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INVESTIGATION OF SEISMIC POUNDING OF ADJACENT MULTI-STORY REINFORCED CONCRETE BUILDINGS

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ABSTRACT

Pounding or collisions between adjacent buildings during strong ground shaking creates additional forces and causes damage to building finishes at the points of collisions. To avoid pounding a separation distance or seismic gap must be provided between adjacent buildings to completely preclude pounding during earthquakes. However, such separation distance, particularly at the expansion joints in the same building, presents significant cost element that needs to be reduced by minimizing the seismic gap to the smallest possible size. The different factors affecting pounding and its mitigation are investigated in this paper. Nonlinear numerical analysis is used for pounding force and displacement calculation. A detailed parametric study is carried out to investigate the effect of various parameters on the structural pounding including the earthquake record, the separation distance, the structural system in terms of stiffness and mass distribution, the building height as well as the effect of structural damage and cracking. Finally, the provisions of international building codes dealing with pounding issues are assessed.

1. Introduction

Pounding is the collision of adjacent structures due to induced out of phase vibrations of the structures during seismic events. Pounding occurs between adjacent units of same building separated by expansion joints, adjacent buildings with relatively small separation distance, and adjacent buildings connected by a bridge. The pounding phenomenon has been the main cause for the initiation of collapse in many recorded earthquakes. Examples of damage are infill wall damage, plastic deformation, column shear failure, local crushing and possible collapse of the structure. Also, it becomes more disastrous if the adjacent structures have different floor levels, because this will lead to it may lead to shear failure in the columns of the taller building causing its collapse (Chris G.Karayannis, 2004). The patterns of the damage vary from minor and

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architectural damages to major structural damages. Pounding can be catastrophic and more dangerous than the effect of earthquake on a single building.

All major earthquakes of the last decades showed damages resulting from pounding (Arnold C, 1982). There are many cases reported where pounding has been identified as a primary cause for the failure. The earthquake of the 1985 in Mexico City is a premiere example of how destructive pounding and structural vibrations are toward large structures. The number of building affected by pounding in Mexico City is the largest ever reported from a single earthquake, with almost half of the collapsed structures having symptoms of pounding. Another example is the Loma Prieta earthquake of 1989 caused severe damage in California. The buildings in this area sustained massive structural damage. There were over 200 pounding occurrences involving more than 500 buildings in SanFrancisco, Oakland, Santa Cruz and Watsonville. Significant Pounding was observed at sites over 90 km from the epicenter, which implies the massive impact of pounding phenomena.

Many factors were suggested by researchers that affect pounding including among others: soil condition, building heights, relative difference between building's heights, separation between adjacent buildings, the lateral load resisting structural system, the collision's points and location, the stiffness of the structures, the peak ground acceleration of the earthquake at the location of building, the fundamental period of the structure, the fill material or expansion joints material (if any), seismic zone, damping mechanisms, building's condition (old, new, retrofitted), the adopted methods of pounding mitigation, and the torsion response of the structure (if any). International building codes are concerned mainly with the separation distance between adjacent building and structural drift. According to the different seismic codes the main factors that affect pounding due to their huge impact on the drift of the structure are building height, separation between adjacent buildings, seismic zones, and lateral load resisting system.

Many methods were suggested and endorsed as effective methods of mitigation of pounding. Those include permanent connectors joining adjacent structures at critical locations, use of fill material to absorb deformations, boosting the stiffness of lateral load resisting systems, etc.(Al-Atrpy,2008). However, the method that was adopted by the vast majority of international codes is adequate separation distance between adjacent buildings. The reason is that it is the most practical, cost effective method compared to the other methods.

2. Parametric Study of Factors Affecting Pounding

The most important four factors or parameters affecting pounding according to majority of code provisions are:1) building height, 2) earthquake records, 3) separation between adjacent buildings, and 4) lateral load resisting system.

