Control of Adjacent Isolated-Buildings Pounding Using Viscous Dampers

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Abstract: The base-isolation system makes the base more flexible than the elements of the superstructure part which make the sliding displacement through the base increases which tend to increase the total displacement. The effect of increasing the total displacement will make a harmful effect if the buildings not have a sufficient separation distance between them. So this paper investigates, through numerical simulation, the effect of the presence of the viscous dampers at the points of the collision in Base-Isolated structures on the reduction of the pounding force. A specialized program has been made in order to efficiently perform numerical simulation and parametric studies on the control system. The effects of certain parameters have been investigated using the developed software such as damper yield force, damper stiffness and post-pre stiffness ratio to find the optimum parameters of the viscous damper which minimizes the energy transmitted to the overall system. The results demonstrated that, the presence of viscous dampers at the floor levels at the points of contact increases the dispersal of energy generated by the collision. Also, after a specific value of connected dampers stiffness, the increase of the stiffness reduces system response.

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1. Introduction

The fundamental principle of base isolation is to set a flexible layer between superstructure and footing base. The objective of the base isolation is to reduce the energy that is transmitted from the ground motion to the structure by buffering it with low stiffness of flexibility layer. Flexibility of the isolation layer causes the fundamental period of a given structure to be extended to a value far away from the dominant period contents of earthquake ground motion ranging from 0.1 to 1.0 sec so that the earthquake-induced loading will be greatly reduced. Theoretically, the fundamental period of base-isolated structure should be as long as possible to avoid this period range through lowering the stiffness of isolation system, but it might result in a large horizontal displacement (Zhou *et al.,* 2003). This large deformation may caused pounding between the adjacent buildings if the separation distance between them not sufficient to avoid this phenomenon. A practical limitation of the implementation of base isolation is the seismic gap that must be provided around base-isolated buildings (BIBs) to facilitate the expected large relative deformations at the isolation level. In the case of far-field ground motions, the isolator displacements generally have manageable magnitudes (Dicleli and Buddaram, 2006); however, under near-fault ground motions, the isolator displacements tend to be considerable and may be more than the allowable seismic gap (Providakis, 2008), leading to an increase in the possibility of pounding between the base-isolated structure and its surrounding buildings (Ye *et al.,* 2009). Based upon these valuable research results, modifications in seismic design codes and various countermeasures for mitigating the hazards caused by pounding of adjacent fixed-supported structures have been proposed. However, very limited research work has been devoted to pounding in base-isolated structures. The first attempt to investigate this problem was carried out by (Tsai, 1997 and Malhotra 1997). Idealizing the superstructure of an isolated building as a continuous shear beam and applying the wave propagation theory (Tsai, 1997). He found that the floor accelerations that developed in the structure were much higher than the peak ground acceleration (PGA) of the input seismic excitation during pounding between the isolators and their surrounding retaining walls at the isolation level.

Malhotra concluded that the base shear increases with the stiffness of the structure or the retaining wall, and can sometimes be higher than the total weight of the building (Malhotra, 1997). The case study carried out by (Nagarajaiah, 2001) on the base-isolated Fire Command and Control Building in Los Angeles during the 1994 Northridge earthquake indicated that the response of BIBs was altered significantly due to the occurrence of impact.

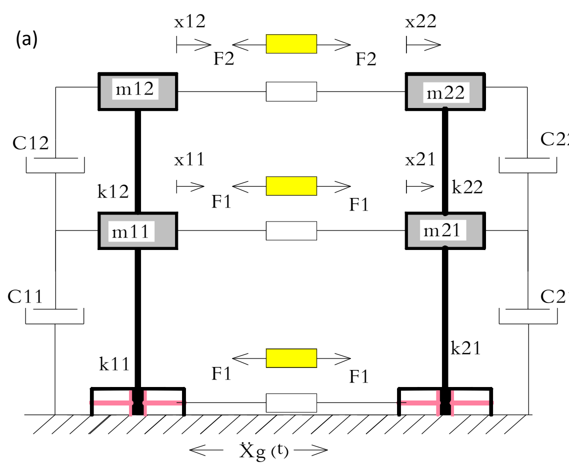
To mitigate the pounding damage between the adjacent superstructures, it is the simple and natural way to adjust the gap size of the adjacent buildings (Jankowski .(1998). However, enlarging the gap size will increase the area under the buildings and around it which increase the overall cost of the building. With the development of the structural control technology, the possibility of using structural control devices, such as viscous damper, crushable device and shock transmission device, to reduce the seismic pounding have been investigated by some researchers (Jankowski .2000 and Zhu *et al.,* 2004).

However, mitigation of pounding and/or impact damages in case of base-isolated and adjacent structures through incorporation of damper linkages between them is untried yet. The objectives of the present paper are investigating the advantages of using viscous dampers between the adjacent base-isolated buildings at all point of contact, and introducing the optimum parameters of the viscous dampers.

2. Theory and Modeling

One of the main aims of this study is to investigate the problem of earthquake induced pounding between two buildings and how to reduce the effect of this problem. Two adjacent Base-Isolated buildings 2DOF are idealized as lumped mass with viscous damper connected the two buildings at all levels at the clearance distance between them are analyzed. To study the pounding control and the behavior of the adjacent base isolated buildings by changing the properties of the connected dampers to find the optimum parameter which minimize the transmitted energy to the overall system.

