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FRICTION DAMPERS FOR SEISMIC REHABILITATION OF EATON BUILDING, MONTREAL

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ABSTRACT: The nine-storey Eaton building was built in several phases, from 1925 to 1959. The structure derived its lateral stability from partial frame action and infill walls of unreinforced masonry. The existing structure was not adequate to resist the lateral seismic forces specified in the current building code. In 2000, it was decided that seismic rehabilitation work be undertaken along with major renovations to protect the existing and new investment.

Of the several schemes, the introduction of supplemental damping using friction dampers in steel bracing was considered to be the most effective and economical solution for seismic upgrade. This novel upgrade approach significantly reduced the drifts and base shear while greatly minimizing the strengthening of the existing members. This paper discusses the design criteria, seismic analysis and its results.

1. INTRODUCTION

The existing Eaton building is located in the heart of the shopping district on St. Catherine Street in downtown Montreal (Figures 1, 2). This nine-storey building was built in several phases, from 1925 to 1959. The different construction phases introduced different structural systems into this building. It has both concrete and steel frames with concrete slabs. The Eaton building has a beautiful façade. As the building has been used to house a department store, there are large open spaces at each level. The structure derived its lateral stability mainly from the perimeter masonry walls, a few interior walls and the concrete frame built in the last construction phase of 1959. A typical floor plan is shown in Figure 3. The preliminary analysis indicated that the existing structure was not adequate to resist the lateral seismic forces specified in the National Building Code of Canada (NBCC) 1995.

In 2000, new ownership of this building prompted a major redevelopment of this building. The planned renovations lead to significant changes in the interior and further diminished its seismic resistance capacity. Among these, a new large atrium with a glass roof and punching of openings in the lower floors for new elevators and escalators. It was necessary that seismic rehabilitation work be undertaken along with the architectural renovations to protect the existing and new investment.

1.1 Seismic Upgrade

There were several alternative methods open for the seismic upgrade of the Eaton building. The conventional methods of stiffening consist of adding 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 seismic energy input. Addition of new shearwalls would have interfered with the open character of the interior plan. In a conventional braced frame, the energy dissipation capacity of a brace is very limited. Several rigid braced buildings have failed in Kobe earthquake. Both conventional methods of upgrade require expensive and time-consuming work of strengthening the existing columns and foundations. The tight budget and "Fast Track" schedule made these conventional options unfeasible.

Supplemental damping in conjunction with appropriate stiffness offered an innovative solution for the seismic rehabilitation of the Eaton building. This was achieved by incorporating friction dampers in new steel bracing. As soon as the structure undergoes small deformations, the friction dampers are activated 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. In contrast to shearwalls, the friction-damped bracing need not be vertically continuous. Since the damped bracing do not carry gravity load, they do not 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. These aspects were particularly appealing to the project architects as they offered great flexibility in space planning. By staggering the bracing at different story levels, the overloading on some columns and foundations was reduced. Hence, expensive and time-consuming work on strengthening of foundations was not required. Higher energy dissipation capacity of friction dampers compensates the lack of ductility and mitigates damage to other nonstructural components.

A total of 161 friction dampers were installed in the Eaton building. Typical friction dampers in single diagonal and chevron bracing are shown in Figures 4 and 5, respectively.

This paper describes the design criteria, seismic analysis and its results. A brief review on dampers has also been included so that the state-of-the-art structural solution can be appreciated.

2. 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 friction dampers (Pall et al. 1979, Pall et al. 1981). 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 et al. 1982). 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. They consist of series of steel plates specially treated to develop most reliable friction. The 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, the 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 (Filiatrault et al. 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 the Earthquake Engineering Research Center of the University of California at Berkeley (Kelly et al. 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.

Friction dampers possess large rectangular hysteresis loops, similar to an ideal elasto-plastic behavior, with negligible fade over several cycles of reversals (Pall et al. 1980, Filiatrault et al. 1986). 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 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 other devices, the maximum force in a friction damper is pre-defined and remains the same for any future ground motion. Therefore, the design of bracing and connections is simple and economical. There is nothing to yield and damage, or leak. Thus, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. These friction dampers are also compact in design and can be easily hidden within drywall partitions.

