Earthquake Pounding Effect on Adjacent Reinforced Concrete Buildings

Mariam Ehab
Assistant lecturer
Postgraduate student
Structural Engineering
Department Cairo University

Hamed Salem
Professor
Structural Engineering
Department
Cairo University

Hatem Mostafa
Professor
Structural Engineering
Department Cairo University

Nabil Yehia
Professor of Concrete Structures
Cairo University

ABSTRACT
During earthquakes, pounding of adjacent buildings occurs due to their different dynamic characteristics as well as insufficient separation distance between them. Although earthquake loading is commonly considered in structural design, pounding of adjacent buildings is not usually considered and usually causes highly unexpected damages and failures. Pounding effect was numerically investigated in this study, where adjacent buildings were designed to resist lateral earthquake loads without taking into consideration the additional applied force resulting from pounding. Nonlinear dynamic analysis was carried using the Applied Element Method (AEM). Pounding of buildings of different structural systems, different gravity loading and different floor heights was investigated. Dynamic behavior in terms of additional base shear, base bending moments and pounding forces was investigated for different gap distances less than the safe gap distance specified by the Egyptian Code of Practice (ECP). Effect of gap distance, building's dynamic characteristics, building's height and gravity loads on additional straining actions due to impact was discussed.

Keywords
Pounding, separation distance, applied element method.

1. INTRODUCTION
In metropolitan cities, buildings are often very close since a maximum land use is required due to high population density. Therefore, for metropolitan cities located in regions of active seismicity, the pounding of adjacent buildings may pose a potentially serious problem. Pounding of adjacent buildings during earthquake excitation is one of the causes of structural damages. Some of the local damages take place due to the unexpected lateral impact force due to pounding which is not usually considered in building design. Sometimes it may cause building's collapse under a stronger earthquake. The Mexico City earthquake in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings, and in 15% of all cases it led to collapse [1] [2]. A survey of pounding incidents in San Francisco Bay area during 1989 Loma Prieta earthquake showed significant pounding cases, over 200, at sites over 90 km from epicenter [3], Several destructive earthquakes, both distant and near, have hit Egypt in both historical and recent times. The annual energy release in Egypt and its vicinity is equivalent to an earthquake with magnitude varying from 5.5 to 7.3 on Richter scale. For example Cairo 1992 earthquake that lead to a catastrophic damages, 350 buildings were completely destroyed and 9,000 other severely damaged and causing 545 deaths, injuring 6,512 and making 50,000 people homeless [4]. After that destructive earthquake, the authorities in Egypt changed the design specifications and included an obligatory for a gap distance between neighboring buildings. The current research is focusing on existing adjacent buildings that are not considering the code limitation gap distance. The effect of pounding that takes place due to the difference in the lateral displacements of the two adjacent buildings at the same level is studied. Different lateral deformations results from the difference in vibration modes of the adjacent buildings, which in their turn, depend on the structural system, height, weight and stiffness of structural elements. Since structural pounding could cause damage, partial collapse or total collapse of pounded structures, in this study, the pounding effect was investigated using nonlinear time history dynamic analysis based on the Applied Element Method (AEM) [5] [6] [7] and [8], which is proved to be capable of simulating structural progressive collapse in an efficient way [9, 10] The Extreme Loading of Structures software (ELS®) [11] was used for this purpose.

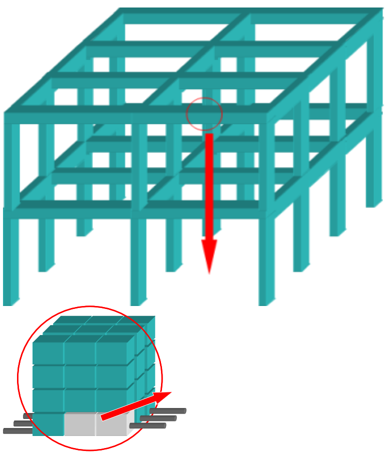
2. LITERARTURE REVIEW
Many researchers studied the pounding phenomenon due to its importance and its effect on the adjacent buildings.