Fig. 1-a provides a schematic diagram of two base isolated adjacent buildings (A) and (B) that include the connected dampers at the points of contact. Fig. 1-b shows the force-deformation curve of the Elasto-Plastic material of the viscous dampers which used at all floor levels of structures.



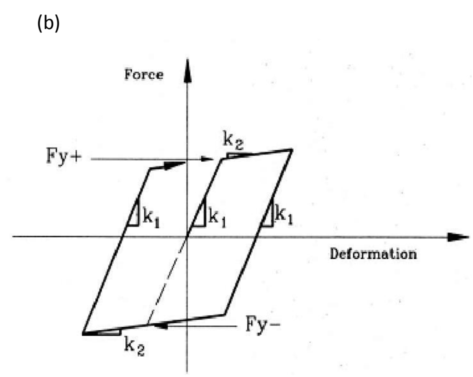


Fig. 1. (a) Schematic Diagram of the Adjacent Building Connected with Viscous Damper (b) Elasto-Plastic Material of the Connector.

2.1 Equations of Motion

For a seismically isolated structure with base mass m_b , the equation of motion can be written for a superstructure part for one building in this form (Naeim *et al.,* 1999):

$$M\ddot{X}'+C\dot{X}'+KX'=-\ M\ R\,(\ddot{u}_g+\ddot{x}_b') \qquad (1)$$

Where R is a vector that couples each degree of freedom to the ground motion, and C, K and M are the damping, stiffness and mass matrices of the adjacent buildings, respectively. And $X', \dot{X}', \ddot{X}'$ are the displacement, velocity and acceleration vectors of the upper stories relative to the base slab, respectively; and $\ddot{x}_b'$ is the relative acceleration of the base with respect to the ground; and $\ddot{u}_g$ is the ground acceleration. The overall equation of motion of the isolated building (Naeim *et al.,* 1999):

$$R^T M \ddot{X}' + \left(\sum_{i=1}^{n} m_{ji} + m_{jb} \right) \ddot{x}'_{jb} + c_{jb}\dot{x}'_{jb} + k_{jb}x'_{jb} = -\left(\sum_{i=1}^{n} m_{ji} + m_{jb} \right) \ddot{u}_g \qquad (2)$$

Where n is the number of stories of the building; m_b, k_b and c_b are the mass, stiffness and damping of the base, and m_{ji} is the mass of the building's i^{th} floor. The general equation of motion for the combination of the seismically isolated building structure and the base slab can be expressed in matrix form as the following:

$$M^* \ddot{X}^* + C^* \dot{X}^* + K^* X^* = -M^* R^* \ddot{u}_g \qquad (3)$$

Where

$$M^* = \begin{bmatrix} M & R^T M \\ MR & M \end{bmatrix} \quad R^* = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad X^* = \begin{bmatrix} u_b \\ X' \end{bmatrix} \quad K^* = \begin{bmatrix} k_b & 0 \\ 0 & K \end{bmatrix} \quad C^* = \begin{bmatrix} c_b & 0 \\ 0 & C \end{bmatrix} \quad M = m_b + \sum_{i=1}^{n} m_i$$

The equations of motion of the coupled structural system subjected to seismic excitation can be expressed as:

$$\mathrm{M_A} . \ddot{\mathrm{X}}_\mathrm{A}(\mathrm{t}) + \mathrm{C_A} . \mathrm{X_A}(\mathrm{t}) + \mathrm{K_A} . \mathrm{X_A}(\mathrm{t}) - \mathrm{f(t)} = -\mathrm{M_A} . \mathrm{I}\, \ddot{\mathrm{x}}_\mathrm{g}(\mathrm{t}) \qquad (4a)$$

$$\mathrm{M_B} . \ddot{\mathrm{X}}_\mathrm{B}(\mathrm{t}) + \mathrm{C_B} . \mathrm{X_B}(\mathrm{t}) + \mathrm{K_B} . \mathrm{X_B}(\mathrm{t}) + \mathrm{f(t)} = -\mathrm{M_B} . \mathrm{I}\, \ddot{\mathrm{x}}_\mathrm{g}(\mathrm{t}) \qquad (4b)$$

$$\mathrm{f(t)} = \mathrm{k_d} . \Delta \mathrm{x_i}(\mathrm{t}) \qquad (4c)$$

$$\Delta \mathrm{x_i}(\mathrm{t}) = \mathrm{x_{Bi}}(\mathrm{t}) - \mathrm{x_{Ai}}(\mathrm{t}) \qquad (4d)$$

Where k_d, X_A and X_B are the damper stiffness, relative displacement of the building A and the relative displacement of the building B for the same floor.

