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Building Pounding Forces for Different Link Element Models

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Abstract

The occurrence of building pounding is one of the possible and important reasons for damage and even collapse of buildings during earthquakes. This phenomenon occurs when two adjacent buildings have a small gap between them providing insufficient separation distance. In past studies experimental and analytical analyses of building pounding have been investigated by many researchers. In this paper, two adjacent reinforced concrete one-storey concrete buildings were modelled using different link element models, to assess analytically the consequences of building pounding in spite of a pre-existing gap between buildings. The investigated structures were subjected to three different near-fault ground motions, whose records have been normalized to have an equal peak ground acceleration (PGA) and different frequency content. Multi-degree of freedom models are assessed by different numerical formulations. Finally, the results of this investigation are compared with the results of using a standard finite element analysis.

Keywords: pounding, impact forces, separation distance, numerical formulation.

1 Introduction

Near-fault ground motion having different properties such as peak acceleration, duration of strong motion and different ranges of frequency content, cause vibrations out-of-phase for adjacent buildings. Commonly, adjacent buildings have different structural story heights and dynamic characteristics, which can cause severe collision types during earthquakes. Near-fault ground motion provides large displacement of buildings that have been found to impact each other under several seismic excitations.

Separation distance required is recommended in the seismic design codes, since having significant gap between two adjacent buildings can decrease collisions when they vibrate under earthquakes. As many crowded cities have old buildings built closely to each other without sufficient separation distance, it can be predicable that these buildings can have significant risk of pounding. Mexico City earthquake is one of the more populous and important cities around the world, where the 1985 earthquake caused (so far) the most damaging pounding effects between adjacent buildings.

Figure 1. Building pounding between two adjacent buildings (Mexico City 1985)

Many researchers have investigated building pounding by experimental and analytical analysis. Anagnostopoulos [1] was among the first researchers that studied this phenomenon in Greece, in which the effects of impact in buildings were model with distributed mass. Cole and Dahkl [2] investigated building pounding, and showed that the impacts depend on the building properties (even on the velocities of the buildings) when they collide with each other. Building pounding in steel adjacent buildings using shaking table has been experimented by Rezavandi and Moghadam [3].

Aldemir and Aidin [4] investigated impacts during pounding between two buildings with different structural systems (passive system, active system and semi-active system) even indicating an active control algorithm to preclude the pounding of adjacent structures. Later, Aidin and Ozturk [5] exemplified the application of viscous dampers to minimize pounding effects complementing the fact that active control can improved the behaviour of buildings subjected to pounding in comparison with passive control.

Also at FEUP (*Faculdade de Engenharia da Universidade do Porto*) two M.Sc. thesis, on the thematic of pounding of buildings during earthquakes [6] [7], initiated in Portugal the R&D on this important thematic within seismic engineering. Recently, Barros and Khatami [8] addressed the importance of the gap or separation distance between adjacent buildings, are prescribed in the Iranian earthquake code.

So far analytical investigation using finite element method, based on specific mathematical assumptions, has shown a need to study the effects of using different links located at the connection level between buildings. This link can be a spring, a dashpot or both links connected with each other in appropriate and specific models. There are many researches describing different connecting links. Herein the Lessloss and Hertz models are simple types of models that use 3 different links between adjacent buildings. Each simple type has a mathematical formulation which simulates impact of pounding. In this paper, using a numerical study, the results of these formulations are compared with each other.

2 Analytical Model

Two reinforced concrete frames of one story were modeled. Each of these structures has span of 4 meters and 6 meters in x-direction. Height of story is considered to be 3 meters. Buildings are called 4M and 6M, respectively. The gap between two adjacent buildings is 1 mm, prior to the studies leading to the collisions. Each frame has two 25*25 cm columns connected with 20*25 cm beam. Three different near-fault ground motions were used: Loma Prieta 1989, Kobe 1995 and Chi-Chi 1999. These original records have different content of the excitation frequencies, different random magnitude of the accelerations in time, and different earthquake durations; besides, their place of occurrence and geological conditions are distinct. But, for the analyses herein, they were normalized as significant records, with equal PGA and different frequency content.

Analytical modeling of the buildings is performed by using SAP 2000 [9]. The objective of the analysis is to compare the numerical results of the building pounding occurring during the seismic response of the considered reinforced concrete buildings under the three near-fault earthquakes.

