MITIGATION OF SEISMIC POUNDING BETWEEN ADJACENT BUILDINGS

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ABSTRACT: Adjacent buildings during an earthquake may collide against each other when, owing to their different dynamic characteristics, the buildings vibrate out of phase and the at-rest separation distance is inadequate to accommodate their relative motions. Seismic pounding can cause severe damage to the structures. Such buildings are usually separated by an expansion joint which is insufficient to accommodate the lateral movements of buildings under earthquakes. While seismic pounding can be prevented by providing adequate safe code specified separation distances, sometimes getting of required safe separations is not possible in metropolitan areas because buildings are built very close to each other due to high land value, limited availability of land space, the need for centralized facilities under one roof and/or often ignoring the likelihood of seismic pounding between adjacent buildings during design. If building separations in metropolitan areas found to be deficient to prevent pounding, then there should be some secure and cost-effective retrofitting methods to mitigate structural pounding. This research work covers the mitigation techniques of pounding between adjacent buildings due to earthquakes. Use of shear wall, bracing system and friction dampers are proposed as possible mitigation techniques.

Key words: Buildings, Earthquake; Seismic Pounding, Mitigation of Seismic Pounding.

INTRODUCTION

Earthquakes have always been a source of great devastation for mankind. It is evident from the past and recent earthquake damages records, that the building structures are subjected to severe damages/collapse during earthquakes (Murty, 2005). Major areas of Pakistan have always under the danger of this natural hazard (earthquake). Several destructive earthquakes have hit Pakistan over the time (October08, 2005 earthquake being the one in limelight recently). Population of Pakistan is growing fast and land limitation is becoming a critical issue in cities. Land prices are also very high in these metropolitan areas and there is no solution but to construct high rise buildings to fulfill future needs. High rise building structures are prone to seismic pounding. 'Pounding' is a phenomenon, in which two buildings strike due to their lateral movements induced by lateral forces (Abdel and Shehata, 2006). Earthquake is one of the major causes for lateral forces on the buildings and an efficient and durable structural design is always required to prevent pounding (Shoushtari, 2010). For example, in dense populated cities, the residential apartments and office building are built in close proximity having a small gap (expansion joint) between them. These buildings are always exposed to various levels of natural and man-made hazards which may cause pounding. Such buildings are usually separated by an expansion joint which is insufficient to accommodate the lateral movements of buildings under earthquakes. Therefore, the safety of these highly congested buildings constitutes a major concern for the authorities in general and structural engineers in particular (Alireza *et al.,* 2002).

There may be various methods to avoid pounding of adjacent buildings. The methods may be grouped according to their approach to mitigate the pounding (Warnotte *et al.,* 2007). The objective of this research work explore the effectiveness of pounding mitigation strategies for closely spaced buildings to reduce the possible damage due to seismic pounding, while minimizing the alteration to the existing structural system. This research work presents the techniques to mitigate of pounding between adjacent buildings exposed to natural hazards. Techniques like safe clear distance between buildings, increasing the stiffness of both building by using shear wall, bracing system and friction dampers are used as effective mitigation techniques to avoid pounding between adjacent building structures during an earthquake.

METHODOLOGY

In order to observe pounding between adjacent buildings, two buildings (seven and four storey) are selected having different dynamic properties. These buildings are separated by an expansion joint and are subjected to gravity and dynamic loading. Both buildings are analyzed in Sap 2000 and designed as per ACI code (ACI, 318).

Building-1 is a seven storey building having 6 no. of bays in x-direction and 5 no. of bays in y-direction.

Widths of the bays are 6.10m and 5.50m in x and y-direction respectively. Height of each storey is 3.65m. Column sizes are (525x525) mm^2 while the beam sizes are (300x525) mm^2 in X direction and (300x450) mm^2 Y direction respectively. Building -2 is a four storey building having 5 no. of bays in x-direction and 5 no. of bays in y-direction. Widths of the bays are 4.88m and 5.50m in x and y-direction respectively. Height of each storey is 3.65m. Column sizes are (450x450) mm^2 while the beam sizes are (300x450) mm^2 in X direction and (300x450) mm^2 Y direction respectively. Both buildings are separated by an expansion joint of 60 mm. Seven storey building is located on right hand side of four storey building. Pounding is considered at fourth floor level. For pounding observation negative displacement of seven storey building and positive displacement of four building is taken under consideration at same time interval

