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Effect of lateral structural systems of adjacent buildings on pounding force

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Abstract. Under strong ground motion, pounding can be caused because of the different dynamic properties between two adjacent buildings. Using different structural systems in two adjacent structures makes a difference in the lateral stiffness and thus changes the pounding force between them. In this paper, the effect of the structural system of adjacent buildings on the amount of force applied by pounding effects has been investigated. Moment resisting frame systems (MRFs), lateral X-bracing system (LBS), shear wall system (SWS) and dual system (DS) have been investigated. Four different cases has been modelled using finite element (FE) method. The number of stories of the two adjacent buildings is different in each case: case 1 with 6 and 4 stories, case 2 with 9 and 6 stories, case 3 with 15 and 6 stories and case 4 with 10 and 10 stories. The structures have been modelled three-dimensionally. Non-linear time history analysis has been done on the structures using the finite element software SAP2000. In order to model pounding effects, the non-linear gap elements have been used.

Keywords: pounding effects; structural systems; time history analysis

1. Introduction

Pounding occurs between two structures when they have different stiffness and mass (Jameel *et al*. 2013). Thus, the amount of pounding force depends on the dynamic properties of the two adjacent structures, i.e., greater difference in the properties of the structures might lead to a more severe pounding force (Jankowski 2006). Several cases of structural damage due to pounding can be found in (Efraimiadou *et al*. 2013). Pounding between structures has been observed in many important earthquakes in past, such as the Venezuela earthquake that occurred in 1967 in Caracas city. In the Managua earthquake of 1972, a five-story hotel hit an adjacent two-story building and therefore the third floor completely collapsed. Over 40% of the severely damaged and collapsed buildings in Mexico City (1985) caused by pounding in adjacent buildings and at least 15% was the primary cause of collapse (Bertero 1987). In addition, pounding caused damages in Northridge earthquake in 1994, Kobe earthquake in 1995 and even in recent earthquakes such as Sikkim (India) in 2006 (Kaushik *et al*. 2006) and Christchurch (New Zealand) in 2011 (Cole *et al*. 2012).

Much research (Polycarpou *et al*. 2015, Chau *et al*. 2003, Anagnostopoulos 1996, Ruangrassamee and Kawashima 2003, Efraimiadou *et al*. 2013) has been done in order to decrease the pounding force between colliding structures and consequently to place the structures closer to each other. It is mentioned that using energy-absorbing materials (Anagnostopoulos 1996) in addition to energy dampers (Ruangrassamee and Kawashima 2003), can reduce the pounding force between structures. For using such methods, accurate calculations must be done to determine the pounding force for each structure. Previous research works have shown that ensuring a suitable distance between the structures can greatly reduce the pounding force or even eliminate it (Hameed *et al*. 2012), but because of the increased cost of land in densely populated cities, it has no economic justification. Therefore, more research works are needed in order to achieve the reduction of the distance between adjacent structures without pounding occurring between them.

The unfavourable effects of pounding of adjacent structures under strong seismic actions have motivated the researchers to investigate this effect using numerical simulation tools. However, the majority of these works have been limited to two dimensions (2D) model (Polycarpou and Komodromos 2010, Cole *et al*. 2012). There are limited studies that have considered pounding effects in adjacent structures in three dimensional (3D) models (Anagnostopoulos and Karamaneas 2008, Jankowski 2009, Pant and Wijeyewickrema 2012, Polycarpou *et al*. 2014, Skrekas *et al*. 2014, Polycarpou *et al*. 2015). There are several computer programs able to model pounding, such as PC-ANSER and SLAM-2 (Muthukumar 2003) (Maison and Kasai 1990). On the SLAM-2 program, modal superposition technique is used to model pounding (Maison and Kasai 1990). However, the solving method of PC-ANSER program is the nonlinear time-step code where

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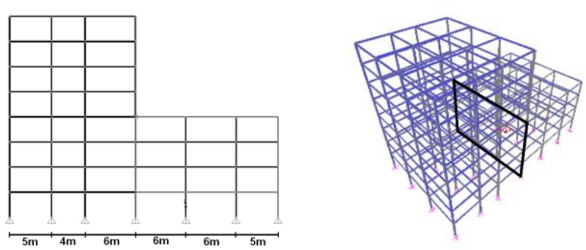
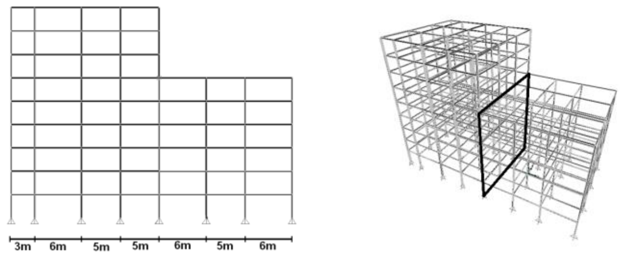
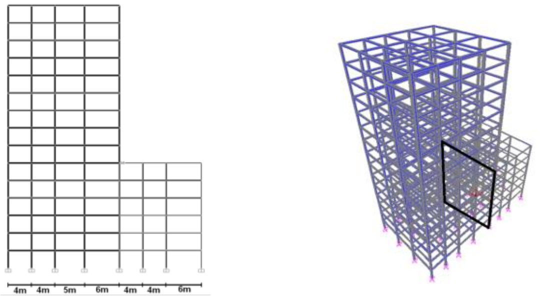


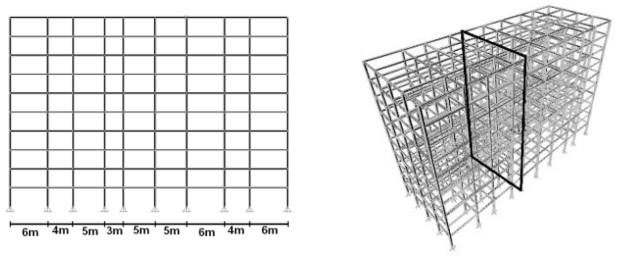
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings



(d) Case 4 with 10-story adjacent buildings

Fig. 1 Specification of four different simulated cases (a-d) of two adjacent buildings

elastic distance elements (gap elements) are used to model the distance between the two structures. These two programs were compared and verified with two laboratory samples in three and eight stories small-scale structures by Filiatrault *et al*. (1996). On SAP2000 program, nonlinear gap elements and the direct time integration technique have been used for modelling pounding. There are some studies that have used the link element, with tension-compression behaviour, to model the connection between the two adjacent structures. Considering the tension-compression element for the connection between the structures might lead to inaccurate results.

