Earthquakes and Structures, *Vol. 16, No. 6 (2019) 715-726*
DOI: https://doi.org/10.12989/eas.2019.16.6.715

Seismic pounding effects on the adjacent symmetric buildings with eccentric alignment

Shehata E. Abdel Raheem[*1,2], Mohamed Y.M. Fooly[2a], Mohamed Omar[3,4] and Ahmed K. Abdel Zaher[1,5b]

[1]*Civil Engineering Department, College of Engineering, Taibah University, Madinah 41411, KSA*
[2]*Civil Engineering Department, Faculty of Engineering, Assiut University, Assiut 71516, Egypt*
[3]*Civil Engineering Department, Faculty of Engineering Rabigh Branch, King Abdulaziz University, KSA*
[4]*Civil Engineering Department, Faculty of Engineering, Aswan University, Egypt*
[5]*Civil Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt*

(Received March 20, 2019, Revised April 5, 2019, Accepted April 6, 2019)

Abstract. Several municipal seismic vulnerability investigations have been identified pounding of adjacent structures as one of the main hazards due to the constrained separation distance between adjacent buildings. Consequently, an assessment of the seismic pounding risk of buildings is superficial in future adjustment of design code provisions for buildings. The seismic lateral oscillation of adjacent buildings with eccentric alignment is partly restrained, and therefore a torsional response demand is induced in the building under earthquake excitation due to eccentric pounding. In this paper, the influence of the eccentric seismic pounding on the design demands for adjacent symmetric buildings with eccentric alignment is presented. A mathematical simulation is formulated to evaluate the eccentric pounding effects on the seismic design demands of adjacent buildings, where the seismic response analysis of adjacent buildings in series during collisions is investigated for various design parameters that include number of stories; in-plan alignment configurations, and then compared with that for no-pounding case. According to the herein outcomes, the effects of seismic pounding severity is mainly depending on characteristics of vibrations of the adjacent buildings and on the characteristics of input ground motions as well. The position of the building wherever exterior or interior alignment also, influences the seismic pounding severity as the effect of exposed direction from one or two sides. The response of acceleration and the shear force demands appear to be greater in case of adjacent buildings as seismic pounding at different levels of stories, than that in case of no-pounding buildings. The results confirm that torsional oscillations due to eccentric pounding play a significant role in the overall pounding-involved response of symmetric buildings under earthquake excitation due to horizontal eccentric alignment.

Keywords: eccentric pounding; adjacent buildings; time history analysis; horizontal eccentric alignment; design demands; earthquake characteristics

1. Introduction

Buildings in very crowded urban cities are a foremost concern for destructive seismic pounding risks. Out-of-phase response to neighboring buildings can be a source for serious damage during strong earthquakes due to pounding. The utmost severe cases of seismic pounding on buildings were detected during the 1985 Mexico earthquake, with heavy damage or collapse of 3 to 4.5% of total damaged buildings (Bertero 1986). Pounding among nearby buildings could cause worse damage as adjacent buildings have inadequate separation gap or energy dissipation systems to accommodate the relative movements of neighboring buildings. Investigations of structural pounding damage during recent earthquakes (Kawashima and Unjoh 1996, Naserkhaki *et al*. 2013, Abdel Raheem 2014) has classified the configurations of buildings according to sensitivity to the pounding damages into three categories: building with equal height of story (floor-to-floor pounding); building with non-equal height of stories (inter-story pounding, Shakya *et al*. 2008, Karayannis and Naoum 2018); massive adjacent buildings pounding; eccentric pounding and buildings in row. The seismic pounding among adjacent structures in row causes a repeated hammer that is exerted on each other, the damage due to end building pounding of in-row adjacent buildings is the utmost prominent among the commonly recognized vulnerabilities (Jeng and Tzeng 2000, Bull *et al*. 2010). The seismic lateral oscillation of adjacent buildings with eccentric alignment is partly restrained, and consequently a torsional movement is induced in the adjacent buildings with eccentric alignment during an earthquake excitation due to eccentric pounding. The eccentric pounding magnifies the response relative to symmetric impact. Torsional response may be induced in symmetric structures because either spatial variation of the ground excitation (Kuo 1974, Tabatabaei 2011) or eccentric alignment.

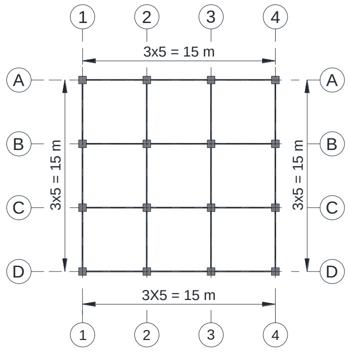
The phenomenon of earthquake-induced pounding between buildings has recently been intensively studied

∗Corresponding author, Professor
E-mail: shehataraheem@yahoo.com
[a]Lecturer
E-mail: eng.myfooly@yahoo.com
[b]Assistant Professor
E-mail: moh_omar77@yahoo.com,
dr.ahmedkamal@hotmail.com

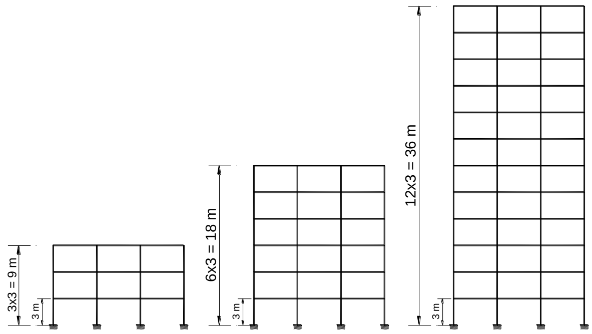
http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

using various structural models and different models of collisions (Anagnostopoulos and Spiliopoulos 1992, Davis 1992, Jankowski 2006, Mahmoud and Jankowski 2011, Abdel Raheem *et al*. 2018a, 2019). However, the analyses for torsional response due to eccentric collisions, are very limited. Buildings may collide in torsion mode arising due to buildings' configuration irregularity (Abdel Raheem *et al*. 2018c) or due to in-plan eccentric alignment arrangement of adjacent buildings causing eccentric pounding. Among seismic torsional pounding studies, Leibovich *et al*. (1996) investigated the influence of impact eccentricity on two symmetric linear elastic single-story models with symmetrically and asymmetrically aligned for numerous gap sizes and torsional eccentricity to lateral frequency ratios. Papadrakakis *et al*. (1996) established a 3D finite element analysis for the simulation of the pounding response of two or more adjacent buildings. The effect of various in-plan configurations of adjacent buildings as well as the consequence of stiffness irregularities in plan are examined. Gong and Hao (2005) used a single-story model subjected to bi-directional earthquake excitation to do a parametric study on the lateral-torsional-pounding responses of adjacent structures. Wang *et al*. (2009) adopted the Hertz contact model to simulate lateral-torsional pounding between two asymmetric single-story buildings. Fiore *et al*. (2013) proposed an analytical model to simulate the coupled lateral-torsional pounding between two equal height adjacent buildings, in view of numerous pounding scenarios conferring to the position of the adjacent buildings during vibration. Rajaram and Ramancharla (2014) studied the eccentric pounding of adjacent buildings with different setbacks, it has been identified that the increase in the setback distance causes magnification in impact force. Torsional coupling of the seismic response of adjacent buildings makes them to impact at the corners. This phenomenon acts like an amplification factor for the torsional response (Farahani *et al*. 2019). Combination of the torsional response and pounding at the corners makes the peripheral frames to be the most critical ones in many cases regarding the nonlinear response and ductility demand (Karayannis and Naoum 2017).

From the above studies, torsional pounding is evident during earthquakes and most of these studies focus only on torsional pounding between two adjacent buildings. However, it is quite usual seismically induced oscillations of a structure in a block of buildings to be partially restrained in lateral displacements and consequently a torsional movement to be introduced in the building due to eccentric pounding. In this paper an attempt to study the influence of the eccentric seismic pounding on the design requirements for reinforced concrete buildings with different story heights is presented. So, three adjacent buildings are considered with different setback eccentric alignment under a set of ground motion records to assess the torsional behavior due to different setbacks between nearby buildings in series. A parametric study on the effects of eccentric impact on the response of symmetric multi-story adjacent buildings with horizontal eccentric alignment and different heights is formulated. The eccentric alignment configuration implies that the earthquake induced oscillations of the tall building is laterally partly restrained by the other structure and therefore a torsional movement is introduced in the adjacent buildings during an earthquake excitation. Therefore, a significant torsional movement is induced as if there was plan asymmetry and building configuration irregularity (Abdel Raheem *et al*. 2018d). The torsional movement depends on the impact interaction area and eccentricity of the impact forces resultant to the stiffness centers of the collided buildings.



