Seismic Response Effect of Shear Walls in Reducing Pounding Risk of Reinforced Concrete Buildings Subjected to Near-Fault Ground Motions

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SUMMARY:
Shear walls reduce the lateral displacement of buildings under near fault earthquake. Large lateral displacements could cause impacts or collisions between adjacent buildings. Collectively these impacts are named building pounding, which can cause unexpected behaviour of buildings during earthquakes. Building pounding analysis is necessary for evaluating the needed separation distance between adjacent buildings. There are many ways to decrease building lateral displacements, such as using shear walls, dampers or providing required gap. The use of shear walls can reduce displacements and risk of pounding by its inherent higher stiffness. This natural behaviour depends significantly on the stiffness of the building, shear walls and on the seismic vibration records. In order to exhibit the benefits of shear walls, a nonlinear time history analysis is carried out under strong ground motion Kobe's earthquake record. In this paper, coupled adjacent reinforced concrete frames are modelled in order to evaluate time history displacements and collisions between them. These frames are three-story height with a critical gap distance of 10 cm, that is going to be labelled 3-3 M. The nonlinear analysis showed the highest number of eleven collisions in the 3-3 M model, when the buildings behave as moment resisting frames. This number has a dramatic decrease to six collisions using shear walls in left frame, and four collisions when both frames are equipped with concrete shear walls. This study demonstrates that using concrete shear walls is an efficient method to control and decrease large displacements. Finally, different responses of the buildings under different characteristics of the link elements between them have been compared, to get the best estimation of the impact force and of the damping effect. Effectiveness of the stiffness and of the restitution coefficient *e* of the represented link element is investigated by a developed mathematical program.

Keywords: Shear wall, Building pounding, Link element, Adjacent frames

1. INTRODUCTION AND GENERAL REVIEW

Seismic excitation usually causes building pounding in adjacent buildings. Regarding the damages caused by building pounding to residential buildings, designing a structure with a critical distance would be needed. In addition, decreasing lateral displacement could decrease hazard of building pounding. Many researchers around the world have studied building pounding, as this subject is a specific alternative for understanding building seismic responses. Researchers have investigated pounding with two different options: experimental analysis and formulations evaluating the dynamic structural response (through nonlinear analysis using various finite element programs). Anagnostopoulos (1998) was among the first researchers who showed the effect of impact and displacement in a building model with distributed mass. He also suggested a formulation for damped linear contact element, and further described that damping constant can be related to the impact coefficient of restitution (Anagnostopoulos, 2004). Karayannis and Favvata (2005) have investigated the floor-to-column pounding on concrete buildings with different heights. In all the examined cases, columns were in a critical condition due to shear action; also, in the cases where the structures were in contact from the beginning of the excitation, the columns were in critical condition due to high ductility demands. Cole and Dhakal (2009) have indicated that building pounding and its impact force depend on the structural properties and on the collision velocity of both buildings; furthermore, they suggested a plan to control the impact. In terms of the link elements used to simulate the contact between buildings, many mathematical formulas have also been recommended by Jankowski (2006), Ye et al. (2008) and Komodromos and Polycarpou (2009). Also at FEUP (*Faculdade de Engenharia da Universidade do Porto*) two M.Sc. thesis, on the thematic of pounding of buildings during earthquakes (Cordeiro, 2011; Vasconcelos, 2011), are thought to have initiated in Portugal the research and development (R&D) on this important thematic within earthquake engineering. Recently, Barros and Khatami (2012-a) addressed the importance of the gap or separation distance between adjacent buildings, as prescribed in the Iranian earthquake code. Further, through comparative numerical simulations, Barros and Khatami (2012-b) estimate the effect of damping ratio on the numerical study of impact forces between two adjacent concrete buildings subjected to pounding. In yet another study, Barros and Khatami (2012-c) compare results of two SDOF frames with different link elements based on mathematic relations. In some of these analyses, structures were modelled as single degree freedom systems and collision was simulated with the help of linear viscoelastic models of impact force. In this paper, special attention is given to the modelling of nonlinear effects of adjacent buildings with and without shear walls, under Kobe's earthquake time history at the foundation interface. Recent building pounding destructive effects are visualized in Figure 1.

