Earthquake-Induced Pounding between Adjacent Structures with Substantially Different Eccentricity on Plan

Mehdi Sadeghi¹, Erfan Khalaghi², Naghmeh Pakdel Lahiji³

¹ Ph.D. Student in Earthquake and Structural Engineering, Department of structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran. Sadeghi.m@Srbiau.ac.ir
² M.Sc. Student in Earthquake Engineering, Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran. Erfan.khalaghi@gmail.com
³ Ph.D. Student in Earthquake and Structural Engineering, Department of Structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran. Naghmeh.pakdel@gmail.com

Biography
Mehdi Sadeghi is currently a Ph.D. student in Earthquake and Structural Engineering at Science and Research Branch, Islamic Azad University of Tehran. He got his M.Sc. in Earthquake Engineering in 2010 and B.Sc. in Civil Engineering in 2006. His strongest subject is Vulnerability Assessment of Infrastructures.

Abstract

Investigations of past and recent earthquake damages in structures have illustrated that are vulnerable to severe damage and collapse due to interaction between adjacent buildings. In fact, in such buildings, due to sudden applied forces on some parts of structure, undesired and unpredicted stresses appear in some members which may result progressive collapse in other parts of structure. Several fields of this subject were discussed by researchers, but in most cases the structures have a symmetric plan (Non-torsional). In this research for more accurate investigation about the effects of eccentricity on plan due to simultaneity affection of pounding forces and earthquake base acceleration; two steel moment frame structures, 7 and 4-story adjacent buildings with a range of eccentricity on plan are used. Two structures are connected with modified gap-link elements. Non-linear Time history analysis was performed by SAP2000 software. In order to determine effectiveness of torsion, maximum base shear, maximum pounding force and its location for each building have been monitored and some 3D diagrams of each monitored component versus the variation of eccentricity have been drawn. Finally the effects of the various eccentricities on type and amount of damages are discussed and also their results are shown. In summery it was seen that the existence of the eccentricity in plan of adjacent structures can vary the base shear, pounding force and its location.

Keywords: Pounding effect, adjacent buildings, Torsional structures, Eccentricity, Nonlinear Dynamic analysis.
Introduction

Structural pounding is a phenomenon which might be seen during the earthquakes. It can occur between girders of a bridge or adjacent buildings which were built without enough separation. One of the main reasons of earthquake damages is adjacent structures with insufficient clear spacing between them. Especially buildings on the main streets of the modern cities are built closely to each other due to limited availability of land and socioeconomic requirements. In general, adjacent structures vibrate out of phase due to different dynamic characteristics. Moreover, in design process, adjacent buildings with insufficient clear spacing are designed as a standalone structure and the pounding forces due to earthquake loading is neglected. This negligence causes pounding of the adjacent buildings and leads to extra shear forces and bending moments on the columns and beams.

It has been known that pounding force of adjacent buildings separated by insufficient clear spacing causes damages on each building in case of earthquake loading (Bertero 1986; Arnold 1989; Rosenblueth and Meli 1986; Kasai et al. 1992). Previous researches investigated the dynamic pounding with different types of idealizations, shake table simulation and parametric study of the building pounding response in case of insufficient clear spacing (Miller 1980; Anagnostopolous 1988; Liolios 1989; Maison and Kasai 1990; Maison and Kasai 1992; Papadrakakis et al. 1993).

Early studies on modeling of the pounding response of the adjacent buildings have been used single degree of freedom (SDOF) systems to simplify the problem. Later, the studies focused on modeling the pounding response of adjacent buildings using multiple-degree-of-freedom (MDOF) systems (Miller 1980, Maison and Kasai 1992; Anagnostopolous and Spiliopoulos 1992). These MDOF models mostly were prepared by two-dimensional models. Very few three-dimensional models were prepared for modeling of the pounding response of adjacent buildings (Maison and Kasai 1992; Papadrakakis and Mouzakis 1994; Papadrakakis 1996). The width of the seismic joints commonly used in practice is 3 cm, which is less than the code requirement (MPWS 1998). In addition, buildings designed with different architectural plan, geometry and numbers of stories behave differently under earthquake loading due to different periods. Therefore, pounding of adjacent buildings occurs during earthquakes and led to the collapse of the weak adjacent building.