2.2 Theory of Impact

The classical theory of impact will be taken in the modeling of pounding between the adjacent buildings. This theory based on the laws of conservation of energy and momentum and does not consider transient stresses and deformations in the impacting bodies (Orlando and Luis, 2008). The formulae for the post-impact velocities v_1' and v_2' of two non- rotating bodies with masses m_1 and m_2 in the case of the central impact are given by:

$$v_1' = v_1 - (1+e)\frac{m_2 v_1 - m_2 v_2}{m_1 + m_2} \qquad (5a)$$

$$v_2' = v_2 - (1+e)\frac{m_1 v_1 - m_1 v_2}{m_1 + m_2} \qquad (5b)$$

Where v_1 and v_2 are approaching velocities before impact and e is a coefficient of restitution which can be obtained from the equation

$$e = \frac{v_2' - v_1'}{v_1 + v_2} \qquad (6)$$

Where e =0.5 to 0.75 for concrete, take it in the modeling=0.65 (Jankowski et al, 2000).

2.3 Equation of Energy for MDOF Structures

The equation of motion of a MDOF structure is written as

$$M\ \ddot{u} + C\ \dot{u} + K\ u = -M\ddot{u} \qquad (7)$$

Where M, C, and K are the mass, damping coefficient, and recovery force, respectively, and $\ddot{u}_g$ is the ground acceleration. The integration of the above equation with respect to the relative displacement x leads to the following energy equation:

$$\int_0^u M\ddot{u}_t\, du + \int_0^u C\dot{u}\, du + \int_0^u f_s\, du = -\int_0^u M\ddot{u}_g\, du \quad (8)$$

Using the relationship $du = \dot{u}\ dt$, the above equation can be rewritten as follows:

$$\int_0^u M\ddot{u}_t \dot{u}\, dt + \int_0^u C(\dot{u})^2\, dt + \int_0^u f_s \dot{u}\, dt = -\int_0^u M\ddot{u}_g \dot{u}\, dt \quad (9)$$

Where the first and the second terms of Eq. 9 represent the kinetic energy (E_k) and the damping energy (E_d), respectively, and the third term represents the strain energy (E_s). The right- hand-side of the equation represents the input seismic energy (E_i). Therefore the energy balance equation of motion of a MDOF structure is written as

$$\mathrm{Ek} + \mathrm{Ed} + \mathrm{Es} = \mathrm{Ei} \qquad (10)$$

Where

$$E_k = \frac{1}{2} m (\dot{u})^2 = \frac{1}{2} \dot{u}_t^T\ m\ \dot{u}_t \qquad (10\,a)$$

$$E_d = \int_0^t c\,\dot{u}^2\, dt = \dot{u}^T\, C\, \dot{u} \qquad (10\,b)$$

$$E_s = \int_0^t k\,\dot{u}\, dt = \frac{1}{2}\, u^T K\, u \qquad (10c)$$

$$E_i = \int_0^t m\dot{u}_g \dot{u}\, dt = x^T\, m\, r \qquad (10\,d)$$

3. Results

Two adjacent Base-Isolated buildings two stories are idealized as lumped mass with viscous dampers connecting them at all levels of collision in order to study the pounding control. The basic parameters of such model with initial values are shown in table 1.

Table (1) Properties of the Studied Buildings

Building	Left	Right	Connected dampers	
mass of each story [sec^2 t/m]	100	50	K_e*	4000 t/m
stiffness of each story [t/m]	10000	10000	F_y**	10 ton
The mass ratio λ_b= [m_b / m_t]	0.6	0.6	α	0.0
The frequency ratio δ = [ω_b /ω_o]	0.6	0.6		
Post- pre stiffness α = [K_{bp}/K_{be}]	0.2	0.2	**Sinusoidal wave**	
The isolator yield force (t) [f_y]	100	100	ω_{ex}	3.0 rad
Structural damping ratio [ζ_s]	5%	5%	t_{max}	20 sec
base damping ratio [ζ_b]	8%	8%		

* Damper elastic stiffness
** Damper yield displacement

3.1 Effect of Pounding on Base-Isolated Buildings versus Fixed-Base Buildings

The effect of the mass ratio (λ) on the building behavior under pounding phenomenon will be studied. The mass ratio is the ratio between the mass of building B and the mass of building A. the mass of the colliding structures is an especially important structural parameter, which has a direct influence on structural response and on pounding force during impact. The numerical analysis has been conducted for two cases of (λ). The first stiff case when (λ) equals 0.5 and the other is flexible case with value of 2.0, where the other parameters still constant. Fig. 2 shows the maximum displacement of the upper floors of the buildings A and B for the two values of λ in case of Fixed-Base structures. Fig. 3 shows the maximum displacement of the sliding base and the upper floors of the buildings A and B for the two values of λ in case of Base-Isolated structures. By observing the two figures, it is shown that, the sliding displacement in the case of Base-Isolated structures is the real problem where the increase of the total displacement in the upper floors makes the chance of pounding increases. Also, it is shown that the increase in the relative displacement in case of Fixed-Base structures when pounding happens less than that in case of Base-Isolated structures. So, this study will be done on the control of Base-Isolated structures.