(a)



(b)

Fig. 1 Three-, six- and twelve-story adjacent buildings: (a) Typical floor plan, (b) Elevation

2. FE modelling for seismic response analysis

2.1 Physical model for the interaction of adjacent Buildings

The medium-rise reinforced concrete buildings has been widely used in the building construction industry. These buildings are constructed with diverse patterns and structural systems. Fig. 1 shows three different selected models with height variety of 3-, 6-, and 12-stories. The story height is 3 m for all the building's stories with bay width 5 m in both directions. The used reinforced concrete material properties in analysis and design has a compressive strength of $f_c = 30$ MPa (M30), unit weight $\gamma_c = 25\ \mathrm{kN/m^3}$ and $E = 24$ GPa of modulus of elasticity. The used reinforced steel has yield strength of $F_y = 360$ MPa and Poisson's ratio $\upsilon = 0.2$. The dead load (DL) and live load (LL) as gravity loads and lateral earthquake loads are included for the building design. The dead loads take account of the own weight of the structural

Table 1 Cross-sections and rebar for columns of all buildings

Building	Story No	From 1 to 3		From 4 to 6		From 7 to 9		From 10 to 12	
	Column position	Size rebar	ρ_s %	Size rebar	ρ_s %	Size Rebar	ρ_s %	Size rebar	ρ_s %
12-Story	corner	60×60 24T22	2.53%	50×50 20T20	2.51%	50×50 20T16	1.60%	40×40 20T16	2.50%
	Edge	70×70 24T22	1.86%	60×60 20T22	2.11%	50×50 20T20	2.51%	40×40 20T16	2.50%
	Internal	80×80 28T25	2.15%	70×70 28T22	2.17%	60×60 24T22	2.53%	50×50 20T22	3.04%
6-Story	corner	50×50 20T16	1.60%	40×40 20T16	2.50%				
	Edge	50×50 20T20	2.51%	40×40 20T16	2.50%				
	Internal	60×60 24T22	2.53%	50×50 20T22	3.04%				
3-Story	corner	40×40 20T16	2.50%						
	Edge	40×40 20T16	2.50%						
	Internal	50×50 20T20	2.51%						

ρ_s % is the dimension ratio of steel to concrete

components, the weight of flooring cover ($1.5\ \mathrm{kN/m^2}$) and panel wall loads intensity of $10\ \mathrm{kN/m'}$ on all beams. As a residential building, a selected $2\ \mathrm{kN/m^2}$ of live load is considered. ECP-201 (ECP 2012) is adopted for the structural and seismic design for the studied buildings. The parameters of the seismic design are 0.3 g as peak ground acceleration PGA regarding to the earthquake zone ($5B$), while the important factor is taken as $\gamma = 1$. The response spectrum of type 1 is considered while soil factor $S = 1.8$ is taken as for soil class (D). For the MRF buildings $R = 5$ is selected as a reduction factor. From structural design which has been carried out according to ECP-203 (ECP 2007, Abdel Raheem 2013, Abdel Raheem *et al*. 2015), the floor slab thickness is 0.15 m as a slab-beam system while the dimensions of floor beams are $0.3\ x\ 0.7$ m. Table 1 shows the columns' cross sections details of reinforcement and cross section dimensions.

2.2 Mathematical modeling and nonlinear dynamic analysis procedures

The computer program used in this research is the finite element analysis package ETABS (CSI 2013, ETABS 2016, Abdel Raheem *et al*. 2018b). The finite element mesh used here for the modelling of each structure utilizes one-dimensional beam-column element for each structural member, where the geometric and material nonlinearities are considered during structural FE modelling and analysis. The beam-column element with lumped plasticity is used, where the inelastic behavior is concentrated in zero-length plastic hinges at the element's ends, a $3D$ interaction surface $N - M_x - M_y$ is used to model the plastic hinge behavior. The equilibrium equations for nonlinear static and nonlinear time history analysis consider the deformed configuration of the structure. The nonlinear relation of force-deformation can capture the nonlinear behavior, which can take the material nonlinearity into consideration within ductility and limit-state behavior. Using the plastic hinge properties, the yielding and post-yielding can be modelled. According to FEMA-356 (FEMA 2000) or ASCE 41-13 criteria (ASCE 2013), based on the material of element and the properties of the section, the properties of hinge could be calculated automatically. The practice on seismic design of buildings demonstrates that masonry infill walls entirely alter the behavior of building's frames due to enlarged initial stiffness and low deformability. However, it is hard to assess the infill contribution to the lateral stiffness and strength and its effects on the behavior of moment resisting frame building, as failure modes could be in either the masonry or the surrounding frame. Thus, due to numerous uncertainties concerning the infill arrangement as non-structural elements and openings through walls, complications in modelling infill wall-frame interaction are hard to be quantified and typically disregarded in structural analysis and design (Karayannis and Favvata 2005a, b, Elwardany *et al*. 2017, Abdel Raheem *et al*. 2019).

2.3 Spectrum compatible input acceleration time histories

In this study, nine-ground motions' time histories have been chosen as input earthquake excitation for seismic pounding nonlinear dynamic analysis. The input excitation in the form of acceleration time histories is required to be well-matched with the design response spectra at the target site. In order to match the proposed elastic design spectrum ECP (ECP 2012), the chosen input excitation records (Ancheta *et al*. 2013) have been scaled using a time domain scaling method. The SeismoMatch software (Abrahamson 2006) is employed to scale the selected records. For the response history analysis, the crucial parameters as an indicator of the damage potential of the earthquake excitation are calculated for real and matched ground motion records and presented in Table 2. The ground

Table 2 key parameters of real and matched nine-ground motion records

Earthquake / Station	M_w	Spectra Match	PGA g	PGV m/sec	PGD cm	Specific Energy	Arias Intensity	Housner Intensity	Period T_s (sec)
San Simeon, CA. / RSN3994-36153090	6.52	Real	0.13	13.10	7.72	497.3	0.21	40.29	0.13
		Match	0.38	33.80	7.93	1133.6	1.27	123.0	0.38
Morgan Hill, USA / RSN457- G03000	6.19	Real	0.19	11.02	3.12	500.3	0.34	48.6	0.19
		Match	0.52	26.20	4.32	856.3	1.42	118.8	0.48
Christchurch, NZ / RSN8124-RHSCN86W	6.20	Real	0.29	33.52	16.99	1479.6	1.13	100.56	0.29
		Match	0.45	37.20	18.14	1667.6	1.82	140.41	0.45
L'Aquila, Italy / RSN4481-FA030YLN	6.30	Real	0.52	35.91	4.47	565.9	1.37	91.60	0.51
		Match	0.63	43.62	3.68	714.3	2.08	111.69	0.62
Loma Prieta, USA / RSN811-WAH090	6.93	Real	0.65	38.12	5.91	1487.2	6.27	128.35	0.64
		Match	0.60	35.35	5.69	1299.5	5.90	119.80	0.58
Imperial Valley, USA / RSN160- H-BCR140	6.53	Real	0.60	46.75	20.22	2655.4	3.97	174.64	0.59
		Match	0.57	40.62	15.79	1721.5	2.92	126.76	0.56
Bam, Iran / RSN4040- BAM-L	6.60	Real	0.81	124.12	33.94	7989.2	7.83	389.31	0.79
		Match	0.65	64.89	20.07	2802.4	4.80	147.44	0.64
Kobe, Japan / RSN1106-KJM000	6.90	Real	0.83	91.11	21.11	7581.8	8.38	363.11	0.82
		Match	0.45	36.94	12.33	2054.2	2.29	139.71	0.44
Chi-Chi, Taiwan / RSN1231-CHY080-N	7.62	Real	0.86	93.16	41.66	10247.2	6.41	395.38	0.85
		Match	0.53	37.16	39.54	3786.0	1.88	141.20	0.52

motions are scaled in accordance with the seismic code provisions (NEHRP 2003) such that for each period between $0.2\,T_1$ and $1.5\,T_1$, the average of the 5% damped response spectra for the suit of ground motion is not less than the corresponding ordinate of the target response spectrum, where T_1 is the fundamental period of the structural system.

