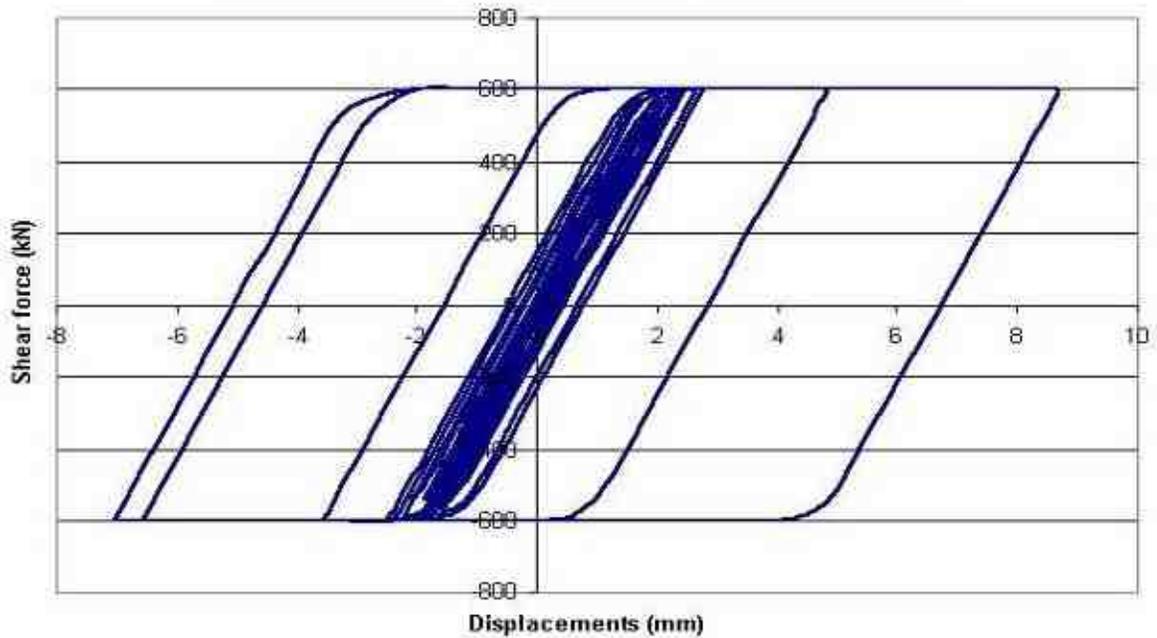


Figure 10. Hysteretic loop of a typical 600kN friction damper

In order to compare the effectiveness of friction-damped frames (FDF), analyses were also conducted on the building using rigid bracing in frames (RBF). The rigid bracing with twice the area of friction damped bracing gave the best response.

DISCUSSION OF RESULTS

1. Time-histories of deflections at the top of building are shown in Figure 9. Maximum deflection at roof is 100mm for FDF and 105 for RBF. The permanent offset of the FDF building at the end of ground motion is negligible, about 2mm.
2. Maximum storey drift in FDF is less than 0.7%. At this low level of deformations, no damage is expected during a major earthquake. In conventional construction, the building codes allow up to 2%.
3. Hysteretic loop of a typical damper in bracing is shown in Figure 10. The slippage in the damper is about 8 mm. The slope in the hysteretic loop is due to the elastic shortening of brace. Unlike rigid bracing, the maximum force developed in the friction-damped bracing and connections are constant for all earthquake records. This results in an engineered solution i.e. the forces are predetermined by the engineer and not by the earthquake.
4. Time-histories of deformations in friction-damped bracing is shown in Figure 11. The permanent offset in the damper after the earthquake is less than 0.5mm.
5. Maximum envelopes for axial load in a column of a FDF and RBF are shown in Figure 12. The axial loads in FDF are about 60% of those for the BMF. The use of rigid bracing would have resulted in significant strengthening of columns and foundations.

CONCLUSION

The use of friction dampers has shown to provide a practical and economical solution for the seismic upgrade of the MUCTC building. As the seismic forces exerted on the structure are significantly reduced, the system offered savings in upgrade costs. The analytical studies have shown that the friction-damped structure should perform well in the event of a major earthquake.

