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A CODE COMPARATIVE STUDY ON SEISMIC POUNDING OF ADJACENT BUILDINGS WITH APPLICATIONS

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ABSTRACT

Pounding or collisions between adjacent buildings occurs as a result of building lateral vibrations during strong ground shaking. Pounding that may also occur at expansion/structural joints of the same building 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, present a significant cost element that needs to be reduced by minimizing the seismic gap to the smallest possible size. Several research works were directed toward accurate calculations of the separation distance which was also specified by international building codes. Factors affecting the pounding phenomenon are presented in this study. The most effective and straightforward method for reducing pounding, as recommended by most of the international codes, is providing the proper separation distance. In this paper, the provision of several international building codes dealing with the pounding issue are assessed and compared to each other where the similarities and differences have been pointed out. Finally, numerical modeling of pounding in several building systems subjected to different earthquake records are used for pounding and separation distance evaluation where the applicability of the different international building codes provisions are numerically assessed.

1. Introduction

The term "Structural pounding" is used to describe the collisions between adjacent buildings during earthquakes. This is common when there is insufficient separation distance between the adjacent buildings. The main cases of pounding are adjacent units of same building separated by expansion joints, adjacent buildings with relatively small separation distance, adjacent buildings connected by a bridge.

The earthquakes induce out of phase vibrations in adjacent structures due to differences in dynamic characteristics, in addition to inadequate separation distance or energy dissipation system, leading to a collision between structures. The pounding phenomenon has been the main cause for the initiation of collapse in many recorded earthquakes. The pounding is a very complex phenomenon it could lead to infill wall damage, plastic deformation, column shear

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failure, local crushing and possible collapse of the structure. Furthermore, adjacent structures with different floor levels are more vulnerable to seismic pounding; this is due to the additional shear forces on the columns causing more damage and instability to the building (Chris G.Karayannis,2004). The patterns of the damage vary from minor and architectural damages to major structural damages.

It is a fact that in all major earthquakes of the last decades, structural pounding was present (Arnold C, 1982, Anagnostopoulos, 1995, Anagnostopolos, 1996). 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 (Rosenblueth E, 1985, Bertero, 1986).

2. Factors Affecting Pounding

It became imperative that the physical aspects of pounding must be understood in order to form a rational basis for methods to mitigate its potentially disastrous consequences. Many papers, researches and code provisions suggested many factors that affect the pounding phenomena. They include: 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), the material of construction (steel, concrete, masonry), storey height, seismic zone of the location , type of induced vibrations (in-phase or out-of-phase), damping mechanisms, building's condition (old, new, retrofitted), the adopted methods of pounding mitigation., and the torsion motion of the structure during earthquake.

While some of above listed factors have trivial impact on the pounding of structures still others are critical and strongly affect the pounding phenomena. The majority of codes are mainly concerned with the separation distance between adjacent building and structure drift (which includes building height, lateral load resisting system adopted in the studied structures, seismic zone and torsional effects). The main factors that affect pounding due to their huge impact on the drift of the structure (according to the different international code provisions) are building height, separation between adjacent buildings, seismic zones, and lateral load resisting system.

3. Methods of Mitigation of Pounding

There are many approaches that have been tried in order to mitigate pounding. Those include: setting the separation distance between adjacent buildings to avoid pounding, use of fill material of special type to absorb the deformation (filling the gap with shock absorbing material), the use of very stiff lateral load resisting system to minimize the expected deformation, increasing the buildings damping capacity by means of passive structural control of energy dissipation system, and the use of permanent connectors (Joining adjacent structures at critical locations so that their motion could be in-phase with one another). The above mentioned methods are suggested by many researchers (Karayannis, 2004; Abdullah, 2001) as an approach to mitigate the pounding phenomenon in an effective and satisfactory way. However, most of the results were not promising because of various reasons, some are too expensive, and others are difficult to apply. The most applicable and convenient method according to many papers and code provisions is setting the adequate separation distance between adjacent buildings.