Figure 1. Building pounding in adjacent buildings (New Zealand 2011)

2. ANALYTICAL MODEL

2.1. Building Model

The reference model is represented by two reinforced concrete frame having three floors, which are called 3-3 M, with a gap of 10 cm, that are seismic moment resistant frames of medium level of ductility. The labelled 3-3 M-LSH model refers to a reference model with shear wall in left frame (LSH). The last model is 3-3 M-SH, which describes a structural model with shear walls in both modelled frames. Each of these 3 floor frames has two 4-meter spans in the X direction (Figure 2).

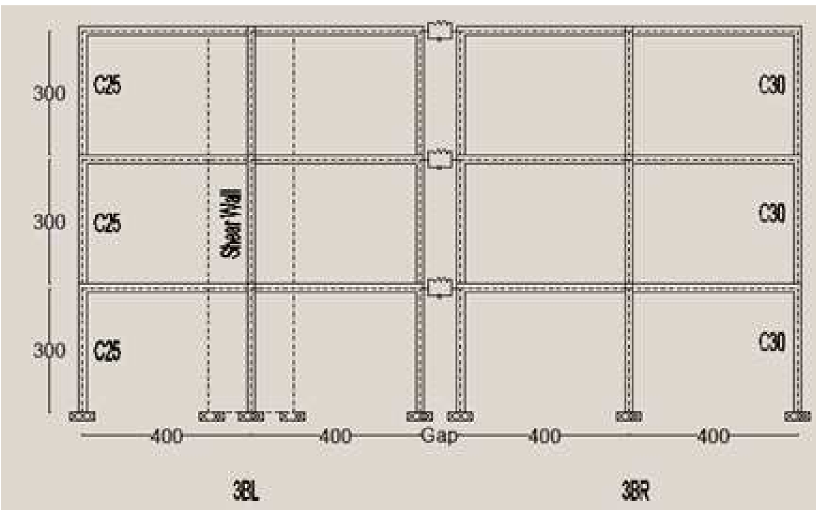


Figure 2. The elevation view of the analysed model

Height of each floor is considered to be 3 meters and the use of the frames is assumed to be residential. Complementary to this assumption, concrete compressive strength is 25 MPa and yielding strength of steel is 400 MPa. To calculate the damping effects of the buildings, damping ratio has been assigned to be 0.05 (ξ=0.05). Dimensions of the columns and of the beams, and thickness of the shear walls are shown in Table 2.1.

Table 2.1. Dimensions of the structural elements

Buildings	Dimension of columns (cm)	Dimension of beams (cm)	Thickness of shear wall (cm)
Left Frame	25*25	25*25	10
Right Frame	30*30	25*25	10

Shear walls are added to the middle span on X direction (adjacent to middle column) to decrease the lateral displacements, as has been depicted in Figure 2. Stiffness of the concrete shear wall causes a decline of the story drift. This inherent behaviour could provide a decrease in impacts, when frames vibrate under seismic excitation. Shear walls also cause an increase of the stiffness and masses of the analysed frames. Nevertheless, the effectiveness in increasing the stiffness is more relevant than the increase of the masses, in terms of reduction of the lateral displacements. Lateral displacements depend on the periods of the adjacent frames, which are important parameters for the potential occurrence of pounding.

2.2. Link Element and Properties of Dynamic Matrices

The contact element used between the frames is a link element called ´Kelvin-Voigt´, represented schematically in Figure 3. The Kelvin-Voigt link model with gap uses a dashpot damper and spring with high stiffness, which are devised for energy dissipation and for restraint of lateral displacements.

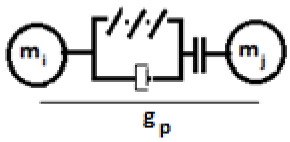


Figure 3. Kelvin-Voigt link element

The impact force-interpenetration relationship is represented as:

$$F_C = k\,(\delta_i - \delta_j - g_p)^{1.5} + c\,(\delta_i - \delta_j) \tag{2.1}$$

In this relation the damping coefficient *c* depends significantly on the restitution coefficient *e* and on the stiffness *k* of the link element (Barros and Khatami, 2012-b). The equation for its determination, according to Komodromos and Polycarpou (2009), is given by:

$$c = \xi(\ \delta_i - \delta_j)^{1.5} \qquad \text{and} \qquad \xi = \frac{8\ k\ (1-e)}{5\ e\ v} \tag{2.2}$$

where δ_i and δ_j are lateral displacement of two bodies and the restitution coefficient *e* ranges between 0 and 1 (with a reference value herein used as 0.3). In particular, *e* values cover elastic and inelastic behaviours of the collision between two bodies (in this case, of the two pounding structures). Finally, *v* is the relative approaching velocity before impact.

