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Evaluation and Mitigation of Earthquake Induced Pounding Effects on Adjacent Buildings Performance

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ABSTRACT

Investigations of past and recent earthquake damage have illustrated that the building structures are vulnerable to severe damage and/or collapse during moderate to strong ground motion. Among the possible structural damages, seismic induced pounding has been commonly observed in several earthquakes. A parametric study on buildings pounding response as well as proper seismic hazard mitigation practice for adjacent buildings is carried out. Three categories of recorded earthquake excitation are used for input. The effect of impact is studied using linear and nonlinear contact force model for different separation distances and compared with nominal model without pounding consideration. Pounding produces acceleration and shear at various story levels that are greater than those obtained from the no pounding case, while the peak drift depends on the input excitation characteristics. Also, increasing gap width is likely to be effective when the separation is sufficiently wide practically to eliminate contact. It is effective to provide a shock absorber for the mitigation of impact effects between adjacent buildings with relatively narrow seismic gaps. The sudden changes of stiffness during poundings can be smoothed by using a natural rubber shock absorber, which prevents, to some extent, the acceleration peaks due to impact. The pounding forces exerted on the adjacent buildings can be satisfactorily reduced.

1. INTRODUCTION

A quake with a magnitude of six is capable of causing severe damage. Several destructive earthquakes have hit Egypt in both historical and recent times from distant and near earthquakes. The annual energy release in Egypt and its vicinity is equivalent to an earthquake with magnitude varying from 5.5 to 7.3. Adjacent buildings subjected to seismic excitations collide against each other when the separation distance is not large enough to accommodate the displacement response of the structures relative to one another. As shown by field observations and by numerical models, seismic pounding can cause severe damage on the affected structures. Investigations of past and recent earthquakes damage have illustrated several instances of pounding damage in both building and bridge structures (Astaneh-Asl *et al.* 1994, Northridge

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Reconnaissance Team 1996, Kasai et al. 1991, Abdel Raheem 2006 & 2009). Pounding damage was observed during the 1985 Mexico earthquake, the 1988 Sequenay earthquake in Canada, the 1992 Cairo earthquake, the 1994 Northridge earthquake, the 1995 Kobe earthquake and 1999 Kocaeli earthquake, 2011 Tohoku earthquake (Moehle 1995, Bertero 1996, Committee of Earthquake Engineering 1996, Sadek *et al.* 2000, Gillies *et al.* 2001). Extensive pounding damage was observed in low-rise unreinforced masonry buildings that were constructed with no building separation. Modern buildings were also endangered by pounding when building separations were in-filled with solid architectural flashings (Cole *et al.* 2011, Takewaki *et al.* 2011). Significant pounding was observed at sites over 90 km from the epicenter thus indicating the possible catastrophic damage that may occur during future earthquakes having closer epicenters. 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 motions of adjacent buildings.

Past seismic codes did not give definite guidelines to preclude pounding, because of this and due to economic considerations including maximum land usage requirements, especially in the high-density populated areas of cities, there are many buildings worldwide which are already built in contact or extremely close to another that could suffer pounding damage in future earthquakes. A large separation is controversial from both technical (difficulty in using expansion joint) and economical (loss of land usage) views. The highly congested building system in many metropolitan cities constitutes a major concern for seismic pounding damage. For these reasons, it has been widely accepted that pounding is an undesirable phenomenon that should be prevented or mitigated (Kasai and Maison 1991, Pantelides and Ma 1998, Hao and Zhang 1999, Hayashikawa *et al.* 2002, Abdel Raheem 2006). Numerical and experimental studies have shown that, in case of structural poundings, both floor accelerations and inter-story deflections are significantly amplified, threatening the functionality of the structure, as well as sensitive equipment that may be housed in the building (Komodromos *et al*. 2007, Masroor and Mosqueda 2012). Moreover, a new generation of structural design codes defines requirements for the design of buildings against earthquake action, new seismic zonations have been defined, the new earthquake zones in connection with the corresponding design ground acceleration values will lead in many cases to earthquake actions which are remarkably higher than defined by the design codes used up to now. Pounding between buildings during earthquakes has been recently intensively studied using different models of colliding structures (Anagnostopoulos 1988, Davis 1992, Chau and Wei 2001, Ruangrassamee and Kawashima 2001, Jankowski 2005 & 2006).

The most simplest and effective way for pounding mitigation and reducing damage due to pounding is to provide enough separation but it is sometimes difficult to be implemented due to detailing problem and high cost of land. An alternative to the seismic separation gap provision in the structure design is to minimize the effect of pounding through decreasing lateral motion (Kasai et al. 1996, Jankowski et al. 2000, Kawashima and Shoji 2000, Abdullah et al. 2001, Ruangrassamee and Kawashima 2003), which can be achieved by joining adjacent structures at critical locations so that their motion could be in-phase with one another or by increasing the pounding buildings damping capacity by means of passive structural control of energy dissipation system.