Friction dampers manufactured by Pall Dynamics Limited have found many applications in new construction and seismic retrofit of existing buildings (Pall et al.1987, Pall et al. 1991, Vezina et al. 1992, Pall et al. 1993, Pasquin et al. 1994, Godin et al. 1995, Hale et al. 1995, Savard et al. 1995, Wagner et al. 1995, Pall et al. 1996, Deslaurier et al. 1997, Pasquin et al. 1998, Pasquin et al. 1999, Balazic et al. 2000, Hale et al. 2000, Pall et al. 2000). To date, more than sixty buildings have already been built and several are under design or construction. Recently, Boeing's Commercial Airplane Factory near Seattle - world's largest building in volume was retrofitted with these friction dampers.

3. 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 show that a 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, various 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 Eaton 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 requirements on structural elements do not surpass their capacities and that the drift in the structure is within the permissible limits. For the MCE, the structure is assessed to ascertain 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 that ±15%. The friction dampers used in this project meet an exacting standard of quality control. Before delivery to site, each damper is load tested to ensure proper slip load.

7. 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. Therefore, 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. The analysis model is shown in Figure 7. 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. In the analyses, friction dampers in single diagonal brace are modeled as damped braces having member stiffness equal to brace stiffness and nonlinear axial yielding equal to the slip load. Friction damped chevron braces are modeled as braces plus dampers. These dampers have nonlinear yield force in shear equal to the slip load.

A series of analyses were made to determine the optimum slip load of friction dampers to achieve minimum response. The damper slip loads are 700kN at ground storey, 600kN for the next five storeys, and 300kN at upper storeys.

Since different earthquake records, even of the equal intensity, give widely varying structural responses, results attained using a single record may not be conclusive. Therefore, different time-history records, suitable for the Montreal 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 gave maximum response and was used for the design. Analyses were carried out for ground motions occurring 100% along x and y directions. Viscous damping of 4% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements.

Analyses were also conducted on frames with concentric rigid bracing in moment frames. 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 almost twice the area of brace than that in the FDF. For smaller or larger brace areas tried, the response of the BMF was higher. The results compared are for the maximum response of the DBE record.

7.1 Discussion of Results

1. The total energy input in the structure for BMF and FDF and the energy dissipated by friction dampers is shown in Figure 8. The FDF has a dual advantage over the BMF. Firstly, the FDF attracts only 50% of the seismic energy input of the stiffer BMF. Secondly, the friction dampers in the FDF dissipate about 50% of the input energy. So the remaining energy left in the FDF is approximately 25% of the energy in the BMF.

2. Time-histories of deflections at the top of building are shown in Figure 9. The peak amplitude in x direction is 156mm, about 54% of BMF. Maximum storey drifts in FDF are less than 1%. At this low level of drift, no damage is expected during a major earthquake.

3. Hysteretic loop of a 700kN friction-damped single diagonal brace is shown in Figure 10. The maximum amplitude of slippage is –25mm. Time history of slippage in this damped brace is shown in Figure 11. The permanent offset in the damper after the earthquake was less than 2mm.

4. Maximum envelopes for axial loads in a column of a braced bay are shown in Figure 12. The column axial forces in FDF are about 50% of that for the BMF.

5. The base shears in FDF are 16000kN and 13000kN in x and y direction, respectively. For BMF, the base shears are 47000kN and 27000kN in x and y direction, respectively.

8. CONCLUSION

The analytical studies have shown that the friction-damped structure should perform well in the event of a major earthquake. The seismic performance of the structure is far superior to the requirements of the building code. As the seismic forces exerted on the structure are significantly reduced, the system offered savings in upgrade costs. Besides savings in the upgrade cost, the saving in life cycle cost could be significant as damage to the building and its content is minimised. The use of friction dampers has shown to provide a practical and economical solution for the seismic upgrade of the Eaton building.