Considering dynamic structural properties present in the matrix equation of motion of the seismically excited buildings, the three dynamic matrices of mass, damping and stiffness can be written as:

$$m_{total} = \begin{bmatrix} m_j & 0 & 0 & 0 & 0 & 0 \\ 0 & m_j & 0 & 0 & 0 & 0 \\ 0 & 0 & m_j & 0 & 0 & 0 \\ 0 & 0 & 0 & m_i & 0 & 0 \\ 0 & 0 & 0 & 0 & m_i & 0 \\ 0 & 0 & 0 & 0 & 0 & m_i \end{bmatrix} \tag{2.3}$$

$$c_{total} = \begin{bmatrix} 2c_j + c & -c_j & 0 & -c & 0 & 0 \\ -c_j & 2c_j + c & -c_j & 0 & -c & 0 \\ 0 & -c_j & 2c_j + c & 0 & 0 & -c \\ -c & 0 & 0 & 2c_i + c & -c_i & 0 \\ 0 & -c & 0 & -c_i & 2c_i + c & -c_i \\ 0 & 0 & -c & 0 & -c_i & c_i + c \end{bmatrix} \tag{2.4}$$

$$K_{total} = \begin{bmatrix} 2k_j + k & -k_j & 0 & -k & 0 & 0 \\ -k_j & 2k_j + k & -k_j & 0 & -k & 0 \\ 0 & -k_j & 2k_j + k & 0 & 0 & -k \\ -k & 0 & 0 & 2k_i + k & -k_i & 0 \\ 0 & -k & 0 & -k_i & 2k_i + k & -k_i \\ 0 & 0 & -k & 0 & -k_i & k_i + k \end{bmatrix} \tag{2.5}$$

where m_i and m_j are lumped masses of each story (here considered to be equal to each other) of the systems used as sample structures; c_i and c_j represent building damping coefficients; k_i and k_j denotes stiffness in models i and j, respectively. Also c and k denote damping coefficient and stiffness of the used link element, respectively.

2.3. Near-Fault Earthquake Record

To investigate building pounding, the three models are analysed when subjected to a near-fault ground motion record. The considered frames are supposed acted upon by the Kobe's earthquake (1995) record shown in Figure 4, which on the 16th January 1995 vibrated the city with the magnitude of 7.2. The Kobe earthquake record was selected to investigate the behaviour of the concrete frames and the effect of the shear walls, when lateral displacement causes building pounding.

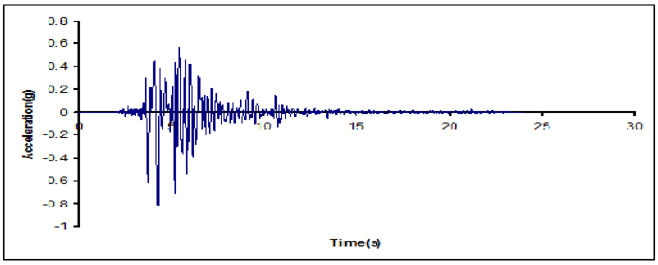


Figure 4. Kobe (1995) Near-Fault Earthquake Record used in analysing the structural models

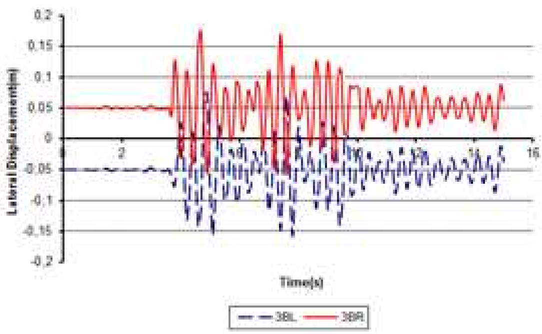
3. SOME COMPUTATIONAL RESULTS OF THE BUILDINGS ANALYZED

Analytical modelling of building pounding is investigated by using the SAP 2000 software package (from CSI). The objective of the investigation is to present building pounding and the amount of reduction in the seismic response under near-fault Kobe's earthquake by using shear walls. Firstly, four different models were analysed under the lateral loading associated with the mentioned record. The modal properties of the first three vibration modes are given in Table 3.1, for each (left and right) building case considered separated or independent (that is, non-colliding), without or with shear walls.