Lateral resisting systems and dual resisting systems under seismic load show different behaviour. There are many investigations on assessment of behaviour of different systems under lateral load (Kioumarsi *et al*. 2016, Kioumarsi *et al*. 2017, Phocas and Sophocleous 2012). Ponding force might be influenced by height and type of the resisting systems of adjacent buildings. In this paper, the amount of pounding force for different lateral resisting systems with different altitude levels has been investigated. For the gap between the two buildings, nonlinear gap elements at the top of the buildings have been used.

2. Pounding of two adjacent structures with the same lateral resisting system

2.1 Specifications of simulated models

In order to assess the effect of structural system on the amount of pounding force, four different cases have been modelled using the finite element (FE) method. The number of stories of the two adjacent structures is different in each case. Case 1 with 6 and 4 stories, case 2 with 9 and 6 stories, case 3 with 15 and 6 stories and case 4 with 10 and 10 stories of two adjacent buildings are shown in Figs. 1(a) to (d). The height of each story is 3 m for all cases. The buildings are next to each other, with a 3 cm distance between them. The gap element with compression behaviour has been used. This element has nonlinear behaviour with bilinear stiffness. In this case, the stiffness of this element is active just when the two structures are connected to each other (i.e., in case of pounding) and it is considered to be zero when the structures are separate from each other (no pounding). In all studied structures, the nonlinear gap element with equivalent spring stiffness equal to 2.75×10^9 N/m has been used (Muthukumar 2003). The amount of pounding force has been quantified for four different lateral systems including moment resisting frame (MRF), lateral X-bracing system (LBS), shear wall system (SWS) and dual system (DS). The Dual system includes a combination of MRFs system and shear wall. According to ASCE7 in the dual systems, moment frames must be capable of resisting 25% of the seismic forces while the moment frames and X-braced frames or shear walls must be capable of resisting the entire seismic forces in proportion to their relative rigidities. All the buildings were designed according to the Iranian code of practice for seismic resistant design of buildings (Iranian Seismic Code 2005). The FE software SAP2000 v10 has been used for modelling and analysing the various cases. In case 3 (with 6 and 15 stories of adjacent structures), the connection of structure and foundation was assumed to be fully rigid, while in other cases the connections are hinged. In addition, in all cases with shear walls, a fully rigid connection between shear wall and foundation was considered. The length of structure spans is shown in Figs. 1(a) to (d). All structures have been modelled three dimensionally (3D) with a rigid slab floor. The designed cross section profiles of beams and columns for cases 1 to 4 are shown in Table 1.

The El Centro earthquake record has been used for the analysis of the structures. The earthquake is applied in the *x*-direction along the two buildings. The properties of this

Table 1 The designed cross section profiles of beams and columns in case 1 to 4 (f_y=235 MPa)

	Case 1		Case 2		Case 3		Case 4	
No. of story	8-story	4-story	9-story	6-story	15-story	6-story	10-story	10-story
Beam	IPE220	IPE160	IPE200	IPE180	2IPE270	2IPE180	2IPE240	2IPE240
Column	2IPE240	2IPE180	3IPE200	3IPE160	3IPE300	3IPE200	3IPE270	3IPE270

Table 2 Specifications of used strong motion

Station name	Year	Magnitude	R_{jb} (km)	R_{rup} (km)	Vs30 (m/sec)
El Centro Array #9	1968	6.63	45.12	45.66	213.44

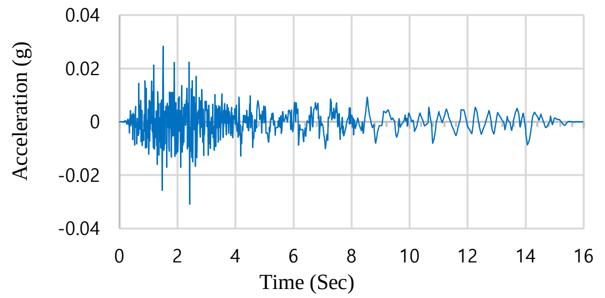


Fig. 2 El Centro earthquake accelerogram

accelerogram are shown in Table 2 and Fig. 2. Time history analysis has been applied by the direct time integration method. The time integration scheme, was selected according to Newmark method and the values of the parameters are as follows: γ= 0.5, β= 0.25 and 5% damping. Nonlinear damping has been applied using Maxwell's model. The roof of all stories has been considered rigid and dead, live and earthquake loads have been applied to entire structure based on national Iran code (Iranian Seismic Code 2005). In addition, the static lateral force is distributed to all floors.

According to the applied conditions in this study, a comparison between lateral stiffness of different structural systems has been done. Since the relation between stiffness and displacement can be explained by the relationship $d = k^{-1} \times f$ in order to determine the stiffness of different structural systems, a constant force can be applied to structures and according to inverse equation of stiffness and displacement, the approximate value of stiffness can be specified. To compare the lateral stiffness of each pair of structures, a constant lateral force equal to 13.75% of the weight of building has been applied to the buildings. Figs. 3a-d illustrates the obtained value of maximum lateral displacement for each case with different lateral resisting systems.

In all the studied cases, MRFs system has the maximum displacement and as a result the minimum of lateral stiffness. Respectively, lateral X-braced, shear wall, and dual systems have more lateral stiffness than MRFs system. The fundamental periods of the systems are shown in Table 3.

2.2 Moment resisting frame (MRF) system

In this part, for the all cases, the two adjacent structures

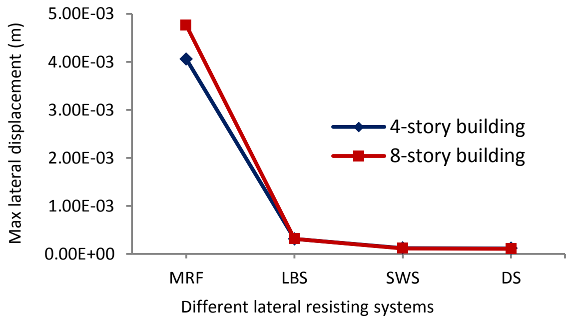
Table 3 Fundamental period of the different lateral resisting systems: moment resisting frame (MRFs), lateral X-bracing system (LBS), shear wall system (SWS) and dual system (DS)

Height (m)	Period, T (Sec)			
	MRF	LBS	DS	SWS
12	0.64	0.52	0.40	0.49
18	0.87	0.69	0.55	0.66
24	1.09	0.87	0.69	0.83
27	1.19	0.96	0.76	0.92
30	1.27	1.03	0.82	0.98
45	1.71	1.41	1.09	1.31

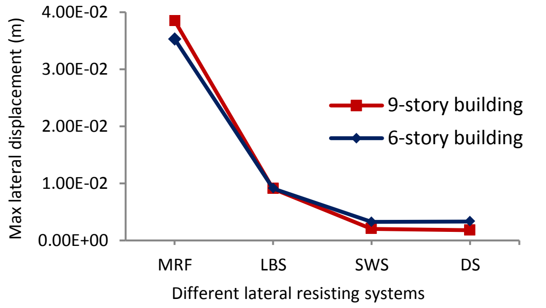
Table 4 The maximum pounding force of cases 1 to 4 with MRFs systems

