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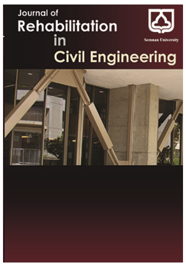

Influence of Seismic Pounding on RC Buildings with and without Base Isolation System Subject to Near-Fault Ground Motions

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ABSTRACT

Building pounding occurs between two adjacent buildings with small gap or without sufficient separation distance. It leads to damage buildings during earthquake due to impact. Many researchers have investigated building pounding based on impact force reduction and energy dissipation increase, when two buildings collide with each other. In numerical investigations, using specific link element, impact force is calculated in order to get the proper evaluation of damage for preventing failure of structural elements. In this paper, focusing on numerical investigation, the effectiveness of impact and energy dissipation is studied. For this challenge, two RC structural models are considered to evaluate the pounding to calculate the impact force and finally, to compare the effectiveness of Base Isolation (BI) support against fixed support. A link element is located at the connection level between two studied dynamic models.

1. Introduction

Building pounding has been a stimulating research topic during the last few decades in earthquake engineering. This phenomenon describes impacts under two adjacent buildings subject to seismic excitations. If adjacent buildings are not separated suitably from each other, impact forces could cause damage to buildings even if structures are well designed. Unfortunately, enough attention has not been paid to the building pounding effects in available building codes. However, several researchers have tried to investigate the effects of such collisions worldwide. Anagnostopolos was among the first researcher who has explained the possible dangers due to building pounding. Investigation of the building pounding has been divided into two parts, experimental tests and numerical analyses [1,2]. Papadrakakis and Mouzakis [3] conducted shaking table experiments on pounding between two-story reinforced concrete buildings without separation distance under the earthquake records. Two steel buildings with three- and eight-story have been tested by shaking table by Filiatrault [4]. The tests were carried out with two different gaps, zero and 15 mm. The experimental results were compared with analytical predictions based on linear elastic spring theory. The comparisons showed that acceleration at the contact level was not well predicted. Watanaba and Kawashima [5] have investigated pounding of distributed masses to model colliding bridge decks. They showed that five elements were used per deck; the collision element stiffness would be five times greater than that of the diagram stiffness. Cole et al. [6] have indicated that building pounding and its impact depend on the structural properties and collision velocity of both buildings. They suggested a technique to control the impact. A theoretical maximum collision force has been determined by them, for a system with two distributed masses. Velocity, mass and stiffness at the time of impact have a relationship, and the number and magnitude of the impacts depend on these three options mentioned. Barros and Khatami [7] addressed some common misrepresentations in Iranian code on the issue of separation distance required between two adjacent concrete buildings under near-fault ground motions. In numerical analyses, link elements are located between two buildings investigated. Komodromos et al [8] also took advantage of link elements extensively in his research.

Barros and Vasconcelos [9] investigated building pounding between two adjacent concrete buildings by numerical analyses. They presented the results of analyses using different stiffness and damping ratios. Two concrete buildings with eight- and ten-story have been modeled by Raj and Wijeyewickrema [10]. Different types of springs with different stiffness or various dampers with different damping ratios have also been used in recent numerical studies at FEUP by Cordeiro [11] and by Vasconcelos [12], in their parametric studies of pounding between adjacent buildings. Barros and Khatami [13] estimated 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 [14] compared results of two SDOF frames with different link elements based on mathematic equation. In some of their analyses, structures were modeled as SDOF systems and collision was simulated with the use of linear viscoelastic models of impact force.

In this paper, two reinforced concrete buildings having three and five stories are modeled. Different link elements are commonly located between investigated buildings to get the best estimation of impact force and energy dissipation. For this challenge, based on dynamic model of spring and damper relation, a new link element is suggested and a new damping term formula is calculated to simulate the maximum energy absorption. Five available suggested formulas for pounding are collected and described. Then, different parameters are evaluated and the effect of story stiffness, base support and other characteristics of damping formula are compared.

2. Impact Model

In order to measure the impact force of collisions and lateral displacement of structures, it is necessary to define a specific link element at the connection level between two buildings. Based on the type of link elements, they are different to guarantee the validation of the results. Many researchers have been interested in link elements and focused on numerical analyses of building pounding. They described several types of link elements with their mathematic equations. These link elements are able to calculate the impact force of pounding. The main different objective of link elements is to use spring and damper in them. Different types of springs with different stiffness or various dampers with different damping ratios are used in numerical studies. Since period of buildings are different, link elements should be able to transfer different response of buildings during seismic excitation.

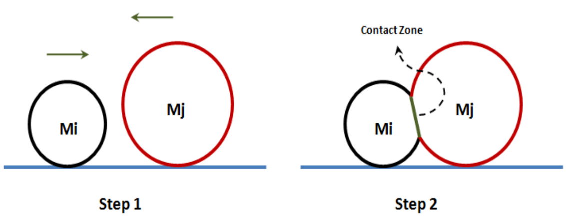


Fig. 1. Schematic model of impact between two adjacent masses

2.1. Kelvin model

The first equation of impact model is Kelvin model, which includes a linear impact spring with a viscous impact damper which are located in parallel with each other. This model prepared by a linear viscoelastic impact model in order to calculate energy loss during impact. In this model, impact force at time t is simulated by the following equation:

$$F_1(t) = k_k.\delta(t) + c\dot{\delta}(t) \tag{1}$$

Where k_k denotes stiffness, C is the impact viscous damping coefficient, $\delta(t)$ is lateral displacement and $\dot{\delta}(t)$ denotes relative velocity between the lumped masses in contact at time t. In this equation, the impact viscous damping coefficient C is related to the coefficient of restitution CR, which is explained by:

$$c = 2\zeta\sqrt{k_k \frac{m_1 m_2}{m_1 + m_2}}$$

and (2)

$$\zeta = -\frac{\ln CR}{\sqrt{\pi^2 + (\ln CR)^2}}$$

CR is a vector varying from 0 to 1, which describes elastic and plastic impact. This formula was based on the assumption of an equivalent SDOF dynamic system that represents the two bodies in contact and the conversation of energy before and after impact.

