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FRICTION DAMPERS FOR SEISMIC UPGRADE OF ST. VINCENT HOSPITAL, OTTAWA

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SUMMARY

St. Vincent Hospital comprises of five blocks of 5-storey concrete frame construction. One of the blocks is new construction and the other four blocks were built between 1890 and the early 1950's. The earthquake resistance of the existing structures was significantly less than that required by the current building codes. Since hospitals are of post disaster importance, the engineers recommended that the existing structures be upgraded along with the new expansion.

Conventional methods of seismic rehabilitation with concrete shearwalls or rigid steel bracing were not considered suitable for this hospital as upgrades with these methods would have required expensive and time consuming foundation work. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of this hospital. This was achieved by introducing Pall Friction Dampers in steel bracing.

INTRODUCTION

St. Vincent Hospital is located in downtown Ottawa, Canada's capital (Figure 1). The hospital complex consists of five blocks of buildings named A, B, C, D and E (Figure 2). Block E is new construction. There is also a new atrium structure in the interior court. The existing structures were built between 1890 and early 1950's. The 5-storey buildings are concrete frame construction and have one basement level. The exterior cladding is stone with terra-cotta backup. The foundations are spread footings. All blocks are separated with expansion joints. As with the majority of buildings built during this time, the earthquake resistance of these existing structures was significantly less than the current building code requirements. The reinforcement detailing of the columns and beams indicate a lack of ductility. Since hospitals are of post disaster importance, the project engineers recommended that the existing structures be upgraded. The upgrade work began in November 2002 and the completion is expected in 2006.

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Conventional methods of seismic rehabilitation with concrete shearwalls or rigid steel bracing were not considered suitable for this project as upgrades with these methods would have required expensive and time consuming foundation work. The tight budget and schedule meant that these conventional options were not feasible. Supplemental damping in conjunction with appropriate stiffness offered an innovative and attractive solution for the seismic rehabilitation of this hospital. This was achieved by introducing Pall Friction Dampers in steel bracing. In contrast to shearwalls, the friction-damped bracing need not be vertically continuous so the work can commence at any floor level depending on availability. This aspect was particularly appealing as it offered flexibility in space planning and construction scheduling.

The paper discusses the results of analysis, design procedure, and details of the seismic upgrade. This paper also discusses the seismic rehabilitation and analyses of one of the blocks. A brief discussion on Pall Friction Dampers is also included so that its application can be better appreciated.

PALL FRICTION DAMPERS

The friction brake is widely used to stop the motion of a moving body because it is the most effective, reliable and economical way of dissipating kinetic energy. In the late seventies, the principle of the friction brake inspired the development of Pall Friction Dampers. Similar to automobiles, the motion of a shaking building can be slowed down by dissipating the energy in friction.

These friction dampers are simple and foolproof in construction. Due to their simplicity, they are inexpensive. They are composed of a series of steel plates specially treated to develop constant and stable friction. These plates are clamped together with high strength steel bolts. These dampers are designed not to slip during windstorms, service loads and minor earthquakes. During a major earthquake, the friction dampers slip at a predetermined optimum load before yielding begins in other structural members and they dissipate a significant portion of the seismic energy, Pall [1,2]. The maximum force is constant for all future ground motions. Therefore, the maximum seismic forces in the braces and connections are known, the design of these members is straightforward and economical. After the earthquake, the building returns to its near original alignment under the spring action of an elastic structure.

These friction dampers have large rectangular hysteresis loops, similar to an ideal elastoplastic material, with a negligible fade over several cycles of reversal. Unlike viscous dampers, the performance of these dampers is independent of temperature and velocity. For a given force and displacement in a damper, the energy dissipated by Pall Friction Dampers is the largest compared to other dampers. Therefore, fewer Pall Friction Dampers are necessary to provide a given amount of damping. There is nothing to damage or leak in these dampers so they do not require repair or replacement after the earthquake. Since they are not active during wind, there is no risk of failure due to fatigue. These dampers are compact and narrow enough to be concealed in drywall partitions.

Pall Friction Dampers have successfully undergone rigorous proof testing on shake tables in Canada and United States. In 1985, a three storey friction damped braced frame was tested on a shake table at the University of British Columbia in Vancouver, Cherry [3]. Even a simulated earthquake with a peak ground motion of 0.9g did not cause any damage to the model frame, while the conventional frames were badly damaged at lower seismic levels. In 1987, a nine storey friction damped braced frame was tested at Earthquake Engineering Research Center at the University of California at Berkeley, Kelly [4]. The friction damped model frame remained elastic for up to 0.84g.