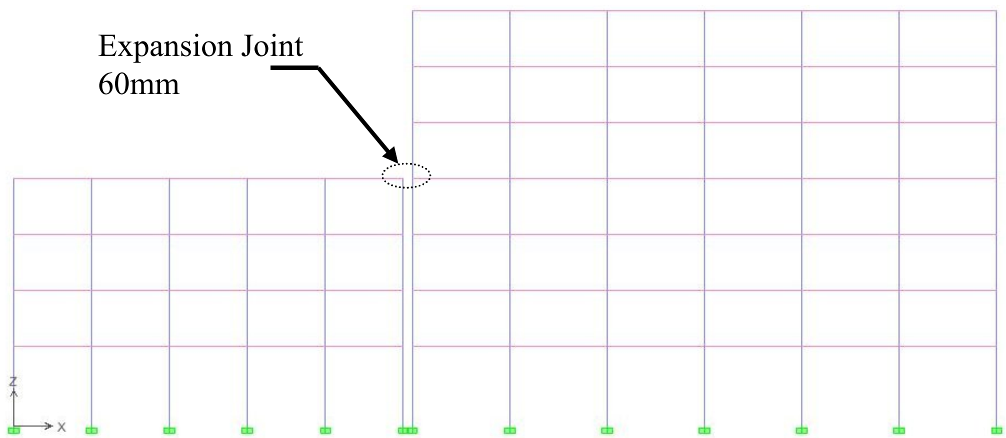


Figure 3-5: Elevation show the position of both buildings

Pounding is observed in above selected buildings and four mitigation measures are considered to avoid the pounding. These mitigation measures are: to provide safe separation distance given by (Federal Emergency Management Agency) (FEMA-273, 1997), using of shear wall, adding bracing system and the use of friction dampers in existing buildings.

MITIGATION MEASURES

(i) To Provide Safe Separation Distance

Pounding between the building occur when separation distance between the buildings is too small, does not accommodate the out of phase relative motion of adjacent buildings. FEMA-273 (Federal Emergency Management Agency) gives the safe separation distance between the adjacent buildings for pounding avoidance (FEMA, 1997).

$Si = \sqrt{(\Delta i_1^2 + \Delta i_2^2)}$ Eq.2.6.1.1

Where

Δi_1 = Peak displacement of building -1

Δi_2 = Peak displacement of building – 2

Si should not be greater than the height above the impact.

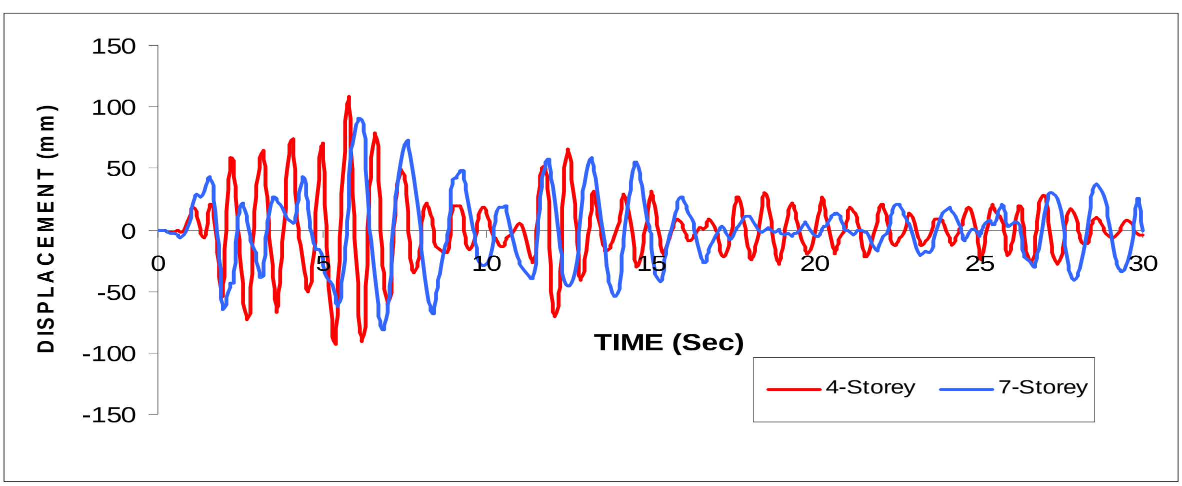


Figure 1: Time displacement graph of both buildings at 4th floor level when there is no preventive measure in building.