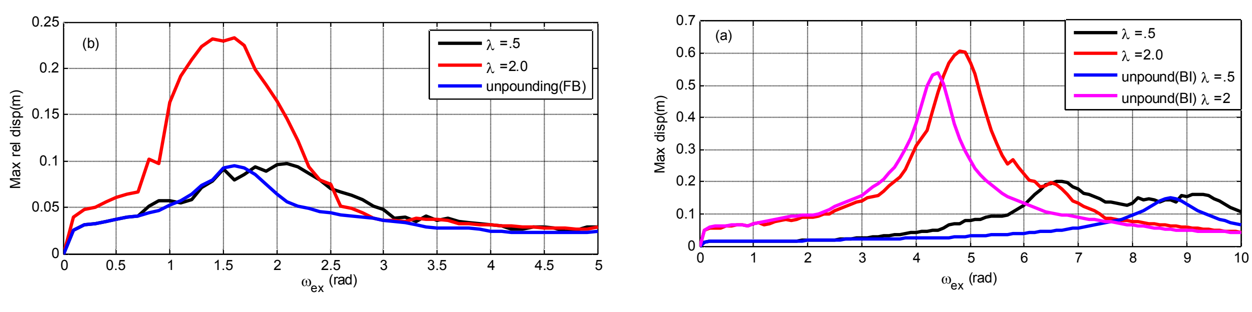


Fig. 2. Max. disp. for the case of FBP (a) second floor of building A, (b) second floor of building B.

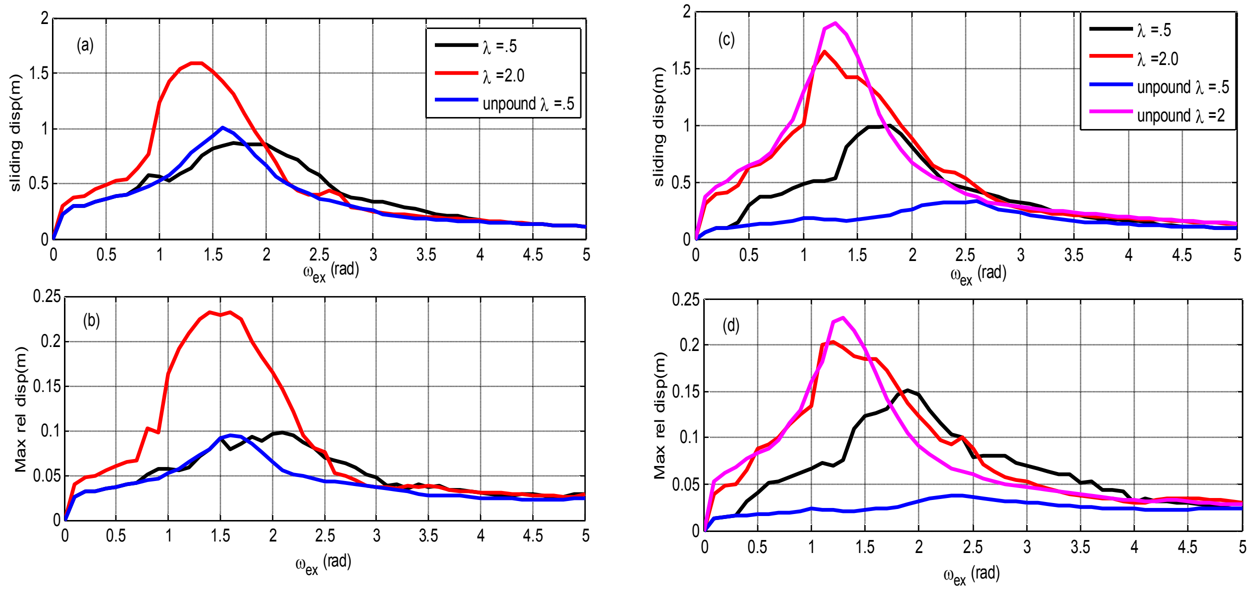


Fig. 3. Max. disp. in case of BIP (a),(b) sliding and second floor disp. of A, (c),(d) sliding and second floor disp. of B.

Figure 4 shows the displacement time history of the two buildings for the controlled and uncontrolled buildings when subjected to harmonic excitation with frequency equal to 3.0 rad for time equal to 20 sec. It is shown that, the peak displacement decreases with the laying of the connected damper between the two buildings. The peak absolute displacement of the top story of the reference building A reduces with 22%. Also, the peak displacement of the upper story of the building B reduces with 44%. On the other hand, the total energy decreases with 14.2% as shown in table 2. This reduction in the total energy occurs due to the absorption of the pounding force in the viscous damper, and this can be attributed to the large stiffness of the connecting link in all cases which make the buildings behaves as one building. Also, this can shift the natural frequencies of the structures away from the dominant frequency of the ground motion.

To determine the optimum parameter of the dampers that used to link the two adjacent base isolated buildings, the principle of minimizing the total energy of the overall system is used. Fig. 5-a shows the total energy of the overall system versus the excitation frequency and the damper yield force f_y as a surface. This figure shows that, the total energy of the overall system have a maximum value at the excitation frequency 2.0 rad, which indicates the resonance of the overall system. The variation of the total energy of the controlled Base-Isolated system is studied separately at resonant frequency (ω_{ex}=2.0 rad) and compared with the total energy of the uncontrolled pounded Base-Isolated system as a ratio and versus the damper yield force as shown in Fig. 5-b. By observing this figure, it is demonstrated that, the energy ratio is decreased with increase of the damper yield force until specific point. After this point the increase in the damper yield force increases the energy ratio. This can be attributed to the fact that, at very low damper yield force, the dampers enter the plastic zone quickly, and then it behaves as elastic damper with small stiffness (plastic stiffness). But at the optimum point (the lowest energy ratio), the damper obeys Elasto-plastic behavior, and then the dampers dissipate the energy of the system. After that, the damper tends to be elastic with small plasticity, and small energy dissipated.

