SEISMIC BASE ISOLATION AND ENERGY ABSORBING DEVICES

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Abstract

Passive energy dissipation systems are described for the control of structures against earthquake vibrations. Classification of passive energy dissipation systems is given and the discussions of the behavior of individual passive devices and systems are provided.

In order to investigate the effects of these systems on the response of structures, a typical model building frame is selected. Passive energy dissipation systems are introduced to the model frame and the results are then compared. Although, the UniformBuilding Code (UBC-97) is taken as a base for all design calculations, a series of formulation is proposed in accordance with the Turkish Earthquake Code.

Firstly, in order to meet with the objectives of the study, a theoretical four-story plane frame is selected without any passive energy dissipation system. Secondly, the structure is assumed to be base isolated using high damping laminated rubber pads. Thirdly, the viscoelastic dampers are diagonally installed at each floor level of the frame and the seismic analyses are repeated with and without base isolation. In each scenario, the calculations have been carried out using both the equivalent seismic load method and also the linear time history analyses. Linear time history analyses have been based on two different earthquake records, with T_1 = 0.13 sec and T_2 = 1.43 sec predominant spectral periods. The N-S component of the earthquake ground motion recorded at the Tofaş automobile factory in Bursa, during the August 17, 1999 Kocaeli Earthquake, is taken as a basis. In each case the maximum ground acceleration has been raised to 0.40g. The results for these two different earthquakes, which represent the hard and soft soil conditions, respectively, have been compared by each other.

The base shears, storey drifts, and the bending moments at the top of the columns, are presented in a comparative fashion. For all these four different structural models, the relative merits of viscodampers and base isolation are discussed in detail.

Keywords: Passive Control, Energy Dissipation, Base Isolators, Viscoelastic Dampers, Damping Devices, Aseismic Design

Introduction

In conventional seismic design, acceptable performance of a structure during earthquake shaking is based on the lateral force resisting system, being able to absorb and dissipate the earthquake energy in a stable manner for a large number of cycles. Energy dissipation occurs in specially detailed regions of concentrated damage to the gravity frame, namely plastic hinges which are often irreparable.

The occurrence of inelastic deformations results in softening of the structural system which itself reduces the absolute input energy. The technique of seismic isolation accomplishes the same task by the introduction of base isolation components at the foundation of a structure. This is a system which is characterized by flexibility and energy absorption capability. The flexibility alone, typically expressed by a period of the order of two seconds and higher, is sufficient to reflect a major portion of the earthquake energy so that inelastic action does not occur. Energy dissipation in the isolation system is then useful in limiting the displacement response and in avoiding resonance.

Another approach to improving earthquake response performance and damage control is that of supplemental energy dissipation systems. In these systems, mechanical devices are incorporated into the frame of the structure and dissipate energy throughout the height of the structure. The means by which energy is dissipated is either yielding of mild steel, sliding friction plates, motion of a piston or a plate within a viscous fluid, orificing of fluid, or viscoelastic action in polymeric materials.

Clasification Of Passive Energy Absorbing Systems

Passive energy dissipation systems are classified herein as hysteretic, viscoelastic and others. Examples of hysteretic systems include devices based on yielding of metals or through sliding friction. Figure 1 shows typical force-displacement loops of hysteretic energy dissipation systems. The simplest models of hysteretic behavior involve algebraic relations between force and displacement. Hence, hysteretic systems are often called displacement dependent.

Viscoelastic energy dissipation systems include devices consisting of viscoelastic solid materials, devices operating on the principle of fluid orificing (e.g. viscous fluid dampers) and devices operating by deformation of viscoelastic fluids. Figure 2 shows force-displacement loops of these devices. Typically, these devices exhibit stiffness and damping coefficients which are frequency dependent. Moreover, the damping force in these devices is proportional to velocity, that is, the behavior is viscous.

Accordingly, they are classified as viscoelastic systems. A purely viscous device is a special case of a viscoelastic device with zero stiffness and frequency independent properties.

Energy dissipation systems which cannot be classified by one of the basic types depicted in Figure 1 and 2 are classified as other systems. Examples are friction-spring devices with re-centering capability and fluid restoring force and damping devices. Figure 3 illustrates the behavior of these devices. These devices originate from either hysteretic devices or fluid viscous devices (Constantinou et al, 1998).