Pall Friction Dampers have been developed and are available for incorporation in tension-only cross bracing, single diagonal tension-compression bracing, chevron bracing, at expansion joints to avoid pounding, and cladding connections, Pall [5]. These friction dampers meet a high standard of quality control. Every damper is tested prior to delivery.

These dampers have found widespread applications in both concrete and steel buildings, elevated water towers, and for new construction and retrofit of existing structures Pall [6], Pall [7], Pall [8], Godin [9], Savard [10], Pasquin [11], Balazic [12], Hale [13]. Boeing Commercial Airplane Factory at Everett, WA - the world's largest building by volume has been retrofitted with these dampers, Vail [14]. The City and County of San Francisco chose Pall Friction Dampers for the seismic control of Moscone West Convention Center as it saved US$2.25 million, compared to alternate viscous dampers, Sahai [15]. To date, more than eighty structures have been built with these dampers. Several more structures are under design or construction phase.

DESIGN GUIDELINES

The quasi-static design procedure presented in the National Building Code of Canada 2000 (NBCC 2000) is ductility based and does not explicitly pertain to friction-damped buildings. However, the Structural Commentary of the NBCC 2000 permits the use of friction dampers for seismic control of buildings. It stipulates that nonlinear seismic analysis confirm that a building with friction dampers will perform as well as the same building conventionally designed following the NBCC requirements. Numerous guidelines on the analysis and design procedure of passive energy dissipation devices have been developed in the US. The most comprehensive is the "NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 356, issued in 2000. The NBCC and the above documents were used as guidelines in the analyses and design of St. Vincent Hospital.

The guidelines require that the structure with energy dissipation devices is evaluated for response to two levels of seismicity – a design based earthquake (DBE) and a maximum credible earthquake (MCE). Nonlinear time history analyses are required for both the DBE and MCE. The DBE is an event with 10% probability of exceedance in 50 years. Under the DBE, the building is evaluated to ensure that the strength demands on structural elements do not surpass their limits and that the structure's drift is within permissible limits. The MCE is the most severe ground motion that the building is ever likely to experience. The building must not collapse under the MCE. Also, in the MCE, the structure is evaluated to ascertain the maximum deformation requirement of the damping devices. It is assumed that if proper detailing has been followed, the building will have enough ductility reserves to resist any over-stress conditions that may occur during the MCE. Since different earthquakes give different structural responses, at least three earthquake records suitable for the region must be used. The maximum response should be used for design.

ANALYSIS

The slippage of a friction damper in an elastic brace constitutes artificial nonlinearity. The quantity of energy dissipated is commensurate to the displacement at each time interval. Therefore, nonlinear time history dynamic analyses are necessary with the application of friction dampers. In this type of an analysis, the structure's response during each moment of time during and after the earthquake can be correctly captured. Nonlinear time history dynamic analyses on a three dimensional model of St. Vincent Hospital was carried out using the computer program ETABS.

The modeling of the Pall Friction Damper is very simple. The hysteretic loop of the damper resembles the rectangular loop of an ideal elastoplastic material. So the slip load of the damper can be considered as the fictitious yield force.

Each block was analyzed individually. The analysis of Block D, which is fairly representative for other blocks, is discussed in this paper. Computer modeling of this block is shown in Figures 3 and 4. Figure 6 shows the time history of the earthquake record that gave the maximum response. Viscous damping of 5% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements. ETABS program takes into account the hysteretic damping due to the slippage of the friction dampers. To take into account any accidental eccentricity due to distribution of mass or variation in relative stiffness, the centre of mass was shifted by 10%. Analyses were carried out for earthquake motions in combined x and y-axes. A series of iterative analyses were carried out to determine the optimum slip load of the friction dampers that gave the minimum response. A total of 183 friction dampers were used in all blocks. The design slip load of friction damper was 300 kN. Some installed friction dampers are shown in Figure 5.