As mentioned above several fields of this subject was discussed by researchers, but in the most cases the structures have 2D frames or 3D symmetric plan (Non-torsional). In this study for more accurate investigation about the effects of eccentricity on plan due to simultaneity affection of pounding forces and earthquake base acceleration; three-dimensional computer models for two adjacent steel moment frame structures with 7 and 4 stories with a range of various eccentricities on plan have been used. Finally the effects of various eccentricities on type and amount of damage indexes are discussed and also the results are shown.

Figure 1. Substantial damage at the places of contact; Kocaeli earthquake, 1999

Pounding Force
The Hertz contact law has been used in many studies to express the pounding forces between objects, which are given by:

\[ F(t) = \beta \delta^3(t) \]  
(1)

Where \( F \) is pounding force, \( \beta \) denotes the impact stiffness parameter which depends on material properties of colliding objects and geometry, and \( \delta \) describes the deformation of colliding objects (Jing and Young, 1990, and Jankowski, 2005). Unfortunately, in equation (2) there is no term to express the energy dissipation during contact. To overcome this problem, the following linear viscoelastic model is employed:

\[ F(t) = k\dot{\delta}(t) + c\dot{\delta}(t) \]  
(2)

Where \( k \) is the stiffness of contact element which describes the local stiffness at contact point and \( c \) denotes the contact element’s damping which is given by:

\[ c = -2\ln e \left( \frac{k m_i m_j}{\pi^2 + (\ln e)^2(m_i + m_j)} \right) \]  
(3)

Where \( e \) is the coefficient of restitution, and \( m_i = i \ (1, 2) \) are the masses of colliding objects (Anagnostopoulos, 1988, Jankowski, 2005). According to Jankowski (2005), for steel to steel impact, the linear viscoelastic model with \( k = 450000 \) KN/m and \( e = 0.60 \) Shows good agreement with experimental results obtained by van Mier et al. (1991). Thus, these values are employed in the present research.

**Link Elements**

Contact of buildings and pounding force has been simulated by link elements which are inserted between buildings (Fig. 2(a)). A link element having gap property (Fig. 2(b)) and one with linear property are used. The purpose of the gap property is to transmit the force through the link element only when contact occurs and the gap is closed. The force-deformation relationship of gap property is given by:

\[ f_G = \begin{cases} 
-k_G \left[ \left( u_i - u_j \right) - \text{open} \right] & \text{if} \ u_i - u_j < \text{open} \\
0 & \text{if} \ u_i - u_j \geq \text{open} 
\end{cases} \]  
(4)

Where \( k_G \) is the spring constant, \( u_i \) and \( u_j \) denote the displacements of the element’s end nodes, and open is the initial gap opening. According to equation 4 this type of links are nonlinear elements.

\[ f = k_L d_L + c_L \dot{d}_L \]  
(5)

Figure 2. (a) Buildings connected by link elements, (b) Link element with gap property, and (c) Link element with gap property combined with Kelvin-Voigt element.

As mentioned before, energy dissipation during contact can be occurred as a result of damping. The link element with gap property which is used in the SAP2000 software does not have damping. Hence, a link element with gap property is combined with a link element with linear property (Kelvin-Voigt element) to obtain the desired contact behavior (Fig. 2(c)). The force-deformation relationship of the link element with linear property is expressed as where \( k_L \) is the spring constant, \( c_L \) denotes the damping coefficient, and \( d_L \)
describes the deformation in the direction across the link element (Eq.5). The stiffness and damping of contact element proposed by Jankowski (2005) are used for linear property. The stiffness of the gap property is set to be 1000 times higher than that of linear element (k_G = 1000 k_L) so that it works nearly rigidly when the gap is closed.