The configurations selected for studying the abovementioned parameters are outlined in this section. Four groups are formed for the four parameters where 144 combination cases among the four groups are analyzed. The four groups are formed as follows:

A. Lateral load resisting systems (frames, shear walls with the extent of two full bays, and mixed frame with shear wall extending 1/2 bay):
   1. Frame hitting frame
   2. Mixed system (frame and shear Wall) hitting mixed system

3. Frame hitting shear wall
4. Shear wall hitting shear wall

B. Building height:
1. 8-stories hitting 12-stories building
2. 8-stories hitting 8-stories building
3. 12-stories hitting 12-stories building

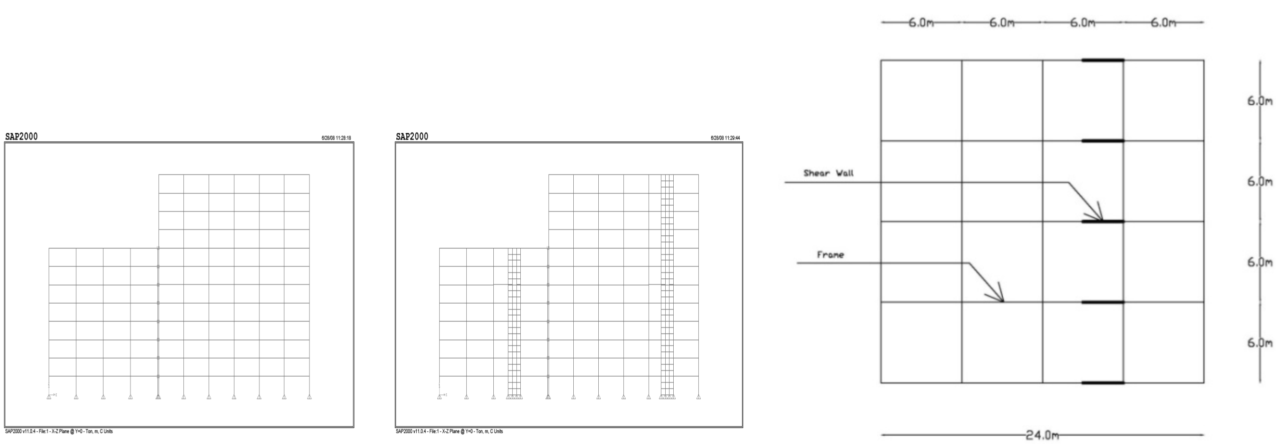
C. Separation distance:
1. 5 mm
2. 20 mm
3. 40 mm

D. Earthquake record scaled to 0.15g:
1. El Centro Earthquake
2. Petrolia Earthquake
3. S. Monica Earthquake
4. New Hall Earthquake

The separation distances above were choosen in order to represent the common practice in Egypt and other countries where the separation distance is not designed and is inadequate as the majority of the codes recommend separation distance ranges from 75mm to 110mm for the studied configuration.

This leaves us with 12 groups (4 cases of lateral load systems for 3 building height cases); each group is analyzed for 12 cases (3 separation distance and 4 earthquake records). The results of such analysis are presented in following section. Due to space limitation, sample dimensions and configuration of the considered systems are shown in Figure 1 and Table 1. More details are found in (Al-Atrpy, 2008).

So, the studied configurations are 8 and 12 stories concrete systems consisting of moment resisting frames and shear walls as shown in Fig.1-c. The systems are going to be 4 bays for 8 stories frame and 6 bays for 12 stories frame.



a) Frame-frame system b) Mixed-mixed system c) Mixed frame/shear wall system in plan