RESULTS

For the purpose of comparison, additional analyses were carried out using conventional rigid braces. The conventional braces that resulted in the best results had two times the cross-sectional area of friction damped braces. All other variables remained the same. The effectiveness of the friction dampers in improving the seismic response is seen in the comparison of results for the two types of braced frames. The results for the building with friction damped braced frames (FD) and the results with rigid braces (RB) are discussed below:

1. Time histories of axial forces in single diagonal brace at fourth floor for the RB and the FD are shown in Figure 7. The maximum force in FD is about 20% of that for the RB. The axial forces in columns in the FD are about 30% of those for the RB. Besides expensive bracing and connections, the use of rigid bracing would have entailed expensive and time consuming strengthening of columns and foundations.

2. The time histories of displacement at the roof level are shown in Figure 8. It is seen that the peak displacement of the FD is approximately 80% of that for the RB. At the end of ground motion, the FD almost returns to its near original alignment. Compared to bare frame of existing structure, the drifts were reduced by more than 50%. The maximum storey drift in the FD was about 0.7%.

3. The hysteretic loop of a friction damper at the fourth floor is shown in Figure 9. The hysteretic loop indicates large energy dissipation during many cycles of slippage. Since there is a constant force for all earthquake records, the design of braces and connections is straightforward and economical.

4. Time histories of energy input for the RB and FD and energy dissipated in the FD are shown in Figure 10. It is seen that the total energy input in the FD is about 80% of the energy in the RB. It is also seen that the friction dampers have dissipated about 80% of the energy input. Therefore, the net energy in the FD is only 36% of the total energy in the RB.

5. The base shears in the FD were about 30% of those for the RB. In general, with the introduction of supplemental damping provided by friction dampers, there was an overall improvement in seismic response.

CONCLUSION

The application of Pall Friction Dampers has provided a practical, economic and time expedient solution to the seismic upgrade of St. Vincent Hospital. Analyses have demonstrated that the dampers dissipate a significant portion of the seismic energy in friction. Therefore, the damped structure experiences reduced displacements and member forces. The nonlinear dynamic analysis demonstrated superior performance of friction damped structure, compared to conventional methods of retrofit.

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Figure 1, Front View of Wing-B (Partial)