Energy Absorbing Devices

Passive energy dissipation systems utilize a wide range of materials and technologies as a means to enhance the damping, stiffness and strength characteristics of structures. The dissipation may be achieved either by the conversion of kinetic energy to heat or by transferring of energy into vibrating modes. The first mechanism incorporates both hysteretic devices that dissipate energy with no significant rate dependence and viscoelastic devices that exhibit considerable rate dependence. Included in the former group are devices that operate on principles such as yielding of metals and frictional sliding, while the latter group consists of devices involving deformation of viscoelastic solids or fluids and those employing fluid orificing. A third classification consists of re-centering devices that utilize either a preload generated by fluid pressurization or internal springs, or a phase transformation to produce a modified force-displacement response that includes a natural re-centering component.

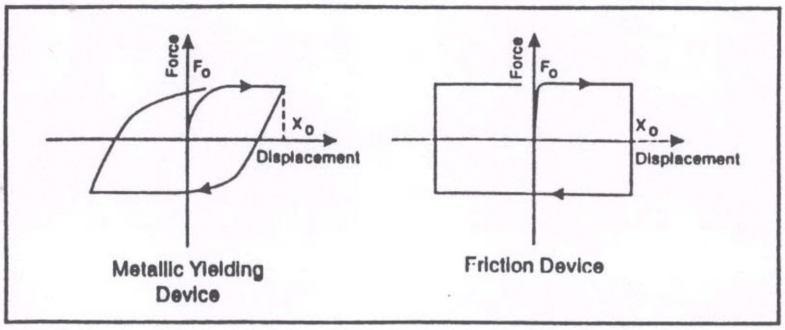

Figure 1: Idealized force-displacement loops of hysteretic energy dissipation devices

Hysteretic systems

Hysteretic systems, by definition, dissipate energy through a mechanism that is independent of the rate of load application. Included in this group are metallic dampers that utilize the yielding of metals as the dissipative mechanism, and friction dampers that generate heat through dry sliding friction plate.

Metallic dampersare very effective mechanisms available for the dissipation of energy, which is achieved during an earthquake, is through the inelastic deformation of metallic substances. In trading steel structures, aseismic design relies upon the post-yield ductility of structural members to provide the required dissipation. However, the idea of utilizing supplemental metallic hysteretic dampers within the superstructure to absorb a portion of the seismic energy began with the conceptual and experimental work by Kelly et al., 1972 and Skinner et al., 1975. During the ensuing years, considerable progress has been made in the development of metallic dampers and many new designs have been proposed.

The mechanism involved in energy dissipation in metallic dampers can be categorized as one form of internal friction. On the other hand, attention will now shift to dampers that utilize the mechanism of friction between two solid bodies sliding relative to one another to provide the desired energy dissipation. An examination of the effects of frictional damping on the response of building structures was conducted by Mayes and Mowbray, 1975, however it appears that Keightley, 1977 was the first to consider frictional devices for building applications. Subsequently, based primarily upon an analogy to automotive brake, the development of passive frictional dampers then continued to improve the seismic response of structures. The objective is to slow down the motion of buildings “by braking rather than breaking” (Pall et al 1982).

Viscoelastic systems

Viscoelastic systems are passive control systems that dissipate energy in a rate dependent manner. This group includes viscoelastic solid dampers and viscoelastic fluid dampers, with the latter expanded to incorporate devices based upon both fluid deformation and orificing. Notice that in many applications, the behavior is confined to linear range. This often greatly simplifies the required analysis procedures. Furthermore, since energy dissipation occurs even for infinitesimal deformations, viscoelastic devices have potential application for both wind and seismic protection.

For viscoelastic solid dampers, viscoelastic solid materials used in structural engineering applications are usually copolymers or glassy substances that dissipate energy when subjected to shear deformation. The response of these viscoelastic materials under dynamic loading depends upon the frequency of vibration, the level of strain, and the ambient temperature.

All of the passive devices described to this point utilize the action of the solids to enhance the performance of structures subjected to transient environmental disturbances. However, fluids can also be effectively employed in order to achieve the desired level of passive control.