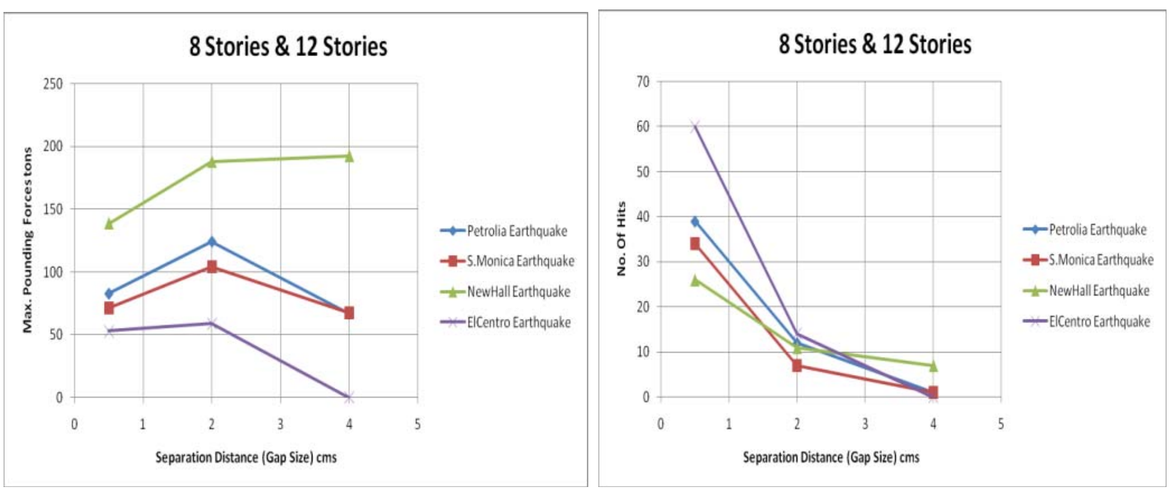
Figure 1: Pounding between 8 and 12 stories building models

Table 1: Typical dimensions of structural elements in a 12 stories mixed system

Floor	Exterior Column (mm)	Interior column (mm)	Beam (mm)	Shear wall (mm)
G & 1st	400x1100	400x1200	300x900	300x3000
2nd&3rd	400x1000	400x1100	300x900	300x3000
4th&5th	400x900	400x1000	300x900	300x3000
6th&7th	400x800	400x900	300x900	300x3000
8th&9th	400x700	400x800	300x900	300x3000
10th&11th	400x600	400x900	300x900	300x3000

3. Analysis of results of the parametric study

Figure 2 shows the effect of building height, structural system, earthquake record and the separation distance on the pounding forces for the considered cases. Figure 3 shows the variation of pounding forces along the building height for 8-storeis frame hitting 12-stories frame system with 5mm separation and subjected to Petrolia Earthquake. The figures show that the pounding forces are very much affected by the characteristic of the earthquake and dynamic characteristics of the building. For some earthquake records large pounding force may be produced for smaller gaps. There is no general trend relating the pounding force to the gap. However as the separation distance increases the number of pounding hits decreases.



a) Maximum Pounding Force b) Number of pounding hits

Figure 2: Effect of separation distance and earthquake record on pounding for 8-storeis frame with 12 stories frame system