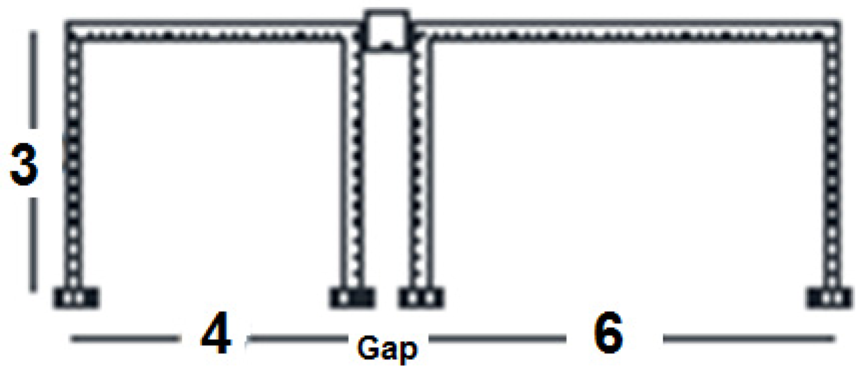
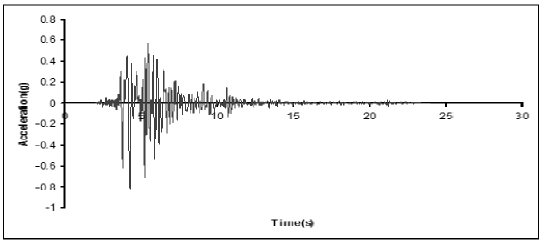


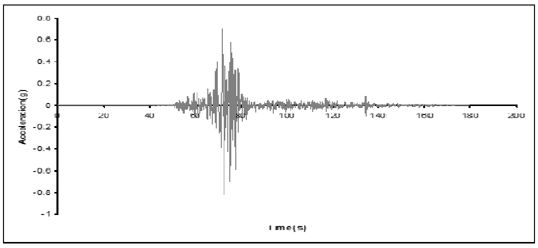
Figure 2. Investigated model

The three earthquake records, after normalization, used in this paper are shown in Figure 3. Kobe's earthquake record has been referenced among the three earthquake records, and was used for normalizing all of records to have an equal PGA. This record has the highest acceleration among the three original records discussed. The Kobe's earthquake had a PGA of 0.821g, with an epicentre distance less than 40 km. This earthquake had occurred in 16th January 1995, and caused an earthquake with a 7.20 magnitude.

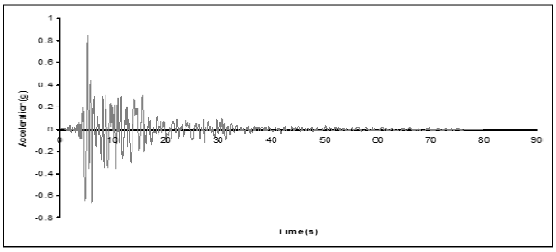
Loma Prieta's earthquake, of 17th October 1989 and with a magnitude of 6.93, had a PGA of 0.4975g that was the lowest PGA among the three mentioned records; this earthquake signal was a near-fault record with an epicentre distance less than 40 km. Finally Chi-Chi's earthquake occurred in 20 September 1999, with a magnitude of 7.60 that was stronger than Kobe's earthquake; in this record PGA was 0.821g, which occurred at an epicentre distance of 88 km. All these earthquakes, once normalized to Kobe PGA, were selected to investigate building pounding.



(a) Kobe Record



(b) Loma Prieta Record



(c) Chi-Chi Record

Figure 3: Three normalized Near-Fault Earthquake Records, used in analysing the building model

3 Formulation of the Pounding

Pounding contact between adjacent buildings can be modeled with link elements, which can be achieved with spring element or with spring and dashpot elements. In Figure 4 is represented two single degree-of-freedom buildings, connected by a spring link.