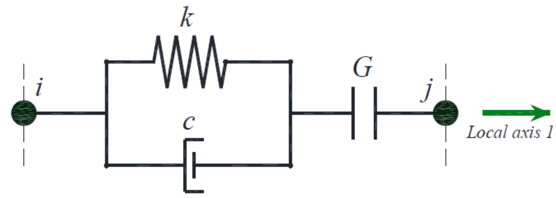


Fig. 2 Viscoelastic impact model

2.4 Structural impact model

Fig. 2 shows the compression-only gap element that can be utilized to simulate the pounding force between the adjacent buildings. To overcome the linear viscoelastic model drawback, the energy dissipation simulation is modeled by introducing the linear dumper. (Zhu *et al*. 2002, Pekau and Zhu 2006, Komodromos *et al*. 2007, Jankowski 2010, Polycarpou and Komodromos 2010). The pounding force of impact model F_I is calculated as

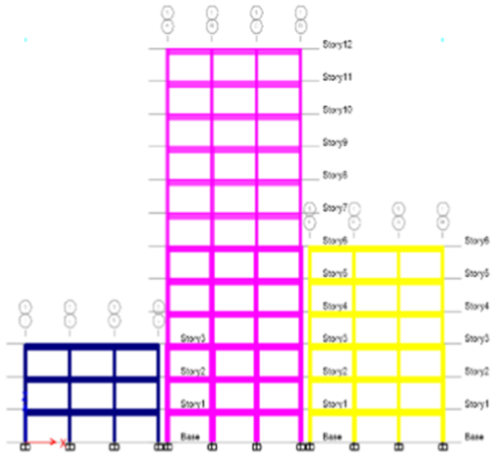
$$F_I = \begin{cases} K\delta + c\dot{\delta} & \delta > G \\ 0 & \delta < G \end{cases} \quad \text{where}$$
$$\delta = u_i - u_j - G\,,\ \dot{\delta} = \dot{u}_i - \dot{u}_j \qquad (1)$$

where δ and $\dot{\delta}$ defines the relative displacement and velocity between colliding elements. K 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. Several studies have been discussed the different potentials for the determination of the gap element stiffness (Wada *et al*. 1984, Anagnostopoulos 1988, Maison and Kasai 1992, Watanabe and Kawashima 2004). For the gap element K, the impact stiffness herein can be determined as the greater value of either the lateral stiffness of the stiffer building or the axial stiffness of the collided floor at the impact level. (Kawashima and Shoji 2000, Unjoh *et al*. 2003, Abdel Raheem 2009, Guo *et al*. 2012, Shrestha *et al*. 2013, Abdel Raheem *et al*. 2019).

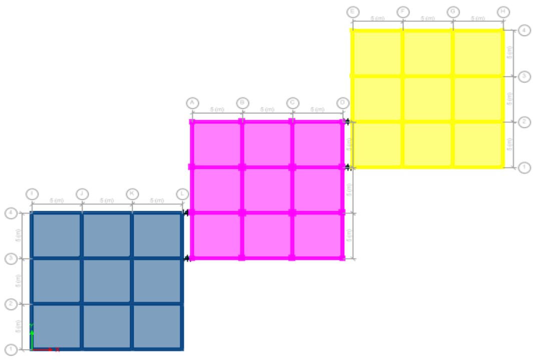
$$K = \gamma\frac{EA}{b} \quad or \quad \gamma\frac{3EI}{h^3} \qquad (2)$$

Where E is the material elasticity Young's modulus, A is the impact contact area, and the building width is expressed by symbol b in the impact direction. The equivalent cantilever model for the stiffer building has the moment of inertia I whereas the building height up to the impact level; h. The stiffness amplification factor; $\gamma = 50$ is selected based on sensitivity analysis. This value was assessed based on some practical considerations, supported by a limited sensitivity study which showed that the system responses are not sensitive to changes in the stiffness of the impact elements. The dashpot constant; c of the impact elements determines the amount of energy dissipated during impact. Rational values of this constant can be assigned by linking it to the coefficient of restitution, in terms of which the plastic impact of two bodies has typically been studied and for which experimental data are (Goldsmith 1960). if two masses m_1 and m_2, which collide with arbitrary velocities, it is easy to express the dashpot constant c of the impact element in terms of the coefficient of restitution r, by equating the energy losses during impact.

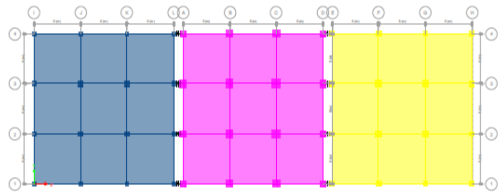
$$c = 2\zeta\sqrt{K\frac{m_1\,m_2}{m_1 + m_2}} \quad , \quad \zeta = \frac{-\ln r}{\sqrt{\pi^2 + (\ln r)^2}} \qquad (3)$$



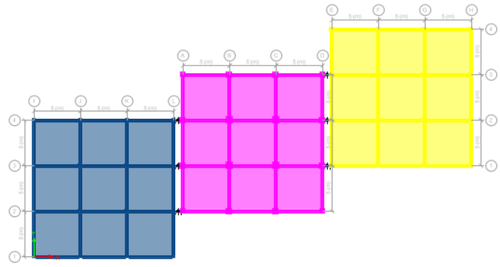
(a) 3-12-6 configuration of adjacent buildings



(d) Two-bay setback (10 *m* setback)



(b) Plan of longitudinal alignment



(c) One-bay setback (5 *m* setback)

Fig. 3 Longitudinal and eccentric alignment of adjacent buildings in series

where K = stiffness of the impact spring. For the applications herein, a value of the coefficient of restitution $r = 0.65$ was assumed, which corresponds to a damping ratio $\zeta = 0.14$. Based on studies from literature it may be admitted that the influence of the damping is rather negligible, and the system response is not noticeably sensitive to changes of the spring stiffness (Anagnostopoulos and Spiliopoulos 1992, Karayannis and Naoum 2018).

3. Numerical results and discussion

To study the effect of torsional pounding on the design demands of adjacent symmetric buildings with eccentric alignment, two different setbacks for eccentric alignment are considered as shown in Fig. 3. A parametric study on the effects of eccentric impact on the response of symmetric multi-story adjacent buildings with horizontal eccentric alignment is formulated. The responses were observed along both x and y directions for all the three adjacent buildings with reference to the four corners A1, A4, D1, D4 of the adjacent buildings as shown in Fig. 1(a). Two cases of eccentric pounding are investigated and compared to the reference case of longitudinal pounding for horizontal in-plane alignment of adjacent buildings: One-bay setback eccentric alignment, where pounding takes places along two-bay of 10 m; two-bay setback eccentric alignment, where pounding takes place along one-bay of 5 m. The initial gap distance between the adjacent structures could help towards ameliorating the consequences of the pounding. The in-contact case most probably exhibits the heaviest consequences due to the pounding in comparison to the corresponding cases with an initial gap distance between the interacting structures. However, it could not be a fact, since the interval of a very small gap size stands for the case of nearly fully continuous structure, the initial gap distance effects significantly depend on its normalized value relative the minimum required gap size to prevent pounding for the considered excitation record, studied response and its impact/ rebound direction, and input excitation (Jankowski *et al*. 2000, Abdel Raheem *et al*. 2018a). The initial gap distance allows the building to generate lager relative velocities before collision, which increases the impact force (Cole *et al* .2011).