Certain mitigation measures have already been proposed by several researchers who investigated this problem in buildings and bridge decks in an effort to alleviate the detrimental effects of structural poundings. A potential mitigation measure for the pounding problem is the incorporation of layers of soft material, such as rubber, which can act as collision bumpers, in order to prevent the sudden impact pulses (Abdel Raheem 2009, Polycarpou and Komodromos 2011, Polycarpou et al. 2013).

The focus of this study is the development of an analytical model and methodology for the formulation of the adjacent building-pounding problem based on the classical impact theory, an investigation through parametric study to identify the most important parameters is carried out. The main objective and scope are to evaluate the effects of structural pounding on the global response of building structures; to determine proper seismic hazard mitigation practice for already existing buildings as well as new buildings and to develop and provide engineers with practical analytical tools for predicting pounding response and damage. A realistic pounding model is used for studying the response of structural system under the condition of structural pounding during moderate to strong earthquakes. An analytical technique based on the contact force-based approach is developed, where the contact element is activated when the structures come into contact. A spring with high stiffness is used to avoid overlapping between adjacent structures. Two adjacent multi-story buildings are considered as a representative structure for potential pounding problem. A simplified nonlinear analytical model is developed to study the response of multi-story building subject to earthquake excitation.

2. NONLINEAR DYNAMIC ANALYSIS PROCEDURES

2.1 Equilibrium Equation Solution Technique

The governing nonlinear dynamic equation of motion for the structure response can be derived by the principle of energy that the external work is absorbed by the work of internal, inertial and damping forces for any small admissible motion that satisfies compatibility and boundary conditions. By assembling the element dynamic equilibrium equation for the time $t+\Delta t$ over all the elements, the incremental FEM dynamic equilibrium equation can be obtained as:

$$[M]\{\ddot{u}\}^{t+\Delta t} + [C]\{\dot{u}\}^{t+\Delta t} + [K]^{t+\Delta t}\{\Delta u\}^{t+\Delta t} = \{F\}^{t+\Delta t} - \{F\}^{t} \quad (1)$$

Where [M], [C] and $[K]^{t+\Delta t}$ = system mass, damping and tangent stiffness matrices at time $t+\Delta t$. The tangent stiffness considers the material nonlinearity through bilinear elastic-plastic constitutive model, $\ddot{u}$, $\dot{u}$ and Δu = accelerations, velocities, and incremental displacements at time $t+\Delta t$, respectively; and $\{F\}^{t+\Delta t}$ - $\{F\}^{t}$ = unbalanced force vector. The Newmark's step-by-step integration method is used for the integration of the equation of motion. These equations for the building structure system subjected to earthquake ground motion input are assembled and numerically solved for the incremental displacement using the Newton-Raphson iteration method. In this study, an equivalent viscous damping is explicitly introduced in the system in the form of damping matrix [C]. A spectral damping scheme of Rayleigh's damping is used to form damping matrix as a combination of mass and stiffness matrices, which effectively captures the building damping and is also computationally efficient.

2.2 Input ground motion

A suite of nine-ground motion records from seven different earthquakes is selected for the purpose of understanding the input ground motion effect, as listed in **Table 1**. The ground motion records are grouped into three levels depending on the peak ground acceleration as, low (0.1g up to 0.3g), moderate (0.4g up to 0.6g) and high (0.7g up to 0.9g). The records are chosen such that the period ratio (T_1/T_g and T_2/T_g; adjacent buildings period over the ground motion characteristic period) has a wide range.

Table 1 Suite of earthquake ground motion records

PGA Level	PGA (g)	Input wave	M_w	Earthquake / Station	Φ°	EPD (km)	PGV (cm/s)	PGD (cm)	T_g (s)
Low	0.21	1MVH	6.0	N. Palm Springs, 1986 / Morongo Valley	135	10.1	40.9	15.0	1.90
	0.30	2A-GRN	6.0	Whittier narrows, 1987 / E-Grand Ave	180	9.0	23.0	3.3	0.70
	0.29	3G06	6.2	Morgan Hill, 1994 / Gilroy Array #6	090	11.8	36.7	6.1	1.20
Moderate	0.48	4CYC	6.9	Loma Prieta, 1989 / Coyote Lake Dam	285	21.8	39.7	15.2	0.65
	0.51	5STG	6.9	Loma Prieta, 1989 // Saratoga-Aloha Ave	000	11.7	41.2	16.2	1.80
	0.59	6NPS	6.0	N. Palm Springs, 1986 / 5070 N-Palm Spring	210	8.2	73.3	11.5	1.10
High	0.60	7D-PVY	5.8	Coalinga, 1983 / Pleasant Valley P.P.	045	17.4	34.8	8.1	0.65
	0.84	8RRS	6.7	Northridge, 1994 / Rinaldi	228	7.1	166.1	28.8	1.05
	1.04	9CPM	7.1	Cape Mendocino, 1992 / Cape Mendono	090	8.5	42.0	12.4	2.00