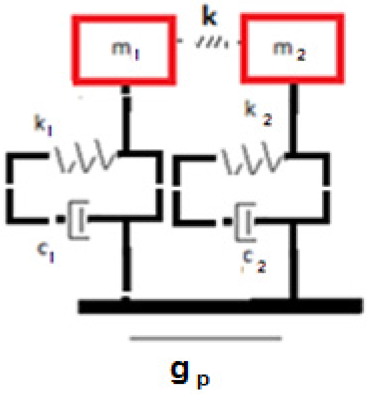


Figure 4. Schematic model of adjacent buildings with spring-link

In this figurative model, there are two systems separated with different masses, stiffnesses and damping. The M_1 and M_2 are lumped masses of each of the systems used as sample structures; C_1 and C_2 represent building damping coefficients; K_1 and K_2 denotes stiffness in models 1 and 2, respectively. Finally, U_1 and U_2 are the relative displacements of each of the individual structures. The equations of motion of this model, taking into account a spring-link with stiffness k, are given by:

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\begin{bmatrix} \ddot{U}_1 \\ \ddot{U}_2 \end{bmatrix}+\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix}+\begin{bmatrix} K_1+k & -k \\ -k & K_2+k \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}=-\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\ddot{U}_g \quad (1)$$

If on the other hand, the link element located between adjacent buildings would be modelled by spring and dashpot damper, the model of the adjacent buildings under pounding would be represented as depicted in Figure 5.

For this link model, the equations of motion would be given by:

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\begin{bmatrix} \ddot{U}_1 \\ \ddot{U}_2 \end{bmatrix}+\begin{bmatrix} C_1+c & -c \\ -c & C_2+c \end{bmatrix}\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix}+\begin{bmatrix} K_1+k & -k \\ -k & K_2+k \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}=-\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\ddot{U}_g \quad (2)$$

The first model, solely with a spring-link, is the so-called Lessloss model [10]. The spring element of high stiffness, can evaluate impact force by:

$$F_c = k(U_1 - U_2 - g_P) \quad (3)$$

In equation (3) g_P is the gap distance pre-existing or pre-imposed between the two adjacent buildings, and k denotes stiffness of the linear spring-link used. The schematic spring-link with gap used in Lessloss-project and here referred as Lessloss model is shown in Figure 6.

The Kelvin-Voigt link model with gap uses a dashpot damper, which is devised for energy dissipation. The schematic model is shown in Figure 7.

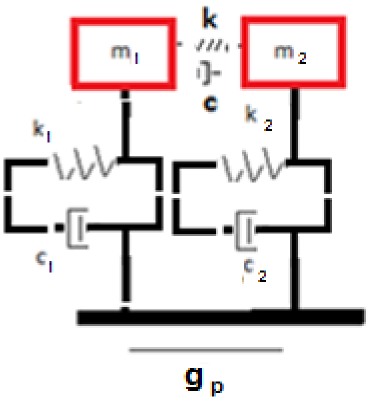


Figure 5. Schematic model of adjacent buildings with link having spring and dashpot damper

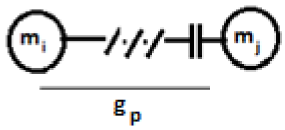


Figure 6. Schematic Lessloss model

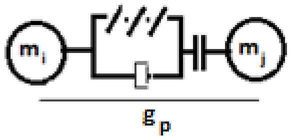


Figure 7. Schematic model of Kelvin-Voigt with gap

The impact force equation of this model can be written by:

$$F_c = k(U_1 - U_2 - g_P)^{1.5} + c\,(\dot{U}_1 - \dot{U}_2) \tag{4}$$

In this relation the damping coefficient c, that depends significantly on the masses and stiffness, is given by:

$$C = \xi\,(U_1 - U_2)^{1.5} \quad \text{and} \quad \xi = \frac{8(1-e)k}{5\,e\,v} \tag{5}$$

where: e denotes a restitution parameter between zero to 1, which is recommended to be 0.65; and v is the relative approaching velocity before impact. Minimum separation distance S recommended in design codes, between two adjacent buildings, can be given alternatively by two mathematical formulations:

$$S = U_1 + U_2 \quad \text{and} \quad S = \sqrt{U_1^2 + U_2^2}) \tag{6}$$

The first expression contains an ABS absolute value criteria (sum of the absolute values of the displacements of the participating structures) and the second expression is termed as SRSS criteria (square root of the sums of the squares).