	Case 1	Case 2	Case 3	Case 4
Maximum pounding force (kN)	8.01	5.86	24.62	138.20

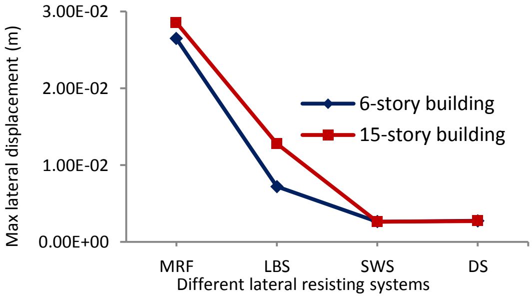
with MRFs system have been analysed. As mentioned before, designed cross sections of beams and columns are presented in Table 1. The reason of using MRFs system is that it has less lateral stiffness than other structural systems. In addition, in this system, the beams have moment connection to columns thus, after the collision of two structures, high moments are inserted to columns. The values of forces after collision of two MRFs systems are shown in Figs. 4(a) to (d). The values shown in Fig. 4 are obtained when the gap element is placed at the highest level of the building that has the maximum chance of a quake. The maximum pounding force for each structure is shown in the Table 4. As shown in Fig. 4, at first the pounding force exerted between the two structures culminates and then along the curved path reaches another point from tapping point and then with high gradient amount of pounding force becomes zero. As previously observed, the MRFs system has less lateral stiffness than other systems. After collision of two MRF systems, suddenly the amount of pounding force reaches its maximum value. Then, because of the lower stiffness, two adjacent structures pass short path together which causes the pounding force to become lower than its primary mode but it doesn't reach the zero point. Suddenly after separation of the two structures the generated pounding force between them becomes zero. The mentioned case is more likely to occur when the two adjacent structures have larger eigenperiods. As can be seen in Fig. 4(a) due to low altitude of 4 stories structure which has a shorter period of time, lower values of pounding force is applied repeatedly. However, in the two 10 stories adjacent structures that have larger period of time, the performance of MRFs system in pounding can be seen more



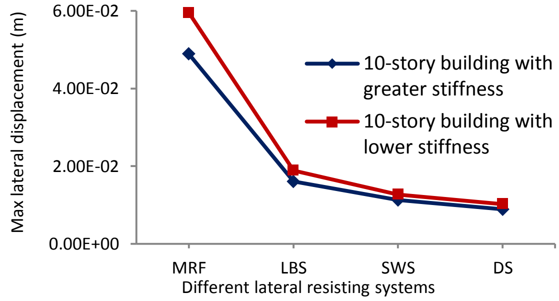
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings

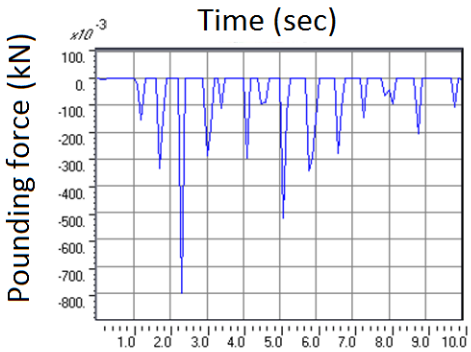


(c) Case 3 with 15 and 6-story adjacent buildings

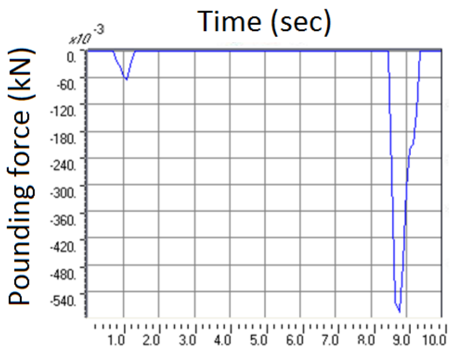


(d) Case 4 with 10-story adjacent buildings

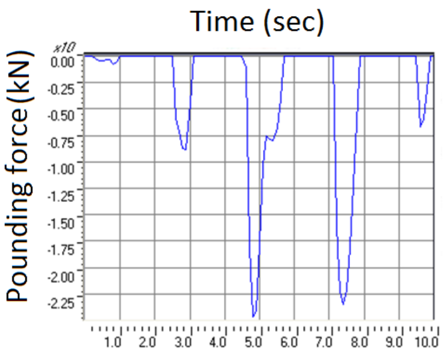
Fig. 3 Maximum lateral displacement cases 1 to 4 under constant lateral force, in horizontal axis, for four different lateral resisting systems: moment resisting frame (MRFs), lateral X-bracing system (LBS), shear wall system (SWS) and dual system (DS)



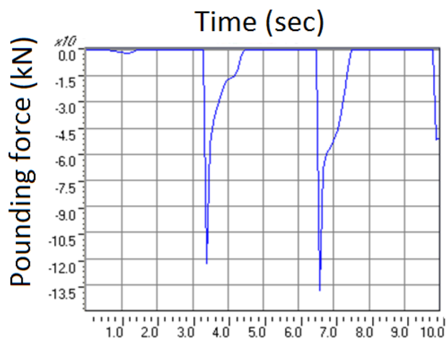
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings



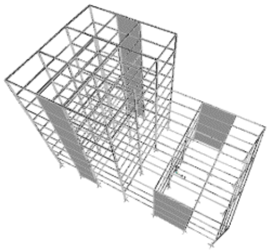
(d) Case 4 with 10-story adjacent buildings

Fig. 4 The values of pounding force of two adjacent buildings with moment resisting frame systems (MRFs)

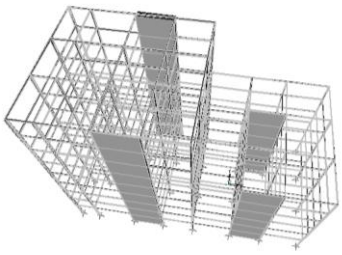
clearly between the two structures with two strong pounding force, see Fig. 4(d).