In figure 1 time displacement graphs of both buildings at fourth floor level are super imposed to observe the pounding in buildings. This figure shows that maximum positive displacement for seven storey building at fourth floor level is 90.04 mm at 6.00 sec and maximum negative displacement observed is 74.67 mm at 6.70 sec. The figure also shows that maximum positive displacement for four storey building is 114.5 mm at 5.80 sec and maximum negative displacement is 99.87 mm at 5.40 sec. According to building position, for pounding observation negative displacement of seven storey building and positive displacement of four building is observed. From this figure it is observed that maximum out of phase movement of both building is 102.57 mm at 2.20 sec. Safe separation distance calculated by FEMA-273 is $\Delta i1 = 90.04$ mm, $\Delta i_2 = 114.5$mm and $Si = \sqrt{(90.04^2 + 114.5^2)} = 145.6$mm. It shows that at time of 2.20 sec buildings are striking (Pounding). The separation joint between the buildings is 60 mm which is unable to accommodate this out of phase movement.

(ii) **Increasing the Stiffness of Both Building by Adding Shear Walls:** Since distance between the buildings cannot be increased due to high cost of land and construction difficulties, increasing the stiffness of one or both buildings by providing the shear wall or lateral bracing in such a way it reduce the lateral displacements which can be accommodate between provided seismic gap/separation distance. In this research both shear walls and lateral bracing are used as effective mitigation strategy. Position of shear walls buildings are selected in such a way that the distance between center of rigidity and center of mass is kept as minimum as possible to reduce the undue additional forces on the structure due to torsion. In seven storey building shear walls are placed at all four corner of the building. The length of shear wall in X-direction is 3.65 m and in Y-direction is 1.83m. Similar pattern of shear walls is used in four storey building. The length of shear wall in X and Y direction is 3.05m and 1.525m respectively.

Figure 2 illustrates the time displacement graph of both buildings at fourth storey level when mitigation measure shear walls are used in building. The maximum positive and negative displacements at fourth storey level for sevens storey building are 52.41 mm at 5.80 sec and 49.83 mm at 2.70 sec respectively. Similarly for the four storey building the maximum positive displacement at fourth storey level is 29.83 mm at 2.90 sec and maximum negative displacement is 37.43 mm at 2.70 sec. From this figure maximum out of phase movement is observed at a time of 5.40 sec. In this time interval, positive displacement of four storey building is 16.52 mm and negative displacement of seven storey building is 41.31 mm. Their absolute sum is 57.38 mm. It means that maximum out of phase movement is within the expansion joint and there is no pounding of the buildings.

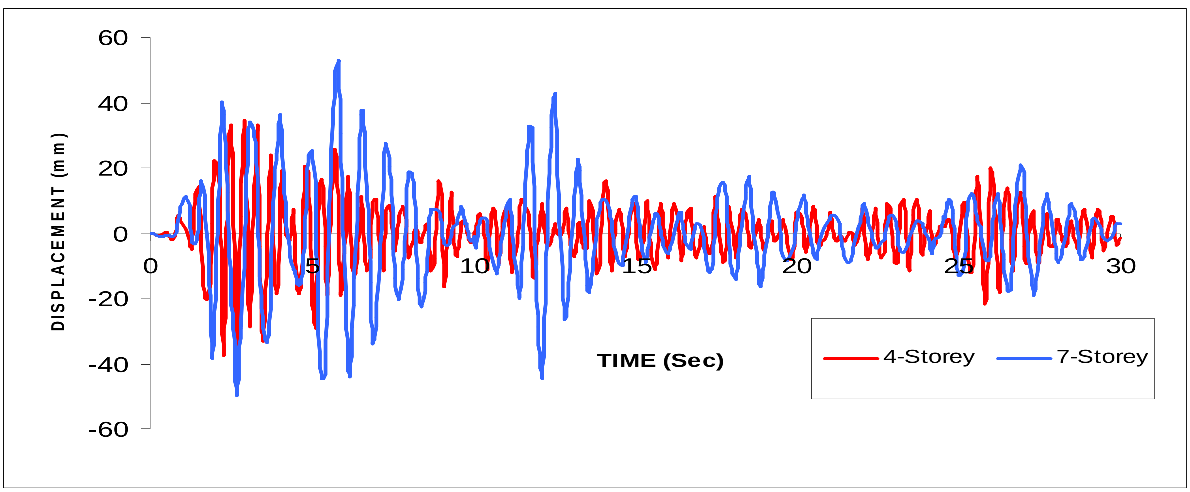
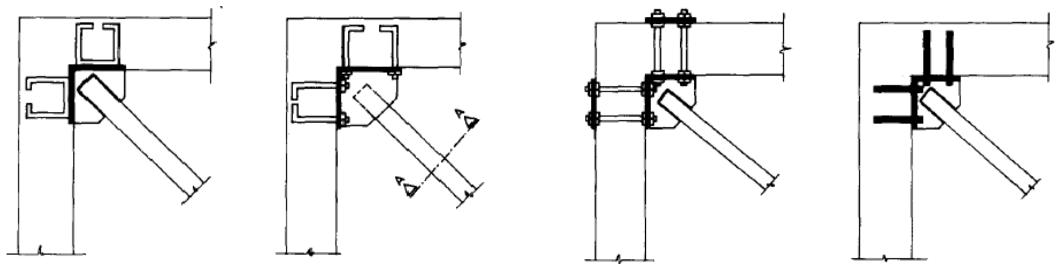