2.2. Hertz model

Another popular model for calculating the impact force between two buildings is Hertz model. According to this model, the impact force acting based on a nonlinear spring is an effort to represent more realistically structural impacts. This equation can be written by:

$$F_{Hertz}(t) = k_k.\delta(t)^n \tag{3}$$

The Hertz coefficient n is usually suggested to be 1.5. For this model, coefficient n provides a nonlinear behavior on the contact element. Also, the main disadvantage is that the equation is focused on static collision between two dynamic models.

2.3. Nonlinear viscoelastic model

By improving the impact models, Jankowski [15] presented an idea, which a nonlinear viscous damper locates parallel to the spring in order to absorb the energy. As it will be shown in the curve, energy was dissipated during nonlinear cyclic and this dissipation of energy is negligible. Consequently, the dashpot used is assumed to be active only during the approach phase. The equation of nonlinear viscoelastic model can be written by:

$$F_2(t) = k_h.\delta(t)^{1.5} + c_h\dot{\delta}(t) \quad (4)$$

C_h is explained by:

$$c_h = 2\zeta\sqrt{k_h\sqrt{\delta(t)}\frac{m_1 m_2}{m_1 + m_2}}$$

and (5)

$$\zeta = \frac{9\sqrt{5}}{2}\frac{1-CR^2}{CR(CR(9\pi - 16)+16)}$$

Incorporating $\sqrt{\delta}$ to equation of damping ratio, which provides the impact damping coefficient, the discontinuity at the beginning of the approach phase, (which is a characteristic of the linear viscoelastic impact model), is theoretically eliminated.

2.4. Hertz Damped Model

A new pounding analytical model is described in this part. Hertz damped model with nonlinear damping was suggested by Muthukumur [16] to calculate the impact force between two dynamic models. The impact force during collision can be expressed as:

$$F_{3and4}(t) = k_h.\delta(t)^n + c\dot{\delta}(t) \quad (6)$$

In which, the nonlinear damping coefficient is explained as follows:

$$c = \zeta.\delta(t)^n \quad (7)$$

where ζ is the damping constant. Using energy equation of motion and developing the mentioned equation, we will have:

$$\zeta = \frac{3k_h(1-CR^2)}{4v_{imp}} \quad (8)$$

Kun Ye [13] has suggested a new ζ, which can be written as:

$$\zeta = \frac{3k_k(1-CR)}{2.CR.v_{imp}} \quad (9)$$

A value of CR equal to 1, will provide perfectly elastic impact and equal to 0 could imply on plastic impact.

3. New Model Presented

Based on energy laws, when two bodies collide with each other, the kinetic energy loss due to impact is explained by:

$$\Delta E = \frac{1}{2}(\frac{m_1 m_2}{m_1 + m_2})(1-CR^2)v_{imp}^2 \quad (10)$$

Where v_{imp} is the impact velocity, which is relative velocity of two bodies before collision. Dissipated energy also can be presented by damping term:

$$\Delta E = \int_0^{\delta_{max}} c\dot{\delta}_0 d\delta = \int_0^{\delta_{max}} \zeta\delta^{1.5}\dot{\delta}_0 d\delta \quad (11)$$

which calculates a hysteresis loop during impact. In order to describe impact between two colliding bodies and using mathematic equations, represented model in figure 2 can be equivalently modeled as the response of a SDOF system. In this model, using three springs with same stiffness and damper, a new model is modified with Kelvin model.

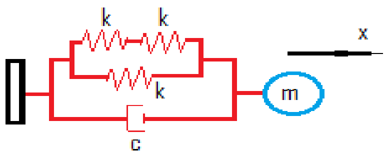


Fig. 2. Suggested dynamic model

Considering THE equation (6) as a reference equation of motion to calculate the impact force and incorporating two springs, some changes in terms of stiffness would appear. According to these changes, equivalent stiffness k_{eff} obtains. Using new system, the force excited in by three shown springs and one damper is simulated. In this relation, firstly, k_{eff} can be written by:

$$k_{eff} = \frac{k}{2} + k \tag{12}$$

Finally, based on equation of nonlinear viscoelastic model and considering that $\delta(t)$ is the same in all mentioned options, we have:

$k_{eq} = \frac{3}{2}k$, with this statement, impact force is estimated to be in the form given by:

$$F_{new}(t) = k_{eq}.\delta(t)^n + c_{new}\dot{\delta}(t) \tag{13}$$

According to Fig. 3, and considering equation (11), energy loss is evaluated. Maximum lateral displacement (D_{max}) and separation time (T_{max}) of collisions between two investigated masses was described in the fig 3. It is also assumed that velocity of two masses is the same at the end of phase 1.