Table 2: Max. Displacement and Total Energy For Control and Uncontrolled Systems.

Building		Left building	Right building
Sliding displacement of base (cm)	Controlled	26.26	18.34
	Uncontrolled	32.95	33.66
Upper floor displacement abs(cm)	Controlled	28.86	21.10
	uncontrolled	37.05	37.66
Total energy (un-control)*10^5 t.m			5.6330
Total energy (controlled)*10^5 (t.m)			4.8562

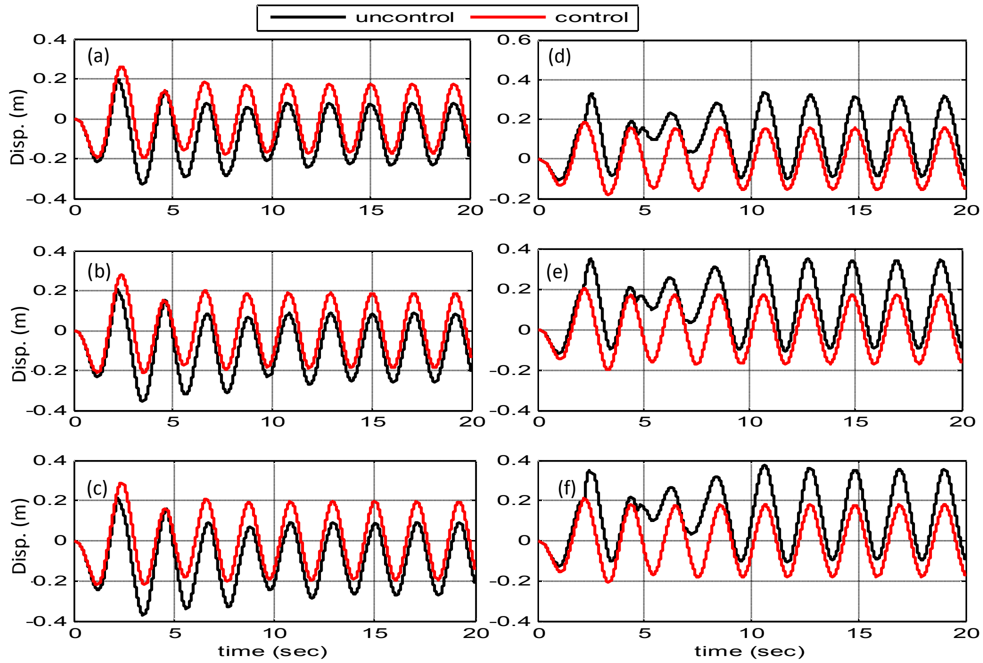


Fig. 4. Uncontrolled vs. controlled system. (a, b, c) time history of building A, (d, e, and f) building B, for the base, first and second story.

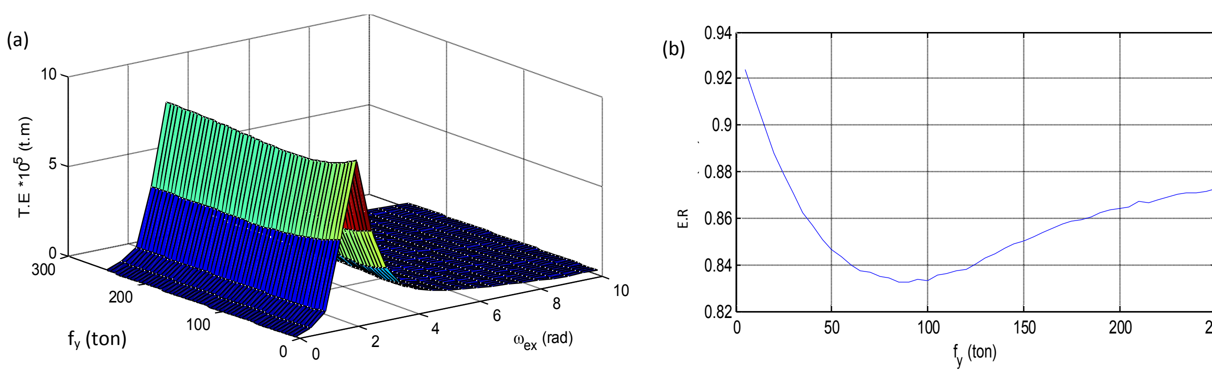


Fig. 5. The total energy versus the excitation frequency and yield force. (a) surface area, and (b) the energy ratio (TEc /TE) at w_{ex}=2.0 rad.