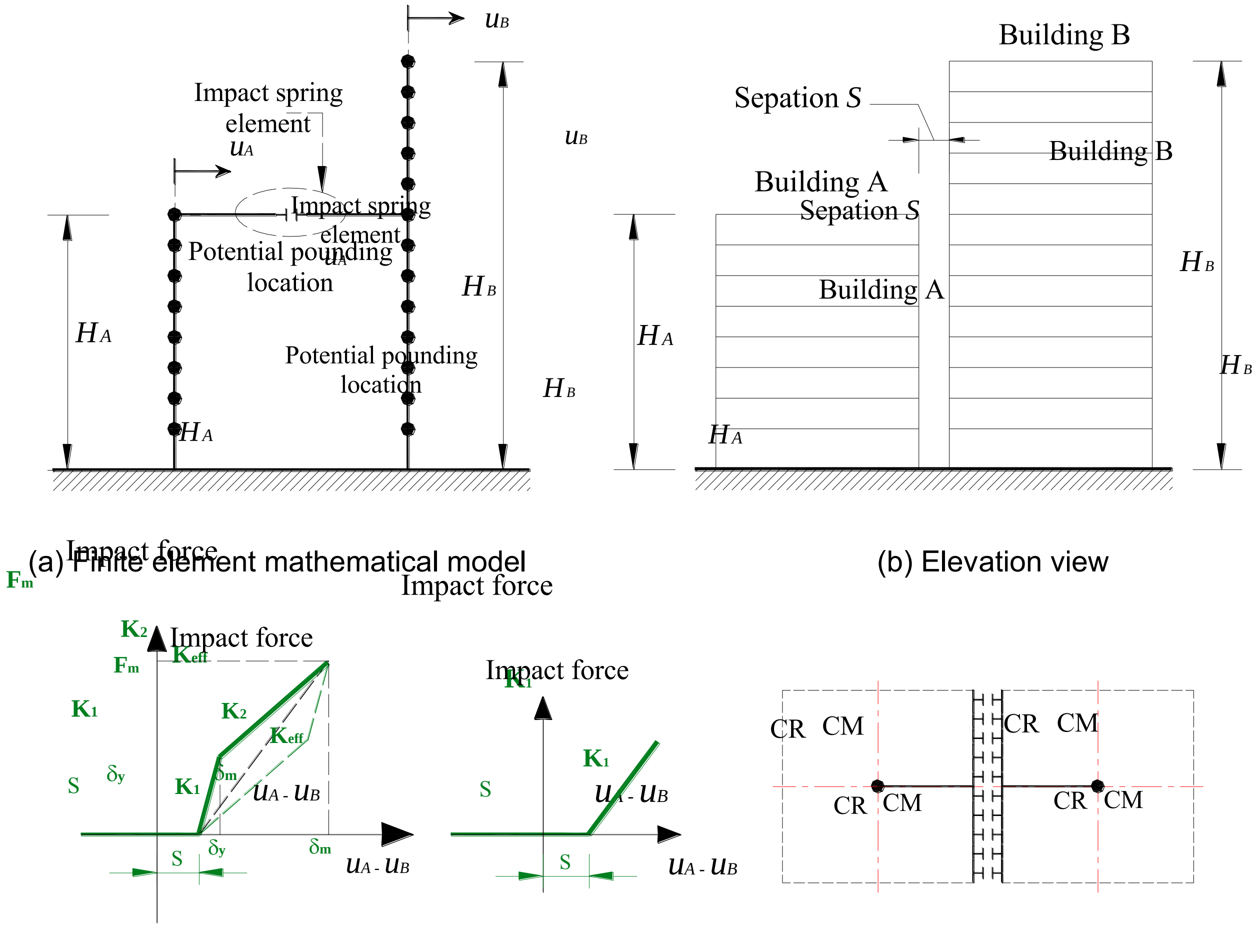
3. FINITE ELEMENT MODELLING

3.1 Building Model

This study investigates pounding of adjacent building structures from an analytical perspective. A simplified nonlinear model of a multi-story building is developed incorporating the effects of geometric and material nonlinearities. A three-dimensional (3D) finite element model has been defined and 3D non-linear time-history analyses have been performed. A new formulation is proposed to model pounding between two adjacent building structures, with natural periods T_A and T_B and damping ratios ζ_A and ζ_B under earthquake excitation, as linear and nonlinear contact force based impact between two multi-degree-of-freedom oscillators. Steel moment resistant frame building of 8-story (building *A*, period = 0.72) is assumed to collide with and adjacent 13-story (building *B*, Period = 1.22), as shown in Fig. 1. In this model, the building floor is assumed to be infinitely rigid in its own plane. The entire mass of the structure is uniformly distributed at the floor level. The model has coincident CR (Rigidity/stiffness Center) and CM (Mass Center) that is located at the geometric center of the floor. For the purpose of evaluating the effect of torsion, a torsional unbalanced model is defined where the mass center lies at a distance *e* from the center of rigidity, and the model has the same stiffness and mass distribution.

3.2 Impact Model

Pounding is simulated using contact force-based model such as linear and nonlinear springs. In addition, a nonlinear contact model accounting for impact energy dissipation is also introduced to model impact. A bilinear truss contact model with a gap is considered for representing impact between closely spaced adjacent structures, as shown in Fig. 1. The model parameters such as the stiffness properties and the yield deformation of the truss element are determined using the Hertz contact law for the effective stiffness and by equating the element hysteresis area to the energy dissipated during impact (Muthukmar 2003, Muthukmar and DesRochs 2004).



(a) Finite element mathematical model (b) Elevation view

(c) Truss contact element for pounding simulation (d) Plan view

Fig. 1 Pounding potential problem modeling

4. REQUIRED SEISMIC SEPARATION DISTANCE TO AVOID POUNDING