Many models with different software has been employed to study this phenomenon , obtain the resulting impact force, studying and comparing the impact force values with the different parameters that affect the pounding, such as: the gap distance , the peak ground acceleration, different building height and structural systems. Anagnostopoulos [12] used a simplified model of several adjacent buildings in a block to study the pounding of such buildings due to strong earthquakes. The structure was modeled as an SDOF system and simulated pounding using impact elements. Maison and Kasai [13] presented the formulation and solution of the multiple degree of freedom equations of motion for a type of structural pounding. They implemented the theory into microcomputer program to perform a sample analysis of an actual 15-storey building in order to study the response behaviors. Their parametric investigation included pounding location elevation, building separation (gap size), local flexibility spring stiffness and initial sway amplitude. Anagnostopoulos and Spiliospolos [14], analyzed the response of adjacent buildings in city blocks to several strong earthquakes, taking into account the mutual collisions, or pounding, resulting from insufficient or non-existing separation distances. The buildings were idealized as lumped mass, shear, and beam type, multi-degree of freedom (MDOF) systems with bilinear force-deformation characteristics and with bases supported on translational and rocking spring-dashpots. Regarding the studied factors, the effect of system configuration is clear. Jeng et al. [15], presented a method to estimate the likely minimum building separation to preclude seismic pounding. The method was based on random vibration theory.

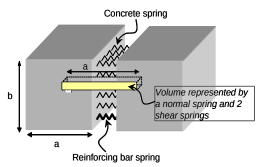
3. APPLIED ELEMENT METHOD (AEM) [16]

The Applied Element Method is an innovative modeling method adopting the concept of discrete cracking. In the Applied Element Method (AEM), the structures are modeled as an assembly of relatively small elements, made by dividing of the structure virtually, as shown in Figure 1.a. The elements are connected together along their surfaces through a set of normal and shear springs. They are responsible for transfer of normal and shear stresses, respectively, from one element to another. Springs represent stresses and deformations of a certain volume as shown in Figure 1.b.

Each single element has 6 degrees of freedom; 3 for translations and 3 for rotations. Relative translational or rotational motion between two neighboring elements cause stresses in the springs located at their common face as shown in Figure 2. These connecting springs represent stresses, strains and connectivity between elements. Two neighboring elements can be separated once the springs connecting them are ruptured.



a-Element Generation for AEM



b- Spring distribution and area of influence of each pair of springs

Figure 1 Modeling of structure to AEM

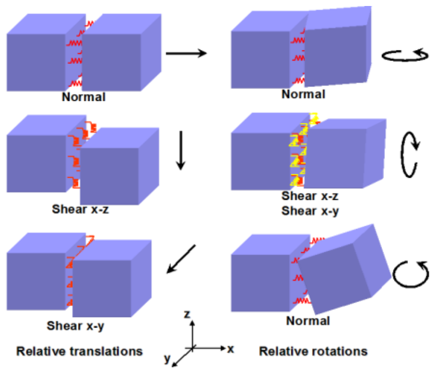


Figure 2 Stresses in springs due to relative displacements

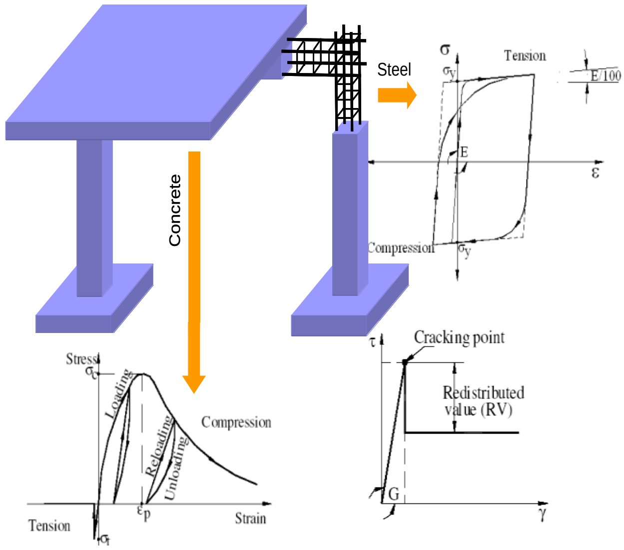


Figure 3 Constitutive models adopted in AEM for concrete and steel.

Fully nonlinear path-dependant constitutive models for reinforced concrete are adopted in the AEM as shown in figure 3. For concrete in compression, an elasto-plastic and fracture model is adopted [17]. When concrete is subjected to tension, a linear stress strain relationship is adopted until cracking of the concrete springs, where the stresses then drop to zero. The residual stresses are then redistributed in the next loading step by applying the redistributed force values in the reverse direction. For concrete springs, the relationship between shear stress and shear strain is assumed to remain linear till the cracking of concrete. Then, the shear stresses drop down as shown in Figure 3. The level of drop of shear stresses depends on the aggregate interlock and friction at the crack surface. For reinforcement springs, the model presented by Ristic et al. (1986) is used [18]. The tangent stiffness of reinforcement is calculated based on the strain from the reinforcement spring, loading status (either loading or unloading) and the previous history of steel spring which controls the Bauschinger's effect. The solution for the dynamic problem adopts implicit step-by-step integration (Newmark-beta) method [19] [20]. The equilibrium equations represent a linear system of equations for each step. The solution of the equilibrium equations is commonly solved using Cholesky upper-lower decomposition. Once elements are separated, the stiffness matrix becomes singular. However, the stability of the overall system of equilibrium equations is kept because of the existence of the mass matrix. Separated elements may collide with other elements. In that case, new springs are generated at the contact points of the collided elements.