3.1 Response demands in longitudinal direction

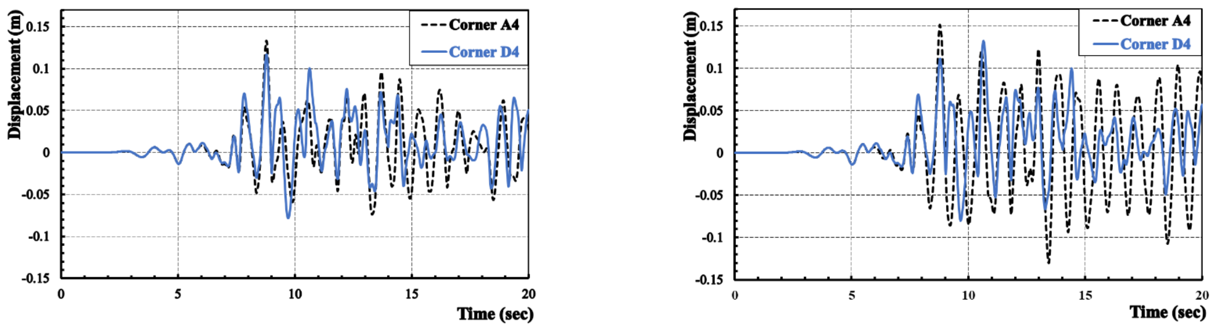
For the three different in-plan Alignment configurations of 5 m and 10 m, in addition to adjacent buildings without a setback, the nonlinear dynamic analysis has been carried out for separation gap of 2 cm between buildings is considered. Table 3 shows peak displacement response at pounding level for the different buildings under San Simeon earthquake. The results are compared to the no-pounding and longitudinal pounding cases. For the 6-story and 3-story exterior buildings and the 12-Story interior one, in both rebound and impact directions, the building peak displacement response demands is reduced by the longitudinal pounding. With the two sided-impacts for the interior 12-Story building at both 3rd and 6th story level, due to the pounding in the impact direction, the displacement

Table 3 Peak displacement responses at pounding level (*m*)

Earthquake	Response	Impact between 3- and 12- Story buildings				Impact between 12- and 6- Story buildings			
		3-Story building		12-Story building				6-Story building	
		(3^{rd} level)				(6^{th} level)			
		Rebound	Impact direction		Rebound	Rebound	Impact direction		Rebound
San Simeon	No pounding	-0.057	0.077	-0.033	0.030	-0.079	0.072	-0.113	0.115
	Longitudinal	-0.049	0.030	-0.033	0.025	-0.080	0.055	-0.071	0.093
	Pounding %	-14	-61	0	-17	1	-24	-37	-19
	One-bay	-0.051	0.044	-0.036	0.026	-0.083	0.064	-0.072	0.098
		D1-D4		A1-A4	D1-D4	D1-D4		A1-A4	
	%	-11	-43	9	-13	5	-11	-36	-15
	Two-bay	-0.055	0.070	-0.035	0.034	-0.090	0.081	-0.097	0.108
		D1-D4		D1-D4		D1-D4		A1-A4	
	%	-4	-9	6	13	14	13	-14	-6

Table 4 Peak pounding forces induced at different story levels under Loma Prieta earthquake (MN)

Story	Impact between 3- and 12- Story buildings			Impact between 12- and 6- Story buildings		
	Longitudinal Pounding	Eccentric One-bay	Eccentric Two-bay	Longitudinal Pounding	Eccentric One-bay	Eccentric Two-bay
Story 6	-	-	-	15.53	14.43	9.27
Story 5	-	-	-	12.98	1.10	6.19
Story 4	-	-	-	9.25	5.32	4.50
Story 3	8.61	6.20	3.96	6.00	4.24	3.62
Story 2	7.72	4.34	1.99	0.00	0.70	0.93
Story 1	0.00	0.00	0.00	0.00	0.00	0.00



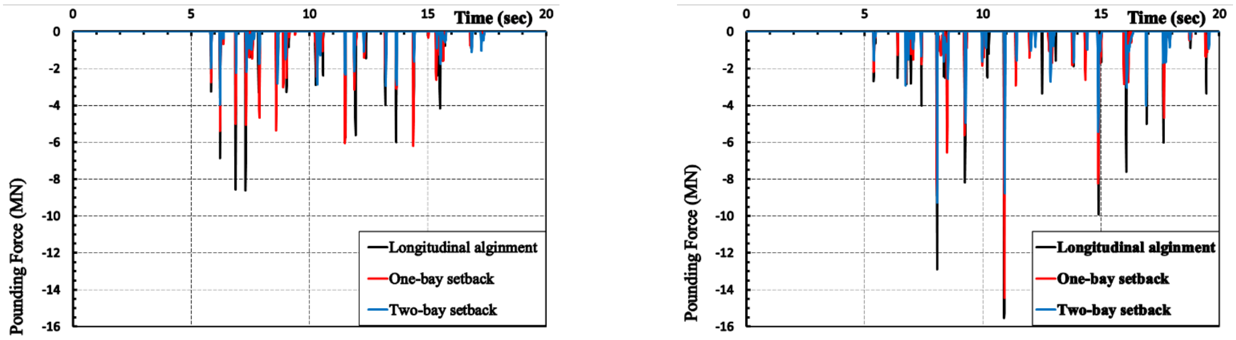
(a) 6-Story Building one-bay setback (b) 6-Story Building two-bay setback

Fig. 4 Longitudinal displacement time-histories for different in-plan alignments during Kobe earthquake

response demand has been increased. The maximum increasing at both 3^{rd} and 6^{th} levels is 24% of that case of no-pounding. In the rebound direction, the displacement response demand decreased with 17% at the 3^{rd} story level of that case of no-pounding.

The eccentric pounding effects on the seismic design demands of adjacent symmetric buildings with eccentric alignment are investigated through one-bay and two-bay setback alignment between adjacent buildings, the displacement responses for buildings' corners and the torsional responses due to eccentric impact were observed as shown in Fig. 4. Moreover, Table 3 shows that as the setback distance increase; i.e., the impact contact interaction between buildings decreases, the longitudinal displacement peak responses for both exterior buildings has been reduced with range 9-43% of that from no-pounding case, while the peak response for interior 12-Story building displacement response demand increases by maximum 14% in both 3^{rd} and 6^{th} levels due to different in-plan alignment. In addition, it can be seen the displacement demand in the direction of the earthquake excitation could decrease/increase due to the movement restraint provided by the adjacent buildings at this point of the building whereas at the same time significant displacement demands are observed in the normal direction.

Table 4 presents peak pounding force induced by Loma Prieta earthquake for different in-plan alignment configurations. For different story levels, the pounding between 3-story and 12-story buildings and between 12-story and 6-story buildings from other side displays the higher value of the impact force for longitudinal pounding case without a setback. In general, the longitudinal pounding introduces the higher impact force compared to the eccentric impact which occur with setback eccentric



(a) 3rd level between 3- & 12-Story Buildings (b) 6th level between 12- & 6-Story Buildings