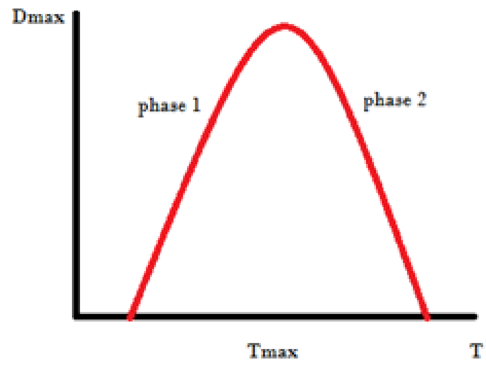


Fig. 3. Defined curve of lateral displacement

For this curve, previous studies have suggested an approximate equation for lateral displacement and velocity of investigated model. This equation of motion can be written as [17]:

$$\left(\frac{\delta}{\delta_{max}}\right)^2 + \left(\frac{\dot{\delta}}{\dot{\delta}_0}\right)^2 = 1 \tag{14}$$

Considering mentioned equation, there is a nonlinear relation between lateral displacement and impact velocity. Proposed curve has two different parts; it can explain two different values for ΔE. Therefor the velocity of phase 1 and phase 2 in T_{max} are assumed to be equal with each other. So, we have:

$$\dot{\delta} = \dot{\delta}_0\sqrt{1 - \left(\frac{\delta}{\delta_{max}}\right)^2} \tag{15}$$

Where $\dot{\delta}_0$ denotes final velocity. Consequently, equation (16) represents the dissipated energy, when two bodies are detached after colliding. In particular, as it could be seen from equation (10) and (11), it can be justified by:

$$\Delta E = \zeta(\dot{\delta}_0)\delta_{max}^{2.5}\int_0^1 x^{1.5}\sqrt{1 - x^2}\,dx \tag{16}$$

Considering the results presented by Kun Ye et al [17], ΔE is based on a mathematic relation, which depends on ζ maximum lateral displacement and velocity. This equation is described by:

$$\Delta E = 0.25\zeta(1+CR)\dot{\delta}_0\delta_{\max}^{2.5} \quad (17)$$

The relationship between momentum and energy balance in the start and end of phases is represented by:

$$\frac{1}{2}m_1v_1^2+\frac{1}{2}m_2v_2^2=\frac{3}{5}k_h\delta_{\max}^{2.5}+0.25\zeta\dot{\delta}_0\delta_{\max}^{2.5}+\frac{1}{2}(m_1+m_2)V^2 \quad (18)$$

In which, $\delta_{\max}^{2.5}$ is given by the following equation:

$$\delta_{\max}^2 = 0.5\left(\frac{m_1m_2}{m_1+m_2}\right)V^2\left(\frac{20}{12k_h+5\zeta\dot{\delta}_0}\right) \quad (19)$$

using $\delta_{\max}^{2.5}$ it is worth to predict an equation for ζ to simulate the damping term of equation (13). This relation can be found as:

$$\zeta = \frac{12(1-CR)k_h}{5.CR.v_{imp}} \quad (20)$$

4. Numerical Model

Two RC moment-frame buildings having three and five stories with regular-plan were modeled. Three different models have been analyzed: fix support, base isolation support and fix-isolation support. In the first model, both buildings have fixed supports. In the second one, one of the models has fixed base and the other is supported by BI, finally in the third model, both models have BI. Structural models are named as RBF, LBF, RBI and LBI, in which R means building is located in Right direction and L indicates Left direction. B considered as the abbreviation for of Building, F and I denote fixed support and Isolation system, respectively. Structural models consist of three spans of 4-meter and two spans of 5-meter in X direction and two 5-meter spans in Y direction. The near-field Loma Prieta and Kobe earthquake records were applied to the structures to investigate the effects of pounding. Adjacent buildings shall be separated by gap, which can be determined by two different expressions:

$$S = u_i + u_J \text{ and } S = \sqrt{u_i^2 + u_j^2} \quad (21)$$

Where u_i and u_j are inelastic displacement of building A and B, respectively.

Gap between two buildings is 20 cm, which separates the two investigated models. It is worth to mention that these equations were suggested by many earthquake codes to provide a limit of separation distance for structures to preclude building pounding during earthquake.

In this study, buildings are modeled with the same floor. Moreover, lumped mass theory is employed for mass modeling at floor levels.

Three-dimensional frame models of the buildings with an assumed rigid foundation are used in SAP2000 [18]. The objective of the analysis is to highlight the building pounding in the seismic response of the considered reinforced concrete buildings under near fault ground motion. Table 1 gives information about columns and beams sections in the analytical models.

Table 1. Dimension of Beam and Columns Section

Model	Column Size in the First Story (cm)	Beam Size in the First Story (cm)
LBF and RBF	40*40	35*35
LBI and RBI	45*45	40*40

Two earthquake records were selected to analyze and evaluate the result of investigation. These are Kobe (1995), and Loma Prieta (1989). These records have different contents of the excitation frequencies, different random magnitudes of the acceleration in time, and different earthquake durations; besides, their location of occurrence and geological conditions are distinct. The two earthquake records used in this paper are shown in Fig 4. Kobe record has the highest acceleration between the two mentioned records. This amount of PGA is 0.821g, with an epicenter distance less than 40 km. This earthquake occurred in 16 January 1995, which vibrated this city with a magnitude of 7.2. Loma Prieta was an earthquake occurred in 1989 with magnitude of 6.93 and the PGA of Loma Prieta earthquake was 0.4975g. This earthquake was a near-fault record with a distance to source of less than 40 km.