One of the main break-through features in the ELS® software, is the automated element contact detection. The user does not have to predict where or when contact will occur. Elements may contact and separate, re-contact again or contact other elements without any kind of user intervention.

4. PARAMETRIC STUDY

The intensity of pounding between adjacent buildings due to earthquake is affected by many factors such as: the Peak Ground Acceleration (PGA) of the earthquake, the separation distances between the buildings, the dynamic properties of the pounding buildings, soil configurations and the structural system for resisting lateral loads.

4.1 Main Assumptions

The main assumptions adopted are as follows; in all cases, the building geometry in plan is kept constant and the foundation is assumed totally fixed to the ground. There is no time lag between the earthquake excitation for the two adjacent buildings due to the short distance between them.

4.2 The Earthquake Record

In this study one type of the recorded earthquakes will be used which is KOBE earthquake wave (Japan, 1995). It is normalized to the Peak Ground Acceleration of Cairo zone (0.15g). The time history analysis adopted in this study.

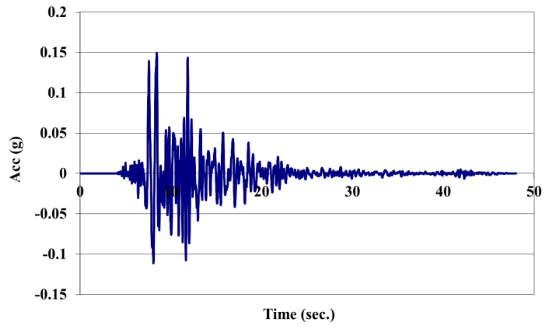


Figure 4 Normalized KOBE earthquake

4.3 Gap Distance

The gap distance between adjacent buildings is usually calculated as the maximum displacement of the two adjacent buildings at the same height (Δmax). In some codes such as ECP 203 (2007) [21] and the UBC (1997) [22], the minimum required gap distance is calculated as the Square Root of Sum of Squares (SRSS) as follows:

$$G.D. = \sqrt{(\Delta_1)^2 + (\Delta_2)^2} \qquad \text{eq. (1)}$$

Where:

$\Delta 1$: the maximum displacement for one of the adjacent buildings.

$\Delta 2$: the maximum displacement for the second building at the same level considered in the first building.

This condition is relaxed in case of corresponding floors; i.e. floor slab hits floor slabs of the adjacent building. In such case, the recommended separation distance of equation 1 is reduced by 30%.

In this study, the calculation for the safe gap distance is carried out according equation 1 and its reduced value in case of corresponding floors. The pounding effect is investigated through assuming different gap sizes smaller than the value recommended by equation 1.

4.4 Description and Configuration of the Numerical Model

In this study, six buildings of different loading type, structural systems and floor heights are designed as shown in Fig. 6. Two lateral load resisting structural systems are considered in this study; moment resisting frame system and shear wall system. According to the ECP 203 (2007), live load is only considered if its value is more than or equal 0.5 t/m^2, where in such case only 50% of its value is considered.

4.4.1 Lateral load moment resisting Frame system

12-storey buildings with different live loads and floor heights are designed to resist the earthquake lateral loading through the framing action between columns and beams.

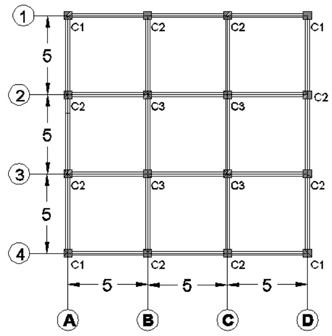
4.4.2 Shear-wall lateral load resisting system

12-storey buildings with different live loading and floor heights are designed to resist the earthquake lateral loading through four shear walls located at mid distance of the four facades. Table 1 shows a detailed description of the six buildings.

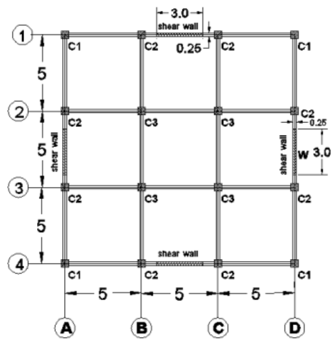
Table 1 Buildings' description.