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Figure 1. Eaton Building.

Figure 2. Eaton Building – View from atrium during construction.

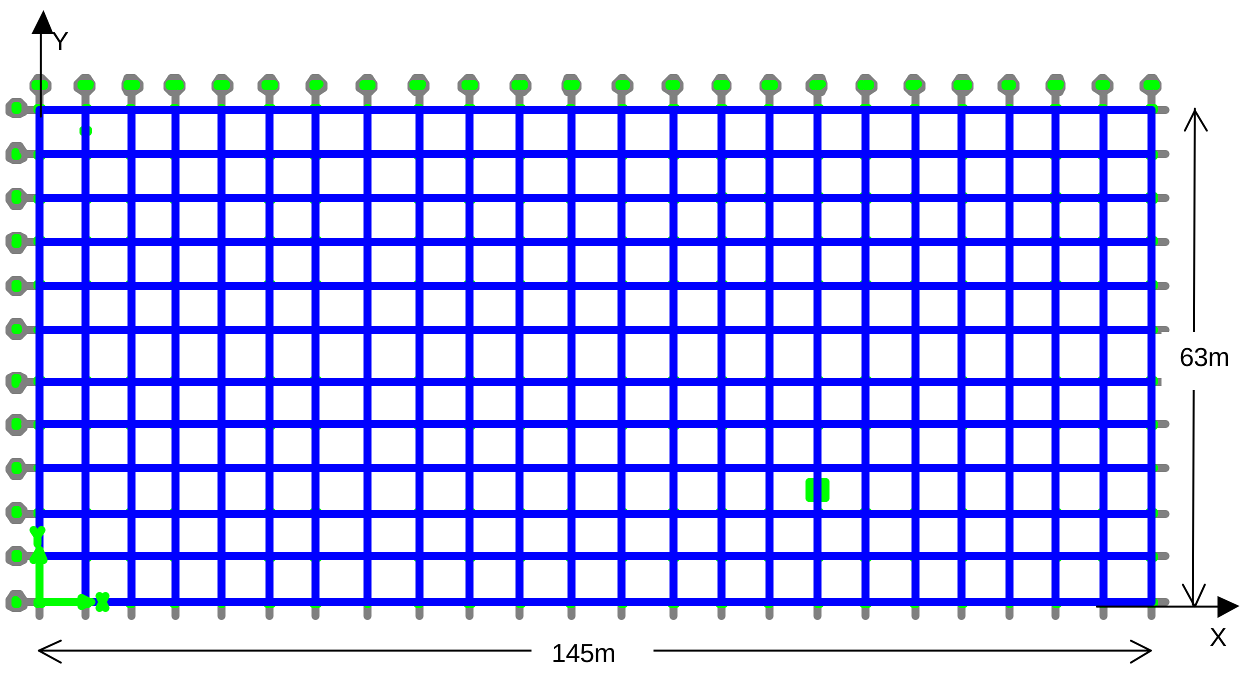


Figure 3. Typical floor plan

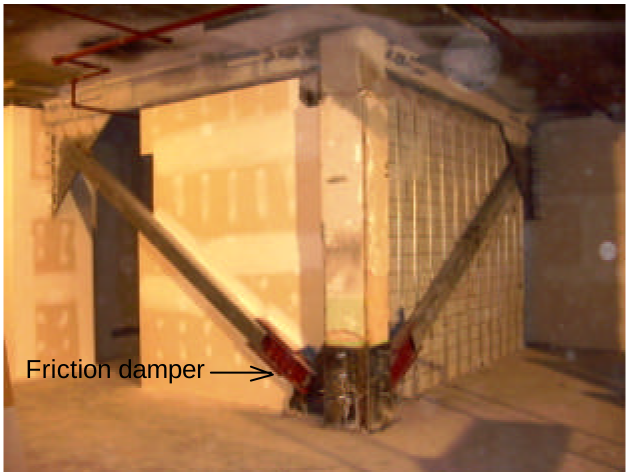


Figure 4. Friction damper in single diagonal brace.