Figure 2: Time displacement graph of both buildings at 4th floor level when preventive measure is shear wall in buildings

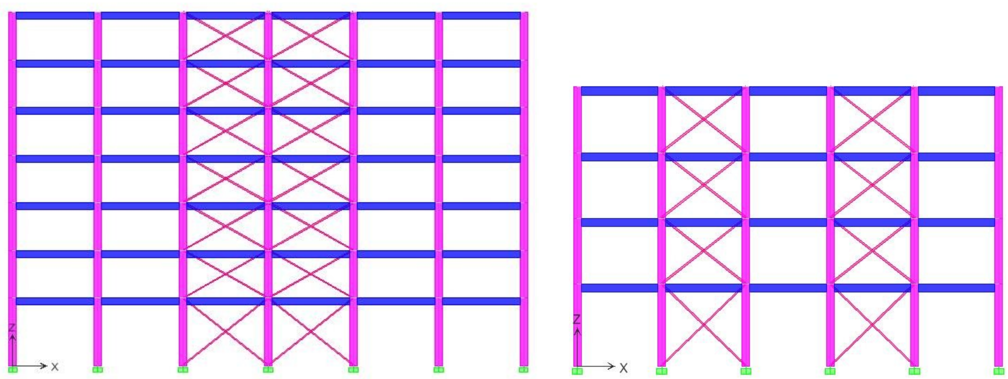
(III) **Increasing the Stiffness of Both Buildings by Providing Lateral Bracing:** According to researchers (Akmal, 2009; Malhotra *et al.,* 2004) diagonal and cross bracing are most effective to resist the lateral load. Inplane shear strength of concrete frame can be increased up to large amount both diagonal and cross bracing. From testing, it is observed that inplane shear strength of concrete frame with steel diagonal brace increases 2.5 times with the frame no brace and incase of cross brace frame it increases up to four times. The connection of steel braces with concrete frame requires very special consideration and the connection should be strong enough to transfer the load from concrete frame to braces safely. In the figures below, connection details of under construction and existing frame are shown (Maheri, 1996).



(a) (b)

Figure 3: (a) Connection detail for under construction frame (b) Connection detail for under construction frame

The figure 4 shows the position of cross bracing in the frames. It is observed that cross bracing system show the best performance and give the cost effective solution if it placed in central panels of frame. In building-1 there are even numbers of panels and cross bracing is applied in central two panels. In building-2 there are odd numbers of panels and cross bracing is placed in 2nd last panel from each end.



(a) (b)

Figure 4: (a) Elevation of building-1 with cross bracing (b) Elevation of building-2 with cross bracing

Figure 5 illustrates the time displacement graph of both buildings at 4th floor when the steel cross bracing is introduced in the building. The maximum positive displacement for the seven storey building takes place at 2.20 sec which is 61.54 mm and maximum negative displacement is observed 52.46 mm at 2.70 sec. Similarly for four storey building the maximum positive displacement observed at 2.50 sec which is 43.96 mm and maximum negative displacement is 53.19 mm at 2.30 sec.