Fig. 5 Pounding force response time histories during Loma earthquake

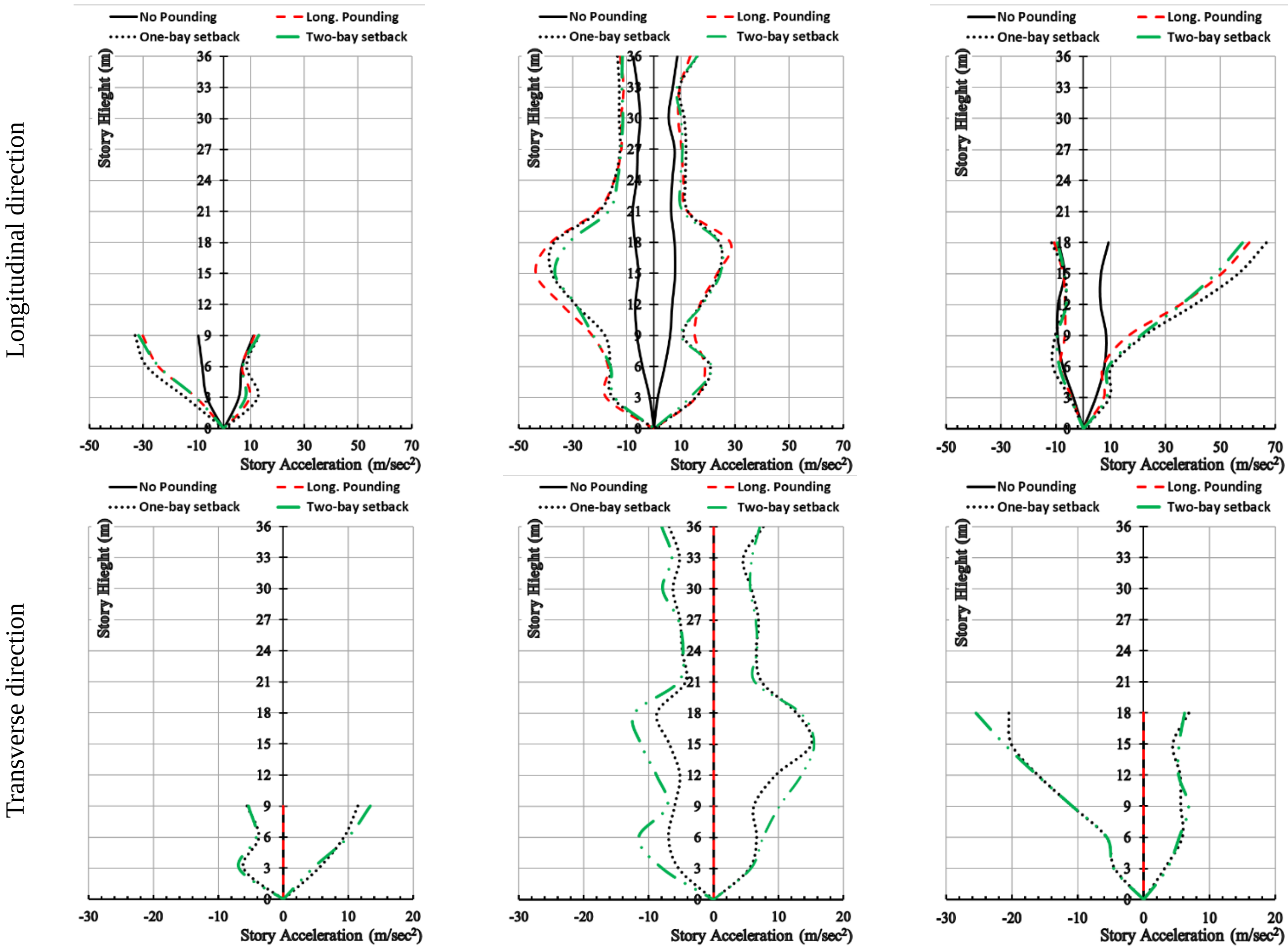


Fig. 6 Response envelops for different in-plan alignments under San Simeon earthquake

alignment cases, which could be attributed to the lager area of impact interaction, the adjacent floors of the buildings experience frontal surface to surface pounding. On the other hand, when different setbacks are considered, the eccentric alignment of mass centers of adjacent buildings floors will lead to torsional responses due to eccentric poundings. As shown in Fig. 5, collisions between adjacent buildings at the 3rd level are 21 times when longitudinal pounding is considered. However, when setback S=5 m is considered, the corresponding pounding events are 27 times. More pounding events but smaller pounding forces are observed when different setbacks are considered. This is because the entire mass of the floor is involved in the pounding if building only responds in one direction, which results in larger pounding force owing to large inertial resistance, whereas only partial mass of the floor will contribute to the inertial resistance when torsional or eccentric pounding occurs. As shown in Table 4, the pounding between 6-story building and 12-story buildings at 2nd story level displays that the value of the impact force for two-bay setback S=10 m higher than that for one-bay setback S=5 m, while no pounding events observed in case of longitudinal pounding, the pounding forces are caused by the torsional rotations of stories.

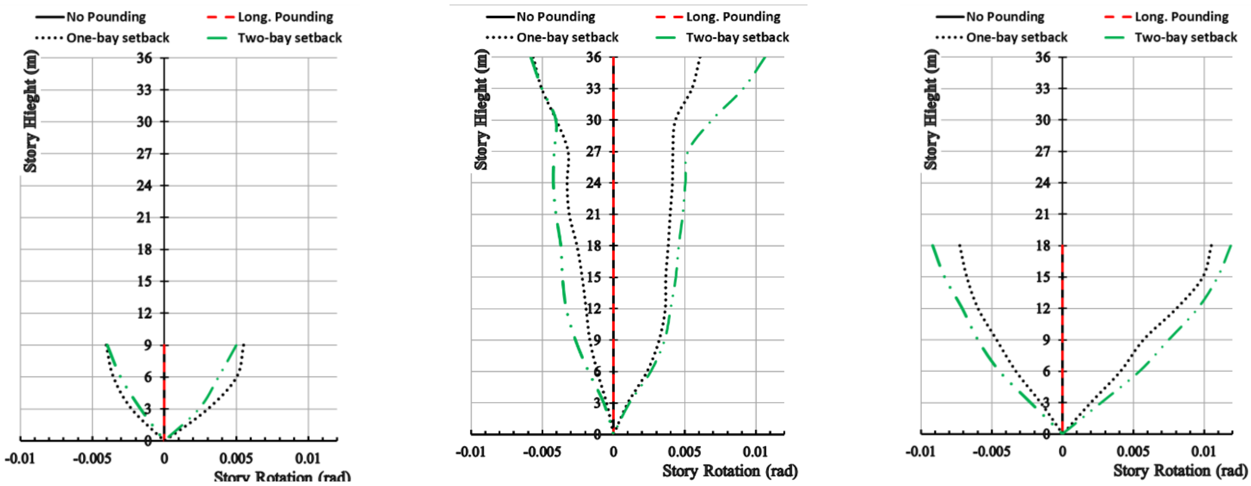


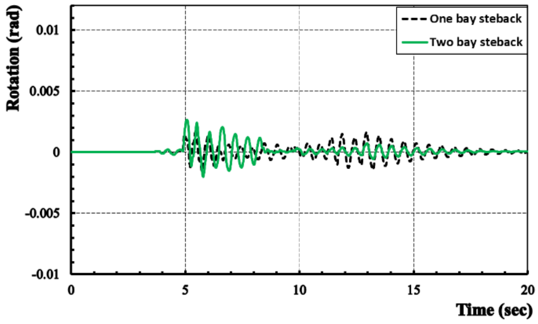
Fig. 7 Maximum envelope of torsional rotation response for different in-plan alignments

3.2 Response demand in the transverse direction

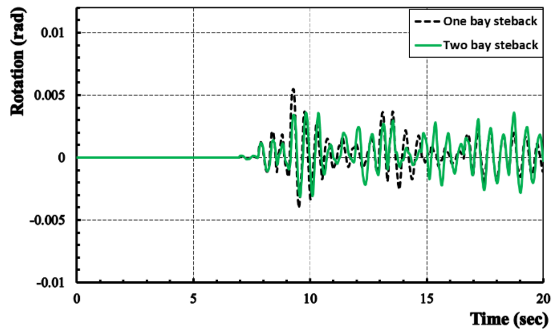
From the symmetry of buildings model, the transverse response not observed in no-pounding and longitudinal pounding cases. While, the transverse response of adjacent buildings is developed due to eccentric pounding because of the difference in in-plan alignment configuration “setback”. Fig. 6 shows the story responses of an adjacent building in the transverse direction. The response of the 3-Story and the 12-Story building was taken at corner “A4” while corner “D1” is considered for 6-Story building response. As shown in Fig. 6, by increasing setback distances the response of building in the transverse direction is increasing. The torsional movement is introduced in the adjacent buildings due to the induced plan asymmetry caused by the restraints imposed by the pounding between the adjacent structures. The results clearly show that high requirements in terms of torsional moments and column shear strength are developed due to the eccentric pounding.

3.3 Torsional response demands

Torsional oscillation has been the cause of major damage to buildings subjected to strong earthquakes, ranging from visible distortion of the structure to structural collapse. The torsional vibrations occurred due to the variation in the displacement responses for corners of the building because of the difference in in-plan alignment configuration of adjacent buildings “setback”. Fig. 7 presents the maximum torsional rotation response envelops for different in-plan alignment configurations that confirms the trend of eccentric impact effect on the torsional rotation response demands of the adjacent building. For the exterior 3-Story building which had a one-sided impact, Fig. 7 shows that the torsional response is decreased by increasing the setback distance. It can be seen however, that the torsional vibrations of the interior 12-Story building which had a two-sided eccentric impact and other exterior 6-Story building are substantially increased as the result of increasing the setback distance. The torsional vibrations of the adjacent buildings due to eccentric pounding are important components of the overall structural responses.