Building's Name	Structural System	Floor Height (m)	Live Load (t/m^2)	Maximum Displacement due to Earthquake (cm)
Building 1	Frame	3	0.2	8.8
Building 2	Frame	3	0.5	9.9
Building 3	Frame	1st floor=4.5 Typical =3.0	0.2	14.7
Building 4	Frame	3	(1-3)*= 0.4 (4-7)*= 0.5 (8-12)*=0.2	9.5
Building 5	Shear-walls	3	0.2	13.5
Building 6	Shear-walls	3	0.5	15.1

*Floor level



a- Buildings 1, 2, 3 and 4



b- Buildings 5 and 6

Figure 5 Typical plan structural system

A suitable meshing pattern has been chosen for each structural element as shown in Table 2.

Table 2 Mesh discretization for different structural elements

Elements	Meshing number
columns	1x1x6
Beams	1x1x10
Slabs	6x6x1

4.4.3 Case study

Six cases of adjacent buildings are investigated in this study as follows:

- Case 1: Building 1 with Building 2 (Both are frames having the same floor levels)
- Case 2: Building 5 with Building 6 (Both are shear walls having the same floor levels)
- Case 3: Building 1 with Building 3 (Both are frames having different floor levels)
- Case 4: Building 1 with Building 4 (Both are frames having same floor levels but with different floor masses)
- Case 5: Building 1 with Building 5 (Frames and shear walls having same floor levels)
- Case 6: Building 3 with Building 5 (Frames and shear walls having different floor levels)

All cases are studied with different gap sizes less than or equal to the code specified gap size; equation 1, as shown in Table 3.

Table 3 Different gap distances for the studied cases.

Case	Case 1	Case	Case	Case	Case	Case
Code Specified	9.5	14.1	17	9	11.5	20
Different Gap distances (cm)	8	12	14	6	8	16
	6	10	12	4	4	12
	4	8	10	2	0.6	8
	2	6	8	0.6		4
	0.6	4	6			0.6
		2	4			
		0.6	2			
			0.6			

5. ANALYSIS AND RESULTS

The analytical results are evaluated in terms of: (1) the maximum impact value and its location, (2) the overall effect of pounding on the buildings, damages and local failure.

5.1 Detailed Results for Case 1

As a sample, comprehensive details of analysis results will be shown for Case 1, while a comparison of the pounding behavior will be discussed for all case studies. It is shown in Figures 6 and 7 the impact history and the maximum impact force per floor during the applied earthquake for gap distances of 8, 4 and 0.6 cm, respectively. It is shown in Figure 8 the location of the collision springs generated at impact locations for different gap distances. These contacts are represented by red bubbles.

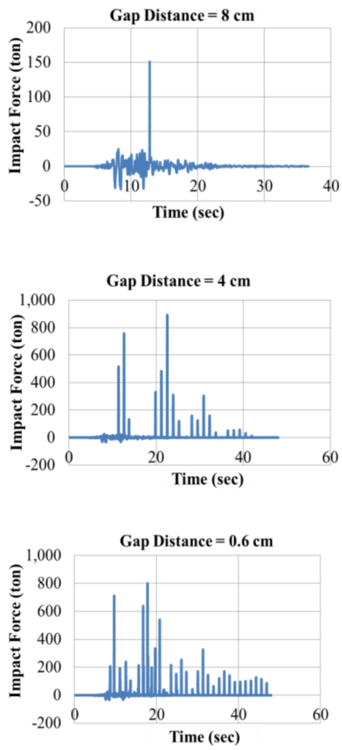


Figure 6 Impact history for different gap distance, Case 1.

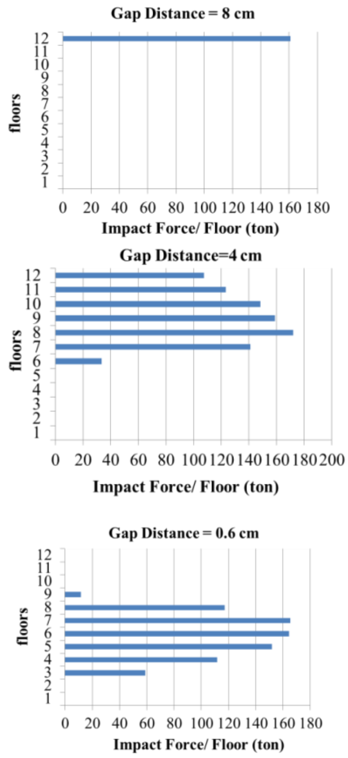
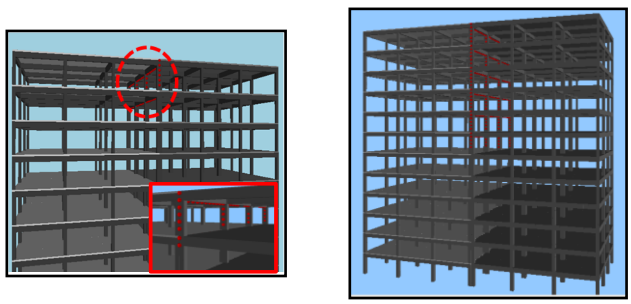