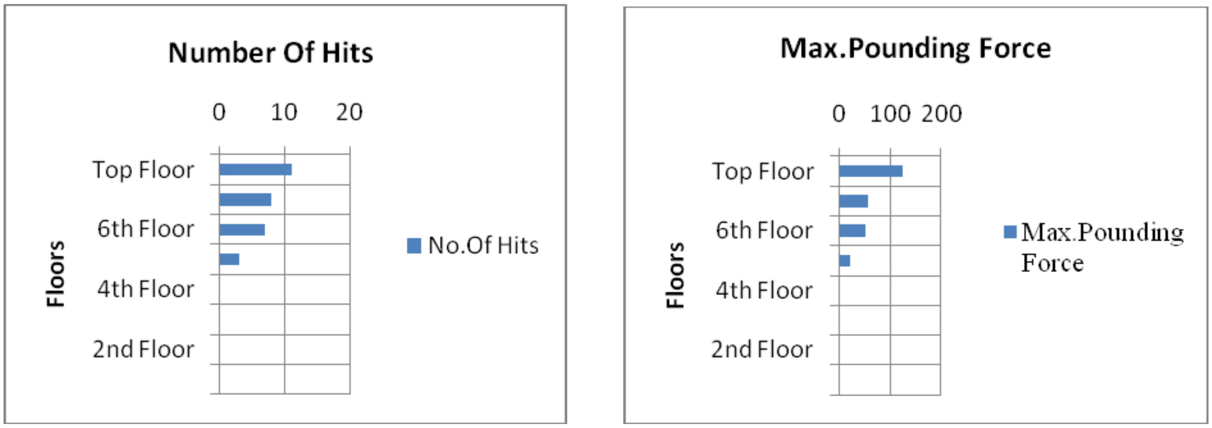
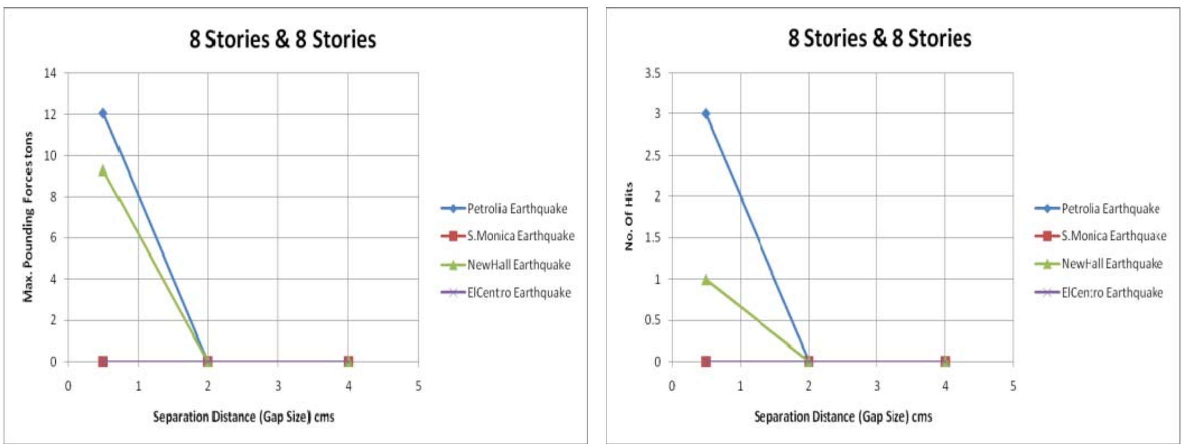
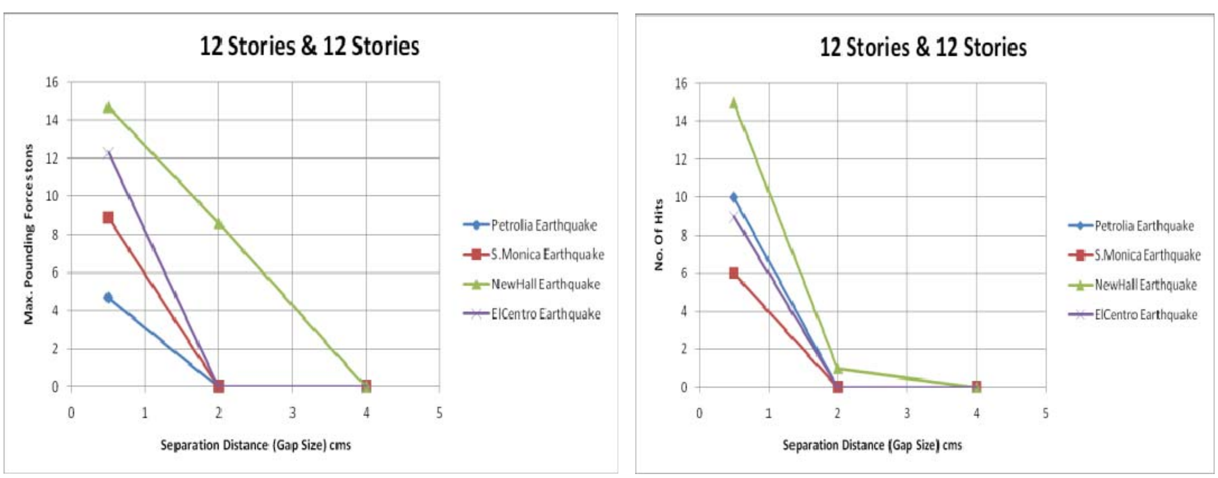