2.3 Shear wall system (SWS)

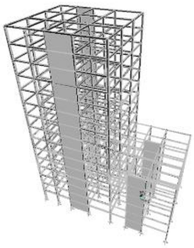
In this part, for all cases, the two adjacent structures with shear wall system have been analysed. The thickness of walls is 25 cm, the specified concrete compressive strength is 21 MPa and in addition, due to concrete



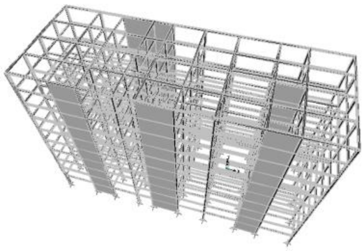
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings



(d) Case 4 with 10-story adjacent buildings

Fig. 5 Locations of shear walls in different cases for SWS and DS

Table 5 The maximum value of pounding force of cases 1 to 4 with shear wall systems

	Case 1	Case 2	Case 3	Case 4
Maximum pounding force (kN)	24.37	43.89	44.95	139.70

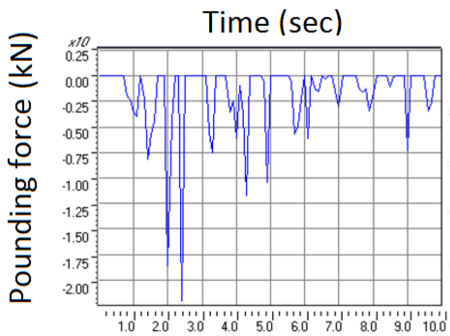
cracking, wall moment of inertia has been considered as 70% of the actual amount. The locations of the walls are shown in 3D in Figs. 5(a) to (d).

In this structural system, the lateral force applied to the structure bears by wall and the connection between beams and columns is hinged. The values of forces after collision of two shear wall systems are shown in Figs. 6(a) to (d).

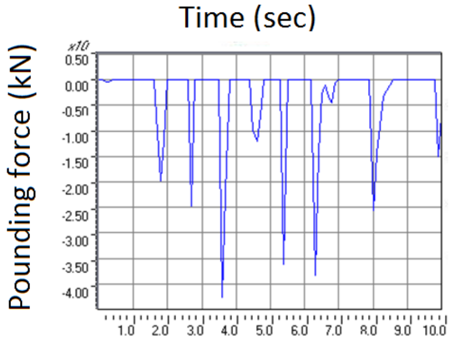
As shown in Fig. 6, the pounding force suddenly culminates and then the force goes to zero with a high slope. In fact, in this case, the two buildings go apart from each other after pounding. It is caused due to the high lateral stiffness of the system. In Fig. 6(c) due to the high difference between the periods of the buildings, in some cases, two consecutive pounding forces have been applied. The maximum values of pounding forces for each case are shown in Table 5.

2.4 Lateral X-braced system (LBS)

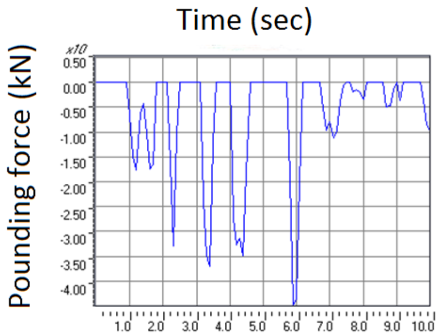
In this part, for all the cases, the two adjacent structures with lateral X-braced system and, concentric bracing, have been modelled and analysed. The location and elevation of the bracing systems are the same as the ones of the shear walls. In this structural system the applied lateral force to the buildings, tolerate by diagonal bracing when the connection between beams and columns is hinged. The lateral stiffness of concentric X-braced frames is high. The pounding forces after collision of the two lateral X-braced systems are shown in Fig. 7.



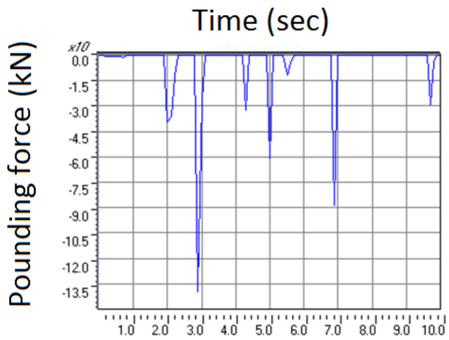
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



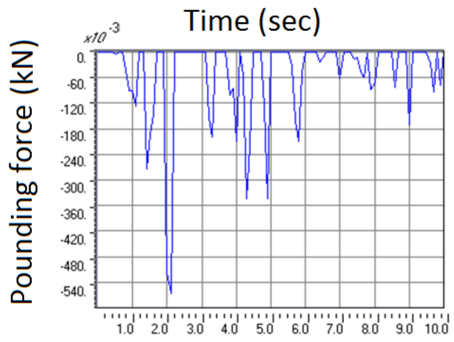
(c) Case 3 with 15 and 6-story adjacent buildings



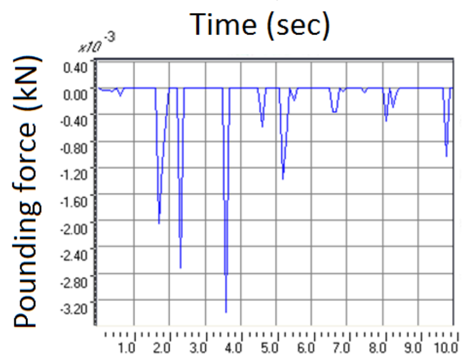
(d) Case 4 with 10-story adjacent buildings

Fig. 6 The values of pounding force of two adjacent buildings with shear wall systems (SWS)

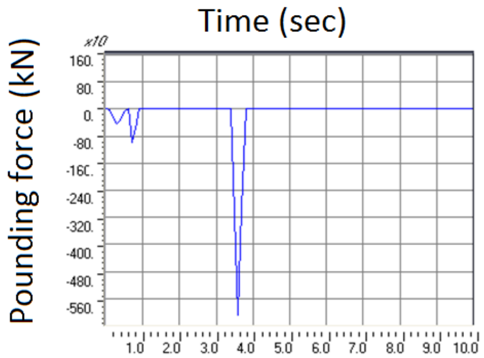
As shown in Fig. 7, in this situation, the pounding force suddenly reaches the peak and then it goes to zero with high slope that shows the sudden nature of the pounding effect. The maximum values of pounding force are shown in Table 6. The performance of lateral X-braced system and shear wall system against pounding effect is similar to each other in all story levels, except case 3 with 6 and15-story levels.