Seismic pounding occurs when the separation distance between adjacent buildings is not large enough to accommodate the relative motion during earthquake events. Seismic codes and regulations worldwide specify minimum separation distances to be provided between adjacent buildings, to preclude pounding, which is obviously equal to the relative displacement demand of the two potentially colliding structural systems. For instance, according to the 2000 edition of the International building code and in many seismic design codes and regulations worldwide, minimum separation distances (Lopez

Garcia 2004) are given by ABSolute sum (ABS) or Square Root of Sum of Squares (SRSS) as follow:

ABS: $S = u_A + u_B$ (2)

SRSS: $S = \sqrt{u_A^2 + u_B^2}$ (3)

where S = separation distance and u_A, u_B = peak displacement response of adjacent structures A and B, respectively. Previous studies have shown that they give poor estimates of S, especially when the natural periods of the adjacent structures are close to each other. In these cases, the ABS and SRSS rules give excessively conservative separation distances, which are very difficult to effectively implement because of maximization of land usage. 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 (Penzien 1997, Lopez Garcia 2004) is given by:

$$S = u_{Rel}(t) = \sqrt{u_A^2 + u_B^2 - \rho_{AB} u_A u_B} \tag{4}$$

where u_A, u_B and u_{Rel} = mean peak values of $u_A(t)$, $u_B(t)$ and $u_{Rel}(t)$, respectively. The correlation coefficient, ρ_{AB} depends on the period on the period ratio $r = T_B / T_A$, as well as ζ_A and ζ_B, (Penzien 1997, Lopez Garcia 2004) and is given by

$$\rho_{AB} = \frac{8\sqrt{\zeta_A \zeta_B}\left(\zeta_A + r\,\zeta_B\right) r^{1.5}}{\left(1 - r^2\right)^2 + 4r\,\zeta_A \zeta_B \left(1 + r^2\right) + 4\left(\zeta_A^2 + \zeta_B^2\right) r^2} \tag{5}$$

where T_A, ζ_A and T_B, ζ_B are natural periods and damping ratios of systems A and B, respectively. 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. Four different criteria to calculate the separation necessary to prevent seismic pounding between nonlinear hysteretic structural systems were examined. None of the criteria evaluated in this study is completely satisfactory in the sense that none of them provides separations that are consistently exact or somewhat conservative. Observations indicate that there is still a need to adequately characterize the correlation between displacement responses of nonlinear hysteretic systems (Lopez-Garcia and Soong 2009)