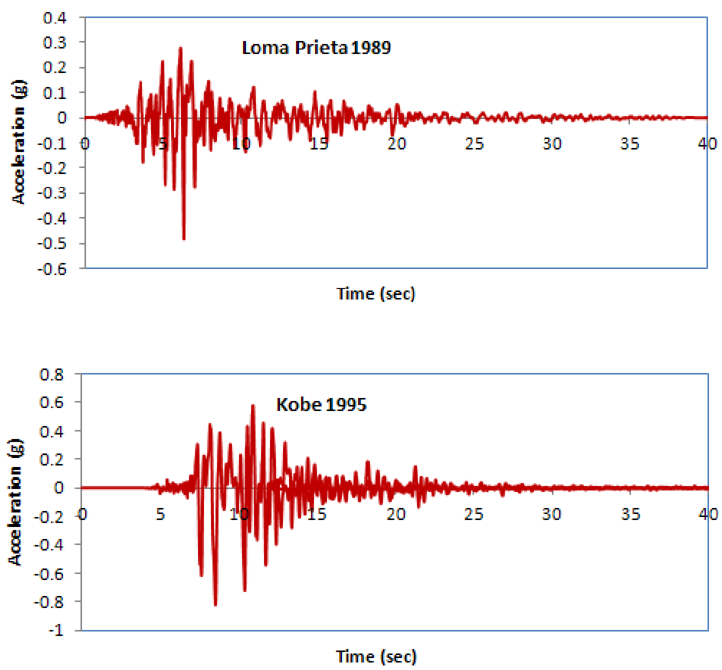


Fig. 4. Earthquake records utilized in analysis

5. Numerical Study

The models were analyzed under mentioned records. New suggested link element was considered to calculate the lateral displacement and impact force between two buildings. In order to compare the discussed models and value of energy absorption, seismic response of models is represented in this section. Firstly, lateral displacement curves show nonlinear behavior in buildings by fixed support. These buildings also had some collisions with each other during earthquake. These collisions cause impact between two investigated buildings, which are depicted in Fig 5. Based on mentioned curve, buildings reflected an irregular nonlinear lateral displacement, when supports are modified by base isolation system.

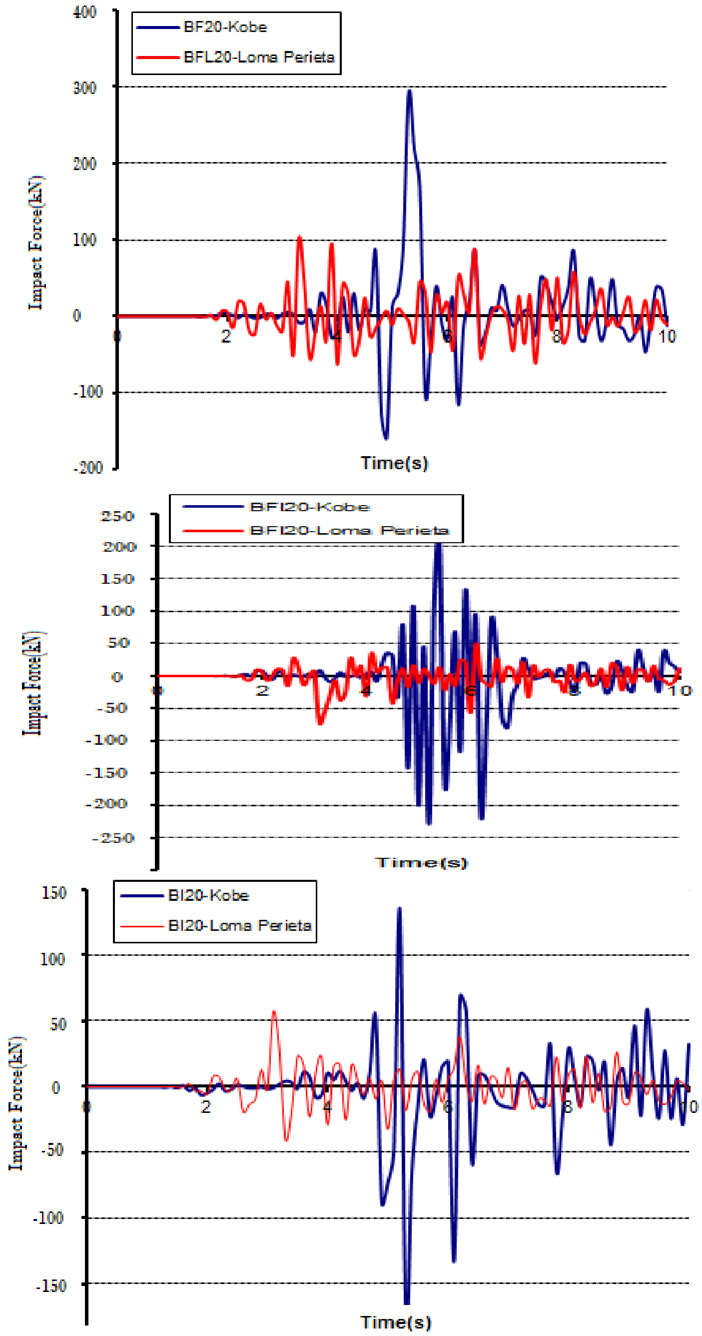


Fig. 5. Time-history of impact force

Maximum impact force was described by two fixed buildings. It shows that lateral displacement of fixed buildings is much more than lateral displacement of base isolation buildings. This behavior causes the impact force of these buildings to be greater in comparison with other models during collisions. Two supported buildings by base isolation have shown good results without collision, by having maximum lateral displacement of 0.4 mm and 0.8 mm under Kobe and Loma Prieta records, respectively. Numerical study has indicated an abnormal result in BFI20, where two buildings have different supports and naturally, they should behave different from each other.