Figure 3: Distribution of pounding forces along the building height for 8-storeis frame with 12 stories frame system 5mm Separation and Petrolia Earthquake



a) Maximum Pounding Force b) Number of pounding hits

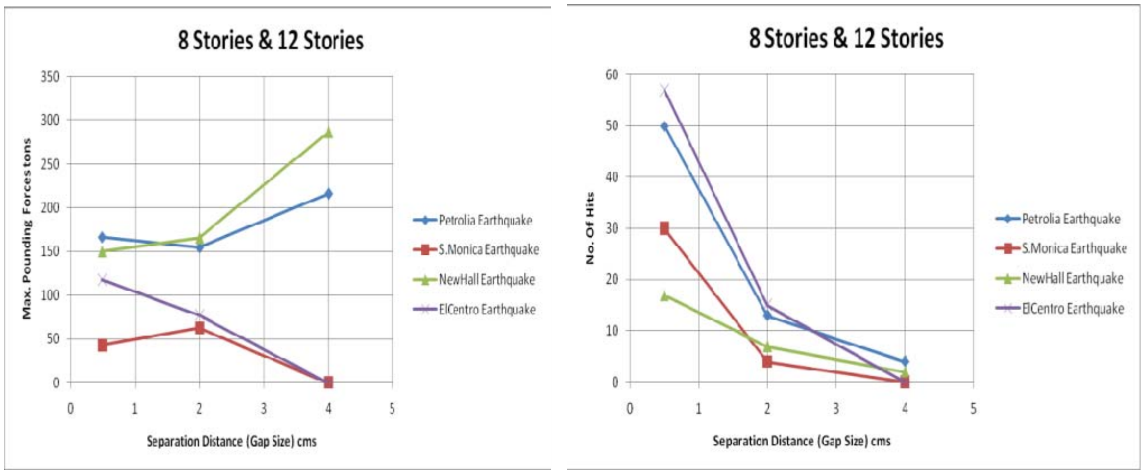
Figure 4: Effect of separation distance and earthquake record on Pounding for 8-stories frame with 8-stories frame system



a) Maximum Pounding Force b) Number of pounding hits

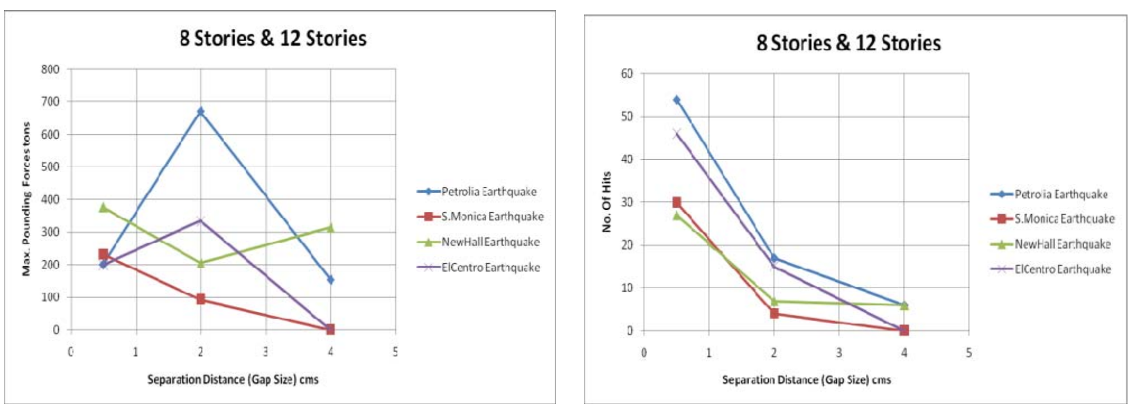
Figure 5: Effect of separation distance and earthquake record on Pounding for 12-storeis frame

with 12-stories frame system



a) Maximum Pounding Force b) Number of pounding hits

Figure 6: Effect of separation distance and earthquake record on Pounding for 8-storeis mixed system with 12-stories mixed system



a) Maximum Pounding Force b) Number of pounding hits

Figure 7: Effect of separation distance and earthquake record on Pounding for 8-storeis frame system with 12-stories shear wall system

Tables 2-4 shows the variation of pounding forces with height for the same seismic gap (20 mm) and the same earthquake record (Petrolia) for different structural system and building height. As the differences in structural system and height get larger, the pounding effect becomes more pronounced in both the value of the force and the frequency of occurrence.