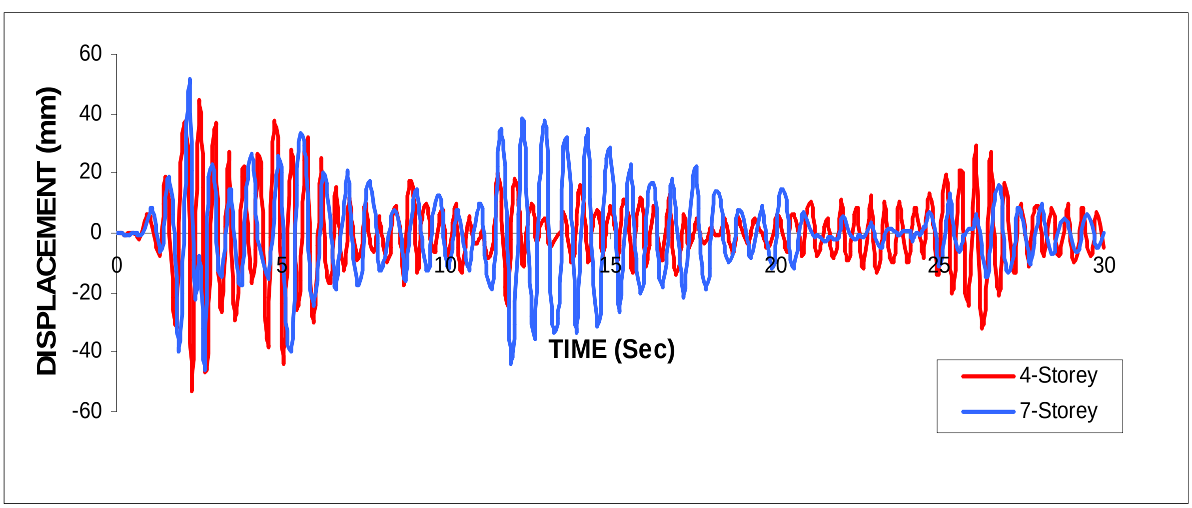


Figure 5: Time displacement graph of both buildings at 4th floor level when preventive measure is cross bracing in buildings.

The figure 5 shows that the maximum out of phase movement is observed 56.92 mm at 5.30 sec. At a time of 5.30 sec, negative displacement of seven storey building is 39.43 mm and positive displacement of four storey building is 17.49 mm. It means that maximum out of phase movement is within the separation joint, when the mitigation measure system is bracing.

(iv) **Increasing the Stiffness of Both Buildings by Providing Friction Dampers:** In the recent era, structural performance of structures against the earthquake can be enhanced by new innovative techniques. These innovative techniques can be classified into three broad areas are base isolation, passive energy dissipation and semi active and active control systems. Of the three groups, friction dampers (passive energy dissipation system) can be considered more matured technology with wider application as compared with the other two groups (Shoushtari, 2010). From the centuries, motion has been controlled by the friction as in case of braking system of automobiles and railways trains. The use of friction to control the seismic response of civil engineering structures was started in late eighties. The working principle of friction damper devices is friction. The friction is developed between two solid surfaces slide relative to each other. The performance of these devices depends upon the amount of energy dissipation by friction during the severe earthquake while at the same time shifting the fundamental structural mode away from the earthquake resonant frequency. These devices have a predetermine slip load and their performance is very satisfactory when load is less than the slip load. When the load exceeds from slip load, these devices slip and do not work. The friction dampers show the non linear behavior during the earthquake excitation (every time the sense of sliding reverts, friction force changes suddenly from μN to -μN) as shown in figure 6.

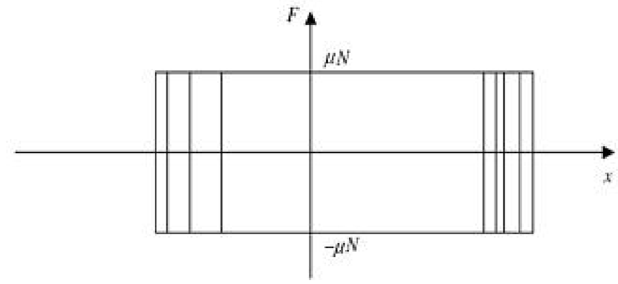
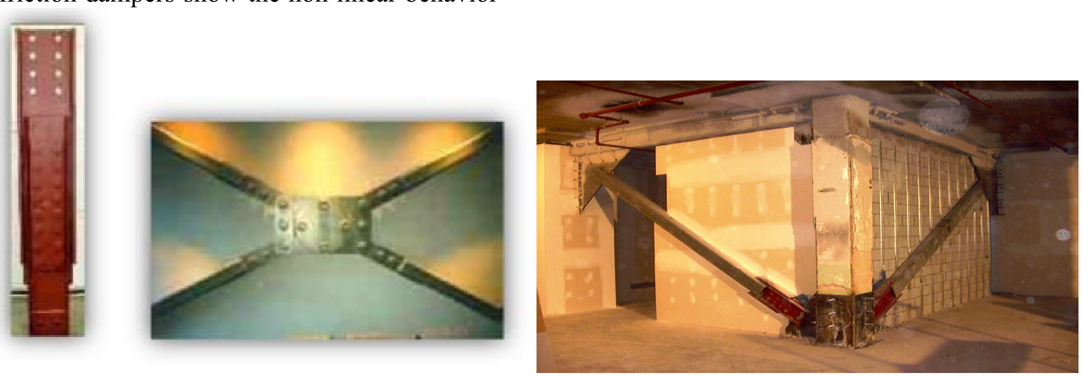