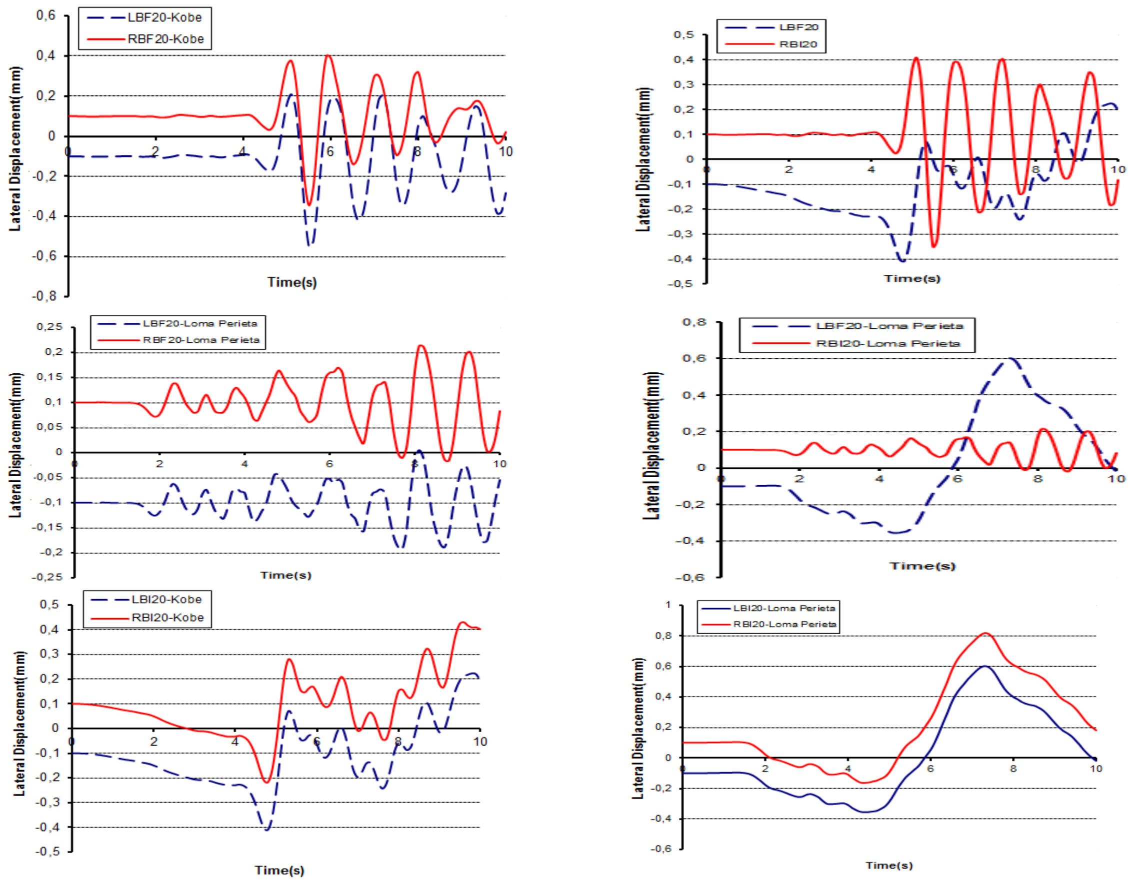


Fig. 6. Lateral displacements for different models

Table 2. Maximum impact and displacement in different analyzed models

	BF20.Kobe	BF20.Loma	BI20.Kobe	BI20.Loma	BIF20.Kobe	BIF20.Loma
Δ_{max}(mm)	0.42	0.12	0.31	0.59	0.32	0.81
F_{imp}(kN)	298	104	149	54	210	51

5.1. Dynamic Model

Dynamic model has been modeled by MDOF. This analytical model is defined based on some mathematic relations to estimate the period of buildings focused on getting maximum lateral displacement, impact force and energy dissipation during impact. For this challenge, three- and five-story dynamic models are presented by a mathematic program, which is able to calculate the mathematical equation of motions and figure their relations out. This program can also estimate the best needed options to select for solving the problems. Investigated MDOF model includes lumped masses, on top of each story, stiffness and damping of stories. Each body (lumped masses) is a representative of each story and they are connected with each other by using new suggested link element. Masses of each building are assumed to be equal and buildings are detached by a gap size, which is devised by link element. In particular, link element is a connection between two same level bodies and shows dynamic model with lumped mass theory. This link is employed for bodies at floor level as stories are considered to be the same with each other. Based on this idealization, results are focused on link element of third floor.