The concrete cracking and local repairable damage significantly effects the displacements and deformations of the structures and consequently the pounding. Concrete cracking is considered in this paper through modified effective moment of inertia I_{eff} instead of gross moment of inertia I_g according to relevant code provisions. Concrete cracking is mainly applied by reducing the stiffness of the building's members to 35% for beams, 50% for shear walls, 70% for columns. The effect of concrete cracking is considered on the mixed frame-shear-wall lateral load resistant system as one of the most common systems in Egypt. Also, the choice of 8-story building hitting 12-story building was to include the whiplash effect. The buildings were subjected the Petrolia Earthquake record with three different separation distances as shown in Table 5. Since pounding depends on the dynamic characteristics of the earthquake record and the building system, some of the considered cases results in significant increse while others in decrease in pounding forces.

Table 2: Pounding variation with height for frame-frame system and 20 mm gap

Story	8-stories / 8-stories		8-stories / 12-stories		12-stories / 12-stories	
	Force kN	No. of hits	Force kN	No. of hits	Force kN	No. of hits
12th					4.7	11
11th					3.6	10
10th					1.5	3
9th					0	0
8th	0	0	124.1	11	0	0
7th	0	0	58.5	8	0	0
6th	0	0	51.4	7	0	0
5th	0	0	21.9	3	0	0
4th	0	0	0	0	0	0
3rd	0	0	0	0	0	0
2nd	0	0	0	0	0	0
1st	0	0	0	0	0	0

Table 3: Pounding variation with height for mixed-mixed system and 20 mm gap

Story	8-stories / 8-stories		8-stories / 12-stories		12-stories / 12-stories	
	Force kN	No. of hits	Force kN	No. of hits	Force kN	No. of hits
12th					5.5	2
11th					3.8	2
10th					0	0
9th					0	0
8th	5.5	2	155.2	13	0	0
7th	24.2	2	91.5	9	0	0
6th	8.5	1	87.7	1	0	0
5th	2.5	1	0	0	0	0
4th	0	0	0	0	0	0
3rd	0	0	0	0	0	0
2nd	0	0	0	0	0	0
1st	0	0	0	0	0	0

Table 4: Pounding variation with height for frame-wall system and 20 mm gap

Story	8-stories / 8-stories		8-stories / 12-stories		12-stories / 12-stories	
	Force kN	No. of hits	Force kN	No. of hits	Force kN	No. of hits
12th					75.8	9
11th					59.2	8
10th					68.7	8
9th					66.6	10
8th	913.2	17	671	12	152.7	9
7th	239.1	22	257	12	142	8
6th	455.1	11	227.7	10	165.9	6
5th	221.6	5	136.70	4	158	3

4^{th}	415	5	96.7	6	0160.4	3
3^{rd}	36	2	52.7	4	0	0
2^{nd}	0	0	0	0	0	0
1^{st}	0	0	0	0	0	0

Table 5: Effect of concrete cracking on pounding forces for different gap values

	Separation distance 5 mm		
	Without cracking	With cracking	% Change
Pounding Force kN	166.8	138.8	- 16.8%
Number of hits	34	34	Zero

	Separation distance 20 mm		
	Without cracking	With cracking	% change
Pounding Force kN	155.2	238.1	+ 53.4%
Number of hits	9	9	Zero

	Separation Distance 40 mm		
	Without cracking	With cracking	% of Change
Pounding Force kN	216.5	76.8	- 64.5%
Number of hits	4	5	+ 25%

4. Pounding Provisions in International Codes

The method of mitigation of pounding "Separation distance between buildings" was adopted by most of the codes all over the world. First of all, because it is the most simple, practical method and it is easy to implement in the design of earthquake resisting structures and sometimes (depending on the situation) the cheapest as well. The differences between codes were mainly a matter of how to calculate proper and safe separation distance between the structures, which is not too small to permit pounding neither too large to be impractical expansion joints and expensive solution (loss of land usage).