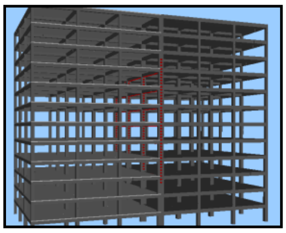
Figure 7 Maximum impact force/floor for different gap distance, Case 1.

It is shown in Figures 9 and 10 the effect of gap distance on both number of hits and maximum impact force during seismic action. It shows that as the gap distance decreases the number of hits and the total impact force increases, respectively. However, the maximum impact force/floor stays almost the same but changes in location. No hit occurs if gap distance equals the code recommended value.

Total shear force at the building base as well as the impact forces history is shown in figure 11. It is noticed that no major change occurs in the maximum base shear values with respect to the different gap distances. This indicates that the impact force is not totally transferred to shear at the building base. It is shown in figure 12 the history of the base moment during pounding. The Figure shows that as the gap distance increases the damping of the base moment increases, i.e. base moment value drops more rapidly with time during the earthquake. In other words, pounding of adjacent buildings retards damping of base moment. This can be explained by the internal forces transmitted to both buildings by the impact forces.



a) GD=8cm, Case 1. **b) GD=4cm, Case 1.**



c) GD=0.6cm, Case 1.

Figure 8 Location of collision springs for different gap sizes, Case 1.

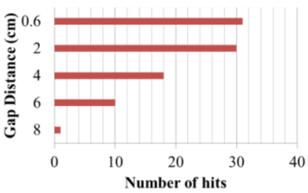


Figure 9 The number of hits vs. gap distances for Case 1.

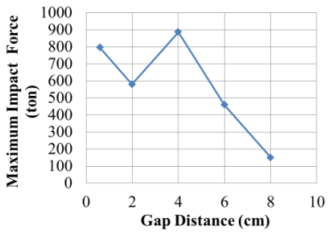


Figure 10 Maximum pounding forces vs. gap distance for case 1.

Impact forces are transferred to different structural elements in the form of different internal stresses; as shear forces in columns , normal forces in slabs and beams parallel to seismic action, torsion in columns , bending in slabs(in plane and out of plane), bending in beams and torsion in beams. The stress mentioned in table 4 represents the major type of stresses transferred by slabs, beams and columns.

The change in the normal stresses from tension to compression and the change in the shear stresses' direction are indicated by negative sign.

Table 4 Effect of pounding on collided members for case 1.

collided structural member	% of impact force transferred	% of average increase in internal stresses due to impact	Type of internal force/stresses
slabs	20.12	80.20%	normal
beams	27.3	-126.80%	normal
columns	8.43	-106%	shear

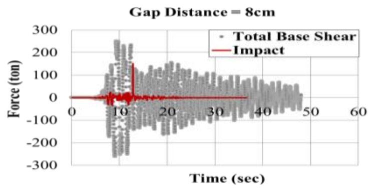
5.2 Comparison of behavior of different case studies

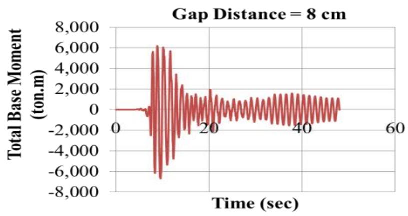
It was numerically observed that, generally for cases of adjacent buildings of the same height, pounding location mainly took place at the top floors of the pounded buildings except for cases with relatively small gap distance ,where pounding tended to take place at the middle or bottom floors.

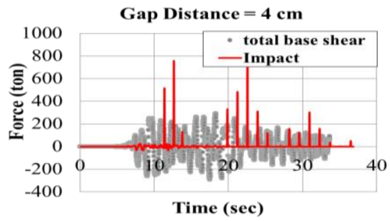
In the following section, a comparison is carried out for the results of the different case studies. Comparison is carried out for different gap distances in terms of each of maximum impact force, contribution of different structural elements in transferring impact forces and the total base shear and base moments.