4. Pounding Provisions in International Codes

Setting the adequate separation distance between buildings was adopted by most of the codes all over the world. First of all, because it is the most simple and accurate method and it is easy to implement in the design of earthquake resisting structures. This is despite its clear disadvantages like impracticality resulting from land loss and the existence of already built structures not to forget the problem of the expensive expansion joints in the same building. 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 and expensive solution.

4.1 Provisions of Eurocode 8 (Jan 2003)

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, calculated according to Eq.1
(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, calculated according to Eq.1. 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

If linear analysis is performed the displacements induced by the design seismic action shall be calculated on the basis of the elastic deformations of the structural system by means of the following simplified expression:

$$d_s = q_d \, d_e \tag{1}$$

where: d_s is displacement of a point of the structural system induced by the design seismic action; q_d is displacement behavior factor, assumed equal to q unless otherwise specified; q is behavior factor; and d_e displacement of the same point of the structural system, as determined by a linear analysis based on the design response spectrum. The value of d_s does not need to be larger than the value derived from the elastic spectrum. When determining the displacements d_e, the torsional effects of the seismic action shall be taken into account. For non-linear analysis, static or dynamic, the displacements are those obtained from the analysis.

4.2 International Building Standards 2006 (Jan 2006)

The design story drift (Δ) as determined in Section 5.3.3 of IBC 2006, shall not exceed the allowable story drift (Δa) for any story. 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 Type 1, the design story drift (Δ) 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 (δ_x).

The design story drift (Δ) shall be computed as the difference of the deflections at the centers of mass at the top and bottom of the story under consideration. The deflections of level x at the center of the mass (δ_x) shall be determined in accordance with the following equation:

$$\delta_x = C_d \, \delta_{xe} / I \tag{2}$$

where C_d is the deflection amplification factor; δ_{xe} is the deflection determined by an elastic analysis; and I is the importance factor

4.3 Seismic Code of India: (2002)

Two adjacent buildings, or two adjacent units of the same building with separation joint in between shall be separated by a distance equal to the amount ***R*** times the sum of the calculated storey displacements to avoid damaging contact when the two units deflect towards each other. When floor levels of two similar adjacent units or buildings are at the same elevation levels, factor ***R*** in this requirement may be replaced by ***R***/2, where ***R*** is as specified in the Code.

The storey drift in any storey due to the minimum specified design lateral force, with partial load factor of 1.0, shall not exceed 0.004 times the storey height. For the purposes of displacement requirements only, it is permissible to use seismic force obtained from the computed fundamental period (***T***) of the building without the lower bound on design seismic force. There shall be no drift limit for single storey building which has been designed to accommodate storey drift.

4.4 Seismic Provisions of the Australia/New Zealand Standards :(Jan 2003)

The design horizontal deflection of any point on the perimeter of a structure shall not exceed the distance from that point on the structure to the boundaries of adjacent sites, except for street frontages. At any point above the ground, the design horizontal deflection of the structure shall be such that, when combined with the design horizontal deflection of any adjacent structure at the same height, contact does not occur.

Where the equivalent static method or modal response spectrum method of analysis is used, the design horizontal deflection at each level shall be taken as the larger of the values determined from (a) and (b), where (a) Elastic deflections found using the equivalent static method or using the modal response spectrum method, both multiplied by a scale factor equal to the structural ductility factor divided by S_p; and (b) Deflections found by adding the elastic deflection profile determined in accordance with (i) to each possible sideway mechanism deflection profile determined in accordance with (ii) in which (i) The elastic deflection profile shall be determined by multiplying the deflections found using the equivalent static method or using the modal response spectrum method by a scale factor of $1/S_p$. and (ii) The sideway mechanism deflection profiles shall be constructed by considering all potential sideway mechanisms except those which are specifically suppressed through the application of capacity design procedures. The deflection for each sideway mechanism shall be consistent with obtaining a deflection at the level of the uppermost principal seismic weight of:

$$d_n = (\mu - 1)d_{el}/S_p \tag{3}$$

where d_{el} is the elastic deflection at the at the level of the uppermost principal seismic weight, and S_p is the structural performance factor

Calculation of design horizontal deflections for the serviceability limit state shall be based on linear elastic response of each element, unless some additional but limited inelastic displacement is considered acceptable and is nominated as such within the appropriate materials standard. If so account shall be taken of the inelastic displacement in calculation.