(a) 3rd level during L’Aquila earthquake



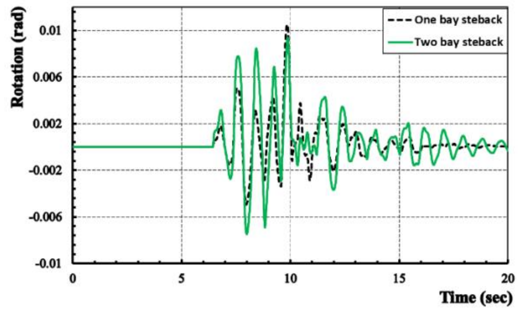
(b) 3rd level during Kobe earthquake

Fig. 8 Story rotation time histories of the 3-Story building for different in-plan alignment configurations

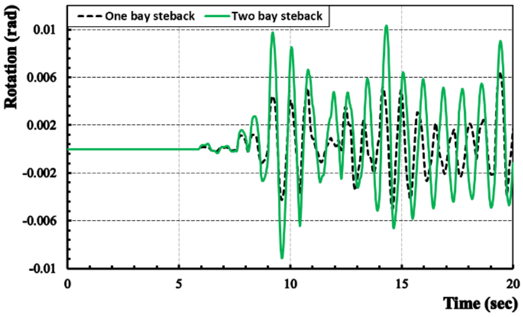
The results indicate, however, that structural pounding may significantly influence the torsional behavior of adjacent buildings. In the case of the 3-storey building, the increase in the peak value of the rotation angle at the top floor is equal to 13.9 %. On the other hand, the torsional response of the 6-storey building significantly decreases due to pounding. The change in the peak value of the rotation angle at the top floor of this structure during the earthquake is as large as 45.7 %. The rotational response of asymmetric-plan buildings leads to unequal displacement demands on the floor diaphragm. The building rotates about its center of rigidity. This causes large increase in the lateral forces and displacement demands in lateral load resisting elements, in proportion to their distance from the center of rotation. In such cases, corrective measures should be taken in the structural design of the building. In effect, the upper part of the building transmits an eccentric shear to the lower part, which causes downward torsion of the transition level regardless of the structural symmetry or asymmetry of the upper and lower floors.

Figs. 8-10 show the comparison between the different setbacks' vibration time histories of the rotation angle at the top floor of the adjacent 3-, 6- and 12-story buildings beside 3rd and 6th levels of the 12-Story building, respectively. The figures indicate that the torsional responses of the building sometimes increase or decrease as the result of increasing the setback distance. For the exterior 3-story building which had a one-sided impact.

Fig. 8 shows that the increase in the peak value of the rotation angle at the top floor of this structure during L'Aquila earthquake is 37.3% while the response is decreased by 34% during Kobe earthquake by increasing the setback distance. Likewise, for the other exterior 6-story building, Fig. 9 reveals that the torsional responses of the building are also increased by 61.4 % during Kobe earthquake and decreased by 10.7 % during Christchurch earthquake as the result of increasing the setback distance. It can be seen from Fig. 10, however, that the torsional vibrations of the interior 12-Story building which had a

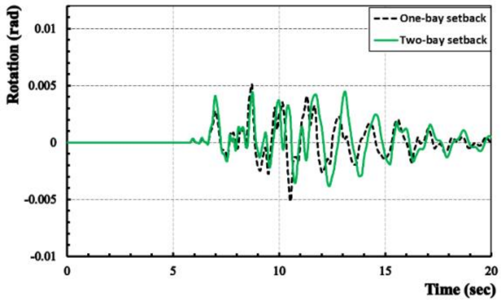


(a) 6th level during Christchurch earthquake

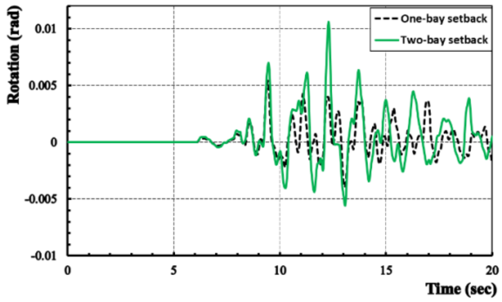


(b) 6th level during Kobe earthquake

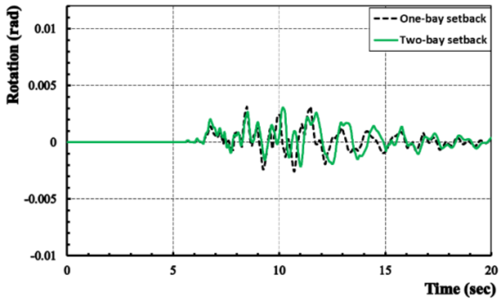
Fig. 9 Story rotation time histories of the 6-Story building for different in-plan alignment configurations



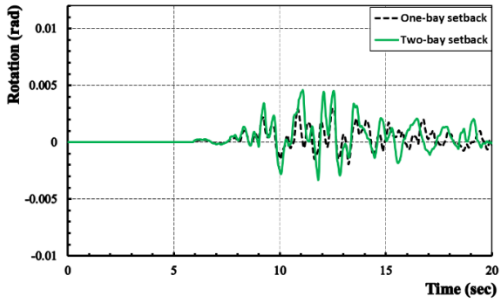
(a) 12th level during Christchurch earthquake



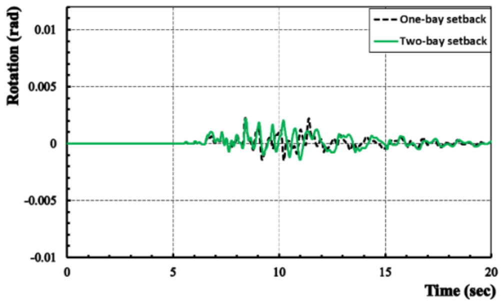
(b) 12th level during Kobe earthquake



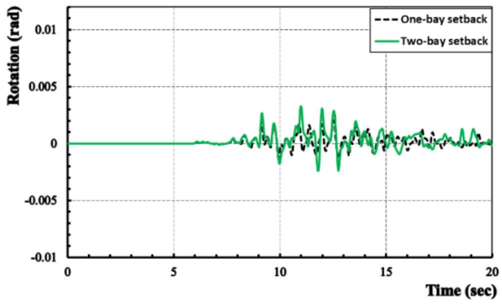
(c) 6th level during Christchurch earthquake.



(d) 6th level during Kobe earthquake



(e) 3rd level during Christchurch earthquake.



(f) 3rd level during Kobe earthquake

Fig. 10 Story rotation time histories of the 12-Story building for different in-plan alignment configurations two-sided eccentric impact are substantially increased as the result of increasing the setback distance during Kobe earthquake. In the case of two-bay setback, the increase of the peak value of the rotation angle at the 3rd and the top level is as high as 61.5% and 96% respectively. While during Christchurch earthquake, these responses have been decreased by increasing the distance of setback. The reduction in the peak value of the rotation angle is found as 2.4% at 3rd level while it is 14% at the top level. These results indicate that the torsional response demands of adjacent symmetric buildings depend on in-plan alignment of the buildings where the relative the positions of the geometric center of the buildings is the main factor that causes torsion. While the magnification in these demands is relying on the vibration characteristics of the building itself and in relation to the dynamic characteristics of the input excitation.

The results of the study show that torsional vibrations of both structures are important components of the overall structural response, affecting both the number of collisions and the entity of overall displacements. Results also indicate that pounding force and torque reach their maximum values at the stories around the impact level. Overall it was found that impact eccentricity amplifies the response relative to symmetric impact, but the effect is not proportional to first impact eccentricity. It can clearly be deduced that eccentric pounding causes significant torsional movement and high value torsional moments in adjacent buildings although its plan view is symmetric and, in the cases, it vibrates without the pounding effect it presents insignificant torsional moment and consequently no torsional movement. It has been observed that the developing torsion increases as the height of the adjacent structure increases. Furthermore, high shear forces are developed in the direction normal to the earthquake direction although the plan view of the building is symmetric in both directions.

The pounding induces, in addition to the local damage it usually causes, an increase in the structural response. The local damage could be around the impacting areas on each building, and is directly related to the collision force, while the global damage can occur through the building as a result of the collision's momentum transfer, which change the velocity of both buildings. The developed shear strength and ductility demand increase for the columns that are close to the impact locations, these demands could be critical and exceed the available shear strength and ductility capacity. In the floor-to-floor interaction, the eccentric story pounding causes significant torsional movement and high value torsional moments in the adjacent building although its plan view is symmetric. The torsional movement which is induced due to the eccentric pounding highly influences the distribution of the developing shear forces in the columns. It is noted as a general remark that floor-to-floor eccentric pounding causes significant torsional movement even in buildings with symmetric plan view. Pounding induced torsional vibration changes significantly the column shear strength and ductility demands and rather increases the shear strength and ductility demands of columns along the perimeter that experience high displacement due to the rotational movement of the building. The torsional movement depends on the impact interaction area and eccentricity of the impact forces resultant to the stiffness centers of the collided buildings.