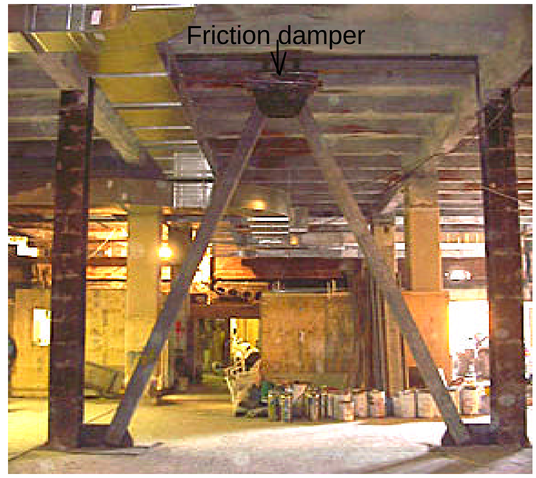
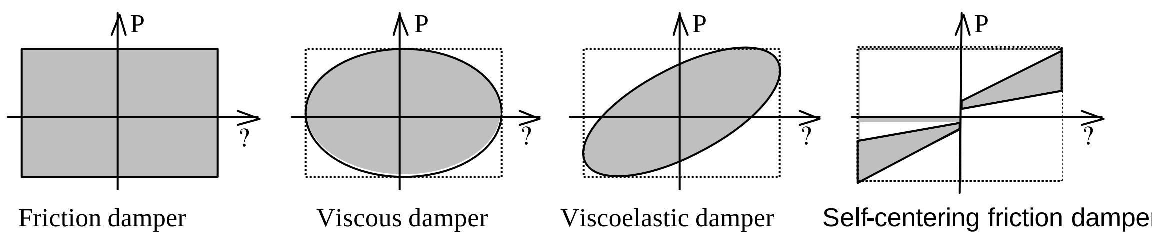


Figure 5. Friction damper at top of chevron brace.



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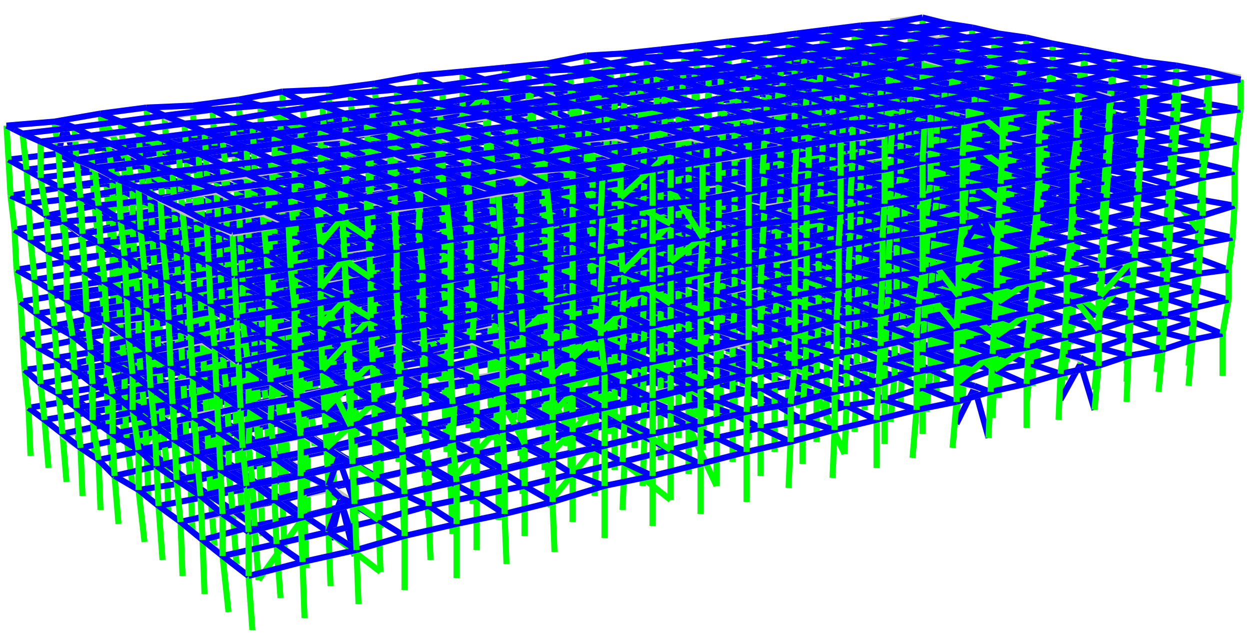

