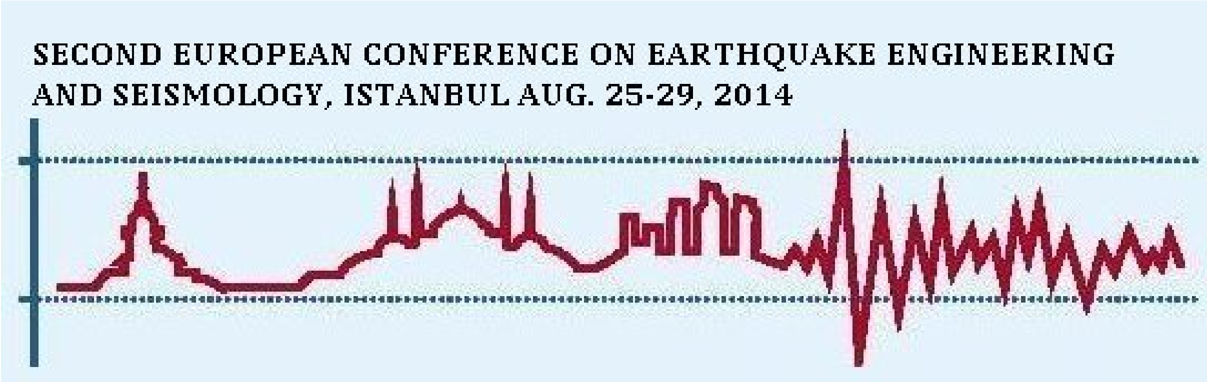

NUMERICAL INVESTIGATION OF POUNDING EFFECTS BETWEEN ADJACENT BUILDINGS

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ABSTRACT

Post-earthquake damage investigations have illustrated that buildings are exposed to suffer severe damage or to collapse during moderate to strong ground motion. Among these damages, seismic pounding has been commonly observed in several earthquakes, especially during the 2003 Boumerdes, Algeria, earthquake of magnitude of 6.8.In this study, a mathematical modelling of adjacent building pounding has been developed and its application in a nonlinear seismic analysis is presented. Numerical investigation, aiming to evaluate accurately the pounding effect on adjacent structures and its effects on global response has been carried out. It focuses on the importance of the dynamic characteristics of adjacent building structures in causing relative responses.

INTRODUCTION

During earthquake, pounding of adjacent buildings could have worse damage as adjacent buildings with different dynamic characteristics, which vibrate out of phase and there is insufficient separation distance or energy dissipation system to accommodate the relative motion of adjacent buildings, this effect introduces potential clashing efforts impact not included in the initial project; they will be superimposed to those resulting from the seismic excitation itself. According to the dynamic characteristics of adjacent structures clashing could cause serious structural damage or in some cases even the possibility of a complete collapse of structures in certain extreme situations.
The simplest way and effective way for pounding mitigation and reducing damage due to pounding is to provide enough separation. The value of the separation distance or critical space (dmin) must be large enough to avoid the risk of contact. According to the seismic codes, this value depends mainly on the displacement due to seismic design forces.

REQUIRED SEPARATION DISTANCE TO AVOID POUNDING

It is recognized and accepted pounding is undesirable phenomenon and should be avoided or mitigated. This is recognized in seismic design codes and regulations worldwide, which typically specify minimum separation distances to be provided between adjacent buildings. However, there seems to be considerable variation on required separation distance to avoid the pounding between two structures. Some of the codes recommended the absolute sum method where the separation distance is given by:

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$$S = u_1 + u_2 \tag{1}$$

Where S is the separation distance and u_1 and u_2 are the displacement responses of the buildings at the potential location (i.e., at the top of the shorter building). Eq. 1 will subsequently be referred to as the ABS rule. In the case of buildings located on the same property, UBC (1997) and IBC (2006) specifies that the separation distance between adjacent buildings is given by:

$$\Delta_{MT} = \sqrt{\Delta_{MA}^2 + \Delta_{MB}^2} \tag{2}$$

Δ_{MA} *and* Δ_{MB} These are the displacement of adjacent buildings

Equation 2 will be subsequently referred as SRSS rule. A more rational approach that is usually referred to as the Double Difference Combination (DDC) rule, for estimation of the critical required separation distance, which is obviously equal to the peak relative displacement response (Lopez Garcia 2004, Penzien 1997), is given by:

$$S = \sqrt{X_A^2 + X_B^2 - 2\rho_{AB} X_A X_B} \tag{3}$$

Where X_A and X_B are the peak values of $X_A(t)$ and $X_B(t)$, respectively. The correlation coefficient, ρ_{AB} depends on the period ratio $\rho_{AB} = T_A/T_B$, as well as ξ_A and ξ_B, (Lopez Garcia 2004, Penzien 1997) and is given by

$$\rho_{AB} = \frac{8\sqrt{\xi_A \xi_B}\left(\xi_A + \xi_B \frac{T_A}{T_B}\right)\left(\frac{T_A}{T_B}\right)^{1.5}}{\left[1-\left(\frac{T_A}{T_B}\right)^2\right] + 4\xi_A \xi_B \left[1+\left(\frac{T_A}{T_B}\right)^2\right]\left(\frac{T_A}{T_B}\right) + 4\left(\xi_A^2 + \xi_B^2\right)\left(\frac{T_A}{T_B}\right)^2} \tag{4}$$