A typical orificed fluid damper for seismic application is illustrated in Figure 4 (Constantinou et al, 1993(a) and Constantinou et al, 1993 (b)). This cylindrical device contains a compressible silicone fluid which is forced to flow via the action of a stainless steel piston rod with a bronze head. The head includes a fluidic control orifice design. In addition, an accumulator is provided to compensate for the change in volume due to rod positioning. Alternatively, the device may be designed with a run-through piston rod to prevent volume changes. High strength seals are required to maintain closure over the design life of the damper. These uniaxial devices, which were originally developed for military and harsh industrial environments, have recently found application in seismic base isolation systems as well as for supplemental damping during seismic and wind-induced vibration.

While viscoelastic fluid damper construction varies considerably from each other and from the viscoelastic solid damper counterparts, mathematical models suitable for overall force-displacement response have a similar form.

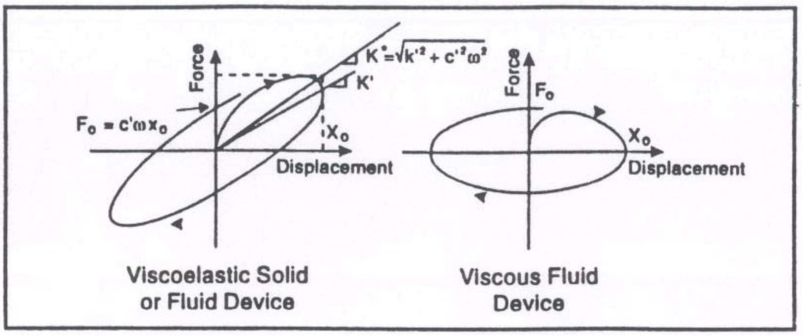

Figure 2: Idealized force-displacement loops of viscoelastic energy dissipation devices

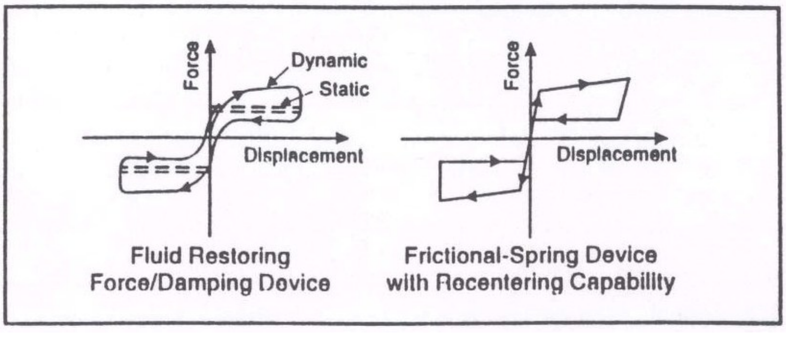

Figure 3: Idealized force-displacement loops of other energy dissipation devices

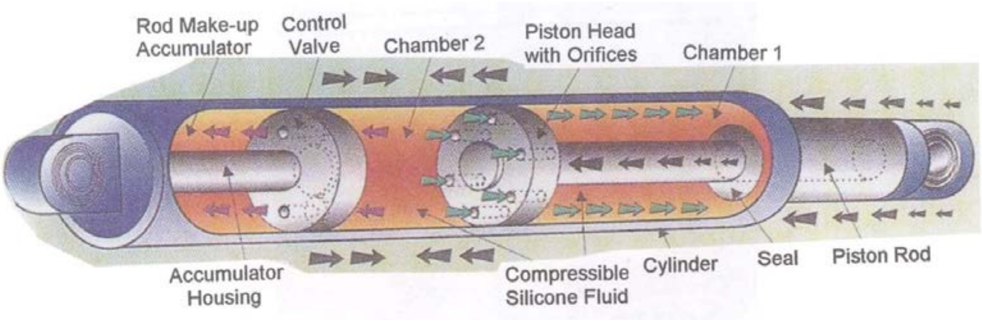

Figure 4: Internal mechanism of a viscoelastic fluid damper

Re-centering systems

Re-centering devices possess distinctly different force-displacement characteristics. Included in this group are pressurized fluid dampers, preloaded spring friction dampers, and phase transformation dampers. The first of these displays some rate-dependence due to the presence of the fluid, while the response of the remaining devices tends to be rate independent. All of these devices retain very little residual deformation upon removal of the applied load, and thus provide an inherent re-centering capability.