5. NUMERICAL RESULTS AND DISCUSSION

5.1 Pounding and Spacing Size Effects

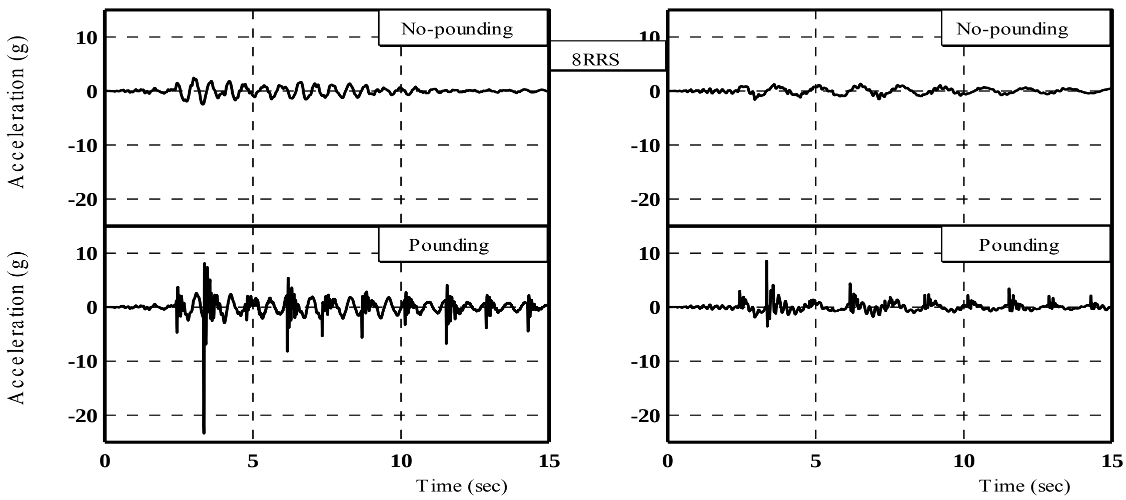
In order to achieve an acceptably safe structural performance during seismic events, a correct seismic design should take into account the relative displacements calculated by means of a nonlinear time history analysis. The maximum displacement for the non-pounding case for stiff and flexible buildings u_A, u_B and the relative pounding displacement u_{Rel} for different input excitation are listed in **Table 2**. Since the absolute sum (ABS) approach assumes complete out-of-phase motion of the adjacent buildings, so the ratio of u_{Rel} to the sum of u_A and u_B could be taken as a measure of out-of-phase of adjacent buildings, which range from 0.73 to 1.0 depending on the input earthquakes characteristic. The out of phase movement between building *A* and *B* is clearly observed due to different periods of the building. The positive and negative peak displacements are essential to determine the degree of biased response of the pounding system. Therefore, seismic poundings between adjacent buildings may induce unwanted damages even though each individual structure might have been designed properly to withstand the strike of credible earthquake events.

Table 2 Non-pounding and relative pounding displacements for different input earthquakes

Input Earthquake	u_A (m)	u_B (m)	u_{Rel} (m)	u_{Rel} / max. (u_A & u_B)	u_{Rel} /($u_A + u_B$)
1MVH	0.06	0.10	0.13	1.30	0.81
2A-GRN	0.24	0.45	0.65	1.45	0.94
3G06	0.09	0.04	0.11	1.22	0.85
4CYC	0.11	0.19	0.27	1.42	0.90
5STG	0.09	0.17	0.19	1.18	0.73
6NPS	0.15	0.14	0.24	1.71	0.83
7D-PVY	0.08	0.13	0.21	1.62	1.0
8RRS	0.13	0.06	0.14	1.08	0.74
9CPM	0.09	0.16	0.19	1.19	0.76

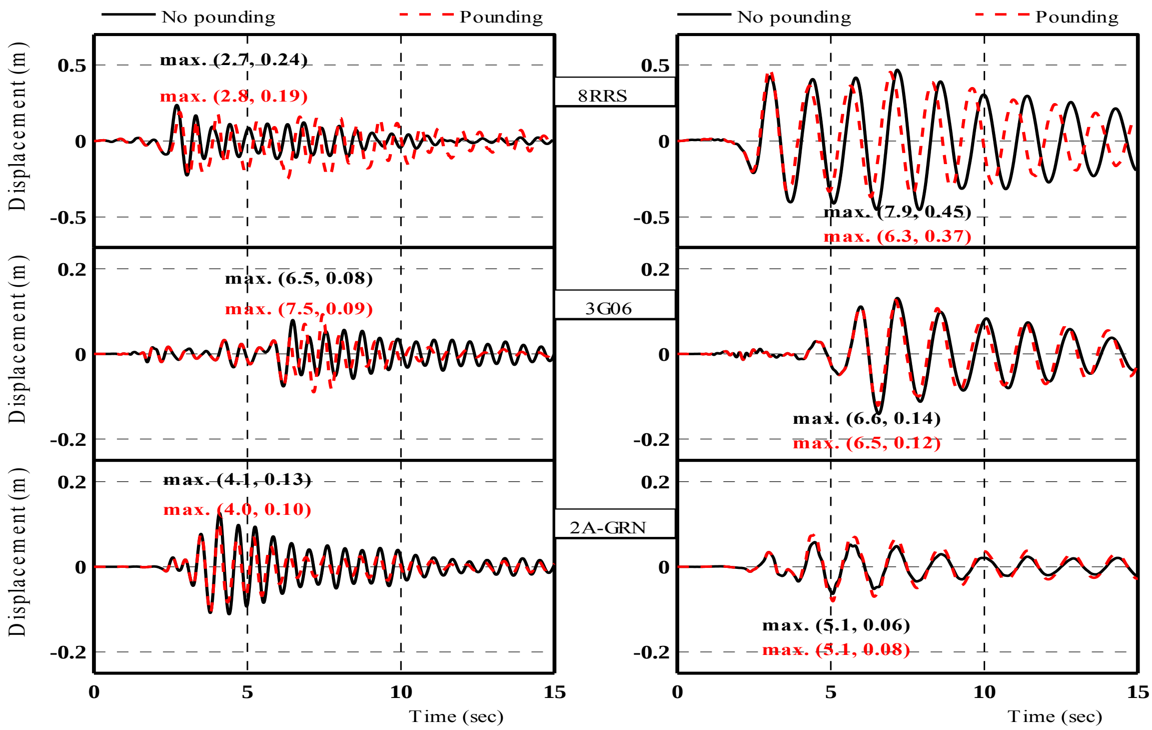
The acceleration variation at the top level of shorter building during impact between adjacent structures under different earthquakes is computed to study the behavior of the building during impact. Pounding is a severe load condition that could result in high magnitude and short duration floor acceleration pulses in the form of short duration spikes, which in turn cause greater damage to building contents. A sudden stopping of displacement at the pounding level results in large and quick acceleration pulses in the opposite direction. The acceleration increases due to impact with adjacent structure and can be more than 10 times those from no-pounding case, as illustrated in **Fig. 2**.