4.5 Seismic Code of Turkey: (2007)

Sizes of gaps shall not be less than the sum of the values of average storey displacements multiplied by the coefficient α, where $\alpha = \mathbf{R} / 4$ if all floor levels of adjacent buildings or building blocks are the same; and $\alpha = \mathbf{R} / 2$ if any of the floor levels of adjacent buildings or building blocks are not the same, in which **R** is the structural behavior factor (Seismic code of Turkey, 2007). Storey displacements to be considered are the average values of those calculated within a storey at the column or structural wall joints. In cases where the seismic analysis is not performed for the existing old building, the storey displacements shall not be assumed to be less than those obtained for the new building at the same stories. In all cases minimum size of gaps shall be 30 mm up to 6 m height. From there on a Minimum 10 mm shall be added for each 3 m height increment. Seismic joints shall be arranged to allow the independent movement of building blocks in all earthquake directions.

4.6 Seismic Code of Peru (2001)

All structures must be separated from the neighbor structures a minimum spacing S to avoid the contact during a seismic movement. This minimum spacing will not be smaller than 2/3 of the sum of the maximum displacements of the adjacent blocks nor smaller than:

$S = 3 + 0.004\,(h - 500)$ (h & S in centimeters)

$S > 3$ cm

where h is the height measured from the level of the natural land to the considered level to evaluate S. The Building will move back from the adjacent limits of property to other lots, or with constructions, not less than 2/3 of the maximum displacement calculated above, nor smaller than S/2.

4.7 Seismic Code of Spain (2002)

Any construction must be separated from the adjacent ones by a minimum distance to mitigate the effects of the shock during the seismic movements. Any construction must be separated from the boundaries edificables of property among all height a distance not less than the maximum lateral displacement for earthquake or nor than 1.5 cm in order to avoid the shock with the contagious structures during the seismic movements. For building of up to ten stories, the lateral maximum displacement "u" in centimeters, can be obtained by means of the expression:

$$u = 33\ \alpha_1 .\ (a_c /g) .\ TF^2 \tag{4}$$

where α_1, a_c, g and T_F are coefficient of value, the seismic acceleration of calculation in m/s2, acceleration of the gravity in m/s^2 and TF is the fundamental period in seconds. The gap between building bodies must be between vertical plans and with a width of at least the sum of the lateral maximum displacement "u" of the two bodies. In the zones with $ac \geq 0.16g$ must not be projected together of support in free dilation, except if a special study is performed.

4.8 National Building Code of Canada (2005)

Lateral deflections of a structure shall be calculated in accordance to the loads and requirements defined in this subsection. Lateral deflections obtained from a linear elastic analysis using the methods explained in the code, and incorporating the effects of torsion, including accidental moments, shall be multiplied by R_dR_o/I_E to give realistic values of anticipated deflections. The largest inter-storey 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. R_d is SFRS Force Modification Factors, Ro is System Over strength Factors, and I_E is Importance Factor

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 required in shall take into account the mass, stiffness, strength, ductility and anticipated motion of the connected buildings and the character of the connection. Rigidly connected buildings shall be assumed to have the lowest R_dR_o value of the buildings connected. Buildings with non-rigid or energy dissipating connections require special studies.