Dynamic vibration absorbers

The final class of passive systems to be considered involves the use of dynamic vibration absorbers in a structure. The objective of incorporating a dynamic vibration absorber into a structure is basically the same as that associated with all of the other passive devices discussed previously, namely, to reduce energy dissipation demand on the primary structural members under the action of external forces. The reduction, in this case, is accomplished by transferring some of the structural vibrational energy to the absorber.

Base Isolation

The concept of seismic isolation has become a practical reality, after 1980 within the last two decades with the development of multilayer elastomeric bearings, which are made by vulcanization bonding of sheets of rubber to thin reinforcing steel plates. These bearings are very stiff in the vertical direction and can carry the vertical load of the building but are very flexible horizontally, thereby enabling the building to move laterally under strong ground motion. Their development was an extension of the use of elastomeric bridge bearings and bearings for the vibration isolation of buildings. In recent years, other systems have been developed that are modifications of the sliding approach. The concept of base isolation is now widely accepted in earthquake-prone regions of the world for protecting important structures from strong ground motion, and there are now many examples in the United States and Japan (Tezcan, 1982 and Tezcan et al, 1980 and Tezcan et al, 1981 and Tezcan et al, 1985 and Tezcan et al, 2003).

Seismic isolation involves introducing to a structure a plane of lateral flexibility that is intended to significantly lengthen the structure’s fundamental period, shifting it away from the destructive frequency range of typical ground motions. In buildings, the lateral flexibility is often achieved through the use of elastomeric bearings, usually near the base of the structure. The accelerations transmitted to the superstructure can be greatly reduced through the damping mechanism provided in the isolators. Thus, high-energy seismic ground motions can be transformed into low-frequency, low energy harmonic motions on the structure, and the structural accelerations acting on the isolated building are significantly reduced. Several key assumptions as summarized below influence the design of seismically isolated structures:

- A significant increase in both fundamental period and damping accompanies the addition of isolators to the structure’s lateral force resisting system. Fundamental period increases of 1.5 to 3 times are typical, while damping increases from a few percent to greater than 15 percent are common.
- Lateral deformations are concentrated in the isolators, and in many cases the remainder of the structure is assumed to behave relatively stiffly (perhaps even rigidly), thus providing no significant dynamic amplification over the height of the building.
- The dependence of isolator response on its deformation history is neglected, the fully developed isolator flexibility and damping is assumed to act during the entire duration of strong ground shaking.

Most systems used today incorporate either elastomeric bearings, with the elastomer being either natural rubber or neoprene, or sliding bearings, with the sliding surface being Teflon and stainless steel. For example, lead-plug bearings are laminated rubber bearings which have two thick steel end plates and many thin steel shims and contain one or more lead plugs that are inserted into holes. The steel plates in the bearing force the lead plug to deform in shear providing damping.

The friction pendulum system isolator has an articulated slider that moves on a stainless steel spherical surface. Friction between the articulated slider and the spherical surface generates damping in the isolators. The effective stiffness of the isolator and the isolation period of the structure are controlled by the radius of curvature of the concave surface.

Case Study

A typical four-story,two-bay, reinforced concrete frame building is selected as shown in Figure 5 and analytically investigated in four different models. It is firstly analyzed as a fixed-base case without any passive energy dissipating system. In the second model, isolators are used at the base level of the building again without any viscodampers. In the third model, diagonal viscoelastic dampers are installed at each bay of each storey assuming a fixed base case. In the fourth model the building is assumed to be base isolated together with viscoelastic dampers installed at each storey. The buildinghas identical columns of dimension 0.4 / 0.7m and beams of dimension 0.4 / 0.5m. The qualities of concrete and reinforcing steel material used are C25 MPa and S220 MPa, respectively. The total weight of one floor is 735.75 kN. The storey height is 3.0 m, typically.