Statement of Problem

Two adjacent 12m x 12m, 7-story (structure A) and 4-story (structure B) buildings are considered. Both of them have moment resisting frames and are consist of 3 equal 4-meter bays in each direction. Story heights are 3 meter for both building. Material of members is ST-37 steel grade with modulus of elasticity E=2.1x10^6 Kg/cm², passion ratio of ν=0.3, yielding stress F_y=2400 kg/cm² and weight per unit volume ρ=7850 kg/m³. Additional dead and live load on the floors were selected as 0.6 t/m² and 0.2 t/m², respectively. At first, each structure designed separately according the codes; Eurocode8 and Eurocode2-2005. All members have been chosen from European steel profile norm (Fig.3a).After final designing members, the two structures connected as described in pervious section. The Mass properties of each floor was concentrated on a master joint of floor and other floor joints constrained with diaphragm constraining option. X&Y-translational mass and Rotational mass were assigned 11745Kg and 281880 Kg.m; respectively. Gap distance (Open Parameter in Eq.4) between two Buildings is set to 5cm. (Fig.3b & 3c)

Analysis and Numerical Results

Buildings are modeled as elastic moment resisting frames with a 5% damping ratio which assumed is proportional to the mass and stiffness matrix (Eq.6). In equation 6 alpha and beta are Rayleigh linear coefficients. Time history analysis are carried out by Nonlinear Newmark-β method with β = 0.25, γ = 0.5 and time step Δt = 0.01 seconds, using the FEM computer program SAP2000.V14.
\[ \alpha[M] + \beta[K] = C \] (6)

The N-S component of acceleration record of the 1995 KOBE earthquake with effective duration 8.2sec is used as input earthquake motion along the x-axis. (Fig.4)

![Figure 4. 1995 KOBE Earthquake](image)

By moving the center of mass along Y-axes, each building is reached at specific eccentricities. The variation of this shifting is according to Table1, the parameter of \( e \) is assigned as amount of moving from symmetrical center and \( r \) is equal to gyration radius of buildings plan (\( r=3.46 \text{m} \)). So totally 121 analysis was preformed.

<table>
<thead>
<tr>
<th>( e )</th>
<th>-3</th>
<th>-2</th>
<th>-1.5</th>
<th>-1</th>
<th>-0.5</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e/r )</td>
<td>-87%</td>
<td>-58%</td>
<td>-43%</td>
<td>-29%</td>
<td>-14%</td>
<td>0%</td>
<td>14%</td>
<td>29%</td>
<td>43%</td>
<td>58%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Table1. Amount of assigned eccentricities to the models

During the analysis some parameter such as top displacement of two structures, base reaction and pounding force of each story has been monitored. Then Maximum amount of each parameter have been plotted versus related \( e/r \) case.

![Figure 5. Base reaction along x-axis](image)  ![Figure 6. Top displacement of 7-story building](image)
Conclusions
From the results it can be shown that large amount of eccentricities (various distance from central mass and stiffness of the structures) can make different pounding forces which will affect on performance of the structure. For example at the upper stories the structures are more sensitive to variation in the amount of eccentricities and make high pounding forces.
In summery the plan eccentricities in adjacent structures have a significant affection on the base shear, pounding forces and its story levels.

Acknowledgments
The authors would like to express their deep appreciation and gratitude to Dr. Mahmood Hosseini who shared his knowledge and experience to help make the publication of this research.

References


S. mahmoud, X. chen and R. jankowski “structural pounding models with hertz spring and nonlinear damper” journal of applied sciences 8(10):1858,2008,ISSN 1812-5654


Ryosuke OHTA, Anil C. WIJEYEWICKREMA, Alireza FARAHANI, END BUILDING POUNDING DURING EARTHQUAKES, Symposium on Infrastructure Development and the Environment 2006, 2006, SEAMEO-INNOTECH