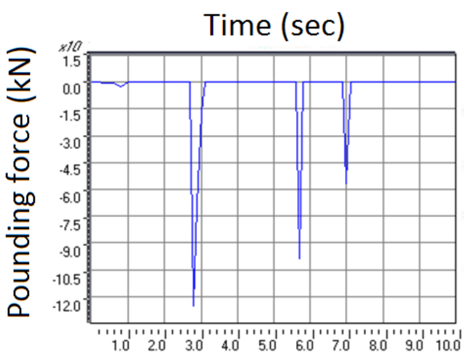
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings

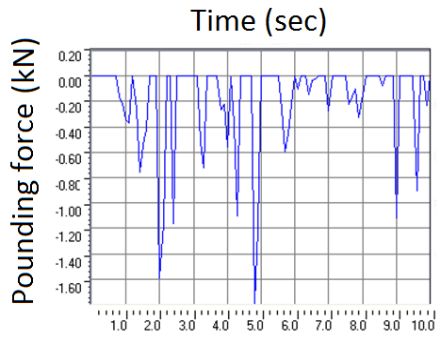


(d) Case 4 with 10-story adjacent buildings

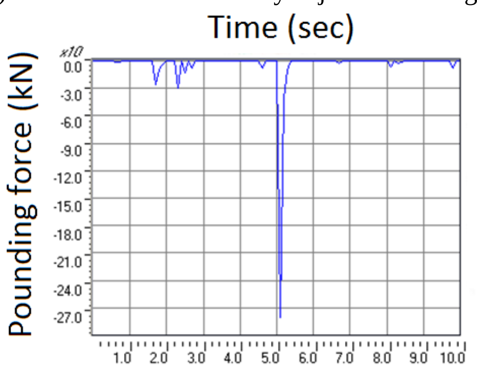
Fig. 7 The values of pounding force of two adjacent buildings with lateral X-braced systems (LBS)

Table 6 The maximum value of pounding force of cases 1 to 4 with lateral X-braced systems

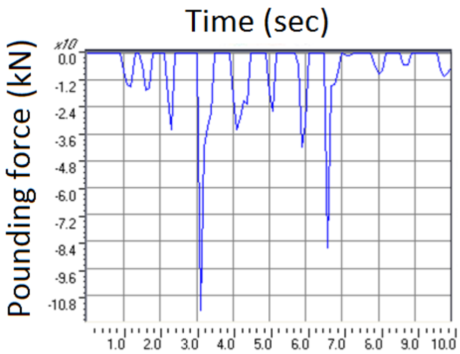
	Case 1	Case 2	Case 3	Case 4
Maximum pounding force (kN)	5.66	33.91	6.10	125.00



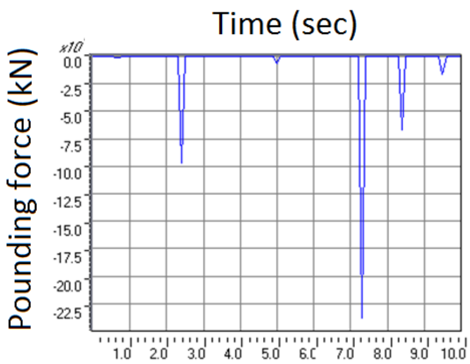
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings

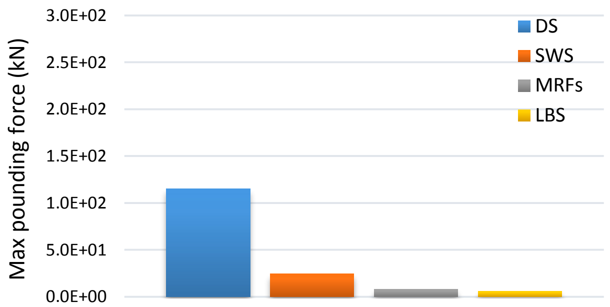


(d) Case 4 with 10-story adjacent buildings

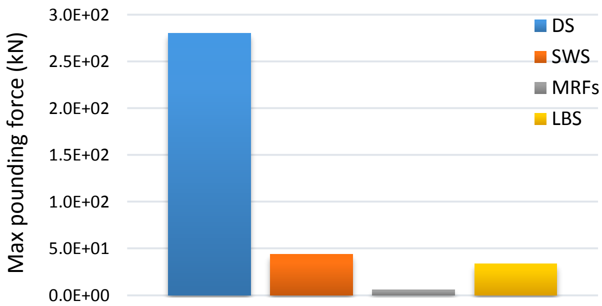
Fig. 8 Values of pounding force of two adjacent buildings with dual systems (DS)

Table 7 The maximum value of pounding force of cases 1 to 4 with dual systems

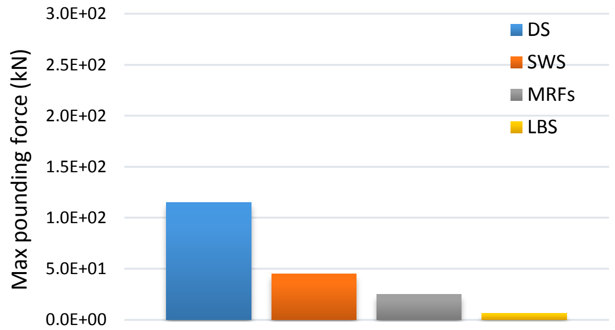
	Case 1	Case 2	Case 3	Case 4
Maximum pounding force (kN)	114.90	280.42	114.90	238.60



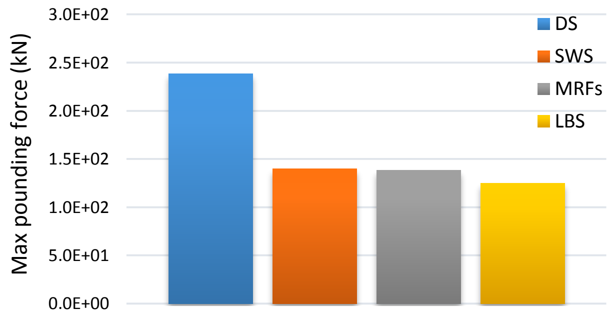
(a) Case 1 with 8 and 4-story adjacent buildings



(b) Case 2 with 9 and 6-story adjacent buildings



(c) Case 3 with 15 and 6-story adjacent buildings



(d) Case 4 with 10-story adjacent buildings

Fig. 9 Maximum values of pounding force of two adjacent buildings different lateral resisting systems: moment resisting frame (MRFs), lateral X-bracing system (LBS), shear wall system (SWS) and dual system (DS)

In case 3, unlike the shear wall systems, the difference between the periods of the two structures leads to no pounding force. Thus, in case 3 with X-braced system in comparison to the shear wall system, the lowest value of pounding force was observed, see Fig. 7(c) and Table 6.

2.5 Dual system (DS)

In this part, the two adjacent structures with dual lateral systems, including MRFs and shear wall systems, have been analysed. In this structural system the applied lateral force to the structures is taken by the walls and the moment connections of beams to columns. The values of the forces after the collision of the two dual systems are illustrated in Fig. 8.

According to Fig. 8, the applied pounding force in this structural system is somehow a combination of MRFs and shear wall system's behaviour, i.e.. the force is applied to the structure in a short period of time and it disappears with less slope.