The intent of this study is to compare the seismic behavior of these four different models under various earthquake ground motions with different durations of shaking and with different predominant spectral periods. The efficiency of the passive energy dissipation devices is closely investigated for fixed base and isolated base cases. The results are then used to evaluate the key assumptions made in the design of the buildings in general and also to shed new light on the earthquake response of buildings with and without energy absorbing devices.

Input data

Two artificial earthquake records are created from the earthquake ground motion recorded by the Kandilli Observatory Seismograph at the Bursa Tofaş Automobile Factory during the Kocaeli Earthquake of August 17,1999. The record is taken from the website of Kandilli Observatory and Earthquake Engineering Research Institute, BoğaziçiUniversity, Bebek, Istanbul.The N-S component of this earthquake record is used. There were a total of 27 711 data points of this record at intervals of Δt =0.005 second corresponding to a total time duration of T_d =138,55sec.

If the time interval Δt of the record is shortened or lengthened without changing the number of time steps N, then only the predominant period of the soil is shortened or lengthened. If the maximum acceleration of the earthquake is also changed simply by multiplying all the ordinates by a scale factor, the shaking intensity of the earthquake is changed. In this way, two characteristic artificial earthquakes; namely the Earthquake-A and the Earthquake-B are produced. The record of the Earthquake-A is shown in Figure 6.

These earthquakes have predominant periods of *0.13* seconds and *1.43* seconds, respectively and both have a maximum acceleration of *3.96* m/sec″. The time interval of $\Delta t = 0{,}005$ seconds of the real record, is reduced to $\Delta t = 0.001$ second for the Earthquake-A, and increased to $\Delta t = 0.01$ second for the Earthquake-B. By decreasing Δt, the time step intervals have been decreased causing a likewise reduction in the predominant period of the earthquake corresponding to relatively stiff soil conditions. Similarly, the increase in the value of time intervals, results in a likewise increase in the predominant of the earthquake ground motion representing relatively soft soil conditions.

