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The pounding mitigation techniques in adjacent structures due to earthquakes

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KEYWORDS

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ABSTRACT

Investigations of past and recent earthquake damage have illustrated that the building structures are vulnerable to severe damage or collapse during moderate to strong ground motion. Among the possible structural damages, seismic induced pounding has been commonly observed in several earthquakes. Adjacent buildings during an earthquake may collide against each other when, owing to their different dynamic characteristics, the building vibrate out of phase and the at-rest separation distance is inadequate to accommodate their relative motion. When impact loads from pounding are too high, the structural system has to be modified to reduce the response. This research work covers the mitigation of pounding between adjacent structures due to earthquakes. The methods may be classified according to their approach to the problem of pounding: Methods to avoid pounding; Methods to increase the stiffness of building; Methods to supplement energy dissipation; Methods to impact absorb material.

1. 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 or collapse during earthquakes. Such as Mexico (1985), Sichuan – China (2008), Haiti (2010), Japan (2011), Pakistan (2013). With the continuous development of today's society, the density of buildings is increasing in metropolitan areas, therefore there are so many adjacent buildings especially in the cramped cities. Hence, the adjacent buildings can completely occur pounding phenomenon under dynamic loads when the gap between those buildings is not enough large. 'Pounding' is a phenomenon, in which two buildings strike due to their lateral movements induced by lateral forces Abdel and Shehata[1]. It can be seen that each building will have different dynamic responses completely depended on the dynamic character of structure system in the building, therefore, there will be also different in the dynamic horizontal displacement of each story in each building which is the major reason induced to pounding force in the adjacent buildings Naserkhaki et al[2]. Additionally, the characteristic ground acceleration of earthquake also is one of the most important causing increase destructions of structural pounding. Many studies also indicated that there have from 20% to 30% structural destruction for which reason is pounding phenomenon during the earthquake Anagnostopoulos[3]. Typically, Mexico earthquake, in the 19th of September 1985, approximately 15% total collapsed buildings induced by structural pounding Rosenbluth and Meli[4]. Loma Prieta earthquake, in 1989, there had more than 200 damaged buildings of 500 buildings in San Francisco, Oakland, Santa Cruz and Watsonville due to pounding phenomenon Kasai and Maison[5]. Therefore, the problem of pounding response analysis in adjacent structures under earthquake has been attracting so many researchers in many past decades Agarwal[6]; Chau et al[7]; Efraimiadou et al[8,9]; Francisco and Alireza[10]; Jankowski et al[11]; Puneeth Kumar and Karuna[12]; Naderpour et al[13]; Namboothiri[14]. 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.

This paper presents the techniques to mitigate of pounding between adjacent buildings due to earthquakes. The objective of this research work explores 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. There may be various methods to avoid pounding of adjacent buildings. The methods may be classified according to their approach to the problem of pounding: methods to avoid pounding, methods to strengthen structures to withstand pounding, and techniques to reduce pounding effects in the structures.

2. Seismic gap

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. The first work for pounding prevention was to establish a good and reliable estimate of the minimum gap required for the design earthquake so that pounding between the structures will not occur. Providing a sufficient gap has been the commonly accepted strategy adopted by building codes throughout the world. The value of the separation

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distance between two structures which is sufficiently large to prevent pounding is known as the seismic gap. For instance, according to the 200 edition of the International building code and in many seismic design codes and regulations worldwide, minimum separation distances Lopez Garcia[15], using four different expressions:

- Gap ≥ factor(sum of individual displacements D_1 and D_2 of building) (1)
- Gap ≥ coefficient (height) (2)
- Gap ≥ fixed distance (3)
- Gap ≥ $\sqrt{D_1^2 + D_2^2}$ (4)

A more rational approach that is usually referred to as the Double Difference Combination (DDC) rule, for estimation of the critical required separation distance Lopez Garcia[15], is given by:

$$Gap = \sqrt{u_A^2 + u_B^2 - \rho_{AB} u_A u_B} \quad (5)$$

Where u_A, u_B design peak displacements of buildings A and B.