3.2 Effect of Damper Stiffness Ratio and Damper Yield Force:

Figs. (6 to 9) introduce the effect of variation of the natural frequency of the two Base-Isolated adjacent buildings, yield force f_y and the elastic stiffness of the connected damper k_R on the total energy of the overall system. These figures show that, by increasing the natural frequency of the adjacent structures, the relative displacement and velocity in all floor levels increase which increases the force in the damper. This increase of the dissipated energy requires smaller value of yield force that makes the damper enter in the plastic stage rabidly, as shown in Fig. 9. Also from these figures, the decrease in the total energy transmitted in the direction of increasing of the damper stiffness at the yield force that minimize the total energy, decreased slowly after certain value that almost equal 0.6 from the reference building stiffness A. This make the increase in the stiffness of the damper after this point will not be cost- effective.

3.3 Effect of Post-Pre Stiffness Ratio:

Fig. 10 shows the total energy of the overall system versus the elastic stiffness ratio k_R and the post-pre stiffness ratio of the damper α of the viscous dampers. The values of the post-pre stiffness ratio will be changed from 0 to 1 and for elastic stiffness ratio from 0 to 2. This figure shows that the total energy decreases with the increase in the damper stiffness until a specific value at which the dampers will be more rigid that make the two buildings behave as one, then the increase in the damper stiffness will not be cost effective. Also, it is shown that the total energy decreases with the decrease in the post stiffness ratio of the damper which minimized at post-pre stiffness ratio equals zero, because the decrease in the post stiffness increases the dissipated energy in the force-displacement curve. When the post-pre stiffness ratio equals 1.0 this means that the plastic the dampers still elastic stiffness all the time which make the dissipated energy equal zero and maximize the value of the total energy of the overall system.

3.4 Effect of Damper Post-Pre Stiffness Ratio and Damper Yield Displacement:

Fig. 11 shows the effect of yield displacement x_y and the post-pre stiffness ratio α of the connected damper on the total energy of the overall system which taken from 0 to 3 cm. It is shown that the total energy of the overall system decreases with the decrease in post stiffness of the connected damper.

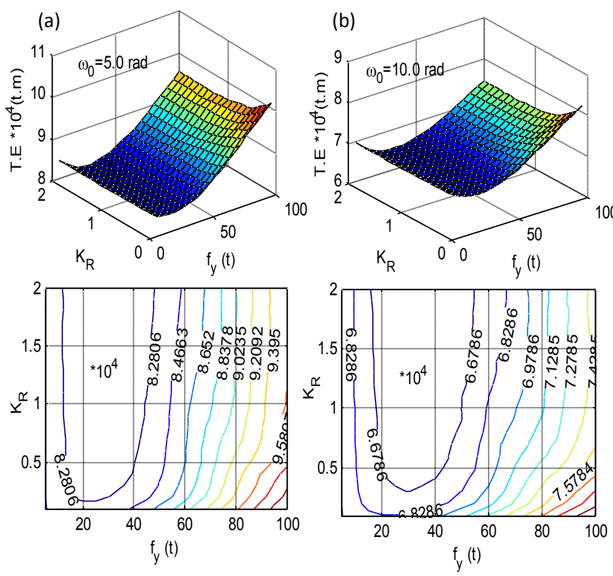


Fig. 6. The energy ratio versus yield force and damper stiffness (a) ω_o=5.0 rad, and (b) ω_o=10.0 rad.

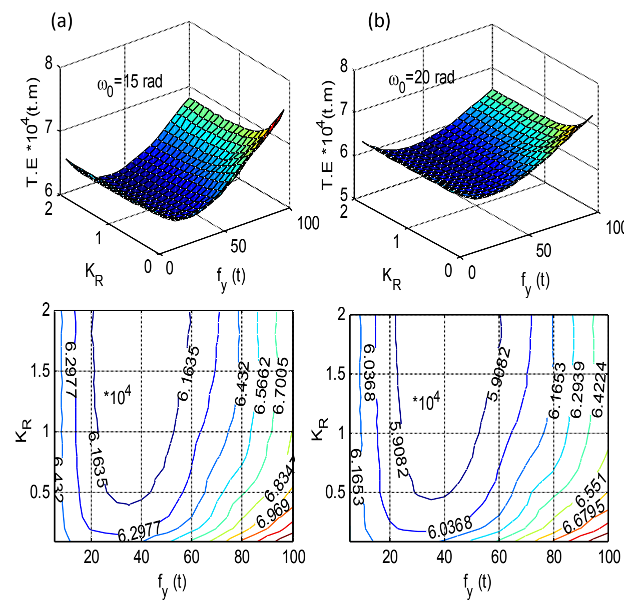


Fig. 7. The energy ratio versus yield force and damper stiffness (a) ω_o=15.0 rad, and (b) ω_o=20.0 rad.