The mathematic models are used to compare the impact force results and energy dissipation of link element among three considered models. As it was noted, the models are assumed to have three and five stories, having lumped masses of 300 ton and horizontal stiffness of 10000 ton/m. Moreover, the effective stiffness of isolation support system is to be equal to 1MN/m. The period of buildings was 0.395 s, 0.541 s, 1.25 s, 1.465 s, 0.541 s and 1.25 s in LBF20, RBF20, LBI20, RBI20, LBF20 and RBI20, respectively. Each dynamic building excited under Kobe and Loma Prieta records.

5.1.1. Effect of Base Support

There are three different displacements of link element, which depend on the time of impact which are summarized as:

y_{BF20}= 0.07995+0.2245 Cos(3.644t)-0.7828 Sin(3.644t)-0.2004 Cos(7.288t)+0.2102 Sin(7.288t),

y_{BI20}= -02082-0.0037 Cos(3.809t)+0.0102 Sin(3.809t)+0.02094 Cos(7.6t)+0.0086 Sin(7.6t),

y_{BFI20}= 0.2847+0.02509 Cos(3.661t)-0.07777 Sin(3.661t)-0.2255 Cos(7.22t)+0.1881 Sin(7.22t),

These equations are considered by Fourier series. Using *CR*=0.5, the results of analysis are compared with each other in three investigated models. BF20, has maximum impact force about 650kN. BIF20 also shows an impact force about 300 kN, which is 350 kN less than that of BF20.

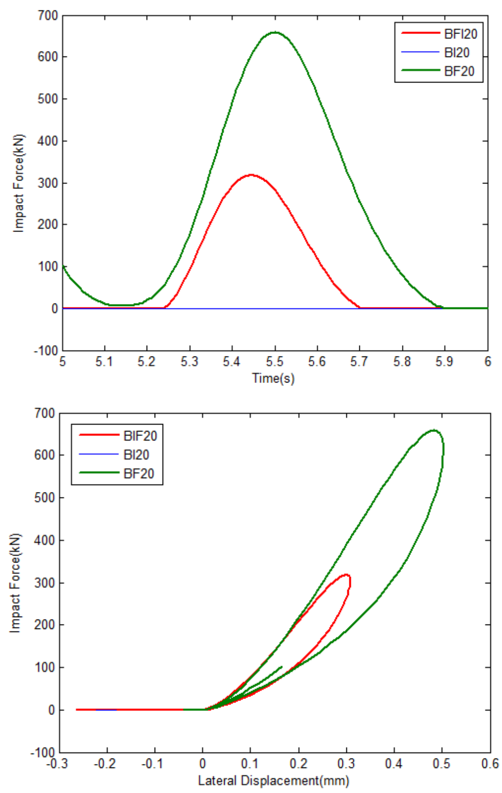
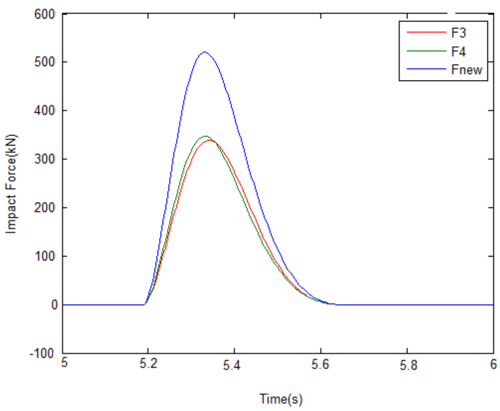


Fig. 7. Numerical results of different base support system

5.1.2. Comparison of Link Elements

In this part of investigation, three main link element formulas based on Hertz damped model by having different values of ζ are evaluated. Fixed supported buildings were assessed. Using *CR*=0.5 andy_{BF20}, link element formulas were analyzed to get the best estimation of the hysteresis loop of impact force. Considering link elements absorb energy, it is assumed that spring and damper behave parallel with each other to decrease the impact force and increase energy dissipation based on hysteresis model of impact, which was suggested by Komodromos [8].



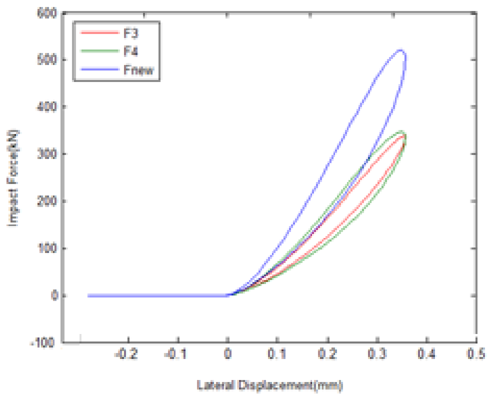


Fig. 8. Numerical results of different link elements

It is an assumption that energy is dissipated by hysteretic model of impact. Therefore, enclosed area of impact force explains energy dissipation of each impact between two bodies. For this challenge, F_{new} describes amount of dissipated energy during impact. Comparison of F_{new} with other areas shows that dissipated energy during impact by new link element model is more than dissipated energy during impact by other suggested link element models. This amount was 28.33261 kN.mm, which is about 11 percent more than that of Hertz damped model. The values of dissipated energy for two hertz damped model are 23.628 kN.mm and 21.9727 kN.mm in F4 and F3, respectively.

5.1.3. Effect of *CR*

Using fixed support model, effect of *CR* in new relation is investigated. As ζ depends on *CR*, and mentioned factor is selected among eleven options, from 0 to 1, it can have different results by solving various *CR*s. The results of analysis show that *CR*=0.1 cannot be true, as during impact, there is no negative impact force and it demonstrates the bodies were detached. So, this *CR* has not explained good results and energy dissipation of this model is not acceptable for this challenge.