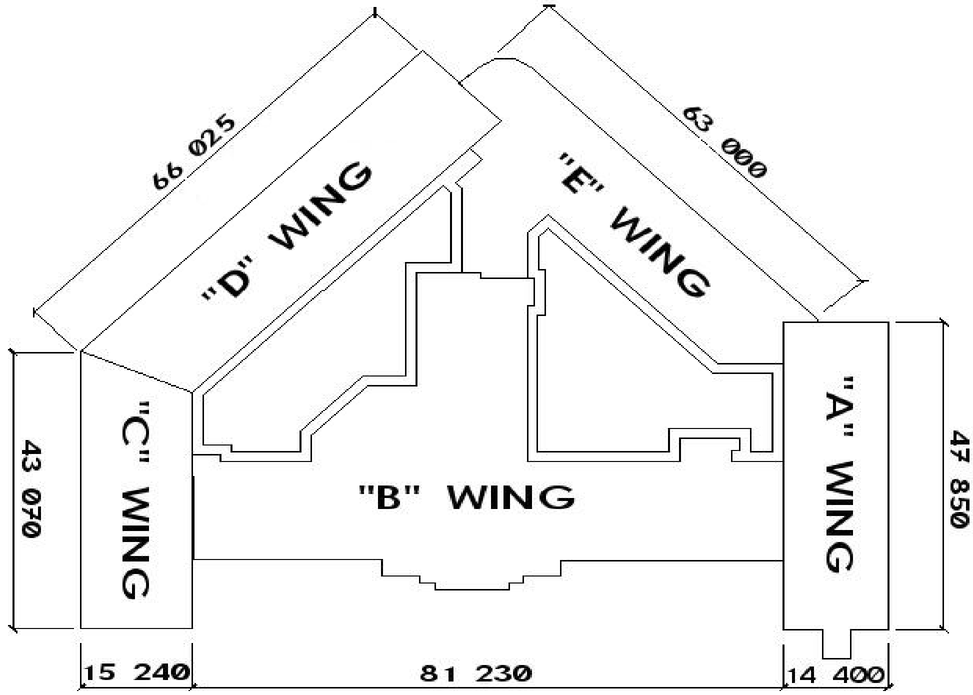

Figure 2. General layout plan of the hospital

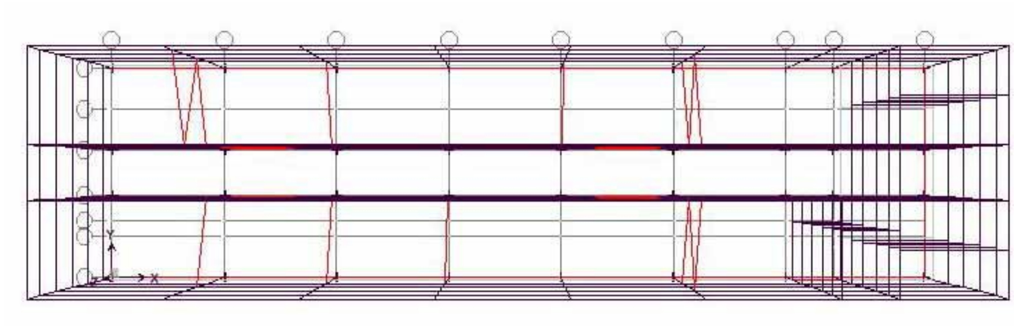

Figure 3. Block D, 3-dimensional analytical model of building, view from top down

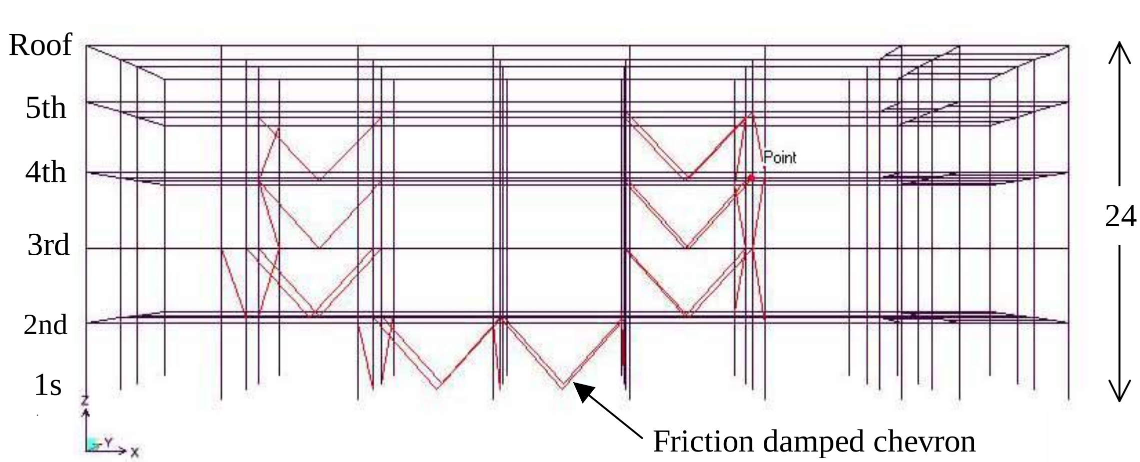

Figure 4. Block D, 3-dimensional analytical model of building, front view

Friction damper in single diagonal bracing

Friction damper in chevron bracing (inverted)