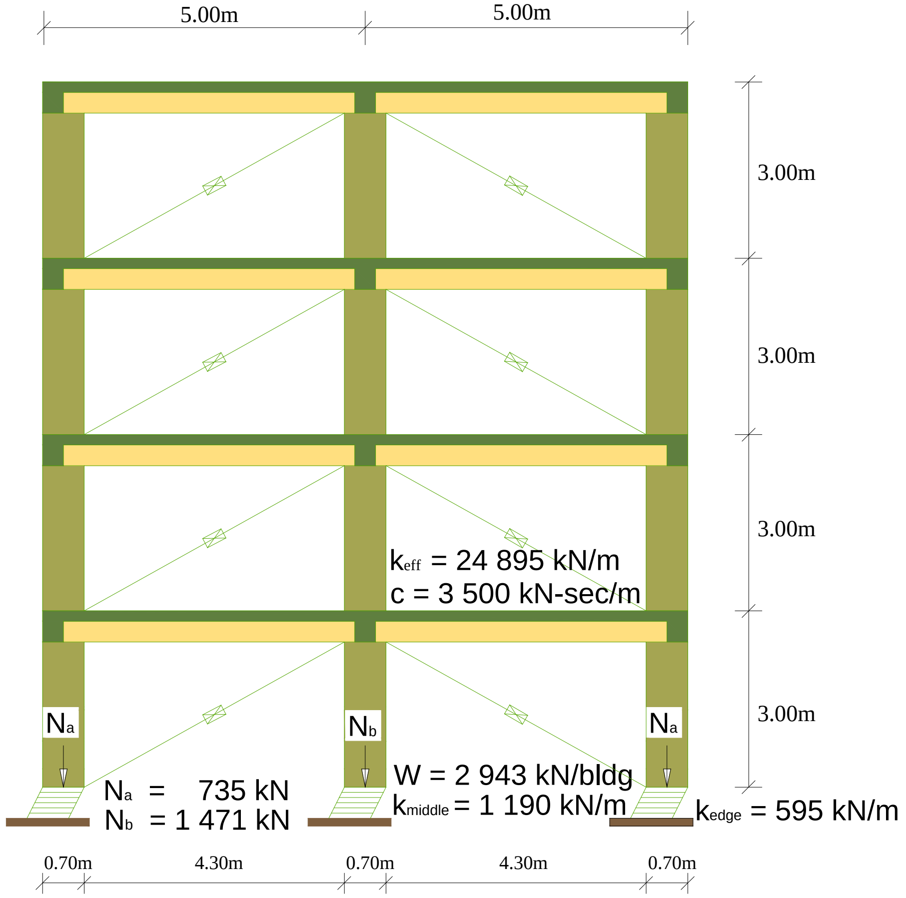

Figure 5: Typical frame building

Seismic load analyses

The structural frames, representing four different models as described above, have been analyzed once using the statically equivalent force methods of both TDY-07 and UBC-97, and then using a time-history response method under two different earthquake ground motions as Earthquake-A and Earthquake-B.

Computer modeling

The viscoelastic dampers and lead-plug bearings have been modeled by the "*NLPROP*" and "*NLLINK*" tools of the *SAP2000n computer program*. Linear time history analyses have been performed for the linear behavior of the viscoelastic dampers and lead-plug bearings. During linear time history analyses, the linear force-deformation relationships are used at all degrees of freedom. Damper and isolator properties are activated by introducing effective stiffness and effective damping for linear degrees of freedom.

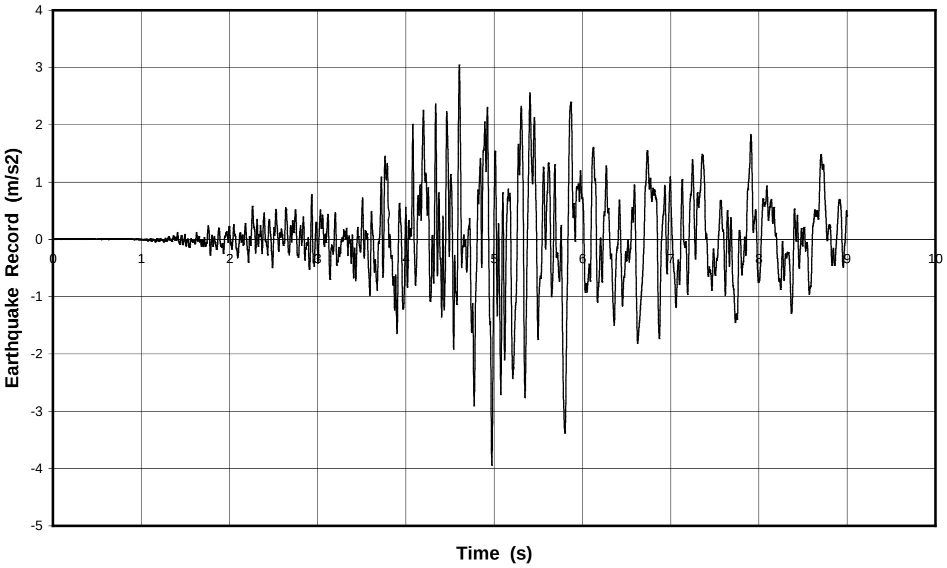

Figure 6: Record of Earthquake A

Effective critical damping ratio

Effective critical damping ratio, β, supplied by the viscoelastic damping devices is obtained by an analogy to the logarithmic decrement curve for one-degree of freedom system. The displacement versus time curve of one-degree of freedom system is a decreasing *sine* curve from which the effective critical damping ratio, β, is calculated by the formula:

$$Ln \frac{u_1}{u_2} = \frac{2\pi\beta}{\sqrt{1-\beta^2}} \qquad \textbf{(1)}$$

where, u_1= the peak displacement at time t_1, when there is no viscoelastic damper, and u_2 = the peak displacement, at time t_1 again, when viscoelastic dampers are installed, β = the effective critical damping ratio. The β value is easily obtained from the above formula, once $u_1$and u_2 displacements are available from the two models with and without viscoelastic dampers.

Therefore, if $u_1$is taken as the maximum top displacement at time t for the undamped system and u_2 is the maximum top displacement at the same time t, for the damped frame, then the effective critical damping ratio supplied by the devices becomes β.