Figure 6: Hysteresis loop of friction damper

Presently, the uses of Pall friction dampers are very common in all over the world because of their high resistance performance in the earthquake and economical solution (it reduces the initial construction cost). The world's largest building by volume "Boeing Commercial Airplane Factory, Everett, WA, USA" is retrofitted by Pall friction dampers. Pall friction dampers do not depend upon velocity and exert a constant force in all future earthquakes. These devices do not require any maintenance after earthquake and ready to use for next earthquake. Usually inherent damping of un damped structures are assume 1-5% of critical and with the application of Pall friction dampers, structural damping 20-50% of critical can be achieved easily. Pall friction damper are available in cross, diagonal and chevron bracing (fig. 7).



(a) (b)

(b) Figure 7: (a) Pall friction dampers, Diagonal and Cross bracing (b) Application of Pall friction damper

Numerical modeling of friction damped frame: The seismic response of a friction damped frame can be controlled by adjusting the bracing stiffness and slip force of the damper unit. The model of SDOF friction damped system excited by ground acceleration $a_g(t)$ consist of a mass M; a viscous damping coefficient C_o simulates inherent structural damping; a supporting frame that provides a restoring forces $f_f\,(t)$ and a friction damping unit combining a brace and friction mechanism that provides an added restoring force $f_a\,(t)$.

The equation describing the relative mass displacement u_t can be expressed as:

$$\ddot{u}(t) + 2\zeta_0 \omega \dot{u} + \frac{1}{M} f(t) = -a_g(t)$$

Where

$\zeta_0 = C_o/(2\omega M)$ = initial structural damping ratio.

$\omega = \sqrt{(k_f + k_a)/M}$ = damped braced natural frequency

k_f = stiffness of frame

k_a = stiffness of added friction damper brace

$f(t) = f_f(t) + f_a(t)$ = is the combining system restoring force as shown in figure 8.

The frame restoring force displacement relationship $k_f(t)$ vs. u_t depends on the frame stiffness k_f and frame yield force P_y, while the added restoring force – displacement relationship $f_a(t)$ vs. u_t depends on the added stiffness k_a and the friction damper slip force P_s.

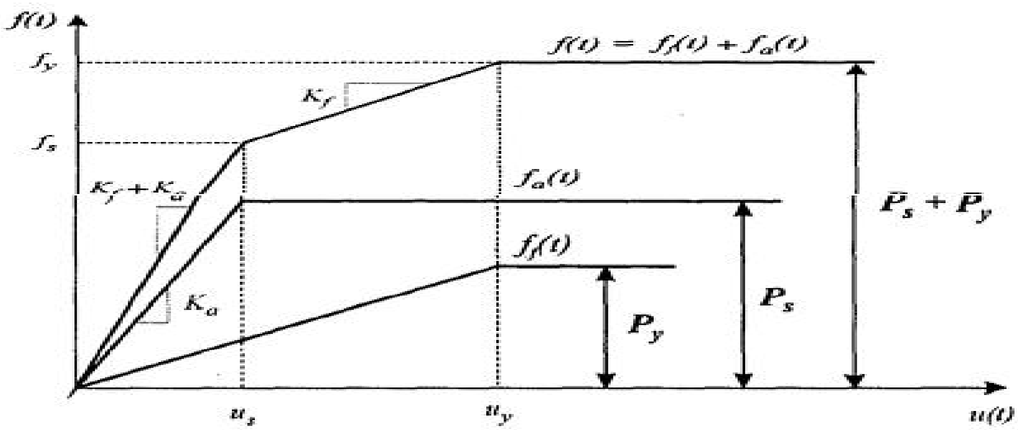
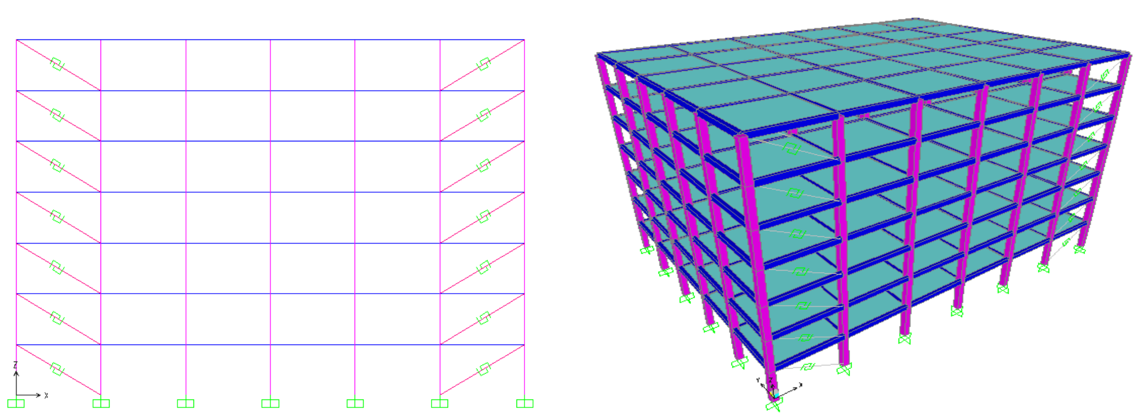