Other results represent same maximum impact force. In these results, *CR*=0.3 has the biggest hysteresis loop, which shows the value of energy dissipation during impact between two bodies. Energy dissipation of these results is represented in Table 3.

Table 3. Dissipated energy of different e model

CR	Energy Dissipation (kN.mm)
0.3	55.40463
0.5	28.33261
0.7	17.38738
0.9	9.25486

Investigation of value of *CR*, can confirm suggested new link element model. For this challenge, BF20 under Kobe records was analyzed. As it was noted, *CR* is a factor, which shows relation between velocity of before impact and velocity of after impact. The accuracy of recommended formula depends significantly on *CR* and select the best choose of coefficient of restitution can calculate and obtain the results of analyses.

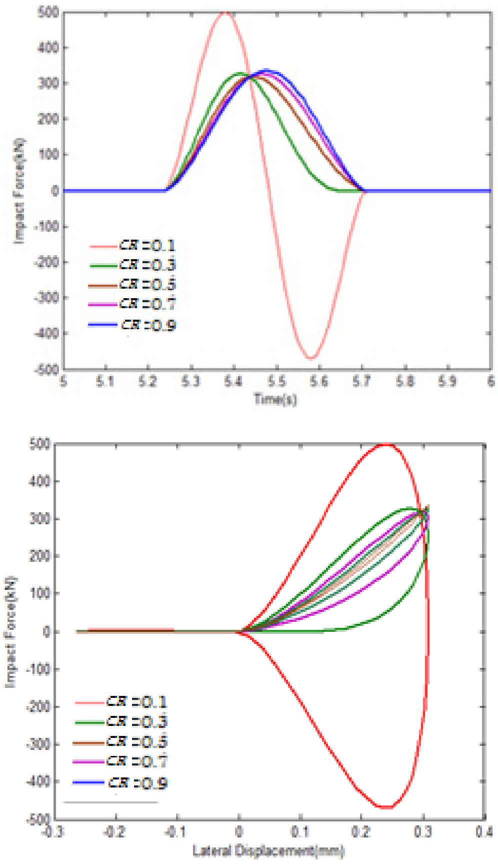


Fig. 9. Different CR values

5.1.4. Effect of Stiffness

In this part, fixed support models are analyzed by different amount of stiffness for link element. Although ζ depends on *K*, *CR* and *v*, but *K* has an incredible effect on the F_c in terms of stiffness. It should be considered that new link element has three springs which are able to absorb energy.

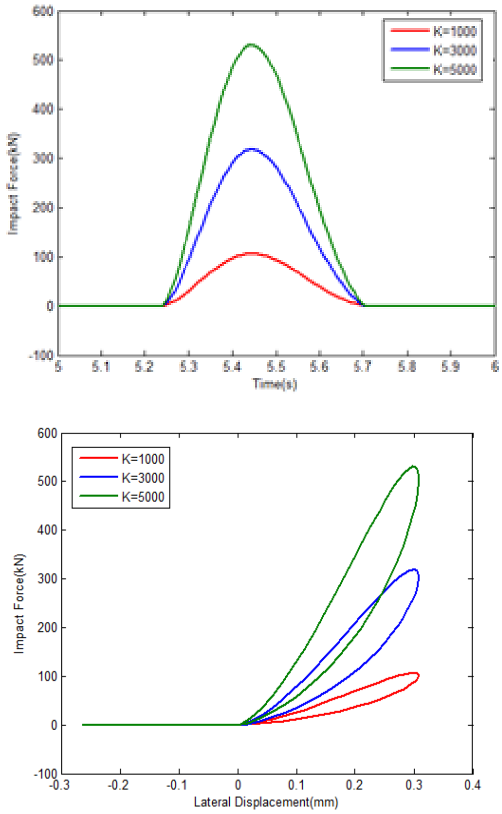


Fig. 10. Results of different stiffness analyze

The increase of the stiffness of springs causes the link element shows rigid behavior and shows small pinching, which describes more energy dissipation.

5.1.5. Effect of height

Two fixed support buildings were analyzed by Kobe record. In this part of study, effect of buildings height and value of impact force between two same stories in buildings are investigated. During earthquake, buildings show different deflection under different modes of analysis.

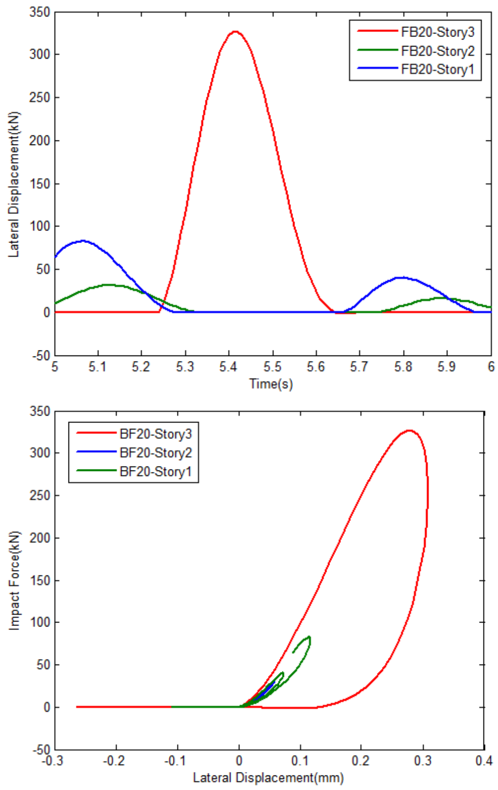


Fig. 11. Different building effect on response

The results of analysis show that impact force in top story is the much more than impact force in other stories. The value of energy dissipation has a considerable discrepancy between top story and other stories. This amount is incredible among investigated stories. Impact force is 350kN in top story of three-story building and 75kN at the second story. This amount is also 50kN at the first story, which is 300kN less than third story.