Table 3.1. Properties of the first three modes, for four structural independent cases

Building	3 M_Left (3 M-L)	3 M_Right (3 M-R)	3 M-LSH	3 M- RSH
1st Mode Period (sec)	1.01	0.764	0.429	0.325
2nd Mode Period (sec)	0.61	0.52	0.162	0.11
3rd Mode Period (sec)	0.42	0.399	0.079	0.058

When analysing the coupled two buildings (with link elements) subjected to earthquake induced pounding, for the 3 structural coupled models mentioned in paragraph 2.1 (3-3 M, 3-3 M-LSH, 3-3 M-SH), the models presented large displacement under the Kobe’s time history seismic excitation. In the first model 3-3 M, there were 11 collisions during the analysis. Lateral top displacement is restricted to 20 mm in first three seconds of the models. After that instant, time history of the top displacement showed a sudden lateral displacement to 12 cm between 3 to 10 seconds for right frame and 13 cm for left frame. As stiffness of the right frame is higher than the stiffness of the left frame, it is expectable that lateral displacement of right frame to be smaller than the lateral displacement of the left frame. These values are the highest for lateral displacements among the three investigated models. The second model is defined as 3-3 M-LSH, which is analysed by using shear wall in left frame. Maximum lateral displacement in the right frame is 12 cm. There is a sudden decline in terms of lateral displacement in the left model to 6 cm. The use of shear walls was the cause in decreasing the lateral top displacement. Subsequently, the number of collision has decreased to 6 times. Last model analysed is 3-3 M-SH, obtained by providing shear walls in both frames. Maximum value for lateral top displacements has decreased to 8 cm and 6 cm, in the left and right buildings respectively (3-3 M-LSH and 3-3 M-RSH, that is, model 3-3 M-SH). The number of collisions has substantially decreased to 4 collisions in comparison with 3-3 M model which had 11 collisions. The results for these three analysed models are presented in Figure 5.



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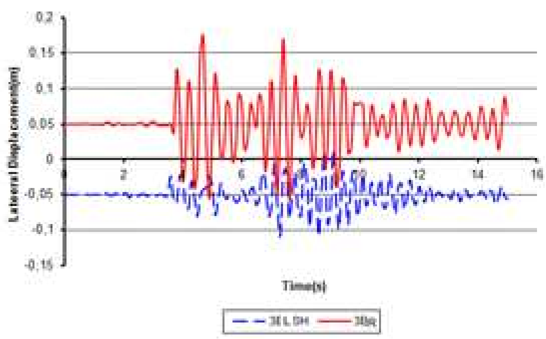

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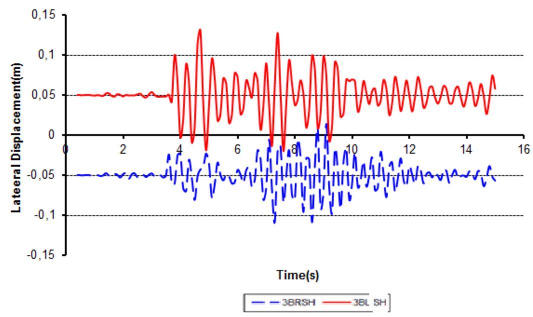
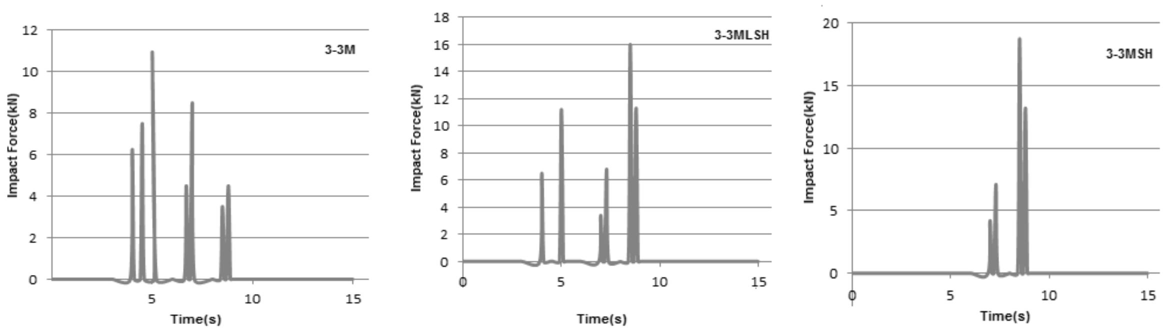