The time history of inward displacements and their extreme values for the pounding and no pounding cases shows that pounding reduces the building response when vibrating near the characteristic period of the ground motion and increases the adjacent building response, as shown in **Fig. 3**. The flexible 13-story building vibrates near the dominant frequency of the 3G06 input earthquake; pounding response is increased in the flexible building while pounding response of the stiff building is reduced. Conversely, the stiff 8-story building demand increases and the flexible building demand decreases due to pounding for the 2A-GRN input earthquake that has dominant period near the fundamental period of stiff building. Pounding slightly decreases both building responses for 8RRS input earthquake. The amplification in building response is a function of each of adjacent buildings vibration period and their ratio as well as the dominant frequency of input excitation.



(a) 8-story building (8th level) (b) 13-story building (8th level)

Fig. 2 Acceleration time histories at pounding level (Pounding versus no-pounding case)



(a) 8-story building (8th level) (b) 13-story building (8th level)

Fig. 3 Displacement time histories at pounding level (Pounding versus no-pounding case)

Furthermore, pounding can amplify the global response of participating structural systems. The effects of impact are found to be severe for both of adjacent buildings. Pounding produces acceleration response and shear force at various story levels that are greater than those from the no pounding case, as shown in **Fig. 4**, while the peak drift depends on the input excitation characteristics. Flexible 13-story building pounding increases shear above impact level and below the third floor slab as well as acceleration at the vicinity of impact, while stiff 8-story building pounding almost increases the peak shear over the entire height. The increase of spacing from 0.12 to 0.25m has the capability for reducing impact effects and could reduce the number of pounding's occasion. Also, increasing gap width is likely to be effective when the separation is sufficiently wide practically to eliminate contact.