The value of maximum pounding force is presented in Fig. 9. As is shown in Tables 4 to 7 and Fig. 9, the applied pounding force between the two dual system structures is greater than in other systems. The observed values of pounding force are less in shear wall system and MRFs and in lateral X-braced system, respectively. The only exception in this case related to the case 2 with two 6 and 9-story level, see Fig. 9(b). The reason of high pounding force in dual system, compared to other structural systems, is the high lateral stiffness of this system. After the collision of two buildings with dual systems, the high lateral stiffness of them results in less lateral displacement in both adjacent buildings. As a result, the most of the pounding force is taken by the lateral X-braced system. In the other structural systems with lower stiffness, after the collision of two buildings, a considerable amount of force will be absorbed by the lateral displacement of the buildings. Therefore, after the pounding effect, less force will be applied to the lateral resistant system.

3. Pounding of two adjacent structures with the different lateral resisting systems

In all mentioned cases each of the two structures had a mutual system but what happens if the adjacent structures have different systems? For answering this question and in order to investigate the two different lateral systems on pounding force, two 10-story adjacent structures were modelled and analysed. Since these two structures are completely same in height, dimensions and type of materials the effect of changes in system of structure can be clearly observed. Six combinations of different lateral resistant systems are investigated. Assumptions are similar to the once of the previous section.

3.1 MRFs and LBS

In this part, one building with MRFs system which has less lateral stiffness and other structure with X-lateral bracing system have been analysed. The values of forces after collision of two MRFs and X-bracing systems are

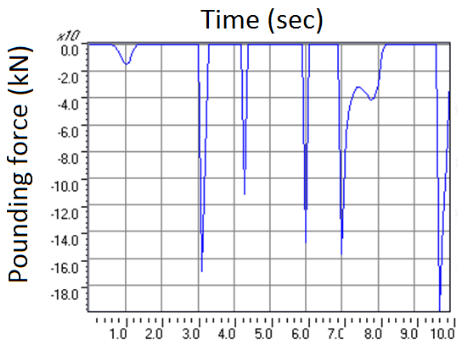


Fig. 10 Pounding force caused by the vicinity of MRFs and X-bracing systems

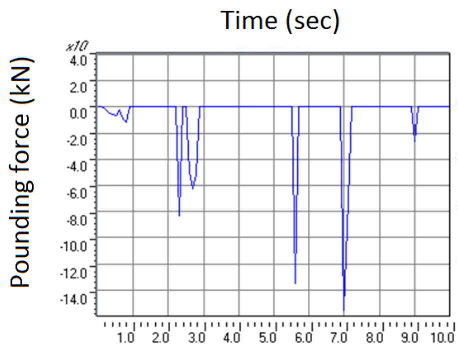


Fig. 12 Pounding force caused by the vicinity of dual system and X-bracing system

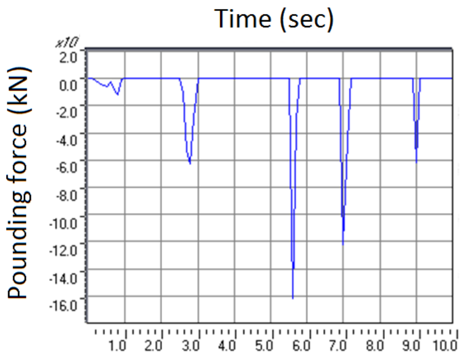


Fig. 11 Pounding force caused by the vicinity of shear wall system and X-bracing system

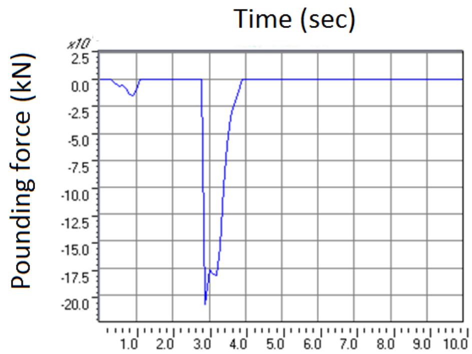


Fig. 13 Pounding force caused by the vicinity of dual systems and MRFs

shown in Fig. 10.

As shown in Fig. 10, in this structural system the pounding force is influenced by both MRFs and X-braced systems. After the pounding, the two buildings become far from each other and behave separately. In this case, the performance of the buildings is similar to X-braced system. In this case the reduction of pounding force is fast. This is shown in second, third, fourth and sixth pounding peaks in Fig. 10. If the adjacent buildings are in contact to each other, the pounding force decreases with gradual slope within a few steps, like first and fifth pounding peaks. In this case the performance of MRFs system in pounding effect is dominant. The maximum value of the pounding force is caused by the sudden connection and its value is equal to 200 kN.

3.2 SWS and LBS

In this part, one structure with shear wall system and another structure with X-lateral bracing system with less lateral stiffness have been analysed. The values of forces after collision of the two shear wall and X-bracing systems are shown in Fig. 11.

As mentioned previously, the performances of shear wall system and MRFs are almost similar. In Fig. 11 the performance of applied pounding force on structures cannot be detected precisely. Due to the increased stiffness of shear wall system, the pounding with higher slope are related to performance of this structural system, like third pounding peak in Fig. 11. The maximum value of the pounding force on structure is caused by the sudden contact and its value is equal to 162 kN.

3.3 LBS and DS

In this part, one structure with dual system which has more lateral stiffness and another structure with lateral X-bracing system that has less lateral stiffness have been analysed. The values of pounding forces are shown in Fig. 12.

The performance of structures in this case is very similar to the vicinity of two shear wall and MRFs systems. The performance of MRFs that has been seen in the two adjacent buildings with dual systems in part 2-5 is not observed here where all pounding force applied suddenly. The maximum value of pounding force on buildings caused by the sudden contact is equal to 155 kN.

3.4 MRFs and DS

The pounding forces after collision of MRFs and dual systems are shown in Fig. 13. The building with dual system has more lateral stiffness than the other one with MRFs system.

Both MRFs and dual systems exhibit bending behaviour. The performance of pounding effect is generally the same as MRFs systems in part 2-2. However, the reduction of the pounding force from peak to zero is similar to the buildings with dual systems, see part 2-5. In this case just two pounding impacts have been observed, because of the equal

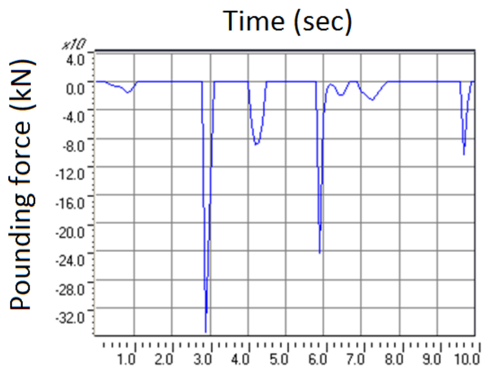


Fig. 14 Pounding force caused by the vicinity of MRFs and shear wall system

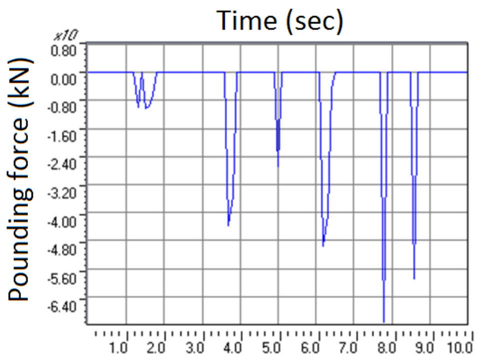


Fig. 15 Pounding force caused by the vicinity of shear wall and dual systems

eigenperiods of the two buildings. The maximum value of pounding force on buildings is equal to 208 kN.