Where T_A, ξ_A and T_B, ξ_B are natural periods and damping ratios of sytems A and B, repectively. The DDC rule is much more accurate than the ABS and SRSS rules, although it gives somewhat un-conservative results when T_A and T_B are well separated (Lopez Garcia 2004, Penzien 1997).

GAP ELEMENT MODEL

Some seismic codes specify simple methods to calculate the adequate joint between adjacent buildings. As an example, in the Algerian seismic code (RPA99/V2003), the joint width should be at least equal to the top displacement of the two building plus 2cm. Here after, a method for computing the adequate joint width is introduced (Figure 1). To simulate the pounding which is highly nonlinear phenomena, contact element method was used. In this study a linear model with a linear spring is used to represent the impact force during the pounding of the adjacent structure.

The magnitude of the contact force, f_c, is simulated using a linear contact model. As illustrated in Figure 2, the adopted contact element is a linear spring having an assumed axial stiffness of the beam. The contact force is governed by Eq. 5 given by:

$$\begin{cases} f_c = k(u_1 - u_2 + d) & if \quad (u_1 - u_2 + d) < 0 \\ f_c = 0 & if \;\; not \end{cases} \tag{5}$$

Where: u_1 and u_2 are the maximums displacements in contact element for building 1 and building 2 respectively, d is the open of contact element model.

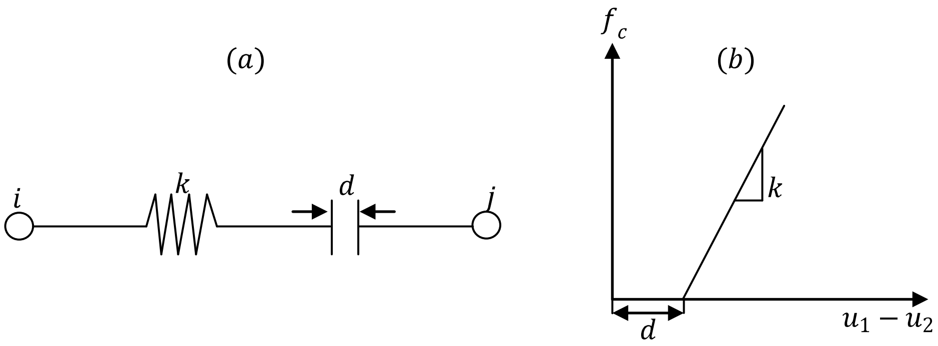

Figure 1. Contact element model, (a) Contact element and (b) behavior of the contact element

CASE STUDY

In order to investigate the effects of the pounding on the adjacent structure with dynamic characteristics (time period) a case of two adjacent structure is selected. In the present case study three buildings are selected as this pair showed constantly high normalized gap for non-linear system.
Eight, six and three-story reinforced concrete plane frame structures are considered in this study (Figure 2). The purpose of this study is to investigate the behavior of each structure under a design earthquake, and to assess the pounding effects on each of the two adjacent buildings. These structures are subjected to a unidirectional El Centro 1940 ground motion record, N-S component. To evaluate the structural performance of the structures in the post-elastic range, the El Centro record is scaled from 0.1 to 1.0. These buildings were modeled using a finite element method that allows the analysis of the collisions impact between the upper stories of the buildings. The periods of these buildings for the fundamental mode shape are 0.81 sec, 0.62 sec and 0.32 sec respectively.