4. Conclusions

Seismic pounding is an extremely nonlinear phenomenon and a severe load case that could be a source of major structural damages. Seismically induced oscillations of a building in a block of buildings in a city center is likely to be partly restrained in lateral displacements and therefore, torsional behavior to be introduced. In this paper, the effects of eccentric pounding on the seismic response demands for the adjacent symmetric buildings in series with eccentric alignment have been studied. The global response demands have been analyzed, where, three adjacent buildings in series with different heights of 3-, 6-, and 12-stories are modelled using the finite element software ETABS. Numerical investigation has been conducted to perfectly describe and evaluate the real behavior of colliding adjacent buildings in series and its impact on global responses. The pounding response of building in series of adjacent buildings is affected by the alignment position of the building in the row, the in-plan alignment of the adjacent buildings, input excitation frequency content and vibration properties of adjacent structures. The torsional response of symmetric buildings under seismic pounding due to horizontal eccentric alignment makes their design for earthquake actions substantially more complicated than the design of symmetric buildings whose response is purely translational. Moreover, maximum stress appears more likely at the corners of the contact owing to eccentric poundings.

The results of this study clearly showed the sensitivity of the system response to the parameters affecting the pounding phenomenon, i.e., characteristics of the earthquake excitation, dynamic characteristics of buildings and their in-plan alignment. The pounding between adjacent buildings that have different in-plan setback alignment causes torsional responses even if it is symmetrical owing to eccentric impacts. The results show that by increasing the setback distance, the response demands of adjacent buildings may be increased or decreased depending on vibration characteristics of the building itself and in relation to the dynamic characteristics of the input excitation. The torsional vibrations of adjacent buildings are important components of the overall structural response, affecting both the number of impacts and the entity of overall displacements. When the setback distance increases, the number of impacts increases but its magnitude decreases due to just partial mass of the floor is involved in the pounding. The results indicate that torsional vibrations due to eccentric pounding play an important role in the overall pounding-involved response of symmetric buildings under earthquake excitations due to horizontal eccentric alignment. In the floor-to-floor interaction, the eccentric story pounding causes significant torsional movement and high value torsional moments in the adjacent building although its plan view is symmetric. The torsional movement which is induced due to the eccentric pounding highly influences the distribution of the developing shear forces in the columns. It is noted as a general remark that floor-to-floor eccentric pounding causes significant torsional movement even in buildings with symmetric plan view. Pounding induced torsional vibration changes significantly the column shear strength and ductility demands and rather increases the shear strength and ductility demands of columns along the perimeter that experience high displacement due to the rotational movement of the building. The torsional movement depends on the impact interaction area and eccentricity of the impact forces resultant to the stiffness centers of the collided buildings.

References

Abdel Raheem, S.E. (2009), "Pounding mitigation and unseating prevention at expansion joints of isolated multi-span bridges", *Eng. Struct.*, **31**(10), 2345-2356. https://doi.org/10.1016/j.engstruct.2009.05.010

Abdel Raheem, S.E. (2013), "Evaluation of Egyptian code provisions for seismic design of moment resisting frames multi-story buildings", *Int. J. Adv. Struct. Eng.*, **5**(20), 1-18. https://doi.org/10.1186/2008-6695-5-20.

Abdel Raheem, S.E. (2014), "Mitigation measures for earthquake induced pounding effects on seismic performance of adjacent buildings", *Bull Earthq. Eng.*, **12**(4), 1705-1724. https://doi.org/10.1007/s10518-014-9592-2.

Abdel Raheem, S.E., AbdelZaher, A.K. and Taha, A.M.A (2018b), "Finite element modeling assumptions impact on seismic response demands of MRF-buildings", *Earthq. Eng. Eng. Vib.*, **17**(4), 821-834. https://doi.org/10.1007/s11803-018-0478-1.

Raheem, S.E.A., Ahmed, M.M., Ahmed, M.M. and Abdel-shafy, A.G. (2018c), "Evaluation of plan configuration irregularity effects on seismic response demands of L-shaped MRF buildings", *Bull. Earthq. Eng.*, **16**(9), 3845-3869. https://doi.org/10.1007/s10518-018-0319-7.

Abdel Raheem, S.E., Ahmed, M.M., Ahmed, M.M. and AbdelShafy, A.G.A. (2018d), "Seismic performance of L-shaped multi-storey buildings with moment-resisting frames", *Proc. Inst. Civil Eng., Struct. Build.*, **171**(5), 395-408. https://doi.org/10.1680/jstbu.16.00122.

Abdel Raheem, S.E., Ahmed, Moh. M. and Alazrak, T.M.A. (2015), "Evaluation of soil-foundation-structure interaction effects on seismic response demands of multi-story MRF buildings on raft foundations", *Int. J. Adv. Struct. Eng.*, **7**(1), 11-30. https://doi.org/10.1007/s40091-014-0078-x.

Abdel Raheem, S.E., Fooly, M.Y.M., AbdelShafy, A.G.A., Abbas, Y.A., Omar, M., Taha, A.M. and AbdelLatif, M.M.S. (2019), "Numerical simulation of potential seismic pounding among adjacent buildings in series", *Bull. Earthq. Eng.*, **17**(1), 439-471. https://doi.org/10.1007/s10518-018-0455-0.

Abdel Raheem, S.E., Fooly, M.Y.M., AbdelShafy, A.G.A., Abbas, Y.A., Omar, M., Taha, A.M., AbdelLatif, M.M.S. and Mahmoud, S. (2018a), "Seismic pounding effects on adjacent buildings in series with different alignment configurations", *Steel Compos. Struct.*, **28**(3), 289-308. https://doi.org/10.12989/scs.2018.28.3.289.

Abrahamson, N. (2006), "Program SeismoMatch v2-software capable of adjusting earthquake accelerograms to match a specific design response spectrum, using the wavelets algorithm", http://www.seismosoft.com/seismomatch.

Anagnostopoulos, S.A. (1988), "Pounding of buildings in series during earthquakes", *Earthq. Eng. Struct. Dyn.*, **16**(3), 443-456. https://doi.org/10.1002/eqe.4290160311.

Anagnostopoulos, S.A. and Spiliopoulos, K.V. (1992), "An investigation of earthquake induced pounding between adjacent buildings", *Earthq. Eng. Struct. Dyn.*, **21**(4), 289-302. https://doi.org/10.1002/eqe.4290210402.

Ancheta, T., Darragh, R., Stewart, J., Seyhan, E., Silva, W., Chiou, B., Wooddell, K., Graves, R., KO-TTKE, A. and Boore D. (2013), "PEER NGA-West2 Database, PEER Report 2013/03, Pacific Earthquake Engineering Research Center", University of California, Berkeley.

ASCE (2013), Publication Anticipated Seismic Evaluation and Upgrade of Existing Buildings, ASCE 41-13, American Society of Civil Engineers, Reston, Virginia.

Bertero, V.V. (1986), "Observations on structural pounding", *Proc. Intern. Conf. Mexico Earthquakes ASCE*, 264-287.

BSSC, N. (2000), Recommended Provisions for the Development of Seismic Regulations for New Buildings and Other Structures, Building Seismic Safety Council, Washington, DC.

Bull, D., Dhakal, R., Cole, G. and Carr, A. (2010), "Building pounding state of the art: Identifying structures vulnerable to pounding damage", *NZSEE Annual Conference*, New Zealand

Cole, G.L., Dhakal, R.P. and Turner, F.M. (2011), "Building pounding damage observed in the 2011 Christchurch earthquake", *Earthq. Eng. Struct. Dyn.*, **39**, 595-611. https://doi.org/10.1002/eqe.1164.

CSI (2013), Analysis Reference Manual for SAP2000, ETABS, and SAFE, Computers and Structures, Inc., California, USA.

Davis, R. (1992), "Pounding of buildings modelled by an impact oscillator", *Earthq. Eng. Struct. Dyn.*, **21**(3), 253-274. https://doi.org/10.1002/eqe.4290210305.

ECP-201 (2012), Egyptian Code for Calculating Loads and Forces in Structural Work and Masonry, Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt.

ECP-203 (2007), Egyptian Code for Design and Construction of Reinforced Concrete Structures, Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt

Elwardany, H., Seleemah, A. and Jankowski, R. (2017), "Seismic pounding behavior of multi-story buildings in series considering the effect of infill panels", *Eng. Struct.*, **144**(1), 139-150. https://doi.org/10.1016/j.engstruct.2017.01.078.

ETABS (2016), Extended Three-Dimensional Analysis of Building Systems, Computers and Structures Inc. Computer software package, Version 16.0.0. CSI, Berkeley.

Farahani, D., Behnamfar, F., Sayyadpour, H. and Ghandil, M. (2019), "Seismic impact between adjacent torsionally coupled buildings", *Soil Dyn. Earthq. Eng.*, **117**, 81-95. https://doi.org/10.1016/j.soildyn.2018.11.015.