4.9 Egyptian Code for load’s Calculation (Dec 2003)

There have to be a minimum spacing between the adjacent buildings to prevent any contact between them during any seismic event. This could be achieved when the minimum distance between the edges of the adjacent buildings is not less than the calculated displacement. If the floor elevations of the building are the same as those of the adjacent building, the above referred minimum distance may be reduced by a factor of 0.7. The previous stated spacing between the adjacent buildings could be neglected, in case of having shear wall on the outside parameter and constructed as bumper walls. And there have to be two walls (same height of the building) at least perpendicular on the direction of the separation. In this case, the minimum spacing could be lowered to 4 cm. If the calculated spacing is not applied, pounding forces should be taken into consideration.

The calculation of the displacement resulting from earthquake based on the elastic deformation of the structural system will be

$$D_s = R_d \, d_e \, \gamma_I \tag{5}$$

where D_s is the displacement resulting from the earthquake design loads at specific point, R_d is the modification factor of the displacement and is assumed to be equal to R unless mentioned otherwise, d_e is displacement of that specific point according to the horizontal design spectrum for elastic analysis, and γ_I is the Importance factor of the structure.

5. Critical Review of Different Code Provisions

Various parameters are implemented in order to compare between the pounding provisions in different codes. These parameters are buildings adjacent to boundaries and buildings adjacent to structures, factors affecting pounding, reduction factor of floor elevations.

The codes which discriminated between the two cases of buildings adjacent to boundaries and buildings adjacent to structures are: Euro Code 8, Australian/New Zealand Standards, Seismic Code of Peru and Seismic Code of Spain.

The codes which took into consideration some of the factors that affect poundings are:
Euro Code 8: Fundamental Period, lateral load resisting system, and regularity in Elevation
IBC 2006: Structure Height, lateral load resisting system, and seismic zone
Code of India: Storey Height, fundamental period, and lateral load resisting system.
Australian/New Zealand Standards: Lateral load resisting system, structural form, and structural damping characteristics
Code of Turkey: Structural system, lateral load resisting system, and structural ductility.
Code of Peru: Structure height
Code of Spain: Peak ground acceleration, and fundamental period
National Building Code of Canada: Lateral load resisting system, and structure height
Egyptian Code: Fundamental period and lateral load resisting system

We can notice from above that there are some common factors appear in almost all the codes, like lateral load resisting system, fundamental period and structure height.

The reduction factor related to floor elevation is a very important because of the huge savings in land usage that could be achieved. The codes that apply a reduction factor to the required minimum spacing incase of floor elevation at same level are: Euro Code 8: Reduction Factor = 0.7, Code of India: Reduction Factor = 0.5, Code of Turkey: Reduction Factor = 0.5, Egyptian Code: Reduction Factor = 0.7

6. Numerical Comparison between different code provisions

A set of numerical models will be studied to compare between different codes. For practicality, only some of the codes will be modeled because of space limitations. The adopted model (shown in the Fig.1and Fig.2) will be a mixed system (Combination of Frames and Shear Wall). This will ensure more adequate model for comparison (the dimensions of the structural elements in the adopted system is shown in Table.1). Finally, the used Earthquake record will be Petrolia Earthquake because it is an average earthquake from frequency and magnitude point of view.

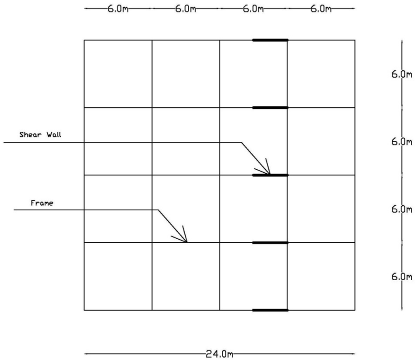


Fig.1 Plan of Shear Wall – Frame Mixed System

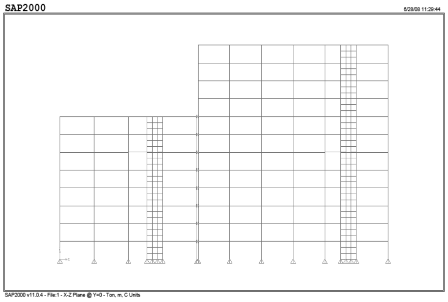


Fig.2 Shear Wall – Frame Mixed System

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

The IBC2006, Euro code 8, Australia/Newzealand standards and Code of India set very conservative limits. The implementation of the requested separation by the code resulted in no pounding occurrences (Fig.3), but that at the expense of the unpractical land loss and technical problems arising from construction of such expansion joint.