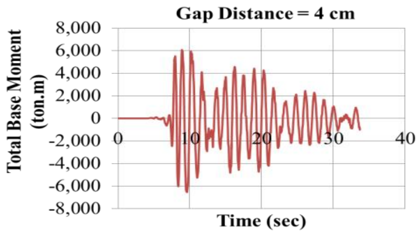
5.2.1 Maximum Impact Forces

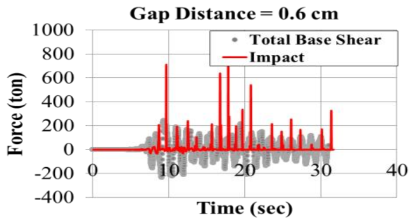
Code specified gap distances are calculated according to the ECP (Egyptian code of practice). Models and runs for the six cases are held by gap distances equal to and less than the code limitation to study the pounding and the impact force resulting from it. For each case maximum impact force is obtained for different gap distances

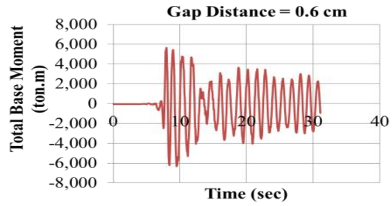












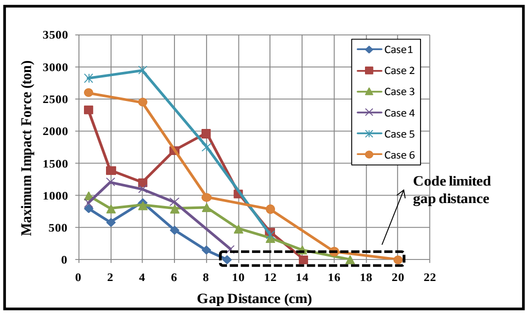


Figure 11 Maximum Impact force versus different gap distances

The calculated maximum impact force for different gap distances is shown in figure 13. It can be observed that the maximum impact force increases with the decrease in gap distance. The ECP code limit for gap distance is sufficient enough to prevent pounding occurrence in cases 1, 2, 3 and 6, while not sufficient in cases 4 and 5. It can be generally concluded that the code equation for safe gap distance calculation is un-conservative for adjacent buildings with different structural systems.

Cases of same structural systems having same floor levels with different live loads showed same tendency in pounding behavior, in which the maximum impact force value drops at a gap distance approximate equal to 25% the value of the code limit for gap distance as shown in case 1 and 2. Cases of different adjacent building dynamic properties, such as cases 4 and 5, showed a drop in the value of the maximum impact force at a gap distance approximate equal to 7% of the limit value for gap distance.

5.2.2 Structural elements contribution in transfer of impact forces

Figure 16 illustrates the percentage of impact transferred as normal stresses in slabs. As observed, the contribution of slabs in transfer of impact force is high due to their high in-plane axial rigidity.

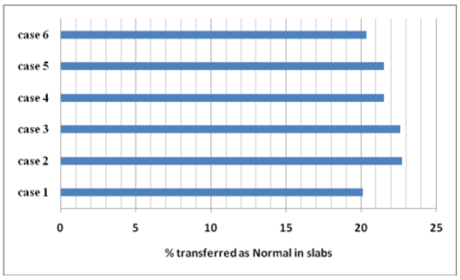


Figure 12 Slab contribution in impact force transfer

The percentage of impact transferred as shear stresses in impacted columns is demonstrated in figure 15. It is noticed that impacted column in cases of different floor levels (3 and 6) are subjected to high shear stresses compared to the cases of same floor levels. In this case floor slabs of one building hit the middle column height of the adjacent one, which will cause additional shear stresses on the impacted columns and higher percentage of column contribution in impact force transfer.

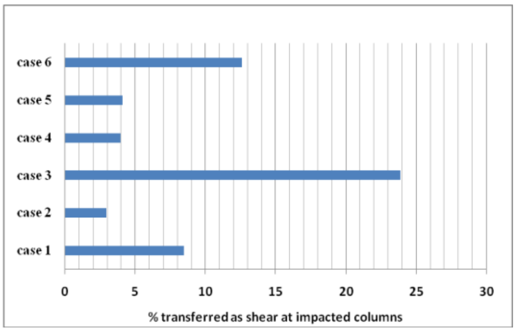


Figure 13 Impacted columns contribution in impact force transfer

It is illustrated in figure 16 the percentage of the impact force that is transferred in the form of shear stresses in the impacted shear walls located perpendicular and parallel to the seismic actions. The force transferred by the walls perpendicular to the seismic action is relatively small compared to that parallel to the seismic action, due to the relatively smaller rigidity of the shear walls in the impact direction.