Figure 5. Typical Pall Friction Dampers

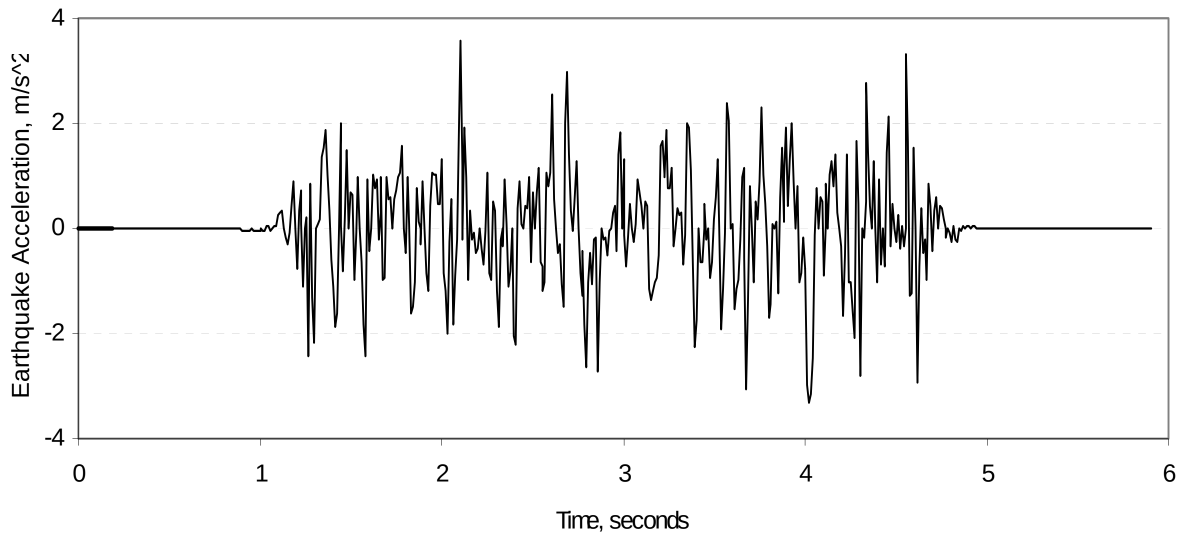

Figure 6. Time history of earthquake record

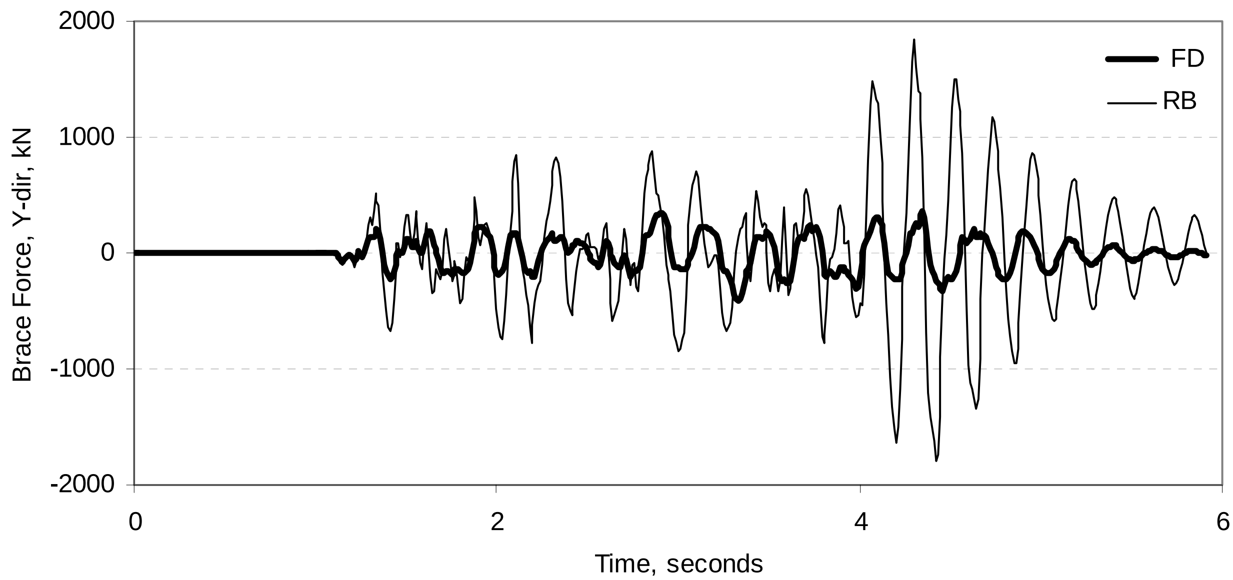

Figure 7. Time history of axial forces in 4^{th} floor single diagonal brace