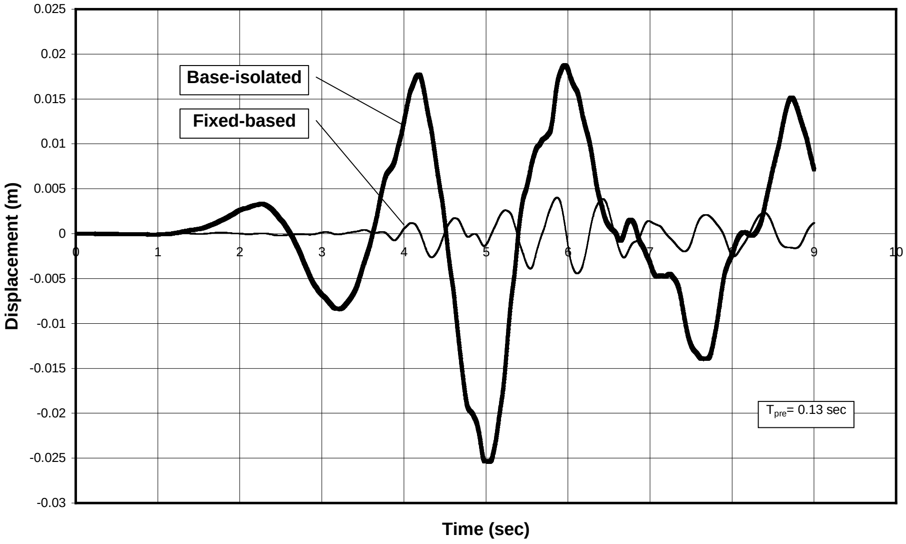

Figure 7: Top displacement time histories of the fixed-base and the base-isolated cases

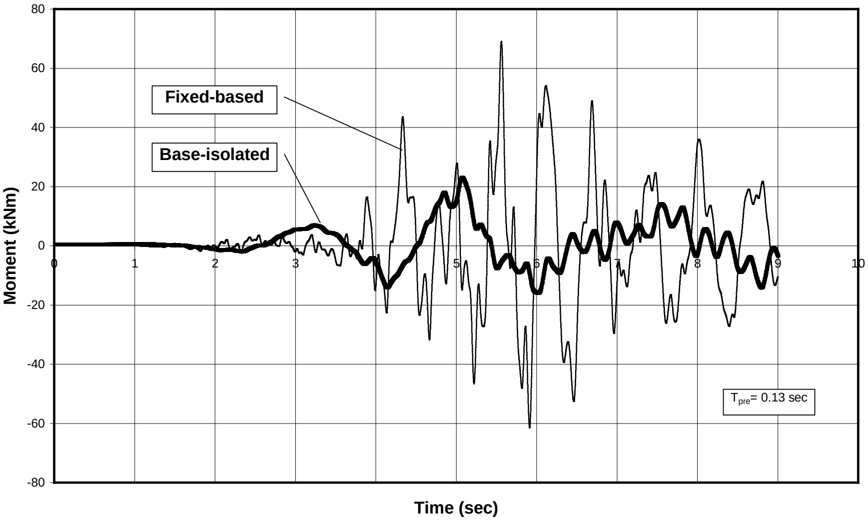

Figure 8: Top column upper part time histories of the fixed-base and the base-isolated cases

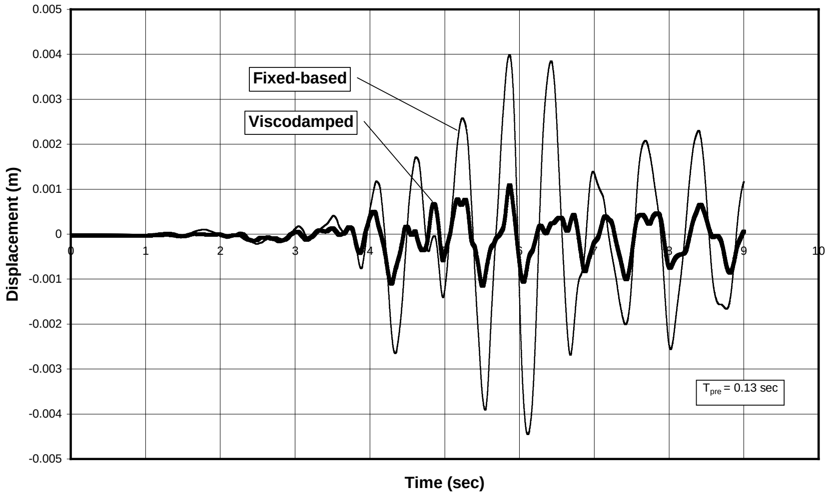

Figure 9: Top displacement time histories of the fixed-base and the viscodampers cases