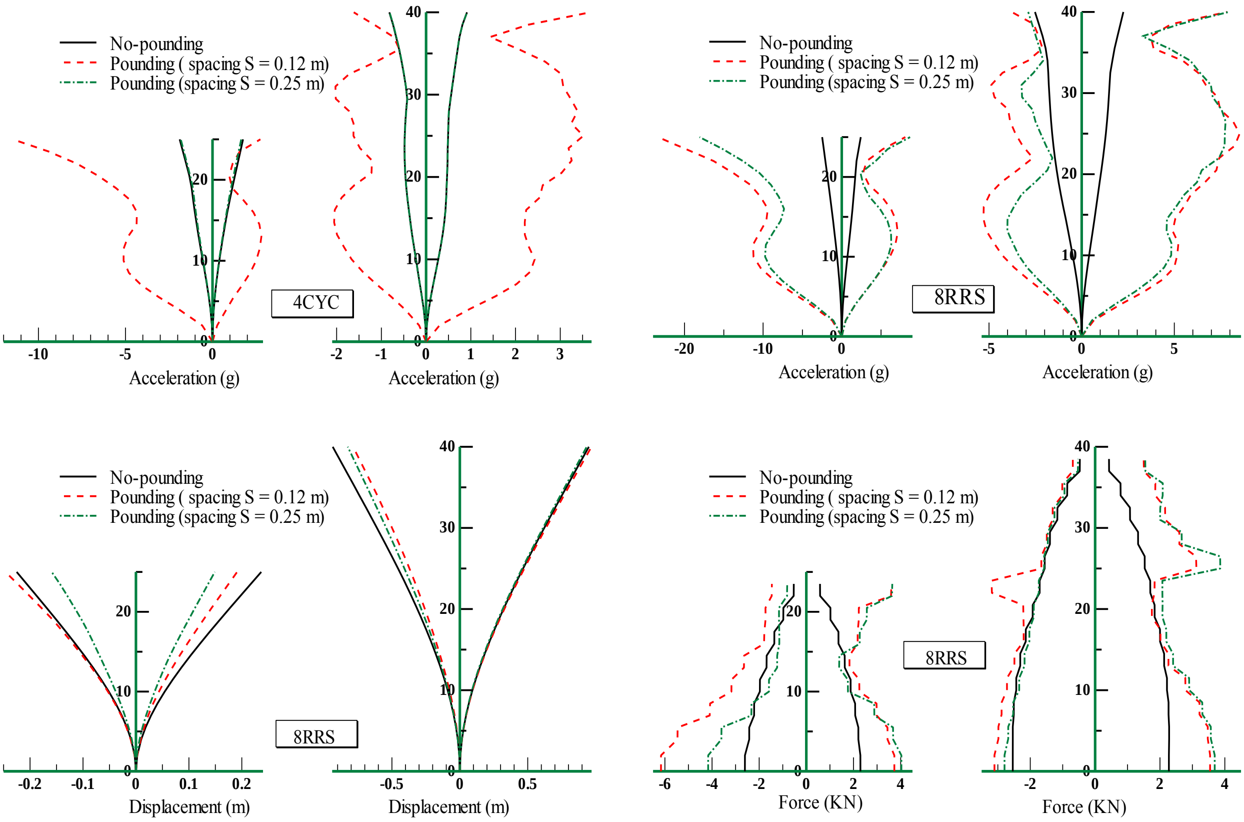


Fig. 4 Response envelops for different spacing size between adjacent buildings

5.1 Impact Energy Dissipation Effect

The nonlinearity and dissipated energy associated with impact are illustrated by the shear response envelop and acceleration time history response at short building top level for linear and nonlinear impact modeling, Figs. 5 and 6. An increase in the damping energy absorption capacity of the pounding element results in reduction of the acceleration amplification, impact force and building global responses. The pounding element can be activated every time for energy absorption whenever the buildings vibrate. Consequently, impact force can be significantly reduced. The failure of buildings occurs not only from the increase of lateral loading, but also from vertical failure. Building upholds their structural integrity by providing a continuous load path to their foundation. As the building displaces laterally the columns are caused to deflect from the p-δ effect, causing them to inadequately transfer the loads of the floors. These deformed members could buckle from the floors weight. The response discloses the significance of the use of the energy dissipation system. Hence, it is clear that an energy dissipation system installed at potential pounding level could be an effective tool to reduce the effect of impact upon adjacent buildings. Consideration of impact energy dissipation through nonlinear impact model amplifies pounding displacement reduces the impact forces and promotes the impact eccentricity due one direction yielding that could lead to localized damage at corners of building.