C

Figure 5. Time history of top displacements for the 3 different structural models:
(A) 3-3 M ; (B) 3-3 M-LSH ; (C) 3-3 M-SH

Furthermore the impact forces between the frames have been studied, as presented in Figure 6. In this investigation, model 3-3 M-SH had four collisions with the maximum impact force of 19 kN. The number of collisions slightly increases to 6 times for the model 3-3 M-LSH (in comparison with the model 3-3 M-SH); in this model the first collision occurred at the 4^{th} second, while the 3-3 M model had 11 collisions occurring between 4^{th} to 9^{th} second. Maximum impact forces of these latter models were 16 kN and 11 kN, in the 3-3 M-LSH and the 3-3 M-SH models, respectively.



A B C

Figure 6. Impact force in the 3 different structural models: (A) 3-3 M ; (B) 3-3 M-LSH ; (C) 3-3 M-SH

4. CHANGING PROPERTIES OF THE LINK ELEMENT

As it was noted, link elements are modelled between two bodies for simulation of the impact force and of the dissipated energy during collision. In particular, researchers have suggested different formulas to get the best results for the two mentioned options, which are based on stiffness of the spring and on damping ratio of the dashpot damper. The discussed options are about the manner to calculate the dissipated energy. Herein, effectiveness of the restitution coefficient *e* (for fixed link stiffness *k*) is investigated considering its effect on lateral top displacement associated with the assessed structural models: 3-3 M, 3-3 M-LSH and 3-3 M-SH.

From the computational results of each structural model, an approximate formula of the lateral top displacements was obtained for each model. These approximate maximum lateral displacement relations are limited to the intervals 5 to 5.5 seconds, 8.5 to 9.1 seconds and 8.6 to 9 seconds (respectively for the mentioned models), since the corresponding maximum impact forces have occurred such intervals (as shown earlier). Such three simulated relations approximately obtained using MATLAB have been obtained using MATLAB (2010) in the mentioned time intervals, are given by:

$Y_{3-3\ M}$ = -0.05137 + 0.01595 cos(13.21t) + 0.09729 sin(13.21t)

$Y_{3-3\ M-LSH}$ = -0.0372 – 0.041 cos(14.3t) + 0.0431 sin(14.3t)

$Y_{3-3\ M-SH}$ = -0.02576 – 0.09164 cos(16.9t) - .021512 sin(16.9t)

where Y_n are lateral displacements and t denotes time.

Using the mentioned three models, the variability of the restitution coefficient *e* is investigated. As ξ depends on *e*, and this factor is selected among several options from 0 to 1, different results of the impact forces for various *e* are here presented. For getting the best estimate of *e* to be used in this example case, firstly the results of the 3-3 M model are compared with the results of SAP 2000 (Figure 7).

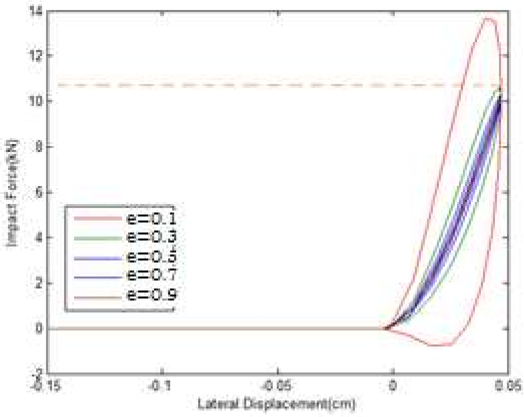


Figure 7. Impact forces on model 3-3 M, for different restitution coefficients

After collision, when the two bodies are detached from each other, the lower curve shows a negative zone during the returning for *e*=0.1. It is shown that in this restitution phase the calculated impact force is much less the impact force evaluated by SAP 2000. Consequently, the value of *e*=0.1 could not be valid. Maximum impact force for 3-3 M model was about 11 kN, which is very close to the one obtained here (of 10.75 kN) using the value *e*=0.3 and the MATLAB approximation. The 2.5% error in the estimation of impact forces (as compared with the value obtained by SAP 2000 for the 3-3 M model) indicates that the calculated results using *e*=0.3 are acceptable. It seems that the mentioned value is the best available estimation to be used, to get optimized results for comparing the effect of shear walls in these studied buildings.

