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A PARAMETRIC STUDY FOR THE INVESTIGATION OF THE EFFECTIVENESS OF RUBBER SHOCK-ABSORBERS AS A MITIGATION MEASURE FOR EARTHQUAKE-INDUCED STRUCTURAL POUNDINGS

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Abstract. *Very often, especially in densely-resided areas and city centers, neighboring buildings are constructed very close to each other, without sufficient clearance between them. Thus, during strong earthquakes, structural poundings may occur between adjacent buildings due to deformations of their stories. The current study presents a simple but efficient methodology that can be used to numerically simulate the incorporation of rubber layers between neighboring buildings with relatively narrow seismic gaps in order to act as collision bumpers and mitigate the detrimental effects of earthquake-induced poundings. The efficiency of this potential impact mitigation measure is parametrically investigated considering the case of two neighboring multistory structures subjected to various earthquake excitations. The results indicate that under certain circumstances the incorporation of rubber bumpers in an excising seismic gap can reduce the amplifications of the peak responses of the structures due to pounding.*

1 INTRODUCTION

Very often, especially in densely-resided areas and city centers, neighboring buildings are constructed very close to each other without sufficient clearance between them. Therefore, during strong earthquakes, structural poundings may occur between adjacent buildings, due to deformations of their stories. Consequences of such pounding incidences, ranging from local light damage to severe structural damage or even collapse, have been observed and reported in past strong earthquakes [1-4]. In case of structural pounding, both floor accelerations and interstory deflections may be significantly amplified, threatening the functionality and the contents of the building [5-7]. The photograph in Figure 1 shows a pounding incidence between two neighboring buildings, as reported from an EERI/PEER reconnaissance team after the L'Aquila Earthquake, which hit Central Italy on April 2009 [8]. During that seismic event, the roof of a 2-story building hit an adjacent 4-story structure causing significant damage to the columns of the latter at that level. Nevertheless, the third and the fourth stories of the building experienced essentially no damage. The confinement of the damage of the 4-story building at the level of impact indicates the destructive effect of structural pounding.

Figure 1: Damage of a four-story conventional building due to pounding with its adjacent two-story building, during the L'Aquila earthquake in Italy, in April 2009

At the pounding floors, short-period impulses of high amplitude are observed in the acceleration response, while their amplitude is affected by the impact stiffness. The presence of high spikes in the acceleration response due to poundings is a very critical issue, especially for buildings that may house sensitive equipment. Therefore, it is very important to consider impact mitigation measures that could be employed in practice.

Certain mitigation measures have already been proposed, by various researchers who investigated this problem in buildings and bridge decks, in an effort to alleviate the detrimental effects of structural poundings [9]. One of the proposed measures is the incorporation of layers of soft material, such as rubber, on certain locations, where impact is likely to happen. Such elastomeric material could act as a shock-absorber. The effectiveness of such an impact mitigation measure is assessed in this paper, through numerical simulations and parametric studies.

2 IMPACT MODELING

Usually, in numerically simulated dynamic systems, such as multistory buildings under earthquake excitations, structural impact is considered using force-based methods, also known as “penalty” methods. These methods allow relatively small interpenetration between the colliding structures, which can be justified by the local deformability at the point of impact. The interpenetration depth is used along with an impact-stiffness coefficient, representing an impact spring, to calculate the impact forces that act on the colliding structures, pushing them apart. Based on the mathematic relation between the impact force and the interpenetration depth, the impact models can be classified as linear and non-linear models. Furthermore, some models assume that an impact dashpot acts in parallel to the contact spring in order to take into account the energy that is dissipated during an impact [10].

2.1 Concrete-to-concrete impacts

In the current study, impacts between concrete surfaces are simulated assuming a linear impact spring and an impact dashpot exerting, in parallel, impact forces to the colliding structures whenever their separation distances are exceeded. In particular, when a contact is detected, the impact force is estimated at each time-step using the following formulas [7]:

$$F_{imp}\left(t+\Delta t\right)=\begin{cases} k_{imp}\cdot\delta\left(t\right)+c_{imp}\cdot\dot{\delta}\left(t\right) & \text{when} \quad F_{imp}\left(t\right)>0 \\ 0 & \text{when} \quad F_{imp}\left(t\right)\leq 0 \end{cases} \tag{1}$$

where $\delta\left(t\right)$, is the interpenetration depth, $\dot{\delta}\left(t\right)$ is the relative velocity between the colliding bodies, k_{imp} is the impact spring’s stiffness and c_{imp} is the impact damping coefficient. The later is computed according to the following formulas, provided by Anagnostopoulos [6]:

$$c_{imp}=2\cdot\xi_{imp}\sqrt{k_{imp}\cdot\frac{m_1\cdot m_2}{m_1+m_2}} \tag{2}$$

$$\xi_{imp}=-\frac{ln\left(COR\right)}{\sqrt{\pi^2+\left(ln\left(COR\right)\right)^2}} \tag{3}$$

In the previous formulas, m_1, m_2 are the masses of the two bodies and *COR* is the coefficient of restitution, which is defined as the ratio of relative velocities after and before impact ($0<COR\leq 1$). In particular, the above impact model is a small variation of the classical linear viscoelastic impact model that had been initially proposed by Anagnostopoulos [1], in which the tensile forces that arise at the end of the restitution period are omitted and a small plastic deformation is introduced, which increases the available clearance between the buildings.

2.2 Simulation of rubber bumpers

A significant part of this numerical problem has to do with the simulation of the behavior of rubber bumpers under impact loading. Anagnostopoulos [6] simulated the usage of a soft material that acted as a shock absorber by simply considering a decreased impact stiffness value for the linear viscoelastic impact model that was used for the simulation of poundings of buildings in series. That research work demonstrated that the use of bumpers may reduce, in some cases, the response due to poundings, although the maximum response values remain higher than the corresponding case without poundings.

Jankowski et al [11] numerically simulated the use of several devises to mitigate structural pounding among bridge segments during earthquakes. That research work examined the case of using dampers and stiffeners, as connectors of the segments in series, or rubber bumpers to absorb impact energy between girders. The rubber bumpers in that case were simulated using a linear spring-dashpot element and the results showed that the incorporation of such devices may substantially reduce the overall response due to poundings.

However, the usage of linear impact models for simulating the response of rubber during impact loading does not seem to be the most suitable, considering the stress-strain curves obtained from experiments [12-15]. In particular, static and dynamic compressive tests of rubber reveal an exponential relationship between compressive load and displacement. