CRITICAL VERTICAL POSITION OF POTENTIAL SEISMIC COLLISION OF ADJACENT BUILDINGS

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ABSTRACT

The collision between two adjacent buildings under seismic excitation may occur due to insufficient separation distance between them. Such collisions, known as seismic pounding, may induce more destruction as nearby buildings have out-of-phase vibration characteristics. A numerical simulation and FE analysis are developed to estimate the influence of potential level of pounding on the seismic response demands of adjacent collided buildings. The seismic response demands of 12-story building are studied due to colliding with different levels of adjacent 3-, 6-, and 9-stories buildings and compared with a nominal model without pounding considerations. According to the herein outcomes, the pounding causes further loads which lead to additional shear forces and acceleration at different story levels that do not appear in the no-pounding case. The vertical location of potential collision extensively influences the distribution of story peak responses through the building height. It is observed that the stiffer building has undergone the most story drift and shear force responses magnification. The acceleration response of the high-rise building at the height levels below the impact levels is significantly amplified, while the response of the floors at the height levels above the impact level is slightly affected. Besides, the maximum responses in the low-rise building are significantly increased in the rebound directions over the whole height of the building, while the response in the impact direction is slightly affected.

Keywords: Seismic pounding, critical vertical position, Time history analysis, response demands, vibration characteristics.

INTRODUCTION

The collision between adjacent buildings which have out-of-phase vibration characteristics and inadequate separation gaps in many highly congested municipal cities have been frequently detected during strong earthquakes [1-10]. Examination of structural pounding damage during recent earthquakes [11-14] has identified building configuration categories that are susceptible to pounding damage: equal story height pounding; non-equal story height (mid-column) pounding; heavier adjacent buildings pounding; eccentric pounding and buildings in series. The Collision among adjacent buildings during earthquakes causes a repeated knock that is exerted on each other, hence could lead to damages that range from insignificant non-structural local damage to serious structural global damage that could prompt buildings total failure. So, the seismic pounding has been intensively investigated recently by employing several structural models and utilizing different models of collisions [14-21].

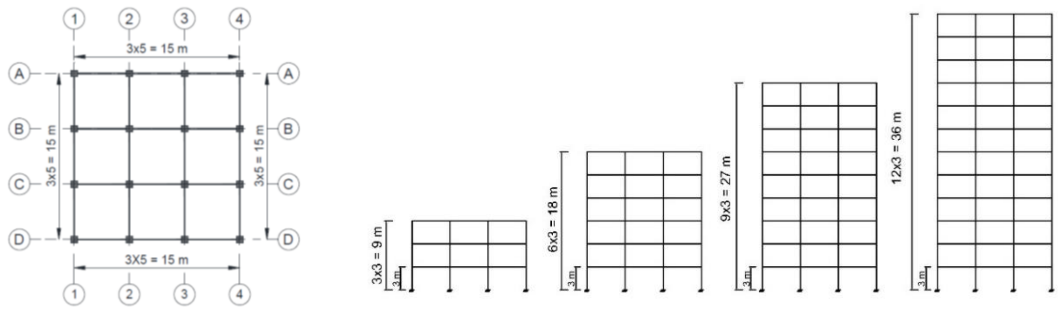
The displacement demands are slightly affected by pounding for the adjacent buildings with a similar number of stories or heights. On the contrary, by increasing the difference between building heights, the pounding effect increases the displacement demands significantly [22]. Anagnostopoulos and Spiliopoulos [15], analyzed series of unequal buildings as lumped masses, MDOF systems with bilinear force-deformation characteristics, and with viscoelastic supports. Maison and Kasai [23, 24], modeled pounding between two buildings with differing heights. The smaller building was assumed to be completely rigid, so only the larger building's performance was considered. The collision was assumed to be only at the top of the smaller building. It was concluded that neglecting the effects of pounding leads to unconservative design, especially in the floors above the point of collision. Filiatrault et al. [25, 26], modeled the elastic pounding interaction between 3-story and 8-story steel frames with zero and 15 mm gap distance. Both separations showed significant increases in recorded accelerations at the third floor.

Kontoni and Farghaly [27] applied a two-dimensional model to study the seismic collision problem between two adjacent buildings resting on a flexible medium using the direct method. The case of unequal foundation level was also studied. Their study highlighted the importance of considering the double pounding and structure-soil-structure interaction effects in the seismic analysis. Cayci and Akpinar [28] created 4 different adjacent building combinations by using 4, 8, 12, and 16 story building models to evaluate pounding effects on typical building structures considering soil-structure interaction. It was concluded that the displacement demands for all models decrease in the collision direction while increase in the free direction. M. Kamal and M. İnel [29], formulated a new simplified equation to estimate the gap distances between adjacent low and mid-rise reinforced concrete (RC) buildings under seismic loads based on the period ratios of neighboring buildings. Abdel Raheem et al. [30], constructed a numerical simulation to evaluate the pounding effects on the seismic response demands of three unequal-height adjacent buildings in series with different alignment configurations; it was observed that the severity of the seismic pounding effects depends on the vibration characteristic of the adjacent buildings and the input excitation characteristic.

To clarify the critical vertical position of potential pounding between adjacent buildings, this study examines four moment-resisting RC framed buildings, that is 12-story building as a case study and 9-, 6- and 3-story buildings which have been combined to produce four different pairs of adjacent RC structures. The inelastic time-history responses of these RC frames are evaluated employing the structural analysis software ETABS [31]. The Loma Prieta, USA earthquake (matched peak ground acceleration PGA = 0.6g) is utilized as the external dynamic excitation. The response demands in form of displacement, acceleration, pounding force, and story shears have been considered as the parameters to investigate the effects of different pounding vertical levels.

FE MODELING FOR SEISMIC RESPONSE ANALYSIS

The physical model for the interaction of adjacent Buildings:



(a) Typical floor plan.   (b) Elevation.

Fig. 1 Three-, six-, nine-, and twelve-story adjacent buildings

The medium rise reinforced concrete buildings have been widely used in the building construction industry. These buildings are constructed with diverse patterns and structural systems. **Figure 1** shows four different selected models with a height variety of 3-, 6-, 9-, and 12-stories. The story height is 3 m for all the building's stories with a bay width of 5 m in both directions. ECP-201 [32] is adopted for the structural and seismic design for the studied buildings. Design details of the buildings and the crucial parameters for real and matched ground motion records can be found in [20].

Nonlinear Dynamic Analysis Procedures:

The finite element analysis package ETABS [31, 33] is adopted for the current study, where the geometric and material nonlinearities are considered during structural FE modeling and analysis. The equilibrium equations for nonlinear static and nonlinear time history analysis take into consideration the deformed configuration of the structure. The material nonlinearity could be captured with the inelastic behavior in the form of a nonlinear force-deformation relation, which affords insight into ductility and limit-state behavior. Yielding and post-yielding behavior are modeled using plastic hinges, hinge properties can be calculated automatically based on element material and section properties according to FEMA-356 [34] or ASCE 41-13 criteria. The Fiber P-M2-M3 hinge simulates the axial behavior of several axial fibers distributed across the frame element cross-section. Each fiber has a location, a tributary area, and a stress-strain curve. The axial stresses are integrated over the section to calculate the values of P, M2, and M3.

Structural Impact Model:

To simulating pounding force between adjacent buildings, the gaps between the buildings are modeled by using a compression-only gap element as shown in **Fig. 2**. A linear damper is introduced to overcome the drawback of the linear viscoelastic model to simulate the energy dissipation [35-39]. The pounding force of the impact model F_1 is determined as:

$$F_1 = \begin{cases} K_G\delta + c\dot{\delta} & \delta > G \\ 0 & \delta < G \end{cases} \qquad \delta = u_i - u_j - G\,, \qquad \dot{\delta} = \dot{u}_i - \dot{u}_j \qquad (1)$$

Where δ and $\dot{\delta}$ defines the relative displacement and velocity between colliding structural elements. K_G and c are the stiffness and damping for the impact model, respectively. u_i, u_j and $\dot{u}_i, \dot{u}_j$ are the displacement and velocity of the element's nodes i, j, and G is the separation gap.

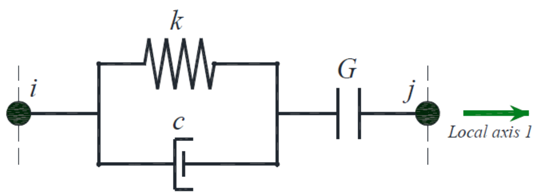


Fig. 2 Viscoelastic impact model.

Numerous investigations have been investigated the different possibilities for the determination of the gap element stiffness. Watanabe and Kawashima [40] have performed a numerical simulation to lighten the suitable stiffness of impact spring and the time interval of numerical integration based on the wave propagation theory, it concluded that the impact stiffness can be defined as the axial stiffness of the contact bodies, a gap element with stiffness equal to the axial stiffness of floor at the impact level is integrated [24, 41]. Anagnostopoulos [42] proposed a gap element with twenty times amplification factor multiplied with the lateral stiffness of the stiff SDOF system. In the current study, the impact stiffness of the gap element K is determined as the greater value of either the axial stiffness of the collided floors or the lateral stiffness of the stiffer building at the impact level [7, 43-46].

$$\mathrm{K} = \gamma\frac{\mathrm{EA}}{\mathrm{b}} \text{ or } \gamma\frac{3\mathrm{EI}}{\mathrm{h}^3} \qquad (2)$$

Where A is the area of the impact surface, E is the modulus of elasticity, and b is building width in the impact direction, I is the moment of inertia of the equivalent cantilever model of the stiffer building, h is the height building up to the impact level. A sensitivity analysis is done for the selection of the value of impact stiffness; on which the stiffness amplification factor is determined, *γ = 50*. Energy dissipation during contact is accounted through damping constant c.

NUMERICAL RESULTS AND DISCUSSION

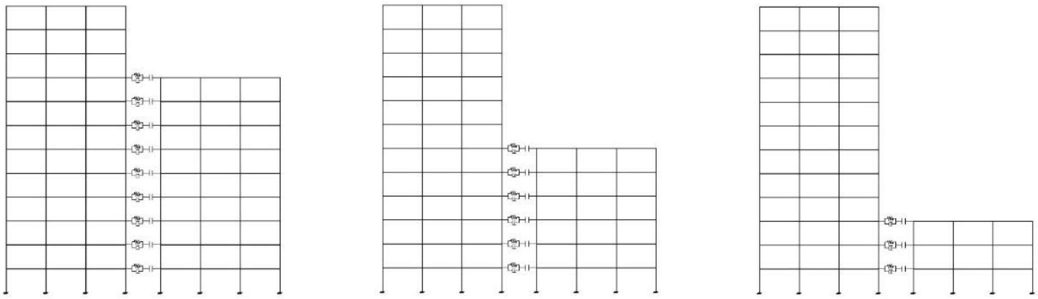
To identify the vibration characteristics of a building, the experimental methods with observation of the dynamic in-situ behavior of the structure can be used or by applying analytical modeling based on the mechanical properties of the components, including all elements contributing either to the mass or stiffness of the system. The vibration characteristics for the studied adjacent buildings in terms of fundamental period and vibration modes as gained from the structural analysis using finite element models and empirical expression in the ECP-201 [32] and other international building codes [47-50] are listed in **Table 1**. The fundamental periods of the four building models based on ECP-201 [32] are 1.102, 0.888, 0.655, 0.390 sec, whereas the fundamental period based on the FE approach are 1.557, 1.242, 0.897, 0.533 sec, which reaches 141, 140, 137, 137% for 12-story, 9-story, 6-story and 3-story buildings that introduced in the code provisions. Hence it is clear that the code formulas have a significant defect in the calculation of vibration period which is considered the main parameter for lateral force procedure.

Table 1 Free vibration characteristics of RC-MRF buildings

Code	Period, T	Fundamental Period (sec)			
		12-Story	**9-Story**	**6-Story**	**3-Story**
3D FE model vibration analysis	1st lateral vibration mode	1.557	1.242	0.897	0.533
	Torsional Vibration mode	1.362/0.511	1.111	0.820	0.503
	2nd lateral vibration mode	0.564	0.446	0.314	0.178
	3rd lateral vibration mode	0.330	0.255	0.184	0.113
ECP-201 (ECP 2012)	$T = 0.075H^{3/4}$	1.102	0.888	0.655	0.390
ECP-201 (ECP 1993)	$T = 0.1\ N$	1.200	0.900	0.600	0.300
IBC (ICC 2003)	$T = 0.073\ H^{3/4}$	1.073	0.865	0.638	0.379
UBC (UBC 1997)	$T = 0.049\ H^{3/4}$	0.720	0.580	0.428	0.255
EC8 (ECS 2004)	$T = 0.075\ H^{3/4}$	1.102	0.888	0.655	0.390
NBCC (NBCC 2005)	$T = 0.05\ H^{3/4}$	0.735	0.592	0.437	0.260

H = the building's height measured from the base and N= number of stories.

To detect the critical vertical location of a potential collision between adjacent buildings, the nonlinear dynamic time history analysis for three different configurations of adjacent buildings has been studied as shown in **Fig. 3**. The Loma Prieta, USA ground motion record was selected to excite the building models with a considered separation gap of 2 cm.



(a)12-9 Pounding. (b) 12-6 Pounding. (c) 12-3 Pounding.

Fig. 3 Different configurations of adjacent colliding buildings

Table 2 presents the peak displacement responses at pounding levels for different configurations and compared to the no-pounding case. For low-rise buildings (9-, 6-, and 3-story buildings), pounding reduces the peak displacement response demand of building in both impact and rebound directions, where the peak responses in the impact direction are significantly decreased about 47%, 51%, and 51% of that no-pounding case, the peak responses in the rebound direction are decreased too with 26%, 38% and 15% of that no-pounding case for 9-, 6- and 3-story buildings, respectively. On the other hand, for the 12-Story building, the displacement response demand slightly decreases due to pounding with 6 story and 3-story buildings in the impact direction at both 6th and 3rd levels with 14% and 4 of that no pounding case, while the displacement response demand has marginally increased in the rebound direction at 6th story level with 8% of that no-pounding case, and at 3rd level, the rebound displacement increased by 23% of that no-pounding case. In the case of pounding with the 9-story building, pounding increases the peak displacement response demand of the building in both impact and rebound directions with 6% and 24% respectively.

Table 2 Peak displacement response (m) at pounding levels

Response	12-9 Pounding			
	12-Story (9th level)		9-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-0.1153	0.1306	-0.1787	0.1740
Pounding	-0.1432	0.1386	-0.0953	0.1296
%	24	6	-47	-26
Response	**12-6 Pounding**			
	12-Story (6th level)		6-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-0.0821	0.0840	-0.1529	0.1507
Pounding	-0.0885	0.0726	-0.0756	0.0927
%	8	-14	-51	-38
Response	**12-3 Pounding**			
	12-Story (3rd level)		3-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-0.04	0.0498	-0.0773	0.0741
Pounding	-0.0492	0.0477	-0.0370	0.0627
%	23	-4	-52	-15

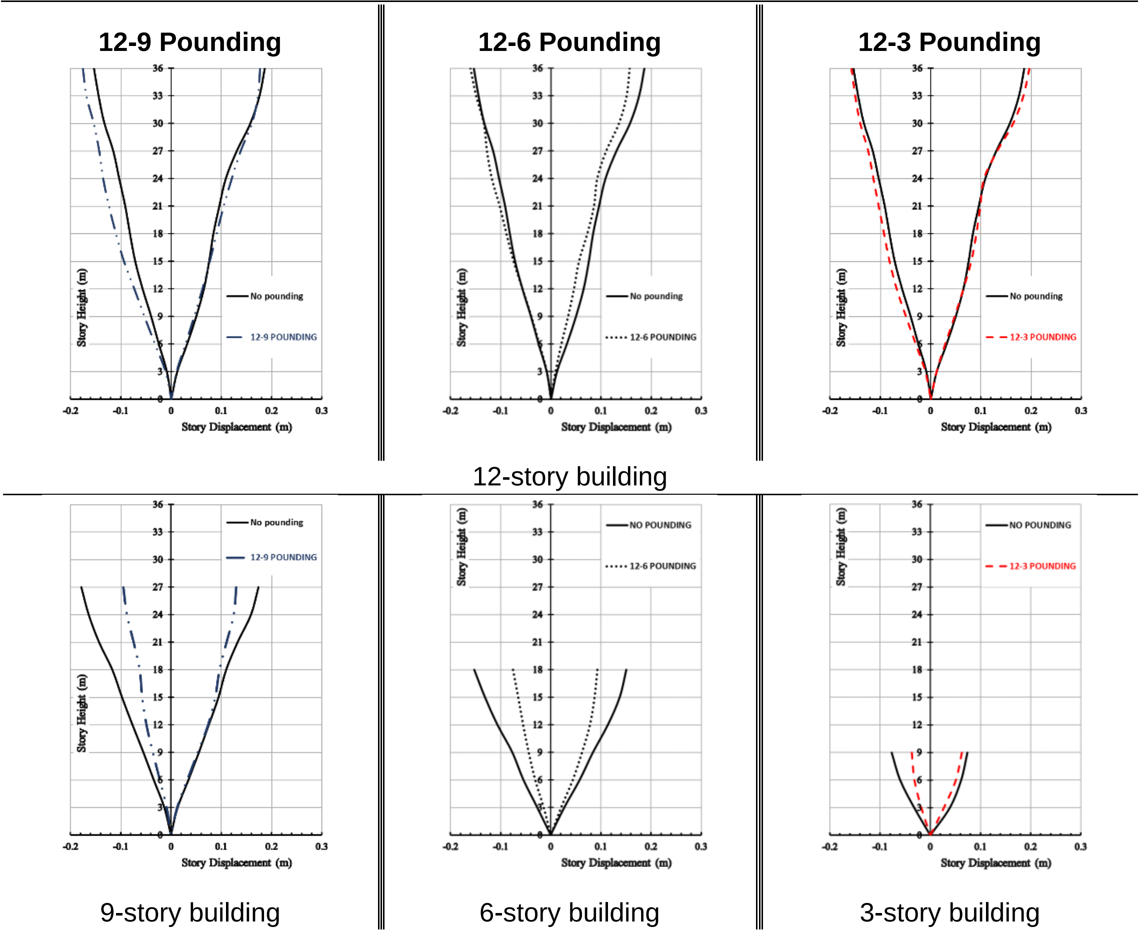


Fig. 4 Displacement response envelops for different Configurations.

Figure 4 shows the displacement response envelopes of adjacent buildings for different configurations. Comparing pounding-involved and independent vibration responses for the adjacent buildings for different configurations shows that the 12-story building is more influenced by pounding because it acts as a stopper for other buildings. Although the 12-story has a long period and higher amplitude of motion and the 3-, 6-, and 9-story shorter buildings have relatively short periods, the 12-story building has relatively high stiffens at the level of impacts. For all configurations, the displacement response demands are significantly reduced for shorter buildings in both impact and rebound directions, while the 12-story high building has an increase of the response over the height in case of pounding with the 9-story building and over the height above the impact level in the rebound direction due to pounding with 6- and 3-story buildings, and response decreases in the impact direction.

Table 3 Peak Acceleration response (m/sec^2) at pounding levels

Response	12-9 Pounding			
	12-Story (9th level)		9-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-8.193	8.136	-9.461	11.772
Pounding	-27.909	16.030	-11.820	32.367
%	241	97	25	175
Response	**12-6 Pounding**			
	12-Story (6th level)		6-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-8.943	7.373	-11.389	14.558
Pounding	-39.593	24.279	-12.085	50.799
%	343	229	6	249
Response	**12-3 Pounding**			
	12-Story (3rd level)		3-Story (top-level)	
	Rebound	Impact direction		Rebound
No Pounding	-11.434	10.655	-12.693	12.792
Pounding	-22.347	15.615	-10.821	36.046
%	95	47	-15	182

Table 3 presents the peak acceleration responses at pounding levels for different configurations and compared to the no-pounding case. For the 12-story building, the acceleration response was increased in all configurations and the maximum acceleration response magnification in both rebound and impact directions was observed in the 12-6 Pounding configuration and could reach 343% in the rebound direction and 229% in the impact direction. Oppositely, for the other low-rise adjacent buildings, the magnification was just observed in the rebound direction, and for the 3-story building, the acceleration response decreased in the impact direction by 15%.

The pounding phenomenon generally leads to higher values of the accelerations in comparison with the case of well-separated buildings. This characteristic can be observed in **Fig. 5**, which depicts the story horizontal acceleration envelopes of buildings for different configurations. It is evident that buildings subjected to pounding generally present higher story acceleration in comparison with the no-pounding case. An abrupt change of velocity direction at the impact level results in great and high acceleration pulses in the opposite direction. The acceleration response has high magnitude and short duration floor acceleration spikes, which in sequence cause foremost damage to building contents. The acceleration response of high-rise building at the height levels below the impact levels is significantly amplified at both directions due to pounding in case of colliding with 6- and 3-story buildings, the response gets its maximum values at the top level of the adjacent building in 12-6 Pounding configuration, while the response of the floors at the height levels above the impact level is slightly affected. Furthermore, the maximum responses in the low-rise building are significantly increased in the rebound directions over the whole height of the building, while the response in the impact direction is slightly affected due to impact.

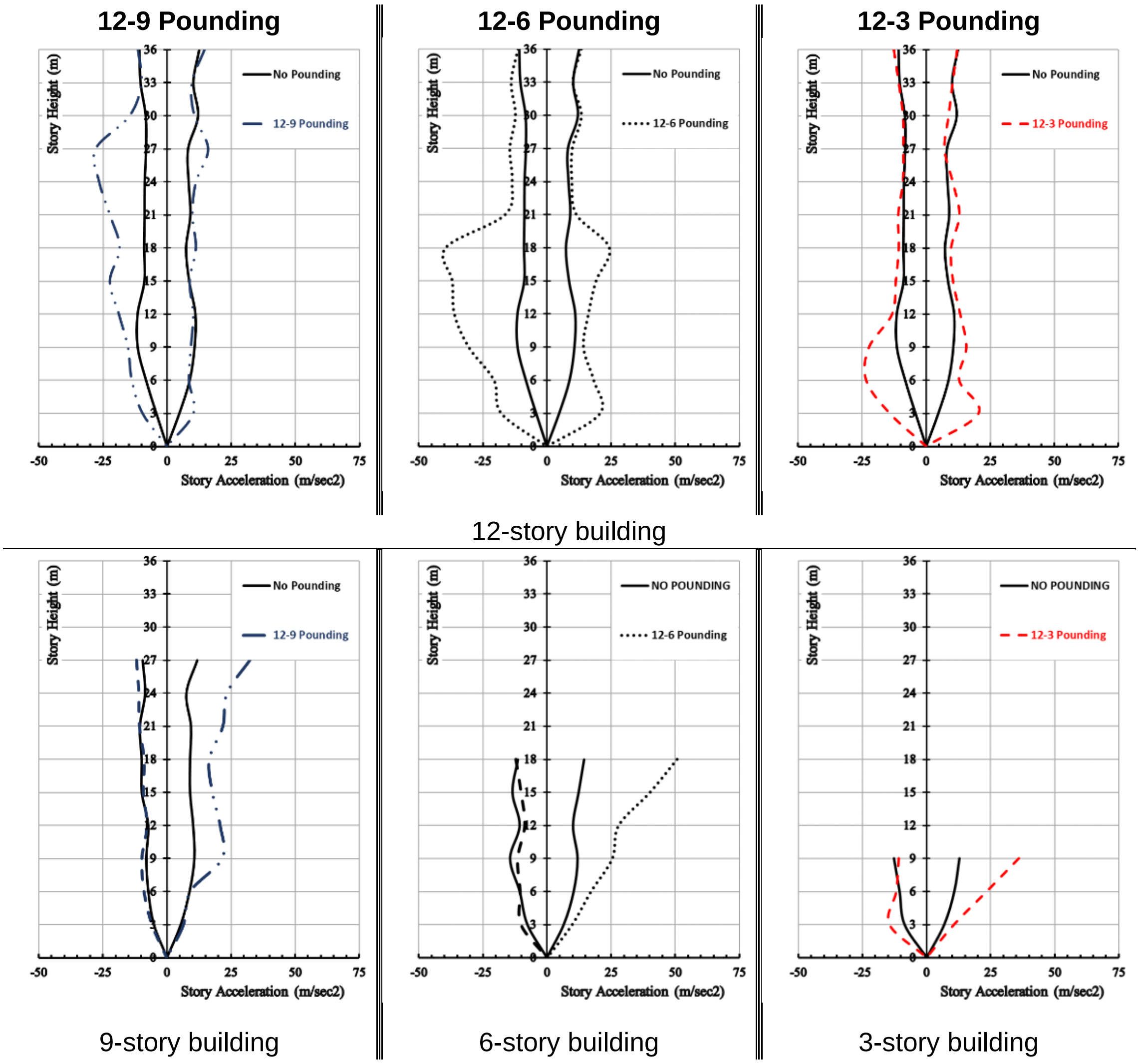


Fig. 5 Acceleration response envelops for different Configurations.

Figure 6 presents the story shear response envelops for different configurations. The sway of the higher building is suddenly limited by the shorter building, and it experiences high story shear forces above the pounding level. For the 12-story building, the impact leads to an increase in the story shear response along with the height above the top level of adjacent buildings in the rebound direction relative to the collided building and reached 27%, 33%, and 22% due to ponding with 3-, 6-, and 9-story buildings respectively. Furthermore, the maximum responses in low-rise buildings are significantly decreased in both directions over the whole height of the building. Contrariwise, pounding with 3- or 9-story buildings leads to an increase in the story shear response of the 12-story building over the whole height of the building in impact direction.

The amplification of shear force response is more significant in the higher adjacent building. The height ratio of the adjacent buildings has a significant role in the pounding effects compared to the vibration period ratio. Due to pounding, the maximum variation in shear forces of the higher building is always observed in the story above the top floor of the shorter adjacent building. This floor is always the location of the first probable collision between the adjacent buildings. The pounding has a considerable effect on the story shear response of the higher building in the stories upper than the top-level of the shorter structure. It is observed that pounding can make the story shear in the stories just higher than the top-level of the shorter building to surpass those of the lower ones.

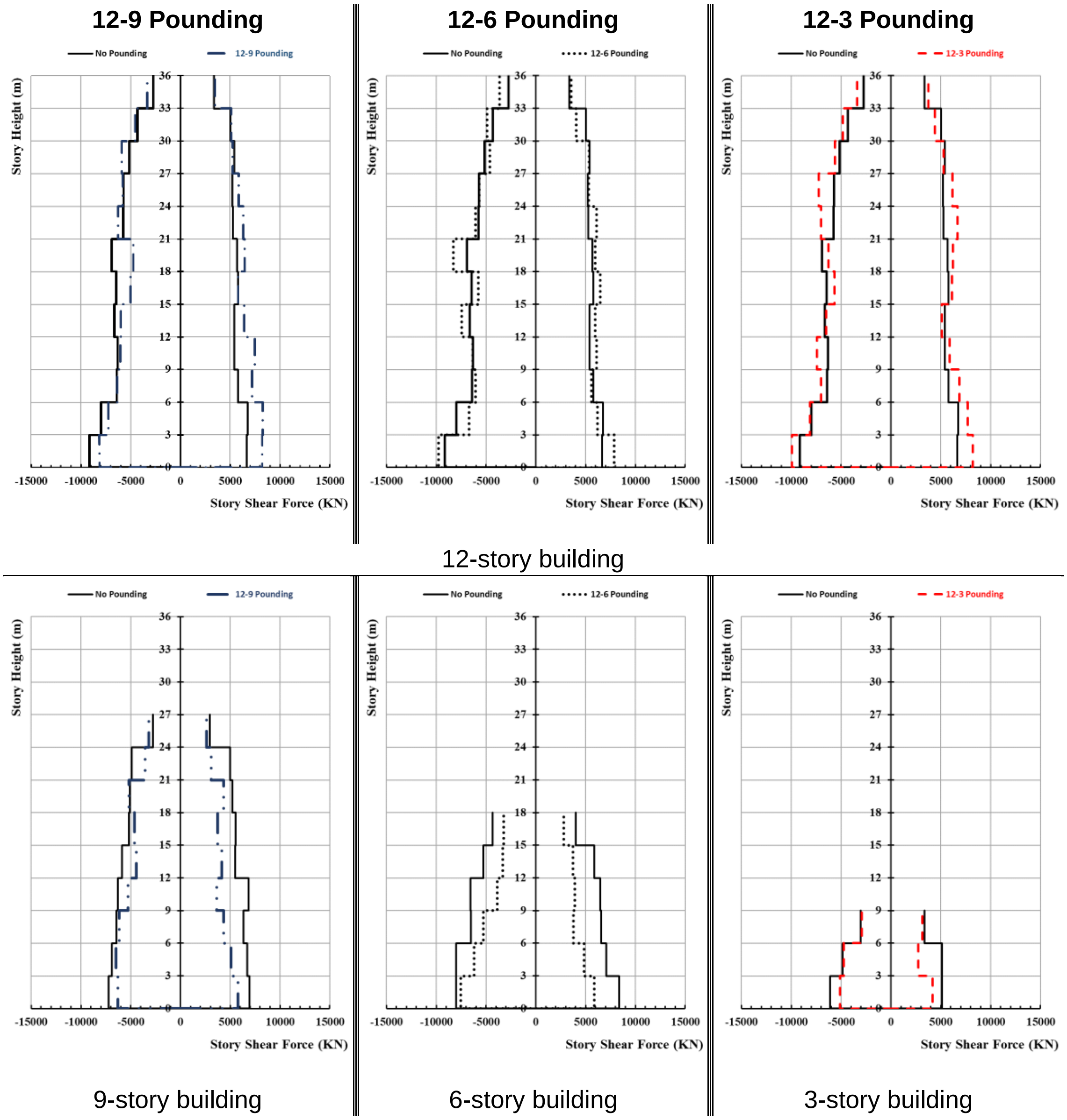


Fig. 6 Story shear response envelops for different Configurations.

CONCLUSION

Seismic pounding is an extremely nonlinear phenomenon and a critical load case that could be a source of major structural damages. This destruction could be inevitable as nearby buildings have out-of-phase vibration characteristics and insufficient separation gap to accommodate the relative displacements of adjacent buildings. Thus, this study target is estimating the influence of the potential vertical position of pounding on the seismic response demands of adjacent collided buildings with unequal height. Based on the obtained results, it has been concluded that the vibration characteristics of the adjacent buildings and height ratio affect the severity of the pounding effects on the response of adjacent buildings. Pounding may occur at different floor levels, allowing the activation of multiple contact locations along with the height of the buildings. The vertical location of potential pounding extensively affects the distribution of story peak responses through the building height.

It is observed that the displacement response demands are significantly reduced for shorter buildings in both impact and rebound directions, while the 12-story high building has an increase of the response over the height in case of pounding with 9-story building and over the height above the impact level in the rebound direction due to pounding with 6- and 3-story buildings, and response decreases in the impact direction. The acceleration response of 12-story building at the height levels below the impact levels is significantly amplified at both directions due to pounding in case of colliding with 6- and 3-story buildings, the response gets its maximum values at pounding with 6-story building, while the response of the floors at the height levels above the impact level is slightly affected. In the case of colliding with the 9-story building which approximately has close vibration characteristics, the acceleration response just amplified in the rebound direction for both buildings. Furthermore, the maximum responses in the low-rise buildings are significantly increased in the rebound directions over the whole height of the building, while the response in the impact direction is slightly affected due to impact. The pounding has a considerable effect on the story shear response of the higher building in the stories upper than the top-level of the shorter structure. It is observed that pounding can make the story shear in the stories just higher than the top-level of the shorter building to surpass those of the lower ones. Although pounding may sometimes reduce the overall structural response of short buildings and thus be considered beneficial, more often it will amplify the response significantly of the relative higher building. Continued research is urgently needed in order to provide the engineering design profession with practical means to evaluate and mitigate the extremely hazardous effects of pounding.

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