4 Calibration of software

In order to compare the results of the mathematical models of this analytical investigation using SAP 2000 as the modelling software, for the two adjacent buildings in Figure 2, a calibration example was chosen to validate SAP 2000 potential usage for the models investigated. For that purpose, two adjacent reinforced concrete buildings 8-story and 10-story that have been modelled by Wijeyewickrema and Raj [11] were used. These structures had member dimensions and properties such that the fundamental natural periods were 1.59 s and 1.63 s, for the 8-story and 10-story buildings respectively.

The buildings-system responses with multiple impacts have been analysed by Open Sees software, as mentioned in [11], for Kobe's specific earthquake input. The link element used between the two buildings was a contact element with parallel spring and dashpot. The maximum impact force detected in the model was 245 kN. For calibration of software purposes, in order to ascertain precision and adequacy of the modelling, the two buildings were also modelled by SAP 2000 [9] using the same properties boundary conditions and excitation parameters used in earlier studies [11]. The results of this calibration comparison are shown in Figure 8, for the multiple impacts. It is obvious that SAP 2000 maximum impact force detected is 241.5 kN, which is 1.2% less than Open Sees software has predicted; nevertheless also constituting a very good estimation under civil engineering purposes and practice.

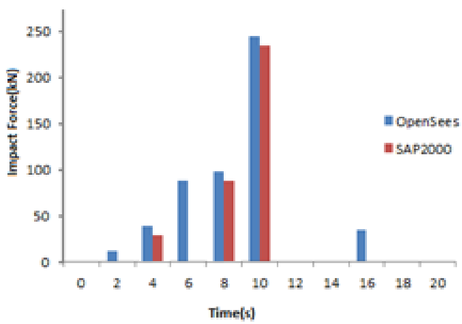


Figure 8. Results for calibration of the software used

5 Results of analyses of the building pounding models

After successful calibration of the modelling software, the adjacent buildings to be modelled with the Lessloss and Kelvin-Voigt link models are analysed (using three normalized earthquakes) for comparison of the results and for assessing practical importance of such aspect in characterizing building pounding. The structural parameters used were: M_1=3.24 kg, M_2=2.16 kg, k=1500 N/m, c=37.64 kN s/m and ξ=5%.

In Figure 9, lateral displacements under the three normalized seismic excitations used are compared with each other, for each of the buildings here coded as 4M and 6M. Kobe normalized record caused the highest lateral displacement, which was 22 mm for building 6M. This lateral displacement was 8.83 mm for Loma Prieta record and 2.24 mm for Chi-Chi record, in building 6M. The maximum lateral displacement in Loma Prieta was 13.2 mm less than Kobe and 5.59 mm more than Chi-Chi displacements. These maximum lateral displacements have occurred at the instant of 4.015 s in Kobe at 6.02 s in Loma Prieta and at 9.1 s in Chi-Chi earthquakes.

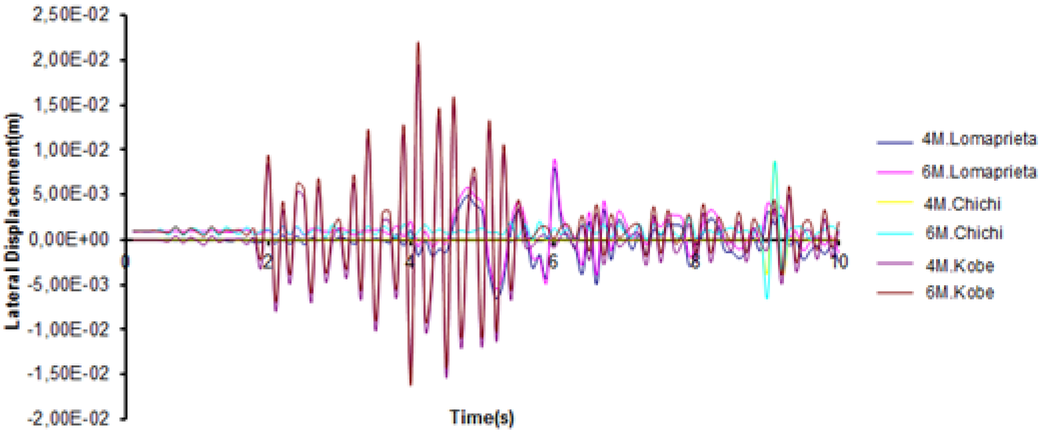


Figure 9. Lateral displacement of models under different records

The results for Loma Prieta record presented in Figure 9, are now zoomed in Figure 10 at the interval of maximum lateral displacements around the instant of 6 seconds. As the maximum lateral displacement was 8.83 mm, and the two building had a collision at the instant of 5.94 second, this curve has been selected to investigate the mathematic relation of lateral displacements.