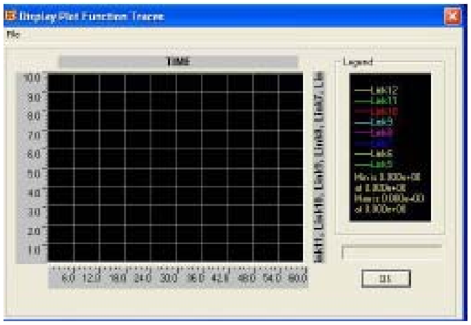
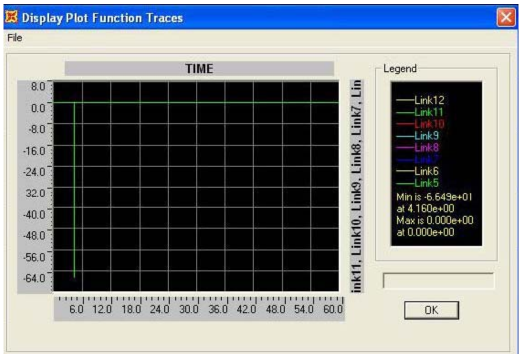


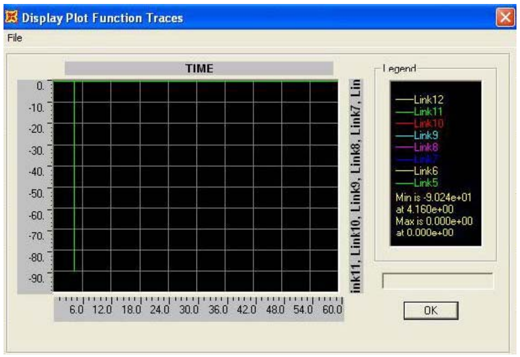
Fig.3 The IBC2006, Euro code 8, Australia/Newzealand standards and Code of India

While the National Building Code of Canada and the Egyptian Code for load's Calculation requested smaller separation values and thus a little bit more logical limits. However, those separations led to occurrence of pounding phenomenon in the two cases (shown in Fig.4 and 5). (The pounding value for the Egyptian code was higher than the Canadian code). But the difference between them, that the Egyptian code noted that in case of smaller separation, pounding forces should be considered (although it is mentioned in very basic and vague way) while the Canadian code missed mentioning this point.



Min is -6.649e+01
at 4.160e+00
Max is 0.000e+00
at 0.000e+00

Fig.4 National Building Code of Canada



Min is -9.024e+01
at 4.160e+00
Max is 0.000e+00
at 0.000e+00

Fig.5 Egyptian Code for load's Calculation

The following table shows summary of the results of the numerical comparison of different building codes for the studied model.

Table 2: Building Code's Comparison

Building Code	Separation Distance (mm)	Satisfaction of the Code Req.	No. Of Pounding Hits
IBC2006	108.1	Yes	0
Euro code 8	108.1	Yes	0
Australia/Newzealand standards	108.1	Yes	0
Code of India	162.2	Yes	0
National Building Code of Canada	76.5	No	1
Egyptian Code for load's Calculation	75.7	No	1

7. Conclusions

Pounding forces can be calculated using simple commercial software packages like Sap 2000. Most of the international building codes adopted the “Separation distance between buildings” method as the main and effective method of mitigation of pounding. There are numerous factors involved in pounding phenomenon. The majority of codes are mainly concerned with the separation distance between adjacent building and structure drift factors. IBC2006, Euro code 8, Australia/Newzealand standards and Code of India set very conservative limits. The National Building Code of Canada and the Egyptian Code for load’s Calculation requested smaller separation distance but resulted in pounding occurrence.

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