Figure 7. 3 dimensional analytical model of Eaton building.

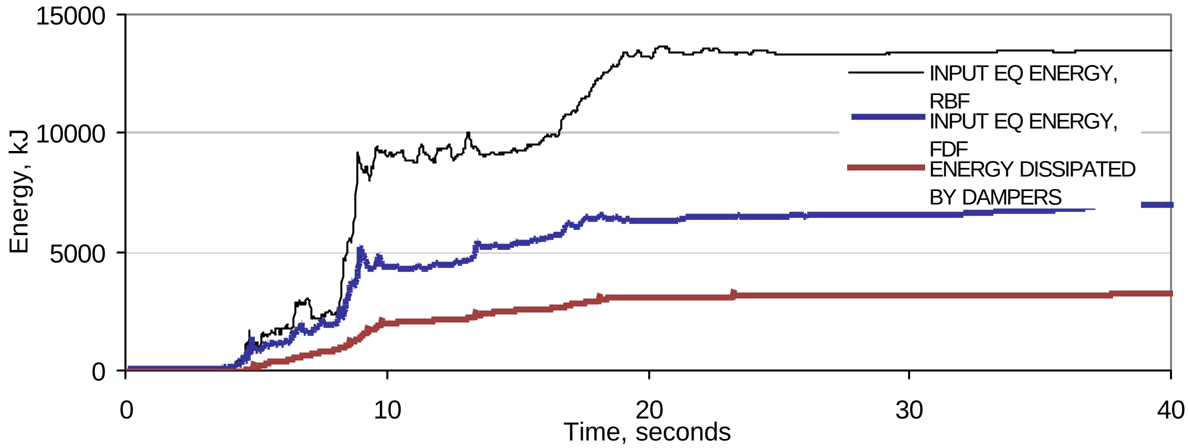

Figure 8. Time histories of energy input and energy dissipated