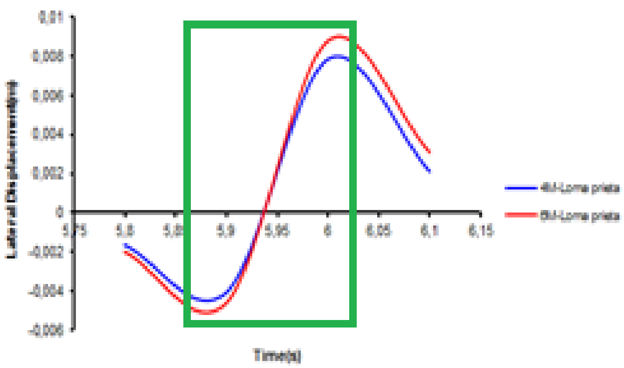


Figure 10 Maximum lateral displacements in Loma Prieta's earthquake

The approximate lateral displacements relations of 6M and 4M building models (Figure 10), obtained using MATLAB [12] in the time interval (5.8, 6.1) seconds, are given by:

Y=0.001274-0.007345 cos(19.32t) + 0.0003433 sin(19.32t) (6M)

Y=0.001506+0.008358 sin(19.03t) (4M)

where Y is lateral displacement and t denotes time. The maximum impact force of collision was 1.181 kN, which occurred at the instant of about 5.94 s.

For the Kobe's record, the approximate lateral displacements relations of 6M and 4M building models (Figure 11), obtained using MATLAB [12] in the time interval (3.9, 4.2) seconds, are given by:

Y=0.0019-0.0017 cos(25.14t) + 0.006403 sin(25.14t) (6M)

Y=0.001695-1.18 cos(31.43t) + 26.59 sin(31.43t) (4M)

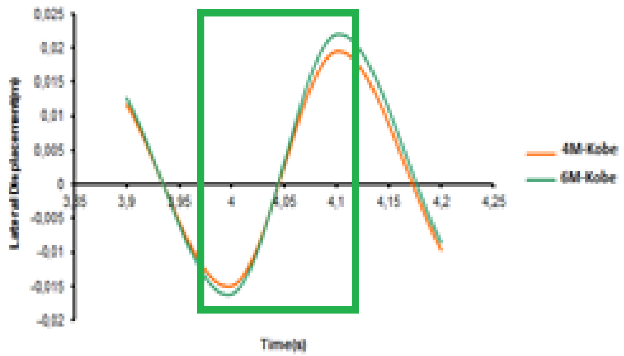


Figure 11. Maximum lateral displacements in Kobe's earthquake

As it was shown in Figures 9 and 11, the maximum lateral displacement is 2.22 mm, which has occurred at the instant of about 4.04 s. In this model, the impact force of collision was 2.46 kN.

For the Chi-Chi's record, the approximate lateral displacements relations of 6M and 4M building models (Figure 12), obtained using MATLAB [12] in the time interval (9.0, 9.2) seconds, are given by:

Y=0.0025-0.0081 cos(12.22t) + 0.007833 sin(12.22t) (6M)

Y=0.0024-0.0079 cos(12.12t) + 0.006233 sin(12.12t) (4M)

Maximum lateral displacement was 8.72 mm and the maximum impact force for this earthquake was 1.97 kN, occurring at the instant of about 9.1 s.

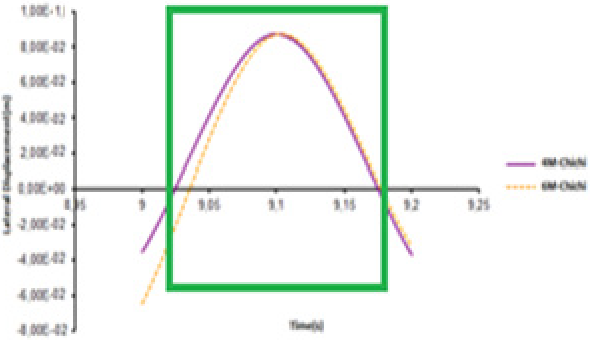


Figure 12. Maximum lateral displacements in Chi-Chi's earthquake

Maximum impact force (and their instants) of the three records used are shown in Figure 13, showing that Kobe's normalized record caused the strongest impact force among three records investigated. Chi-Chi's record caused a maximum impact force of about 1.97 kN, which is 0.49 kN less (about 20%) than impact force of Kobe's record. The minimum impact force, among the three normalized records considered, is about 1.181 kN (for Loma Prieta's earthquake) at the instant of 6 s.