Using the three different models assessing lateral top displacements, and based on equations (2.1) and (2.2), energy dissipation for the considered models has been calculated using MATLAB (2000). Energy dissipation is the most important option to show the behaviour of the used link element. Having shear walls included in the frames caused a decreasing number of collisions and increased the hysteresis loop area of the force in the link elements. The shown enclosed area in Figure 8, expresses dissipated energy when two structures collide with each other during seismic excitation. The energy dissipation (kN*cm) at the link element for the three models is given in Table 4.1.

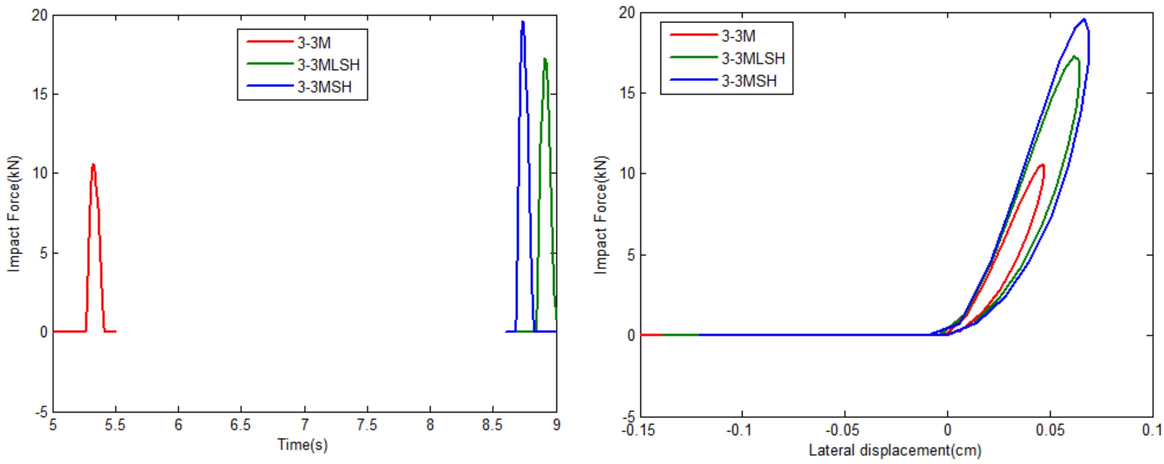


Figure 8. Comparison of the impact forces in the link element for the different models

Table 4.1. Dissipated energy of different structural models (for *e*=0.3)

Model	Energy Dissipation (kN.cm)
3-3 M	8.36177
3-3 M-LSH	26.4921
3-3 M-SH	34.75409

The results obtained from the analyses show that shear walls have substantial influence to decrease the lateral displacement. As frames have been separated by a gap, reduction of lateral displacement can decrease the number of collisions between two adjacent frames during earthquakes. Moreover, shear walls help to avoid the large lateral displacements based on natural separated independent behaviours. As shear walls act in the first phase of resistance against seismic excitation, this element cracks sooner than other structural elements during seismic excitation and absorbs more energy than other elements. This structural system has shown better behaviour in comparison with moment resisting frames, as regards to the energy transference to the link elements during seismically induced pounding of the structures.

5. CONCLUSIONS

Seismic excitation can cause large lateral top displacements in buildings, which can produce collisions between adjacent buildings. Adjacent buildings can be different in material properties, heights, periods and lateral resisting systems. In this study, two adjacent concrete frame models with and without shear wall have been studied. This investigation has shown the effective role of shear wall to decrease the number of collisions between two adjacent frames. The carried out study has shown that shear walls are able to decrease lateral top displacement of each modelled building and the number of impacts during earthquakes. It has also indicated that the link element, in the case of using the shear walls on both buildings, can absorb more energy than any of the other cases. By the transferred energy to the link elements, it can be shown that the shear wall systems provide at the link element stronger impact forces than for other structural systems. Although these strong poundings can cause many damages in buildings, it can be justified that this system is able to absorb more energy (than moment resisting frames) and present higher resistance against destructive earthquakes.

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