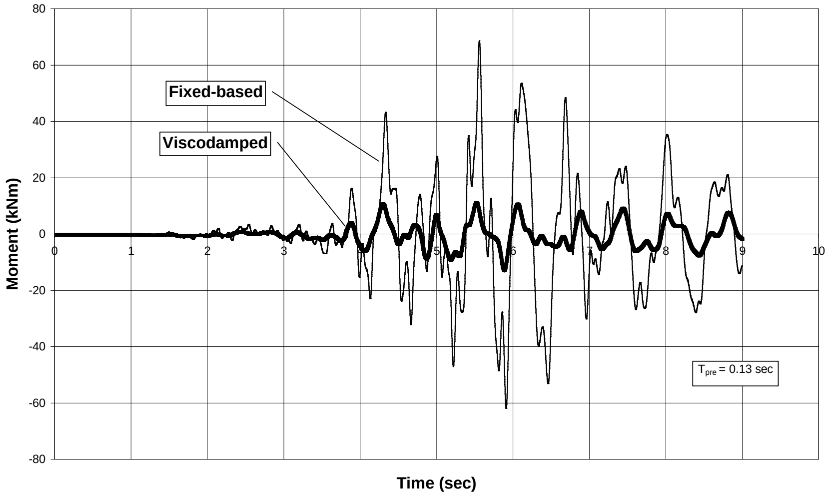

Figure 10: Top column upper part time histories of the fixed-base and the viscodampers cases

Conclusions

When the results of each structural model are compared with each other, certain conclusions may be reached as follows:

- When lead-plug bearings are used to isolate the building from ground motions, the fundamental period of the building is increased from T=0.57second to T=2.23second. Thereby, the response of the building to earthquake ground motion is significantly reduced. For instance, under the statically equivalent loads, the storey drift ratio at the 2ndstorey dropped from a high value of s=1.2 per mil to a low value of s=0.325 per mil. Similarly, the bending moment at the exterior column at the 2ndstorey is reduced from M=159.3kNm to M=48kNm, when a unified response reduction factor of R = 8 is considered for both cases.

- When the building has viscoelastic dampers at each storey, the column bending moments, the storey displacements and the storey drift ratios decrease significantly compared to the fixed-base case. The reductions are not however, as much as those occurred in the base-isolated case.
- When the base-isolated building however, is installed with viscodampers, the performance becomes excellent. The building behaves almost exactly like a rigid body. While the storey displacements remain almost the same as the storey displacements of the base-isolated building, the column bending moments, storey drift ratios and base shear values decrease remarkably. In fact, under the statically equivalent loads compared with the fixed-base case, when base isolation and viscodampers are used, the second storey drift ratio drops from s=1.2 per mil to s=0.21 per mil, almost 1/6th of the fixed-base case. Similarly, the column bending moment drops from M=159.3 kNm to a mere M=31 kNm. In these comparisons, a unified response reduction factor of R = 8 is considered for both fixed-base case and base isolation combined with viscodampers case.
- It is also determined that, the base isolation becomes more effective if the building rests on relatively strong ground conditions. That is, if the predominant spectral period of the input ground motion is in the short period range, such as T=0.10 second to T=0.30 second, then the influence of base isolation becomes significantly pronounced. The effectiveness of the base isolation decreases however considerably, as the soil conditions become softer. This was the case, when the earthquake type-B record is used with a predominant spectral period of T=1.43 seconds.
- As seen in Figure 7 to Figure 10, the time history response values of the fixed-base case, in displacements and in column bending moments are drastically reduced when the structure is base-isolated and/or is supplied with viscodampers.

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