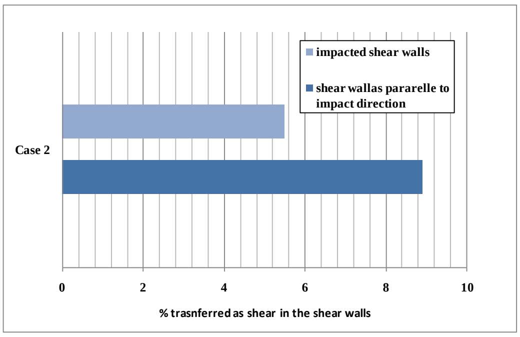


Figure 14 impacted shear walls contribution in impact force transfer

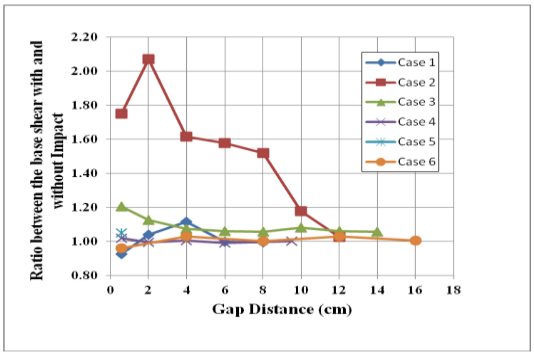


Figure 15 Ratio of total base shear for the pounded cases to that for un-pounded cases

Figure 17 shows the ratio of the total base shear for the cases of pounded structures to that for the cases of un-pounded structures, for different gap distances. As seen, the base shear increase is of an average of 10% for all cases except for case 2 where a maximum of 110% is observed for a gap distance of 2 cm. This is due to the fact that both colliding buildings are shear wall type where the maximum displacement for each individual one is the highest as shown in Table 3.

Figure 18 shows the ratio of the total base moment for the cases of pounded structures to that for the cases of un-pounded structures, for different gap distances. As seen, the base moment increase is of an average of 20% with a maximum of 55% for case 5 for a gap distance of 4 cm.

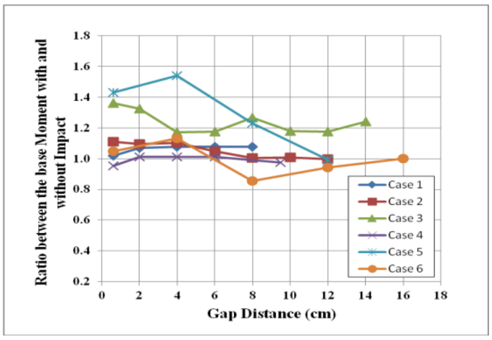


Figure 16 Ratio of total base moment for the pounded cases to that for un-pounded cases

It was also observed that the number of hits increased as the gap distance between adjacent buildings decreased. However, maximum impact force seems not to be affected by the increase in the number of hits.

5.3 Failure and damages

It is noticed that local damages occurred in the cases of adjacent buildings of different floor levels (Case 3 and Case 6).This is due to the lateral impact of the mid-height of the columns of a building by slabs of the other. It is noticed that the damages mainly occur at the last floor due to the small column cross section dimensions compared to the columns of the lower floors as shown in Figure 19.

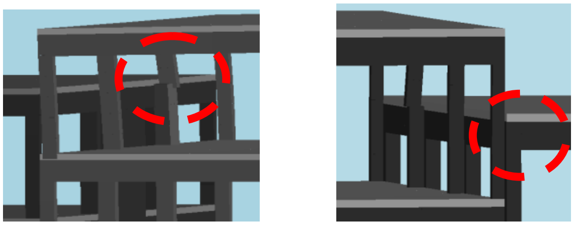


Figure 17 local damages in last floor columns in cases 3 and 6.

6. CONCLUSIONS

Neglecting the soil-structure interaction, considering foundations as rigid enough, and neglecting potential seismic phase difference between adjacent buildings, the following conclusion could be drawn for the scaled Kobe earthquake:

Adjacent buildings of the same loading, same structural system and same floor levels encountered same oscillation and same mode of vibration. As a result, no pounding occurred. On the other hand buildings of different mode of vibration experienced pounding during earthquake excitation. When impact took place, the impact forces acted as external additional lateral forces that changed the mode of vibration of the pounded buildings. Impact forces were distributed on the impacted side and transferred to the different structural members as internal normal and shear stresses. Impact force distribution on the collided members varied according to the in-plane member's stiffness and arrangement.

The slabs were found to have a high contribution in the impact force distribution due to its infinite in-plane stiffness. However, the case of non-corresponding floor levels in which the slab of one building hits the mid height of column of the adjacent building, unexpected increase in the shear stresses in columns was observed. This unexpected stress causes local damage in the collided columns increasing the possibility of the buildings collapse.