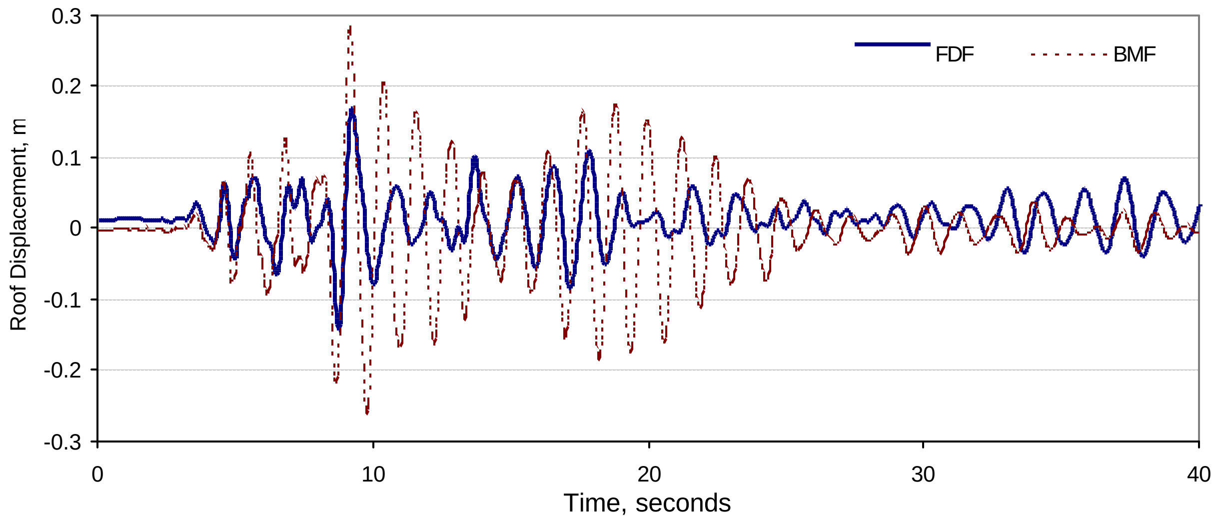

Figure 9. Time histories of displacements at roof

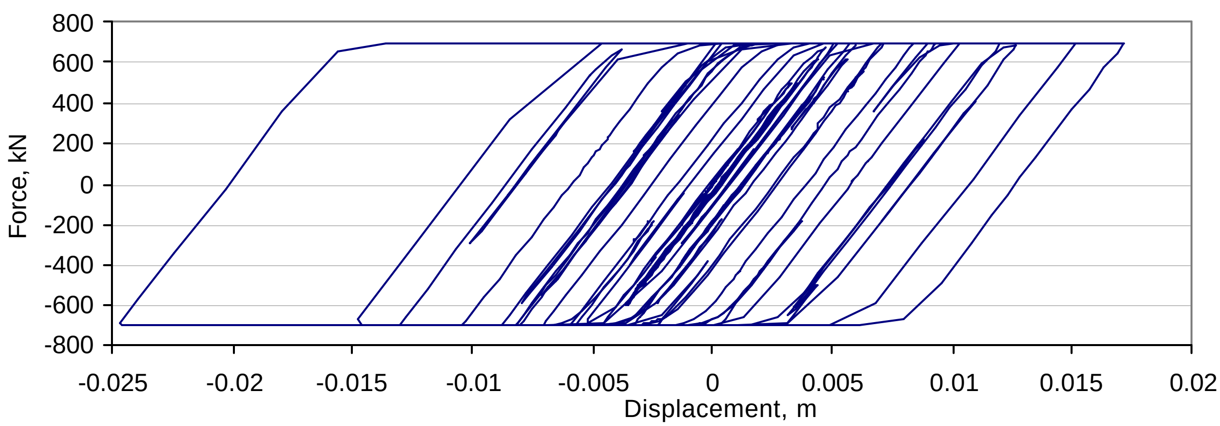

Figure 10. Hysteretic loop of a 700kN friction damper in a diagonal brace