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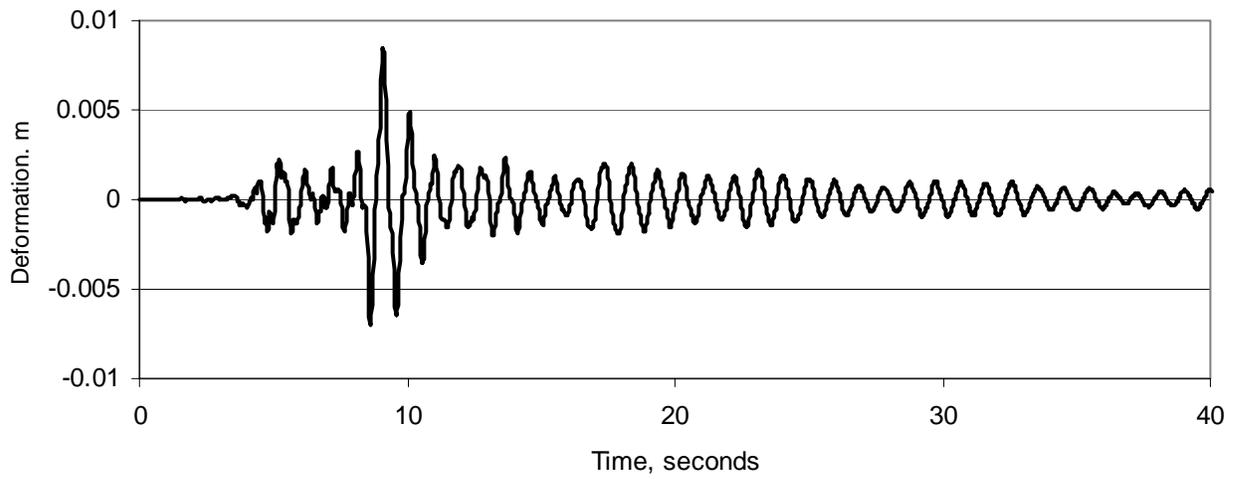


Figure 11. Time history of slippage of a typical 600kN friction damper

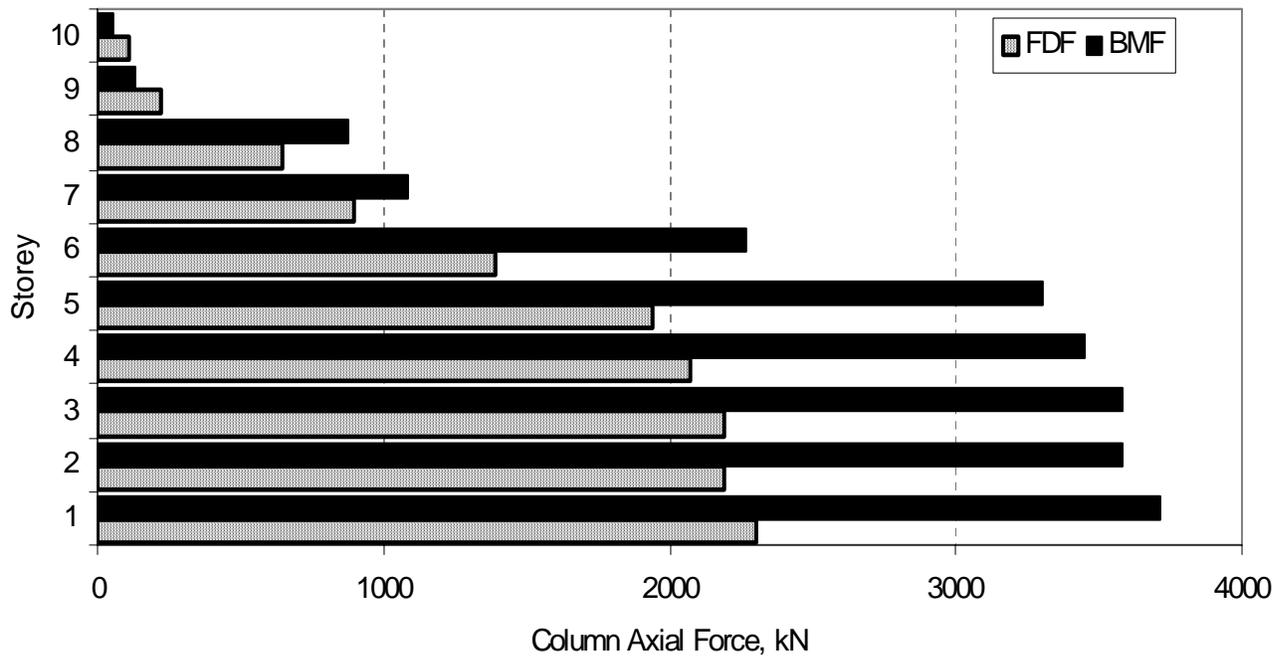


Figure 12. Envelope of column axial force

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