Figure 8: Force relationship of friction damped model.

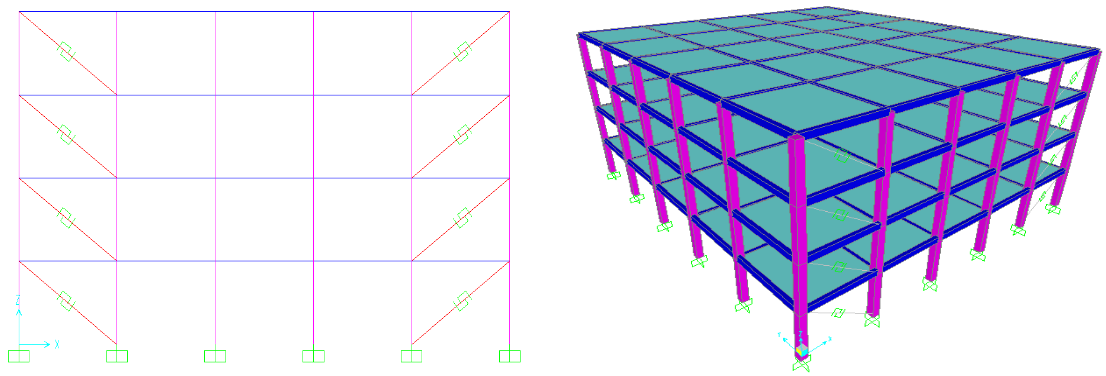
The total system restoring force $f(t)$ is non linear due to the friction unit slipping and frame member yielding. As the displacement u(t) increases, the system restoring force increases with stiffness $k_f + k_a$. When u(t) exceed u(s) (slip displacement) the added friction damper slips, and the system restoring force is define by stiffness k_f alone. Further, when u(t) exceed u(y) the frame members yield and assuming a perfect elasto plastic behavior, the combining system restoring force is limited to f_y where $f_y = P_s + P_y$. When the displacement decreases, the strain energy stored in the frame members and added component is recovered (Pall and Pall, 2004).

Friction dampers in single diagonal brace are modeled as damped braces having the member stiffness equal to brace stiffness and axial yielding equal to slip load. Friction dampers of 600 KN are modeled in SAP 2000. The friction damper is placed in last panels of frame. Figure 9 shows the position of friction damper in a frame of building-1. Similar pattern is used for building-2 (Fig. 10).



(a) (b)

Figure 9: Elevation of building-1 with friction damper (b) Three Dimensional view of Building-1 with friction damper in the outer frames.



(a) (b)

Figure 10: Elevation of building-2 with friction damper (b) Three Dimensional view of Building-2 with friction damper in the outer frames.

Figure 11 depicts the time displacement graph of both building when damper are added in buildings. It illustrates that the maximum positive displacement of seven storey building at fourth floor level is observed 51.65 mm at 2.20 sec and maximum negative displacement is 44.76 mm at 5.30 sec. Similarly the maximum positive displacement of four storey building at roof level is observed 29.18 mm at the time of 2.50 sec and maximum negative displacement is 38.53 mm at the time of 2.70 sec. From this figure maximum out of phase movement is observed at 2.50 sec. At 2.50 sec positive displacement of four storey building is 29.18 mm and negative displacement of seven storey building is 26.48 mm. Their absolute sum is 55.66 mm. It means that maximum out of phase movement is within the expansion/separation joint.