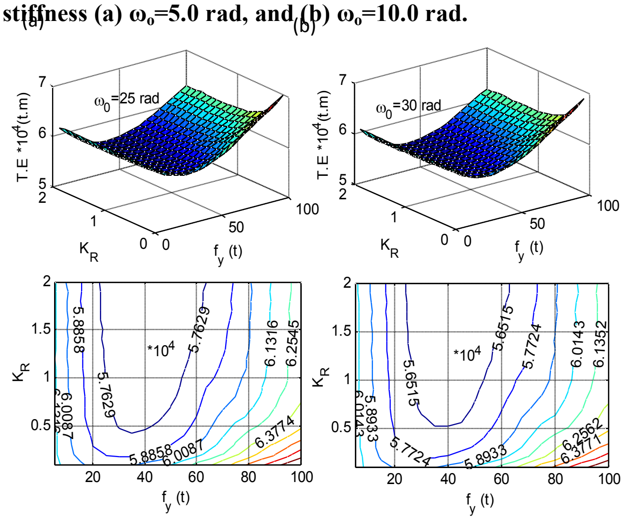


Fig. 8. The energy ratio versus yield force and damper stiffness (a) ω_o=25.0 rad, and (b) ω_o=30.0 rad.

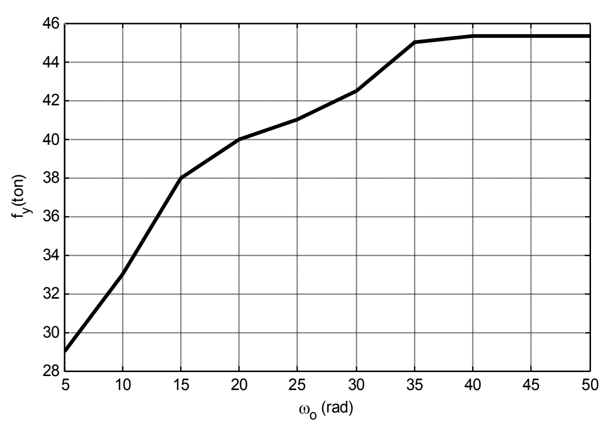


Fig. 9. Effect of the variation of the natural frequency of structures and yield displacement which minimize transmitted energy.

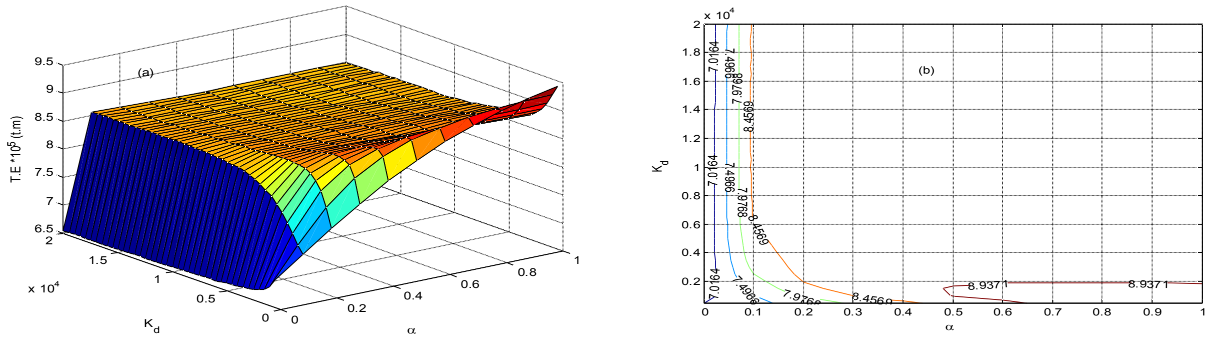


Fig. 10. Total energy versus with damper stiffness and post stiffness, (a) surface area, and (b) contour line.

Also, this figure shows that the total energy is decreased with the increase of the damper yield displacement until specific point. After this point the increase in the damper displacement force increases the energy. Because at very low damper yield force, the dampers enter the plastic zone quickly, then it behaves as elastic damper with small stiffness (plastic stiffness). But at the optimum point (the lowest energy ratio), the damper obeys Elasto-plastic behavior, and then the dampers dissipate the energy of the system. After this point, the damper tends to be elastic with small plasticity, and then small energy dissipated, which the same results as in Fig. 5-b.

3.5 Effect of Structure Damping Ratio and Yield Displacement of the Damper:

The total energy of the overall system at various yield displacement of the connected damper and damping ratio of the adjacent structures will be studied. The values of damping ratio will be taken from 0% to 20% and the yield displacement from 0 to 2.5 cm. Fig. 12 shows that the total energy decreases with the increase in the yield displacement until the optimum point and then return to increase that obey the discussion in Fig. 5-b. Also, the figure shows that the control effectiveness will be improved by increasing the damping of the two adjacent buildings which decreases the overall energy.

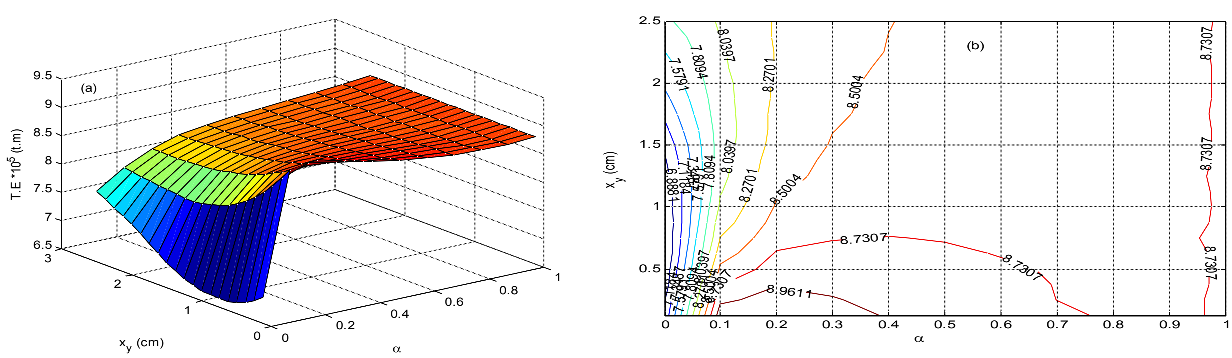


Fig. 11. Total energy versus yield displacement and post stiffness ratio. (a) surface area, and (b) contour line.