FEMA (2000), Pre-standard and Commentary for the Seismic Rehabilitation of Buildings, FEMA-356, Federal Emergency Management Agency, Washington, DC.

Fiore, A., Marano, G.C. and Monaco, P. (2013), "Earthquake-induced lateral-torsional pounding between two equal height multi-storey buildings under multiple bi-directional ground motions", *Adv. Struct. Eng.*, **16**(5), 845-865. https://doi.org/10.1260/1369-4332.16.5.845.

Goldsmith, W. (1960), *Impact: the Theory and Physical Behavior of Colliding Solids*, Edward Arnold, London.

Gong, L. and Hao, H. (2005), "Analysis of coupled lateral-torsional-pounding responses of one-storey asymmetric adjacent structures subjected to bi-directional ground motions Part I: Uniform ground motion input", *Adv. Struct. Eng.*, **8**(5), 463-479. https://doi.org/10.1260/136943305774858043.

Guo A., Cui, L. and Li, H. (2012), "Impact stiffness of the contact-element models for the pounding analysis of highway bridges: experimental evaluation", *J. Earthq. Eng.*, **16**(8), 1132-1160. https://doi.org/10.1080/13632469.2012.693243.

Jankowski, R. (2006), "Pounding force response spectrum under earthquake excitation", *Eng. Struct.*, **28**(8), 1149-1161. https://doi.org/10.1016/j.engstruct.2005.12.005.

Jankowski, R. (2010), "Experimental study on earthquake-induced pounding between structural elements made of different building materials", *Earthq. Eng. Struct. Dyn.*, **39**(3), 343-354. https://doi.org/10.1002/eqe.941.

Jankowski, R., Wilde, K. and Fujino, Y. (2000), "Reduction of pounding effects in elevated bridges during earthquakes", *Earthq. Eng. Struct. Dyn.*, **29**, 195-212. https://doi.org/10.1002/(SICI)1096-9845(200002)29:2.

Jeng, V. and Tzeng, W. (2000), "Assessment of seismic pounding hazard for Taipei City", *Eng. Struct.*, **22**(5), 459-471. https://doi.org/10.1016/S0141-0296(98)00123-0.

Karayannis, C.G. and Favvata, M.J. (2005a), "Inter-story pounding between multistory reinforced concrete structures", *Struct. Eng. Mech.*, **20**(5), 505-526. https://doi.org/10.12989/sem.2005.20.5.505.

Karayannis, C.G. and Favvata, M.J. (2005b), "Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights", *Earthq. Eng. Struct. Dyn.*, **34**(1), 1-20. https://doi.org/10.1002/eqe.398.

Karayannis, C.G. and Naoum, M.C. (2018), "Torsional behavior of multistory RC frame structures due to asymmetric seismic interaction", *Eng. Struct.*, **163**, 93-111. https://doi.org/10.1016/j.engstruct.2018.02.038.

Karayannis, C.G., Naoum, M.C. (2017), "Inter-story pounding and torsional effect due to interaction between adjacent multi-story RC buildings", *6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2017*, Eds. M. Papadrakakis and M. Fragiadakis, Rhodes Island, Greece, June.

Kawashima, K. and Shoji, G. (2000), "Effect of restrainers to mitigate pounding between adjacent decks subjected to a strong ground motion", *12th World Conference on Earthquake Engineering-12WCEE*, Auckland, New Zealand.

Kawashima, K. and Unjoh, S. (1996), "Impact of Hanshin/Awaji earthquake on seismic design and seismic strengthening of highway bridges", *Struct. Eng. Earthq. Eng.*, **13**, 211-240. https://doi.org/10.2208/jscej.1997.556_1.

Komodromos, P., Polycarpou, P.C., Papaloizou, L. and Phocas, M.C. (2007), "Response of seismically isolated buildings considering poundings", *Earthq. Eng. Struct. Dyn.*, **36**(12), 1605-1622. https://doi.org/10.1002/eqe.692.

Kuo, P.T. (1974), "Torsional effects in structures subjected to dynamic excitations of the ground", Ph.D. Thesis, Rice University.

Leibovich, E., Rutenberg, A. and Yankelevsky, D. (1996), "On eccentric seismic pounding of symmetric buildings", *Earthq. Eng. Struct. Dyn.*, **25**(3), 219-234. https://doi.org/10.1002/(SICI)1096-9845(199603)25:3.

Mahmoud, S. and Jankowski, R. (2011), "Linear viscoelastic modelling of damage-involved structural pounding during earthquakes", *Key Eng. Mater.*, **452**, 357-360. https://doi.org/10.4028/www.scientific.net/KEM.452-453.357.

Maison, B.F. and Kasai, K. (1992), "Dynamics of pounding when two buildings collide", *Earthq. Eng. Struct. Dyn.*, **21**(9), 771-786. https://doi.org/10.1002/eqe.4290210903.

Naserkhaki, S., Daneshvar-Ghorbani, S. and Tayyebi-Tolloei, D. (2013), "Heavier adjacent building pounding due to earthquake excitation", *Asian J. Civil Eng., (BHRC)*, **14**(2), 349-367.

Papadrakakis M, Apostolopoulou C, Zacharopoulos A. and Bitzarakis S. (1996), "Three-dimensional simulation of structural pounding during earthquakes", *J. Eng. Mech.*, **122**(5), 423-431. https://doi.org/10.1061/(ASCE)0733-9399(1996)122:5(423).

Pekau, O. and Zhu, X. (2006), "Seismic behavior of cracked concrete gravity dams", *Earthq. Eng. Struct. Dyn.*, **35**(4), 477-495.

Polycarpou, P.C. and Komodromos, P. (2010), "On poundings of a seismically isolated building with adjacent structures during strong earthquakes", *Earthq. Eng. Struct. Dyn.*, **39**(8), 933-940. https://doi.org/10.1002/eqe.975.

Raheem, S.E.A., Ahmed, M.M., Ahmed, M.M. and Abdel-shafy, A.G. (2018c), "Evaluation of plan configuration irregularity effects on seismic response demands of L-shaped MRF buildings", *Bull. Earthq. Eng.*, **16**(9), 3845-3869. https://doi.org/10.1007/s10518-018-0319-7.

Rajaram, C. and Ramancharla, P.K. (2014), "Three-dimensional analysis of pounding between adjacent buildings", *J. Struct. Eng.*, **41**(2), 1-11.

Shakya, K., Wijeywickrema, A.C. and Ohmachi, T. (2008), "Mid-column seismic pounding of reinforced concrete buildings in a row considering effects of soil", *14th WCEE*, Beijing, Paper ID 05-01-0056.

Shome, N., Cornell, C.A., Bazzurro, P. and Carballo, J.E. (1998), "Earthquakes, records, and nonlinear responses", *Earthq. Spectra*, **14**(3), 469-500. https://doi.org/10.1193/1.1586011.

Shrestha, B., Hao, H. and Bi, K. (2013), "Pounding and unseating damage mitigation on bridge structures subjected to spatially varying ground motions using restrainers and rubber bumpers", Australian Earthquake Engineering Society, Tasmania.

Tabatabaei, R. (2011), "Torsional vibration of eccentric building systems, recent advances in vibrations analysis", Natalie Baddour, IntechOpen. https://doi.org/10.5772/21997.

Unjoh, S., Kondoh, M. and Mikami, T. (2003), "Collision analysis between Bridge deck and abutments during earthquakes", *Civil Eng. J.*, **45**(4), 64-69.

Wada, A., Shinozaki, Y. and Nakamura, N. (1984), "Collapse of building with expansion joints through collision caused by earthquake motion", *Proceedings of the 8th World Conference on Earthquake Engineering*, San Francisco, California,

Wang, L., Chau, K. and Wei, X. (2009), "Numerical simulations of nonlinear seismic torsional pounding between two single-story structures", *Adv. Struct. Eng.*, **12**(1), 87-101. https://doi.org/10.1260/136943309787522678.

Watanabe, G. and Kawashima K. (2004), "Numerical simulation of pounding of bridge decks", *13th World Conference on Earthquake Engineering*, Vancouver, CA, August.

Zhu, P., Abe, M. and Fujino, Y. (2002), "Modelling three-dimensional non-linear seismic performance of elevated bridges with emphasis on pounding of girders", *Earthq. Eng. Struct. Dyn.*, **31**(11), 1891-1913. https://doi.org/10.1002/eqe.194.

AT