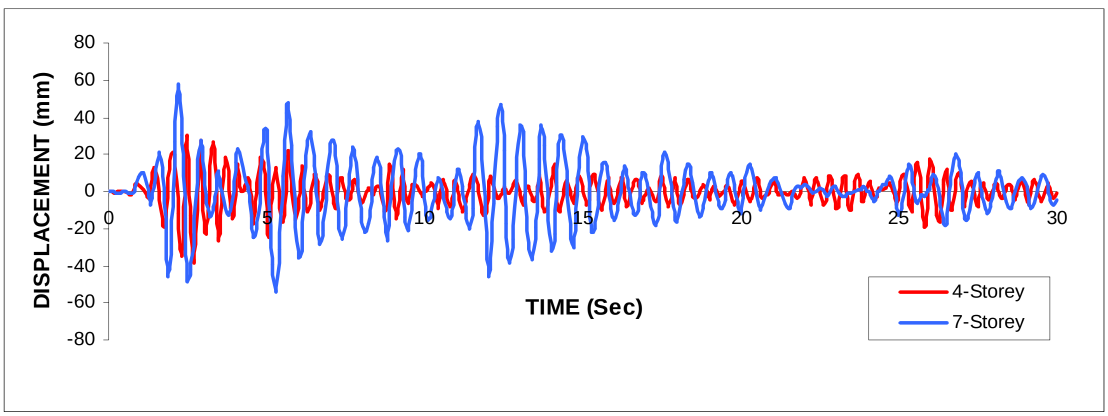
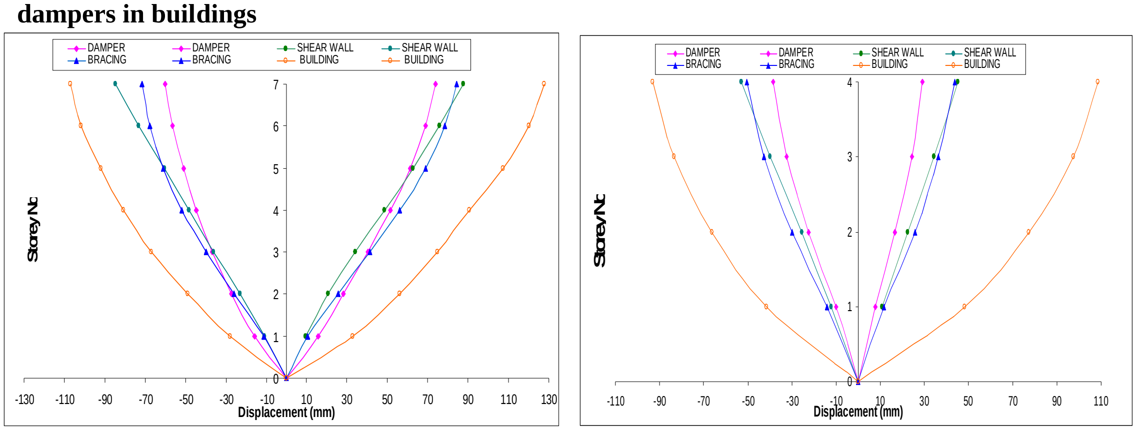


Figure 11: Time displacement graph of both buildings at 4th floor level when mitigation measure is friction dampers in buildings



(a) (b)

Figure 12: (a) Storey displacement graph of building-1(b) Storey displacement graph of building-2

Figure 12 represents storey displacement graph of both buildings. It is clear from figure that lateral displacements are reduced when the mitigation measures are used in the buildings thus reducing the probability of pounding of the buildings. The maximum reduction of lateral displacement takes place in case of dampers.

Conclusions: On the basis of analysis and results, following conclusions are drawn:

- Pounding of the structures produce impact loads which are superimpose on those caused by the ground acceleration. When the impact loads from pounding of the structures are too high, the structural system has to be modified to reduce the response.
- While designing the buildings pounding must be checked to avoid the damages.
- If the buildings are in planning stage the easiest way to avoid pounding is to provide the safe separation distance between buildings as given by code**.**
- Safe separation distance according to FEMA –273 is 146 mm for the case understudy which is greater than the maximum out of phase movement between buildings**.** It means that FEMA-273 give the conservative results.
- For retrofitting of existing buildings three efficient and cost effective mitigation measures are assessed to avoid pounding induced collapse of buildings. Use of shear wall, bracing system and friction dampers are proposed as possible mitigation techniques. All the three mitigation strategies are proved to be effective to avoid the damage in the buildings because of the pounding effects.

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