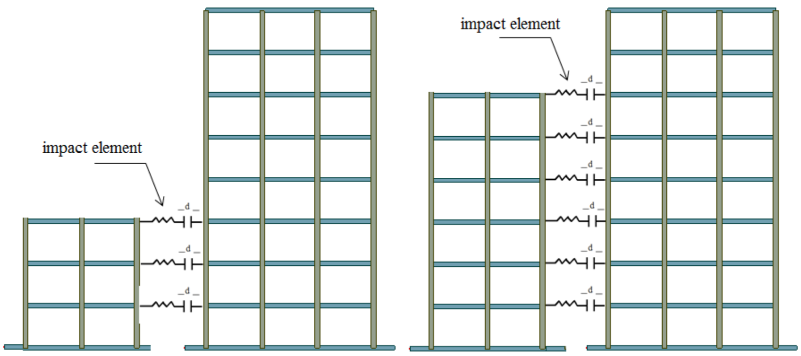

Figure 2.Finite element mathematical model and Elevation view

During the study pounding response of the structured subjected to simulated ground motion with different separation distance was studied. The gap distance were adjusted to represent no gap condition, 10%, 25%, 50% and 75% of the required separation distance to avoid contact pounding was also conducted for comparison with the pounding cases. Table 1 presents the different separation gaps calculated by various codes with the analytical separation distance for a case with two adjacent buildings of (0.81 sec and 0.62 sec) and (0.81 sec and 0.32 sec). The analytical separation distance required to avoid the pounding for non-linear cases was 31.56 cm for the buildings of 8 and 6 story and 32.17cm for the second system. The separation gaps calculated according to the buildings codes were normalized to the required separation gap for non-linear Multi Degree-of-Freedom (MDOF) system.

RESULTS AND DISCUSSION

The results of the nonlinear analysis are presented in figure 1. The presented results show that absolute method represented by ABS is conservative and the conservatism is excessive especially when the two adjacent structures have nearly similar natural period. SRSS method predicts the separation distance which are conservative when the both the MDOF have nearly similar dynamic characteristics. DDC method could predict the separation distance required fairly accurately when the adjacent structures have nearly similar dynamic property. The results of the nonlinear analysis are shown in figure 1.

Table 1. Separation gap required by codes and normalization to required gap ($d = 10.02cm$)

Case study	ABS (cm)	SRSS (cm)	DDC (cm)	Analytical (cm)
(8-3) levels	32.27	27.54	27.51	32.17
(8-6) levels	46.01	32.91	31.68	31.56

Table 2. Separation gap required by codes and normalization to required gap ($d = 4.5cm$)

Case study	ABS (cm)	SRSS (cm)	DDC (cm)	Analytical (cm)
(8-3) levels	4.49	4.38	4.37	4.49
(8-6) levels	13.58	10.10	9.81	10.01

Table 3 present the pounding response of the two adjacent non-linear (for 8 and 3 story) with the different gaps sizes normalized to the gap size required to avoid the pounding. The table indicates unlike as in the linear case the increase in normalized separation distance does not result in the reduction of the pounding force. The result presented indicates the maximum impact force of 1517.8 KN is found for the 0 % of the required separation gap and minimum of 0 KN when gap is 100% of the required separation gap.

Table 3: Pounding response of nonlinear (8 and 3 story)

(%)	Separation gap (cm)	Impact force (*KN*)
0	0	1.5178e+003
10%(d)	0.45	1.3658e+003
25%(d)	1.12	1.1395e+003
50%(d)	2.25	7.5789e+002
75%(d)	3.37	3.7964e+002
d	**4.5**	**0**

Table 4. Pounding response of nonlinear (8 and 6 story)

(%)	Separation gap (cm)	Impact force (KN)
0	0	3.3707e+003
10%(d)	1.00	3.0330e+003
25%(d)	2.50	2.5264e+003
50%(d)	5.00	1.6821e+003
75%(d)	7.51	8.3441e+002
d	**10.02**	**0**

The result presented indicates the pounding of structures may result in detrimental response of both the adjacent structures when there is no separation or the separation gap is too small. However poundings may have beneficial impact on the ductility demand of both adjacent structures when there is liberal gap provided even though the pounding force is higher for such cases.

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The Hamering problem between adjacent structures occurs when the separation, joint, between adjacent structures is insufficient to accommodate the out of phase movement of the two adjacent structures. As an example, Figure 3 shows the impact force for 8 and 6 story buildings.

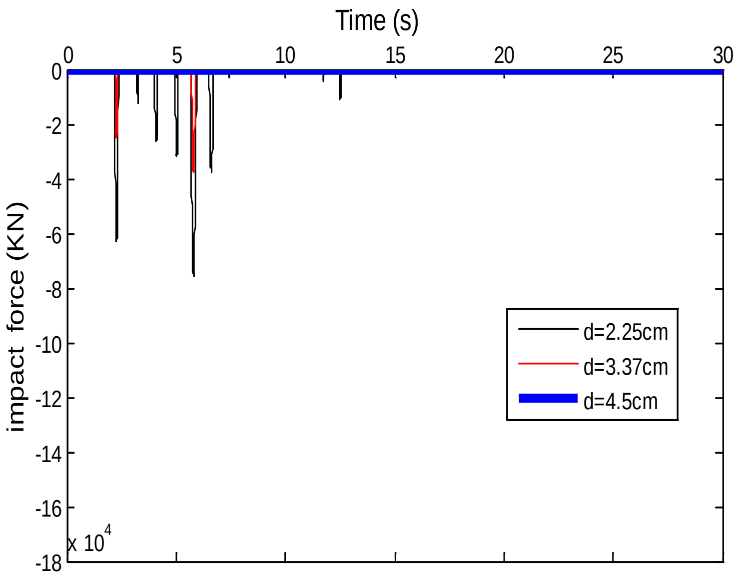

Figure 3.Impact force time history, nonlinear MDOF (8-3) for 50%, 75% and 100% of required gap.