The correlation coefficient ρ_{AB} is calculated according to the simplified formulas for white noise input:

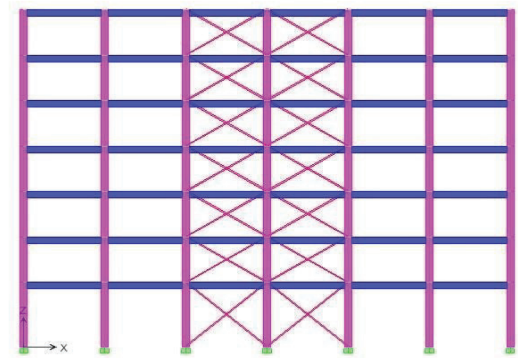
$$\rho_{AB} = \frac{8\sqrt{\zeta_A \zeta_B}(\zeta_A + r\zeta_B)r^{1.5}}{(1-r^2)^2 + 4r\zeta_A\zeta_B(1+r^2) + 4({\zeta_A}^2 + {\zeta_B}^2)r^2} \quad (6)$$

ζ damping ratio and $r = \frac{T_B}{T_A}$ ratio of the fundamental periods of the two buildings.

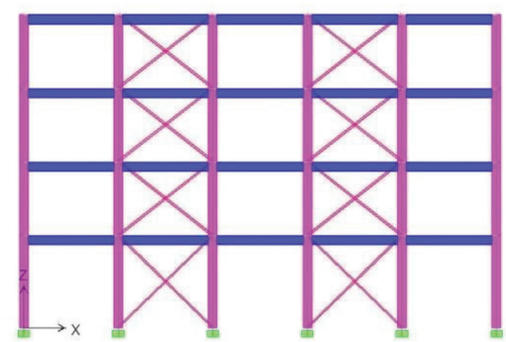
3. Increasing the stiffness of building

Since distance between the buildings cannot be increased due to high cost of land and construction difficulties. Increasing the stiffness of one or both building by providing the shear wall or lateral bracing in such a way, it reduce the seismic deformations which can be accommodate between provided existing gap. Position of shear walls building 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.

According to researchers Malhotra et al[16] diagonal and cross bracing are most effective to resist the lateral load. In plane shear strength of concrete frame can be increased up to large amount both diagonal and cross bracing. From testing, it is observed that in plane 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. The position of cross bracing in the frames are shown as the figure 1. 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 1. **(a)** Elevation of building-1 with cross bracing **(b)** Elevation of building-2 with cross bracing.

Additionally, permanent connections of the adjacent buildings have been investigated. A permanent linkage would provide a continuous force to the structures which is proportional to the stiffness and thus more in line with the dynamic behavior of the unlinked frames. Linking adjacent buildings has a number of disadvantages, including possible high forces in the link, the fact that the dynamic characteristics and the design failure mechanisms are changed, and the uncertainties inherent when the two structures of different characteristics must become one. Nevertheless if those problems are solved, linking two structures will reduce the possibility or the influence of pounding interactions Plumier et al[17]. If an energy dissipation device is used between the two structures, pounding will occur if the stroke of the element is not sufficient.

4. Supplemental energy dissipation

Another method to reduce pounding is the use of supplemental energy dissipation devices in the buildings. Using supplemental energy dissipation devices reduces the maximum lateral deflections of the building. Even if the reduction in the maximum energy levels provided may not be sufficient to avoid pounding, the amplification effects of impacts in the structures will be smaller.

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 seismic isolation, passive energy dissipation, semi-active and active control. 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[18]. 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 nonlinear behavior during the earthquake excitation (every time the sense of sliding reverts, friction force changes suddenly from μN to - μN) as shown in Figure 2.

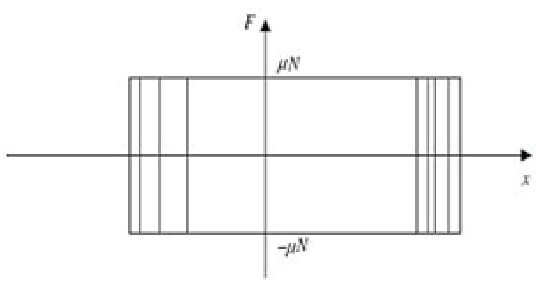
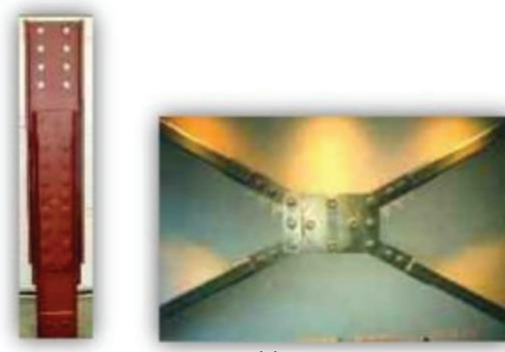


Figure 2. Hysteresis loop of friction damper.

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, Figure 3.