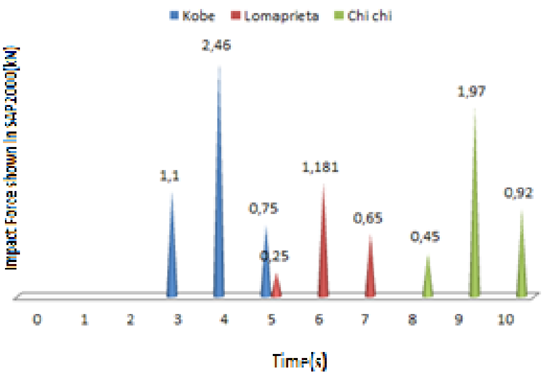


Figure 13. Impact forces for the three analysed records

It was predictable that maximum impact occurs in the time interval of maximum lateral displacements, during which the buildings have to provide their maximum strength corresponding to the adjacent buildings colliding with each other.

The following Table 1, shows different results for maximum displacements (mm) and maximum velocities in buildings 4M and 6M, for the three normalized earthquakes. In this Table 1 U_c is the common displacement (mm) of buildings at collision; U_{eff} denotes the effective displacement (mm) when two buildings collide with each other, defined as the maximum lateral distance between the maximum lateral displacement and the displacement at collision. This latter distance provides one of the best available estimates of the impact characteristics between buildings.

Record	$U_{6M,max}$	$U_{4M,max}$	$\dot{U}_{6M}$	$\dot{U}_{4M}$	U_c	U_{eff}
Kobe	2.22	1.948	0.51884	0.472	2.3	7.5
Loma Prieta	0.883	0.784	0.219	0.1544	1	5.18
Chi-Chi	0.872	0.874	0.0012	0.0248	9	17

Table 1. Displacements and Velocities comparisons for the three records

Table 2 shows the results of the maximum impact forces (kN) calculated by the expressions of each of the link-models for the earthquake studied, and the one's obtained using software SAP 2000. These results are also shown in the Figure 15, which also contains for each earthquake case the corresponding average value of the evaluations F_{ave} and the quantity $\Delta F/F_{ave}$ as a measure of the precision and dispersion of the results.

Record	$F_{SAP2000}$	$F_{LessLoss}$	$F_{Kelvin-Voigt}$	F_{ave}	$\Delta F/F_{ave}$
Kobe	2.46	2.7	4.43	3.196	0.475
Loma Prieta	1.181	1.5	3.93	2.2036	0.964
Chi-Chi	1.97	2.91	3.41	2.763	0.374

Table 2. Maximum impact forces for the three records

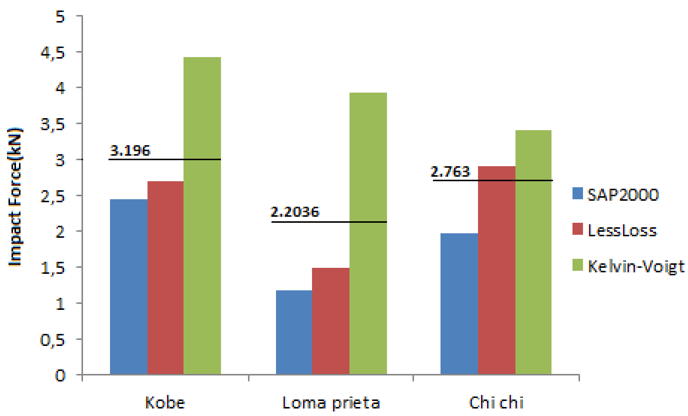


Figure 14. Comparison of impact forces among three mentioned records

The maximum impact force of the buildings under Kobe's record was 2.46 kN, when simulated by SAP 2000. This force was 2.7 kN with the Less-Loss formulation, which is 10% higher than SAP 2000. Finally, Kelvin-Voigt model presents an impact force of about 4.43 kN (80% increase). This value is by far the highest impact force among all of the earthquakes considered.