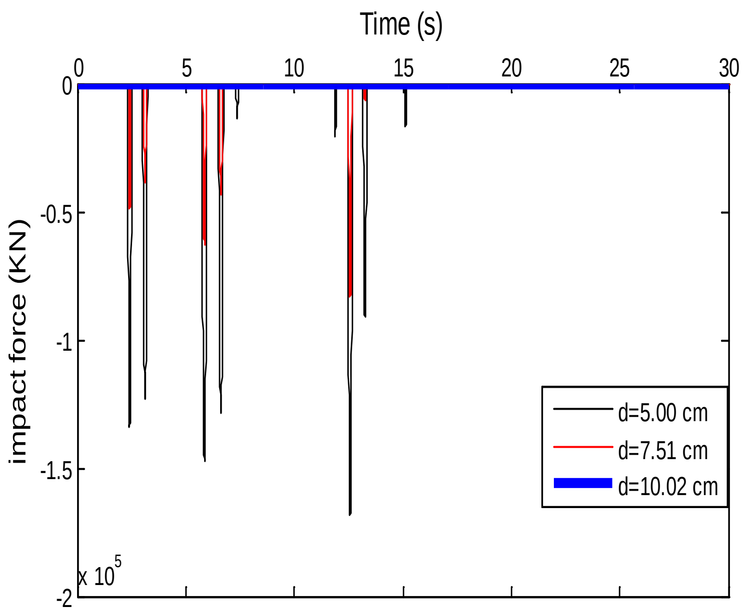

Figure 4.Impact force time history, nonlinear MDOF (8-6) for 50%, 75% and 100% of required gap

The importance of the contact force on the adjacent structures with different joint width revealed that increasing the distance of separation result in the contact force reduction. The non-linear dynamic analysis was performed to estimate the separation distance and the number of impacts for adjacent buildings according to the seismic demand. The obtained results were compared in terms of the size of the separation distance (Figure 5).

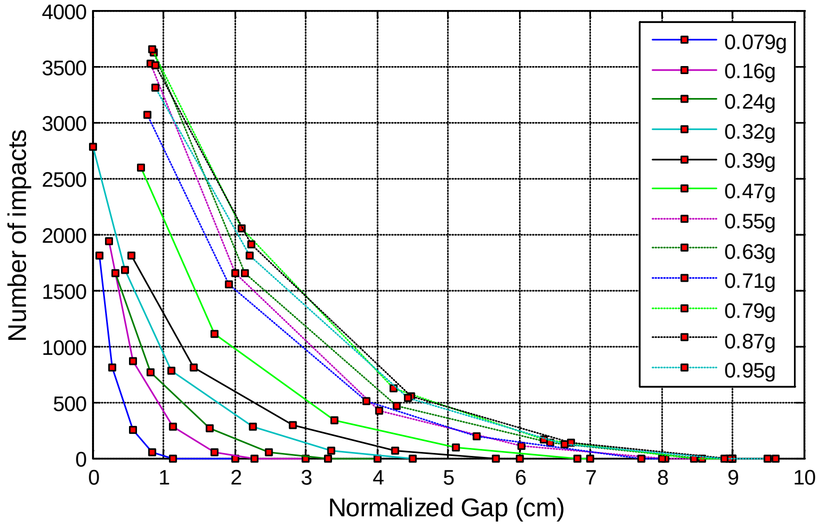

Figure 5. Total number of impacts for adjacent buildings (SP8-SP6) in terms of the size of the separation distance

CONCLUSION

Evaluation of the separation gap based on the displacement due to seismic forces can only be a single criterion, but it also depends on the characteristics of the seismic action and the relationship between the fundamental periods of adjacent structures.
The analytical study described in this paper show that SRSS and DDC rules gives results are conservative or un-conservative depending on the relationship between the natural periods of the systems. It is worth mentioning that the results presented were based on a single simulated ground motions need to be observed. The ABS method resulted in conservative results and at times the conservatism is excessive making it difficult to implement (especially when two MDOF has nearly similar dynamic property). Only DDC method capable of considering the vibration phase difference of the adjacent structure.
Pounding response analysis of the adjacent structures considering the different normalized separation distances revealed that when the nonlinear material behavior is considered, the stiffer structures suffers detrimentally whereas the flexible structure benefits. The impact force in general decreases as the separation distance increase. However pounding response of the nonlinear MDOF exhibits that the pounding may even result in detrimental response of both the adjacent structures.

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