3.5 MRFs and SWS

In this part, one structure with shear wall system with increased lateral stiffness and another structure with MRFs system with less lateral stiffness have been analysed. The values of force after collision of MRFs and shear wall systems are shown in Fig. 14.

The notable point in this case is the coordination of first, third, fourth and fifth pounding impacts with dual adjacent system while the dual system has the combined performance of shear wall and moment resisting frame. The second pounding impact is suddenly applied to structure and shows the same performance as the shear wall system. In this case the maximum value of pounding force is equal to 354 kN.

3.6 SWS and DS

The building with dual system has more lateral stiffness than the other building with shear wall system. The pounding forces between two structures are shown in Fig. 15.

The first and fourth pounding impacts are similar to the pounding behaviour of two dual adjacent systems. The second, third, fifth and sixth impacts have been applied to the structures quite suddenly and have the same behavior

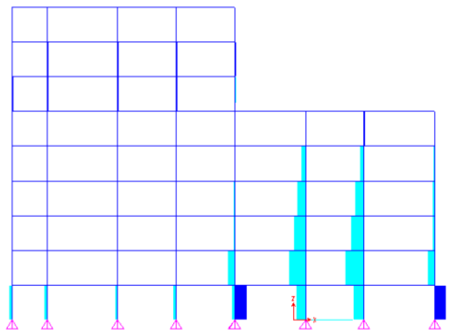


Fig. 16 Pounding shear force in a shorter building with shear wall system

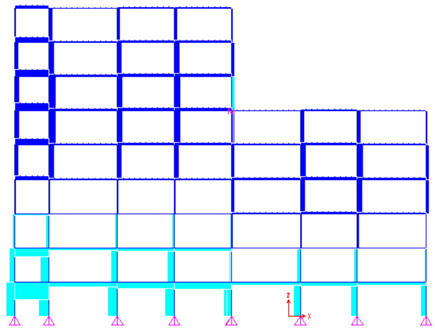


Fig. 17 Reversing the impact shear force in MRFs

as shear wall system. The maximum value of pounding force on structure is equal to 714 kN that is increased compared to previous cases is more and can be considered as the most critical case.

4. The effect of shear force on structure caused by pounding

After the pounding of two adjacent structures, a great value of pounding force might cause stress and strain in the structural elements. The pounding forces are opposed to direction of lateral force applied to the structure that have different effects on a shorter and taller structures. In the shorter structure, pounding force applied on the upper level of the structure. So, in the higher level of shorter structure minimum amount of shear force and in the base will have the maximum amount of shear force (similar to distribution of shear due to lateral force). It indicates that the pounding force also apply to the other levels of structure. The shear force due to pounding effect in shear wall system is presented in Fig. 16. In this Figure, two frames of two adjacent 6 and 9-story buildings are presented. The frame of 6-story building includes shear wall while the selected frame of 9-story building does not have shear wall.

As can be seen, the increased shear force caused by the pounding effect, has been tolerated by frame. The pounding force has been suddenly applied to the structure and the structure has been subjected to the lateral force at the same time. The structure has been faced with great forces in opposite directions, which caused motional complex modes on it.

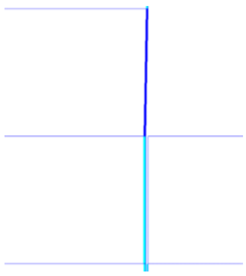


Fig. 18 Reversed shear force in column due to the pounding force at location of impact

At the first stage of collision of two structures, low shear force created at different height levels of structure while the shear force caused by lateral force is very high. At this stage, the shear force of pounding only decreases a part of the shear due to applied lateral forces to the structure. With more contact of two structures, pounding shear force increases gradually until the shear force reaches its maximum value. If the impact force has high value, removes or even reverses the direction of the shear force on the lower level of the structure. The reversed shear force is transferred wavy to the upper level of the structure. With more stiffness of structure this shear wave transmitted more quickly to the higher levels of structure. Shear force in beams also suddenly reverses after pounding effect and then returns to the original state. Fig. 17 displays the reversed shear force in MRFs system. As shown in this Figure the shear force is tolerated by all beams and columns of structures. The shear force is reversed up to the level of the third floor. This reversed shear force is leading to the upper stories level. Shear force at lower levels is also incrementally increased.

In the taller structure after the pounding effect, the pounding force is applied at the top of the shorter building. At this time, in column under level of impact, the shear force is initiated with the same direction as the lateral force and in the column above the level of impact, the shear force is applied in the opposite direction. If the pounding force is big enough, it will cause dissociation of the column in the taller structure at the height of impact. Fig. 18 illustrates the reversed shear force in column due to the pounding force at the location of impact.

Another issue that may arise in structure due to the pounding effect is torsion. Fig. 19 shows the torsion in both structures after the pounding effect. The taller building starts twisting in two opposite directions at the contact place of impact, see Fig. 19. Torsion distribution of two 8 and 4-story adjacent structures with X-braced frame are selected to be presented in this figure. Torsion in X-bracing and shear wall systems that their mass and stiffness centres are too far apart, is intensified. While high pounding force caused disconnection of the entire structure which is taller than level that pounding force applied on it.