6. Conclusion

Building pounding between two adjacent buildings subjected to dynamic excitation was investigated. Results of previous analyses have shown that pounding can cause damage to structural elements of buildings. Researchers have investigated pounding by different formula by using different link elements. New impact model with three springs and dashpot has been suggested. Based on mathematic relation, a new damping ratio is suggested to calculate dissipated energy. For this challenge, two three and five-story dynamic models were connected with each other by discussed link element. The results of different kind of link elements have been compared with each other. New suggested formula has shown considerable discrepancy in terms of dissipated energy. It seems to be the best available suggestion among all of mentioned formula. The study has also experienced that most impact force has been inflicted on the top story and most damage has also been shown by fixed support buildings.

REFERENCES

[1] Anagnostopouls, S.A. (1998). "Pounding of building in series during earthquakes". Earthquake Engineering and Structural Dynamic. Vol. 16, No. 3, pp. 443-456.

[2] Bertero, V. (1986). "Observation of structural pounding". Proceedings of the ASCE International Conference on the 1985 Mexico City Earthquake, ASCE, NY, NY, USA, pp. 264-278.

[3] Papadrakakis, M., Mouzakis, H. (1991), "A Lagrange multiplier solution method for pounding of building during earthquake". Journal of Earthquake Engineering and Structural Dynamic, Vol. 20, pp. 981-998.

[4] Filiatrault, A., Wagner, P. (1995). "Analytical prediction of experimental building pounding". Journal of Earthquake Engineering and Structural Dynamic, Vol. 24, pp. 1131-1154.

[5] Kavashima, C.G, Watanaba, K. (2005). "Earthquake Induced Interaction between adjacent reinforced concrete structural with non-equal heights". Earthquake Engineering and Structural Dynamics, Vol. 34, No. 1, pp. 1-20.

[6] Cole., G.L., Dhakal, R.P. (2009). "The effect of diaphragm wave propagation on the analysis of pounding structures". Proceedings of the 2nd International Conference on Computational Method in Structural Dynamic and Earthquake Engineering (COMPADYN), Paper CD 200.Rhodes. Greece.

[7] Barros, R.C., Khatami, S.M. (2012). "Importance of separation distance on building pounding under near-fault ground motion, using the Iranian earthquake code". Proceedings of the 9th International Congress on Civil Engineering, Isfahan University of Technology (IUT), Isfahan, Iran.

[8] Komodromos, P., Polycarpou, P. (2010). "On the numerical simulation of impact for the investigation of earthquake-induced pounding of building". Proceedings of the Tenth International Conference on Computational Structures Technology, Civil-Comp Press, Stirlingshire, Scotland.

[9] Vasconcelos, H. (2011). "Study about collision between reinforced concrete building and comparison of their resistance envelope by push over analysis". MS.c Thesis, FEUP. Portugal.

[10] Raj, P., Wijeyewickrema, C. (2010). "Seismic pounding between reinforced concrete buildings: A study using two recently proposed contact element models". Proceedings of the 14ECEE, Ohrid, Macedonia.

[11] Cordeiro, J.M.C. (2011). "Study of the collision between buildings without and with base isolation". MScThesis in Civil Engineering (Structures), Porto, Portugal.

[12] Vasconcelos, H.E. (2011). "Study of the collision between reinforced concrete buildings and comparison of their pushover capacities". M.Sc. Thesis in Civil Engineering (Structures), Porto, Portugal.

[13] Barros, R.C., Khatami, S.M. (2012). "An estimation of damping ratio for the numerical study of impact forces between two adjacent concrete buildings, subjected to pounding". Proceedings of the 15th International Conference on Experimental Mechanics (15th ICEM), FEUP, Porto, Portugal.

[14] Barros, R.C., Khatami, S.M. (2012). "Building pounding forces for different link element models". Proceedings of the Eleventh International Conference on Computational Structures Technology, CIVIL-COMP Press, Stirlingshire, UK, presented at the Eleventh International Conference on Computational Structures Technology, Dubrovnik, Croatia.

[15] Jankowski, R. (2005). "Non-linear viscoelastic modeling of earthquake-induced structural pounding". Earthquake Engineering and Structural Dynamics, Vol. 34, pp. 595-611.

[16] Muthukumar, S. (2006). "A Hertz contact model with non-linear damping for pounding simulation". Earthquake Engineering and Structural Dynamics, Vol. 35, pp. 811-828.

[17] Ye, K., Zhu, H. (2008). "A note on the Hertz contact model with nonlinear damping for pounding simulation". Earthquake Engineering and Structural Dynamics, Vol. 38, No. 9, pp. 1135-1142.

[18] CSI. Computers and Structures, INC. SAP2000. Verion 8.