Internal shear and normal stresses in the collided members are affected severely by the impact force. An increase of normal stresses of up to 208% and 138 % was observed in slabs and transverse beams, respectively, while shear stresses in columns increased by 275%.

The ECP code limit for gap distance is un-conservative for adjacent structures with different structural systems. Therefore, it needs a refinement to take into consideration such a case.

The potential of the local damage of edge columns is high for adjacent structures with different floor levels.

For pounded structures with pounding different gap distances, maximum base shear and moment didn't encounter any major changes in their magnitudes during pounding except case 2 for pounding of adjacent building with shear-wall system.

For existing adjacent structures that were not constructed with the code regulations for minimum safe gap distance, it is highly recommended to make an assessment for potential pounding under seismic excitations, so that necessary strengthening for beams and columns can be carried out.

7. REFERENCES

[1] Rosenblueth, E. and Meli, R. "The 1985 Earthquake: Causes and Effects in Mexico City", Concrete International, Vol. 8, No. 5, 1986

[2] Bertero, V. "Observation of Structural Pounding", Proceedings of the International Conference: The Mexico Earthquake-1985, ASCE, 1986

[3] Kasai, K. and Maison, B. "Structural Pounding Damage, Loma Prieta Earthquake Reconnaissance Report, Chapter 6, Structural Engineers Association of California, 1991

[4] www.engineeringcivil.com

[5] Tagel-Din; H. and Meguro; K.," Applied Element Method for simulation of nonlinear materials: theory and application for RC structures. In Structural Engineering, Earthquake Engineering Japan Society for Civil Engineers (JSCE) ; 17 (2): pp. 137-148, 2000.

[6] Meguro; K. and Tagel-Din; H. "Applied Element Method for structural analysis: theory and application for linear materials", In Structural Engineering, Earthquake Engineering., Japan Society for Civil Engineers (JSCE); 17(1): pp. 21-35, 2000

[7] Meguro; K., and Tagel-Din; H. "Applied Element Simulation of RC Structures under Cyclic Loading", ASCE, 127(11), pp. 1295-1305, 2001.

[8] Meguro; K., and Tagel-Din; H."AEM Used for Large Displacement Structure Analysis", Journal of Natural Disaster Science, 24(1), pp. 25-342, 2003.

[9] Galal K, El-Sawy T., Effect of retrofit strategies on mitigating progressive collapse of steel frame structures, Journal of Constructional Steel Research, 2010, 66 (4), 520-531.

[10] Hartmann, D., Breidt, M., Nguyen, V., Stangenberg, F., Hohler, S., Schweizerhof, K., Mattern, S., Blankenhorn, G., Moller, B., and Liebscher, M. (2008), Structural Collapse Simulation under Consideration of Uncertainty –Fundamental Concept and Results, Computers and Structures, 86, 2064–2078.

[11] www.extremeloading.com Extreme Loading of Structure software Manual.

[12] Anagnostopoulos; S. "Pounding of Buildings in series During Earthquakes", Earthquake Engineering and Structural Dynamics, Vol. 16, pp.443-456 (1988)

[13] Maison; B. and Kasai; K., "Dynamics of pounding when two Building Collide", Earthquake Engineering and Structural Dynamics, Vol. 21, pp.771-786, 1992.

[14] Anagnostopoulos; S. and Spiliopoulos; K. "An Investigation of Earthquake Induced Pounding between Adjacent Buildings", Earthquake Engineering and Structural Dynamics, Vol. 21, pp228-302, 1992.

[15] Jeng;V, Kasai;K. and Jagiasi; a., "The Separation to avoid Seismic Pounding", Earthquake Engineering, Tenth World Conference, Balkema, Rotterdam, 1992.

[16] www.appliedelementmethod.org.

[17] Maekawa K, Okamura H. The deformational behavior and constitutive equation of concrete using the elasto-plastic and fracture model. J Faculty Eng Univ Tokyo (B) 1983; 37(2):253–328.

[18] Ristic D, Yamada Y, Iemura H. Stress–strain based modeling of hysteretic structures under earthquake induced bending and varying axial loads. Research report No. 86-ST-01, School of Civil Engineering, Kyoto University, Kyoto, Japan; 1986.

[19] Bathe K. Solution of equilibrium equations in dynamic analysis. Englewoods Cliffs, NJ: Prentice Hall; 1982.

[20] Chopra; A."*Dynamics of Structures: Theory and Applications to Earthquake Engineering"*, Prentice Hall, Englewoods Cliffs, N.J, 1995

[21] Egyptian Code of Practice for Design of Reinforced Concrete structures, ECP 203-2007, Vol. 3, Edition 2008.

[22] Uniform Building Code, Structural Engineering Design Provision, Vol. 2, 1997.