There is a considerable discrepancy in Loma Prieta's record. In this record impact force was 1.181 kN when evaluated by SAP 2000, with a slight increase to 1.5 kN (27% increase) when using the Less-Loss formulation, and a sharp increase to 3.93 kN (150% increase) when using the Kelvin-Voigt formulation.

Chi-Chi's record impact force results show a general decrease in comparison with Kobe's record. The impact force evaluated by SAP 2000 was about 2 kN, increasing (about 45%) to 2.91 kN when evaluated by Less-Loss formulation, and finally increasing (about 70%) to 3.41 kN when using the Kelvin-Voigt formulation (17% increase over the Less-Loss impact force estimation).

Impact forces of this building system calibration model have been calculated by MATLAB [12] for the three normalized records mentioned, and using the approximate expressions of each building displacement in the vicinity of maximum lateral displacements. In Figure 16 estimations of maximum impact forces are shown near the peak of each curve, corresponding to the validated representative sub-interval of the approximations used.

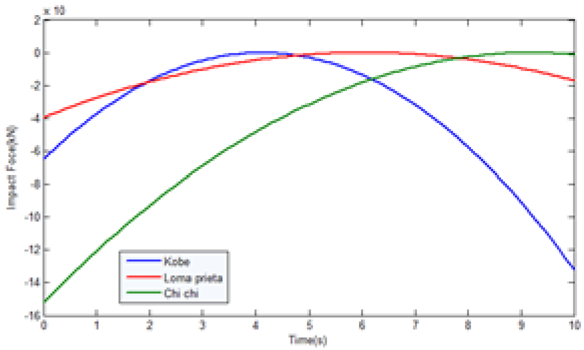


Figure 15. Approximate maximum impact forces calculated by MATLAB

For instance, in Kobe's record the peak impact force is about 2.2 kN, which is shown at the instant of 4 seconds. For the Loma Prieta impact force line, only representative in the sub-interval of (5.8, 6.1) seconds, at the initial instant it starts at the ordinate of -40 kN. The impact force for this record was found to be 1.5 kN at the instant of 6 seconds. Accordingly for the Chi-Chi impact force line, only representative in the sub-interval of (9.0, 9.2) seconds, at the initial instant it starts at the ordinate of -155 kN to reach a maximum of about 2 kN in this record around the instant of 9 seconds. Last observation is about separation distance calculated by SRSS rule inherent to equation (6). As the gap between the two buildings was 1 mm, the displacements values (mm) in Table 3 indicate that the considered gap does not provide enough separation distance required to avoid the building multiple poundings.

Record	$\mathbf{U_{6M,max}}$	$\mathbf{U_{4M,max}}$	$\sqrt{\mathbf{U^2_{6M,max} + U^2_{4M,max}}}$	**Gap**
Kobe	2.22	1.948	2.95	1
Loma Prieta	0.883	0.784	1.18	1
Chi-Chi	0.872	0.874	1.23	1

Table 3. Comparisons of maximum lateral displacements with design code criteria

6 Conclusions

This paper analysed building pounding using analytical and computational methods. Two RC frames have been analysed using SAP 2000. Three near-fault earthquake records were normalized to have the same PGA, and were used as reference ground acceleration records of different frequency content. Time history displacements and impact forces studied have shown that high lateral displacements can cause a strong impact force between two adjacent buildings.

From a few ways to assess building pounding by mathematical formulations, and consequent impact forces in the contact element used between buildings, the so-called Kelvin-Voigt and the Less-Loss link models were the first link-elements used for a comparison of pounding scenarios. Therefore, the methodologies comprehensively addressed here.

Impact forces in the contact elements mentioned have been compared with results obtained using SAP 2000 for the three normalized earthquake records. While SAP 2000 and Less-Loss results are similar, the Kelvin-Voigt model (with gap, spring and dashpot elements) showed a considerable discrepancy in the impact force calculation for the three records considered.

Investigation of separation distance showed that the considered pre-existing gap could not cover required separation distance between buildings, in such a way that the caused collisions might endanger the safety of the two studied buildings.

Acknowledgements

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