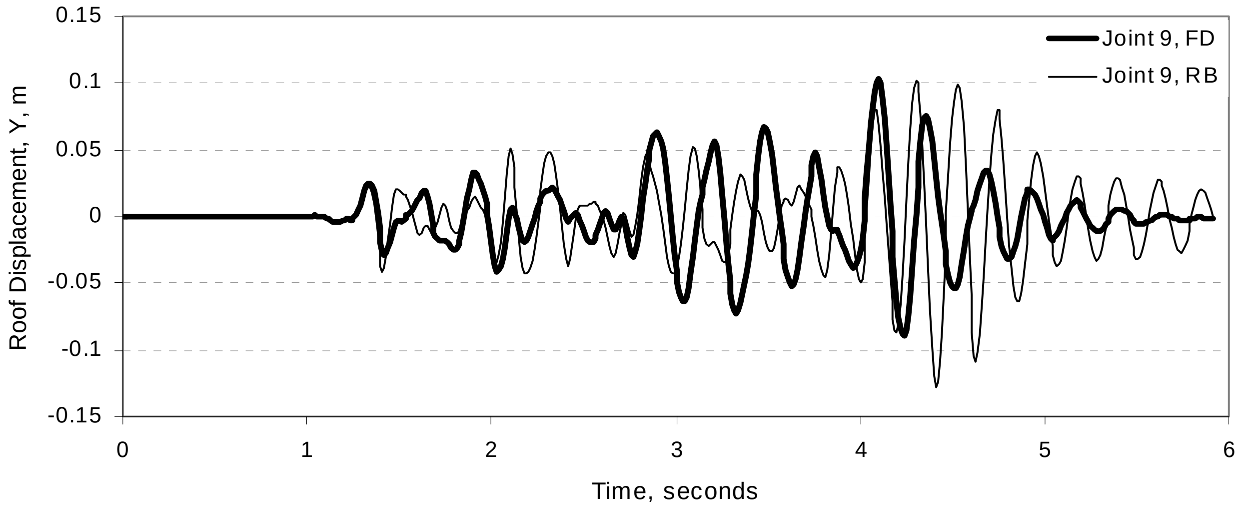

Figure 8. Time history of roof displacement

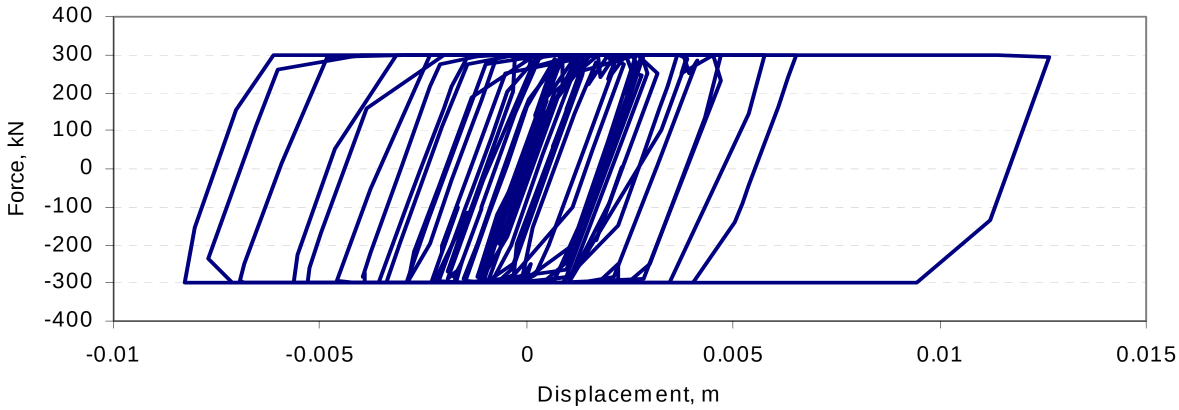

Figure 9. Hysteretic loop of friction damper

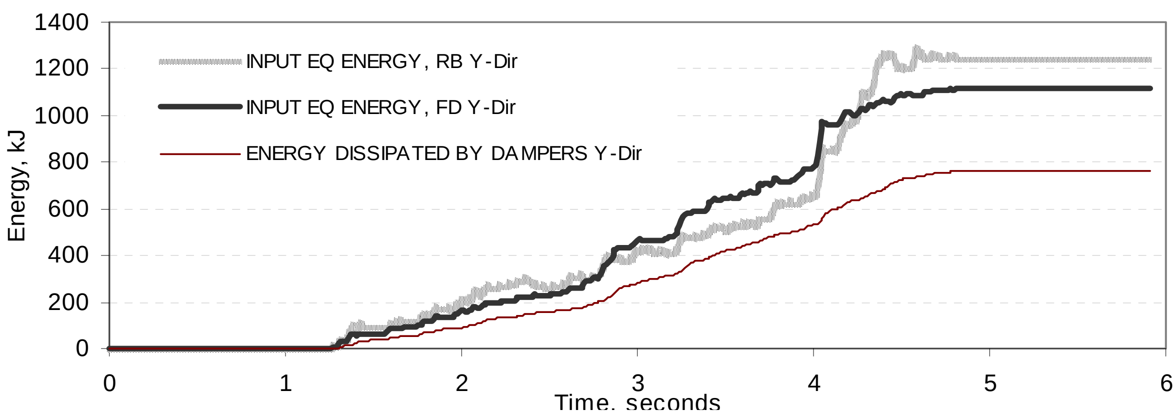

Figure 10. Time histories of energy input and energy dissipated