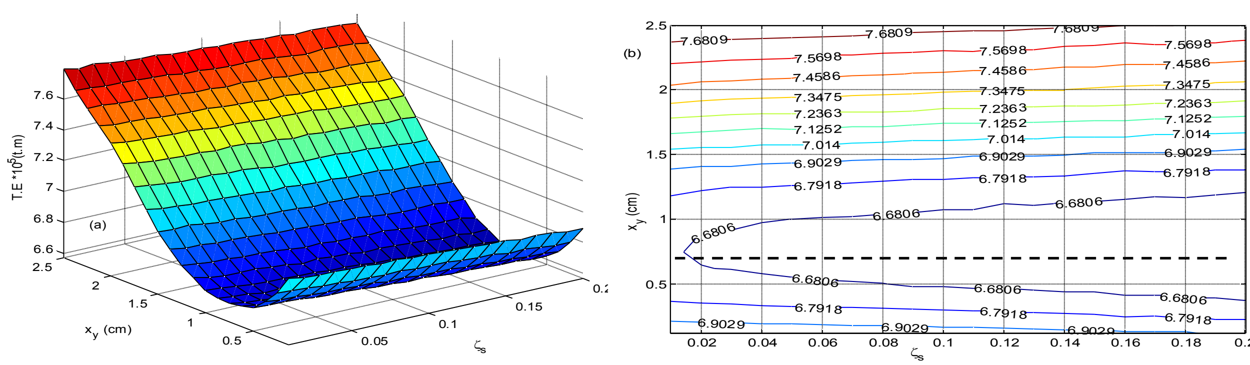
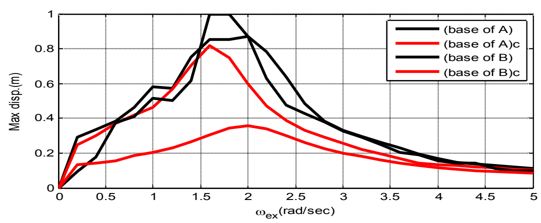


Fig. 12. Total energy against damping ratio and the yield displacement of the damper, (a) surface area , and (b) contour line.

3.6 The effect of optimum parameters on the reduction of the displacement:

In order to check the feasibility of the parametric study that conducted to obtain the optimum parameters that reduce the system energy, these optimum parameters such as, K_d =20000 t/m, α=0.0, and the yield force = 33.0 ton are used to check the reduction of the system response. Figure 13 shows the maximum displacement of the controlled and uncontrolled bounded Base-Isolated buildings for the sliding and second story respectively versus a different harmonic excitation frequency. Figure 13a shows that the maximum displacement of the base of building A (the flexible building) decreases from 100.0 m to 87.0 cm with decreasing ratio equals 13% and decreases in the base of building B (the stiff building) from 80.0 cm to 37.0 cm with decreasing ratio equals 53%. Also, Fig. 13-b shows how the viscous dampers decrease the relative displacement of the upper floor of the two buildings. This results show that the effect of the viscous damper on the reduction of the pounding response take place on the different values of harmonic excitation frequency.



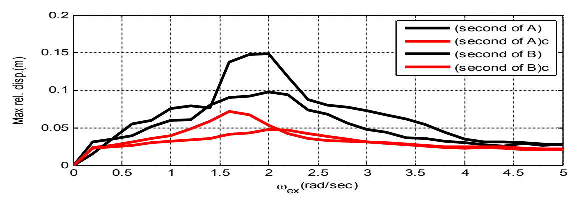


Fig. 13. The max. disp. Of the controlled and uncontrolled bounded Base-Isolated buildings (a) the base of the two buildings, and (b) the upper floor of the two buildings.

4. Conclusions

In this study, a mathematical modeling of adjacent building pounding has been demonstrated and its implementation in a MATLAB program seismic analysis is presented. Numerical investigation, aiming to make the comparison between the earthquakes induced pounding involved behaviors of the two adjacent buildings modeled many points can be concluded from this research:

1.When the floors of the two adjacent base isolated buildings are connected with viscous dampers, these damper have optimum yield force that minimize the overall energy of the system.

2. The optimum yield force for the connected dampers increases the stiff buildings rather than the flexible ones.

3. Connected dampers with small post-pre stiffness ratio are more efficient than that with large values for all cases of dampers.

4. The change of the system damping doesn't change the values of the optimum yield force.

5. After a specific value of connected dampers stiffness, the increase of the stiffness reduces system response.

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