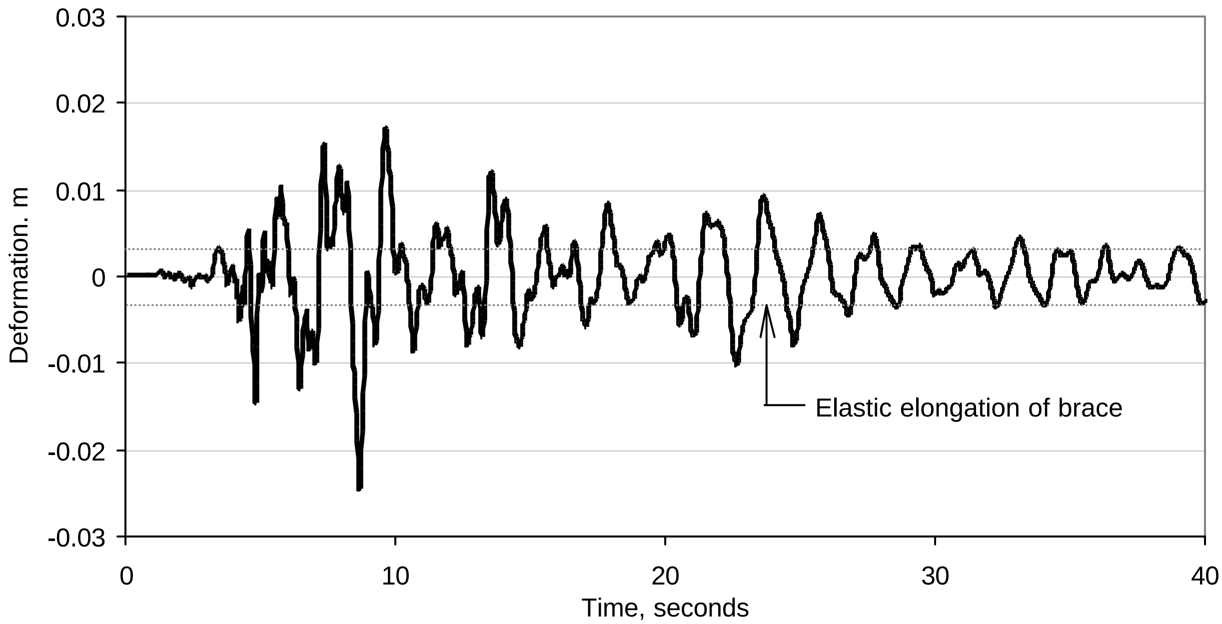

Figure 11. Time history of deformation of damped bracing

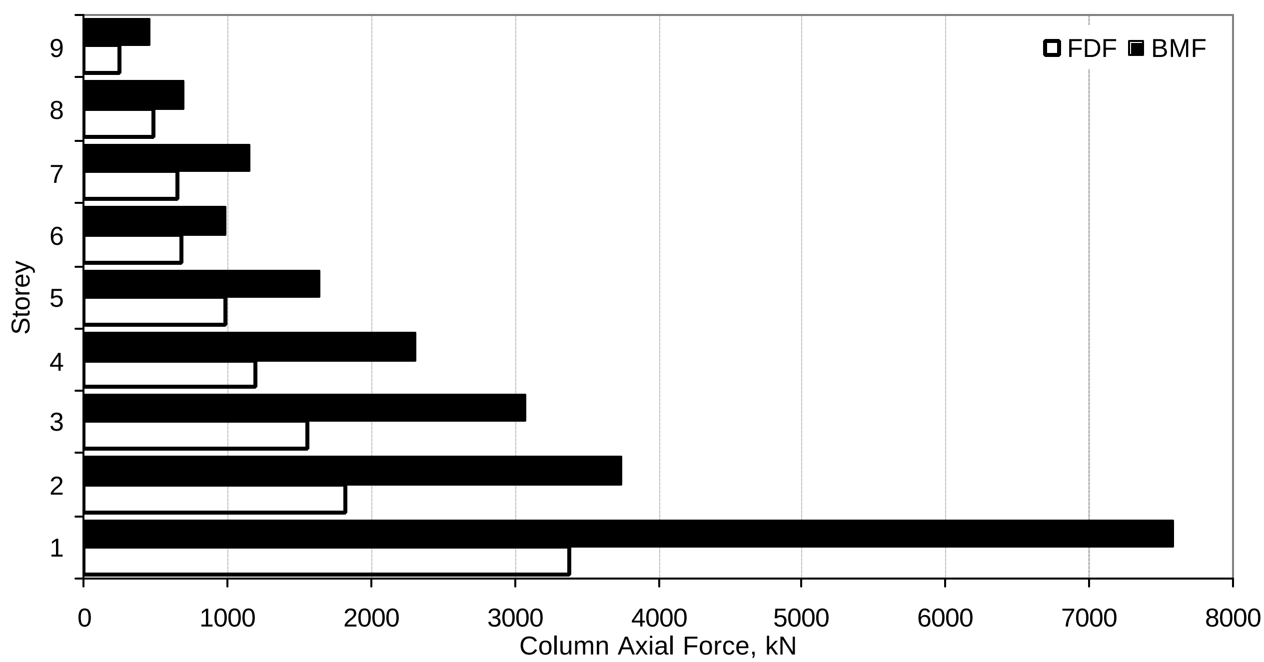

Figure 12. Envelope of column axial force.