Outstanding studies on solutions to use energy dissipation equipment are as follows: The fluid dampers are proposed by Y.L.Xu et al[19]; Agarwal et al[6] analyzed the effect of using friction bearing base isolation systems; Viscous dampers are used by Elsalam[20]; Fluid – viscous dampers are applied in reinforced concrete buildings by Sorace, Terenzi[21] .



(a)

(b)

Figure 3. (a) Pall friction dampers, Diagonal and Cross bracing (b) Application of Pall friction damper.

5. Impact absorbing materials

A measure for reducing the effects of pounding, while maintaining small separation distances, would be to fill the gap with a special, shock absorbing material (bumper dampers). Bumper damper elements must be dissipative to reduce pounding accelerations and forces during contact. Under bumper damper elements, all energy dissipation devices available that can be placed between the structures, but connected only to one of them, are considered. Bumper dampers are therefore energy dissipation links that are activated when the gap is closed. The presence of the bumper damper element will reduce the impulsive forces transmitted from one structure to the other. If the element provides only stiffness the impulse loads will still be reduced since the impacting bodies will encounter a spring element reducing the kinetic energies of the structure before the stroke of the element is reached, at which point the full pounding of the masses will take place, but the impacting velocities will be smaller. Although the velocities at the onset of pounding are smaller, the linear spring will increase the velocities after pounding, but the high frequency accelerations observed will be reduced.

Recently, rubber shock – absorber as soft material is as known as one of the simplest method used for reducing pounding response in the structures due to the earthquake (Jankowski et al[11]; Kajita et al[22]; Polycarpou and Komodromos[23-25]. There are two approaches for simulating of the behavior of the rubber bumpers under impact load based on the linear impact load model and non-linear impact model. But, based on the static and dynamic compressive tests of rubber reveal an exponential relationship between compressive load and displacement indicated that the non-linear impact model would be more appropriate to simulate the incorporation of rubber-bumpers. Hence, regarding the usage of rubber bumpers based on the non-linear impact model with hysteretic damping as an impact mitigation measure for earthquake-induced poundings of buildings has been proposed and verified in relevant research works[23-25]. The response of rubber bumpers under impact loading of the proposed non-linear impact model, the diagrams of force-time and force-displacement are shown in Figure 4.

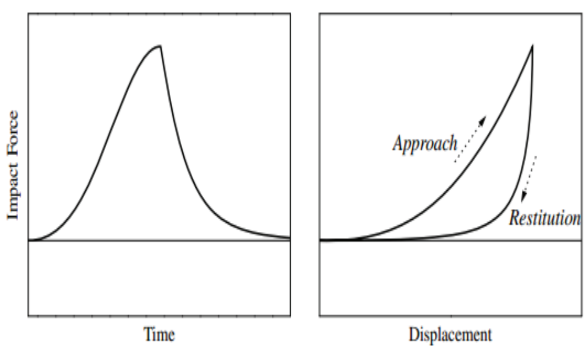


Figure 4. Impact force in terms of time and displacement of the proposed nonlinear impact model with hysteretic damping**.**

The research results indicated that the pounding phenomenon is more increasing the dynamic response of the adjacent structures due to earthquake excitations than without this phenomenon. Those increases depend significantly on many characteristic parameters of structure system such as gap size, dynamic character of the structures and magnitude of earthquake excitation. It is one of the main reasons for increasing ability destruction in the adjacent structures due to earthquake-included pounding. Therefore, the rubber shock-absorbers are used to reduce the effects of pounding phenomenon in the adjacent structures.

6. Conclusions

This paper analyzes the pounding mitigation techniques in adjacent structures due to earthquakes. Following conclusions are drawn:

- Pounding introduces impact loads which are superimposed on those caused by the ground acceleration. When these impact loads from pounding are too high, the structural system has to be modified to reduce the response.
- The pounding mitigation methods may be classified: Methods to avoid pounding; Methods to strengthen structures to withstand pounding; Methods to reduce pounding effects in the structures.
- The easiest way to avoid pounding is to provide the seismic gap between buildings as given by code.
- Adding shear walls or cross bracing is the way to increase the stiffness of one or both building, but the initial dynamic characteristics are changed.
- The use of supplemental energy dissipation devices in the buildings is the method to mitigate pounding phenomenon. These devices include: seismic isolation, passive energy dissipation, semi-active and active control.
- Rubber shock-absorber as soft material is as known as one of the simplest methods used for reducing pounding response in the structures due to the earthquake.

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