Provisions of Eurocode 8 (Jan 2003)

According to Eurocode, buildings shall be protected from earthquake-induced pounding with adjacent structures or between structurally independent units of the same building. This is deemed to be satisfied: (a) For buildings, or structurally independent units, that does not belong to the same property, if the distance from the property line to the potential points of impact is not less than the maximum horizontal displacement of the building at the corresponding level, (b) For buildings, or structurally independent units, belonging to the same property, if the distance between them is not less than the square-root-of-the-sum-of-the squares (SRSS) of the maximum horizontal displacements of the two buildings or units at the corresponding level. If the floor elevations of the building or independent unit under design are the same as those of the adjacent building or unit, the above referred minimum distance may be reduced by a factor of 0.7.

International Building Code 2009 (Feb 2009)

IBC specifies that the design story drift shall not exceed the allowable story drift values set by the code. For structures with significant torsional deflections, the maximum drift shall include torsional effects. For structures assigned to seismic design category C, D, E or F having horizontal irregularity, the design story drift shall be as the largest difference of the deflections along any of the edges of the structure at the top and bottom of the story under consideration. All portions of the structure shall be designed and constructed to act as an integral unit in resisting seismic forces unless separated structurally by a distance sufficient to avoid damaging contact under total deflection. The minimum separation distance shall allow for the maximum inelastic response displacement of the adjacent structures, so that separation distance is not less than square root of the summation of square value of maximum inelastic displacement of each structure.

National Building Code of Canada (2005)

Lateral deflections obtained from a linear elastic analysis incorporating the effects of torsion, including accidental moments, shall be multiplied by a factor to give realistic values of anticipated deflections. The largest interstorey deflection at any level based on the lateral deflections shall be limited to $0.01h_s$ for post-disaster buildings, $0.02h_s$ for schools, and $0.025h_s$ for all other buildings, where h_s is the storey height. Adjacent structures shall either be separated by square root of sum of all squares of their individual deflections or shall be connected to each other. The method of connection shall take into account the mass, stiffness, strength, ductility and anticipated motion of the connected buildings and the character of the connection. Buildings with non-rigid or energy dissipating connections require special studies.

7. Summary and Conclusions

In this paper, structural pounding was defined; the factors affecting seismic pounding of adjacent buildings were identified and critically examined. Also, the various methods of mitigation of pounding were presented. Parametric study on seismic pounding phenomenon is conducted to examine the effects of various factors on seismic pounding. The effect of structural damage and concrete cracking on seismic pounding is illustrated. Finally, the main provisions related to pounding in thof some of the most widely used international codes are assessed.

Pounding forces can be calculated using commercial software packages like Sap 2000 where nonlinear gap elements between the adjacent building floors are used to calculate pounding forces. The variation in the stiffness of the gap element has negligible effect on the calculated pounding forces. However, the size of the gap significantly affect the calculated forces their frequency of occurrence.

Pounding forces depends very much on the characteristics of the earthquake records and the dynamic characteristics of the adjacent buildings. The Effect of earthquake record is not limited to just the value of force; it affects the frequency of hits also.

Pounding forces increases as the difference in the structural systems in the adjacent buildings increases. The largest pounding forces occur when there is a difference in height of the adjacent buildings due to the whiplash effect. Highest values of pounding forces occur near the top of the building.

In generally pounding forces decreases as the separation distance increases. However, very small separation distance may prevent the build-up of momentum of the moving masses thus reducing the impact forces. However, this depends very much on the characteristics of earthquake record. It is observed that the number of pounding hits consistently decreases as the separation distance increases.

Pounding forces are significantly affected by concrete cracking which can be modeled using the effective moment of inertia instead of the gross moment of inertia according to the relevant codes.

Most of the international building codes adopted the "Separation distance between buildings" method as the main and effective method of mitigation of pounding. Those separations the codes proposed, usually prevent the pounding but at the expense of practicality, and sometimes the spacing required is difficult to apply due to technical and economic issues. Further research is required to minimize the required spacing while considering the possibility of acceptable pounding forces.

Finally, the conclusion (based on the scope of structures studied), is that the structures with more shear walls and bigger seismic gap will experience less pounding damage.

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