5. Conclusions

The effect of lateral structural systems of adjacent buildings on pounding force have been investigated using three-dimensional non-linear time history analysis. The following results are obtained:

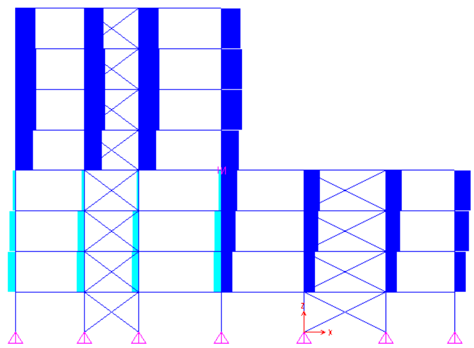


Fig. 19 Torsion of impact in X-braced frames

- In MRFs system, the pounding force suddenly reaches its maximum value. In this case, the interaction force between the two structures continues where the amount of the impact forces are less than the initial impact. The pounding force is reduced, but doesn't reach the zero point before separation. After the separation of the two structures the pounding force suddenly becomes zero.
- Two structures with lateral X-bracing system show quick impacts between the two buildings. After pounding effects, the two structures fall apart quickly due to higher lateral stiffness of lateral X-bracing system than MRFs.
- In systems with shear wall, the pounding effects happen suddenly and poundings fall apart faster than in the case with X-braced frame. In fact the pounding effect happens in a shorter time.
- Dual system includes combination of MRFs and shear wall. While pounding occurs, dual system behaviour includes combination of MRFs and shear wall performances.
- In the case where each structure has an independent structural system, the performance against pounding will be a combination of the behaviours of the adjacent systems.
- During collision of two structures, with the same lateral systems and different height level, shear force by pounding effects is applied in the opposite direction of the shear force caused by lateral forces in the shorter structure. The distribution of the pounding shear forces in height are similar to the one of the lateral shear forces. In the taller structure, at the column under the level of impact, the shear force is distributed with the same direction as the lateral force and in the column above the level of impact, the shear force is initiated in the opposite direction.
- When the pounding force is big enough, torsion is caused due to the collision of the two structures. The torsion will be in opposite directions over and under the junction of the two structures.

It is emphasised that the primary goal of the paper was comparing the pounding effect of different structural systems and the obtained results of this study were limited to only one ground excitation. The effect of earthquake characteristics in combination with the structural properties would require further investigation.

References

Anagnostopoulos, S. (1996), "Building pounding re-examined: how serious a problem is it", *Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Oxford, UK.

Anagnostopoulos, S. and Karamaneas, C. (2008), "Use of collision shear walls to minimize seismic separation and to protect adjacent buildings from collapse due to earthquake-induced pounding", *Earthq. Eng. Struct. Dyn.*, **37**(12), 1371-1388.

Bertero, V.V. (1987), *Observations on Structural Pounding. The Mexico Earthquakes-1985*, Factors Involved and Lessons Learned, ASCE.

Chau, K., Wei, X., Guo, X. and Shen, C. (2003), "Experimental and theoretical simulations of seismic poundings between two adjacent structures", *Earthq. Eng. Struct. Dyn.*, **32**(4), 537-554.

Cole, G.L., Dhakal, R.P. and Turner, F.M. (2012), "Building pounding damage observed in the 2011 Christchurch earthquake", *Earthq. Eng. Struct. Dyn.*, **41**(5), 893-913.

Efraimiadou, S., Hatzigeorgiou, G.D. and Beskos, D.E. (2013), "Structural pounding between adjacent buildings subjected to strong ground motions. Part I: The effect of different structures arrangement", *Earthq. Eng. Struct. Dyn.*, **42**(10), 1509-1528.

Filiatrault, A., Wagner, P. and Cherry, S. (1996), "An experimental study on the seismic pounding of buildings", *Eleventh World Conference on Earthquake Engineering*.

Hameed, A., Saleem, M., Qazi, A., Saeed, S. and Bashir, M. (2012), "Mitigation of seismic pounding between adjacent buildings", *Pakistan J. Sci.*, **64**, 326-333.

Iranian Seismic Code (2005), Iranian Code of Practice for Seismic Resistant Design of Buildings, Standard No. 2800-05, 3rd Edition, Building and Housing Research Center, Iran.

Jameel, M., Islam, A., Hussain, R.R., Hasan, S.D. and Khaleel, M. (2013), "Non-linear FEM analysis of seismic induced pounding between neighbouring multi-storey structures", *Latin Am. J. Solid Struct*., **10**(5), 921-939.

Jankowski, R. (2006), "Pounding force response spectrum under earthquake excitation", *Eng. Struct.*, **28**(8), 1149-1161.

Jankowski, R. (2009), "Non-linear FEM analysis of earthquake-induced pounding between the main building and the stairway tower of the Olive View Hospital", *Eng. Struct.*, **31**(8), 1851-1864.

Kaushik, H.B., Dasgupta, K., Sahoo, D.R. and Kharel, G. (2006), "Sikkim Earthquake of 14 February 2006", NICEE Reconnaissance Report, National Information Center of Earthquake Engineering, Kanpur.

Kioumarsi, B., Gholhaki, M., Kheyroddin, A. and Kioumarsi, M. (2016), "Analytical study of building height effects over steel plate shear wall behavior", *Int. J. Eng. Technol. Innov.*, **6**(4), 255-263.

Kioumarsi, B., Kheyroddin, A., Gholhaki, M., Kioumarsi, M. and Hooshmandi, S. (2017), "Effect of span length on behavior of MRF accompanied with CBF and MBF systems", *Procedia Eng*., **171**, 1332-1340.

Maison, B. and Kasai, K. (1990), "SLAM-2: A computer program for the analysis of structural pounding", Extended Version, Available from the National Information Service for Earthquake Engineering, University of California, Berkeley, CA.

Muthukumar, S. (2003), "A contact element approach with hysteresis damping for the analysis and design of pounding in bridges", Georgia Institute of Technology.

Pant, D.R. and Wijeyewickrema, A.C. (2012), "Structural performance of a base-isolated reinforced concrete building subjected to seismic pounding", *Earthq. Eng. Struct. Dyn.*, **41**(12), 1709-1716.

Phocas, M.C. and Sophocleous, T. (2012), "Numerical verification of a dual system's seismic response", *Earthq. Struct.*, 3(5), 749-766.

Polycarpou, P.C. and Komodromos, P. (2010), "Earthquake-induced poundings of a seismically isolated building with adjacent structures", *Eng. Struct.*, **32**(7), 1937-1951.

Polycarpou, P.C., Papaloizou, L. and Komodromos, P. (2014), "An efficient methodology for simulating earthquake-induced 3D pounding of buildings", *Earthq. Eng. Struct. Dyn.*, **43**(7), 985-1003.

Polycarpou, P.C., Papaloizou, L., Komodromos, P. and Charmpis, D.C. (2015), "Effect of the seismic excitation angle on the dynamic response of adjacent buildings during pounding", *Earthq. Struct.*, **8**(5), 1127-1146.

Ruangrassamee, A. and Kawashima, K. (2003), "Control of nonlinear bridge response with pounding effect by variable dampers", *Eng. Struct.*, **25**(5), 593-606.

Skrekas, P., Sextos, A. and Giaralis, A. (2014), "Influence of bi-directional seismic pounding on the inelastic demand distribution of three adjacent multi-storey R/C buildings", *Earthq. Struct.*, **6**(1), 71-87.

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