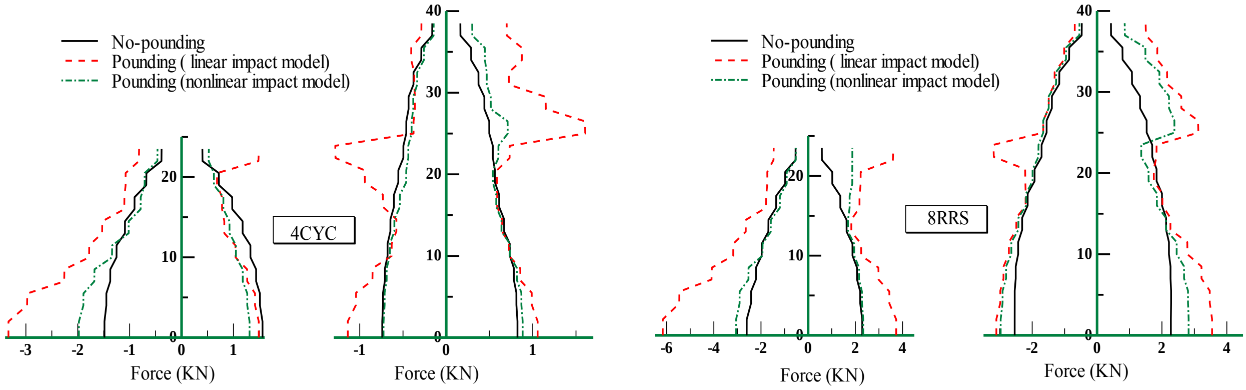
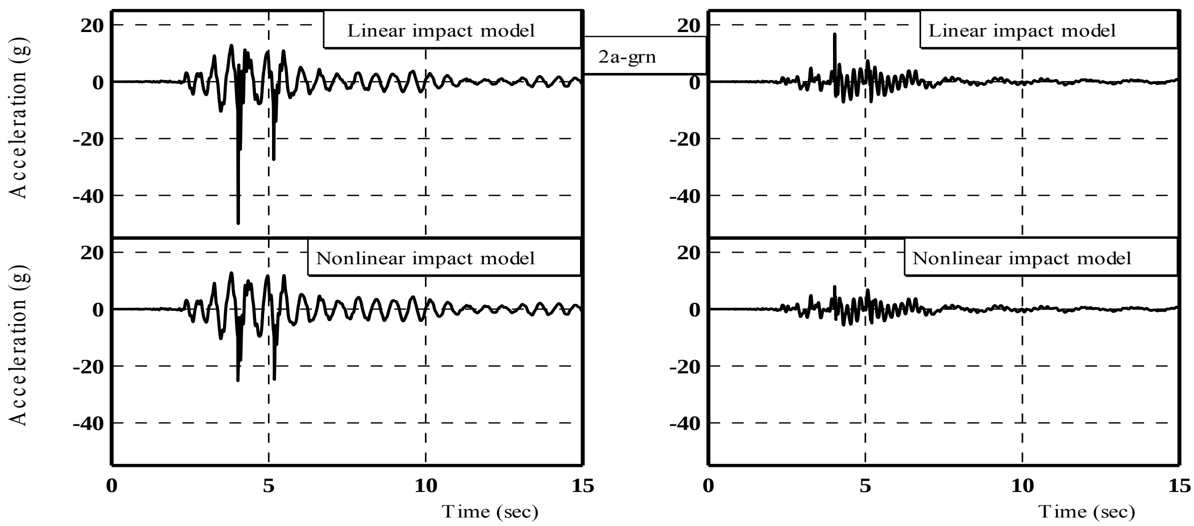


Fig. 5 Shear response envelops for linear and nonlinear impact modeling



(a) 8-story building (8th level) (b) 13-story building (8th level)

Fig. 6 Acceleration time history response for linear and nonlinear impact modeling

6. CONCLUSIONS

In this study, a mathematical modeling of adjacent building pounding has been demonstrated and its implementation in a finite element nonlinear seismic analysis is presented. Numerical investigation, aiming at accurate description and evaluation of colliding adjacent structures real behavior and its effects on global response has been conducted. It studies the relative importance of dynamic characteristics of adjacent building structures in causing relative responses. The effect of vibration properties of adjacent structures is significant to those of high-rise adjacent structures if they have noticeably different vibration periods.

Pounding is a highly nonlinear phenomenon and a severe load condition that could result in significant structural damage, high magnitude and short duration floor acceleration pulses in the form of short duration spikes, which in turn cause greater damage to building contents. A sudden stopping of displacement at the pounding level results in large and quick acceleration pulses in the opposite direction. Furthermore, pounding can amplify the global response of participating structural systems. The vertical location of pounding significantly influences the distribution of story peak responses through the building height. The acceleration response at pounding level indicate that pounding is especially harmful for equipment or secondary systems having short periods, where the existing industrial design spectra does not cover this effect. More importantly, pounding can amplify the building displacement demands beyond those typically assumed in design. Existing design procedure should account for dynamic impact. Adjacent building period ratio should be carefully selected to reduce the pounding effects.

Analyses of pounding have shown that there is considerable scatter in the amplification of action effects caused by pounding. This study clearly shows the sensitivity of the system response to parameters affecting the pounding phenomenon, i.e., characteristics of buildings, plan layout, structural system and frequency content of the input ground motions. The results depend on the excitation characteristics and the relationship between the buildings fundamental period. The impulse found when pounding occurs increases suddenly the acceleration and the velocity. These accelerations generated by the impacts may cause significant damage to the structural components, especially in the contact area of pounding. Non-structural components (electrical/mechanical units and architectural features) in some buildings are important to the building's function.

The results depend on the excitation characteristics and the relationship between the buildings fundamental period. In addition, unwanted period shift of an existing structure imposed by the construction of a new building in its neighborhood may lead to unprepared and unexpected damages of the former during earthquakes. Therefore, seismic poundings between adjacent buildings may induce unwanted damages even though each individual structure might have been designed properly to withstand the strike of credible earthquake events. Pounding produces acceleration and shear at various story levels that are greater than those from the no pounding case, while the peak drift depends on the input excitation characteristics. An increasing gap width is likely to be effective when the separation is sufficiently wide practically to eliminate contact.

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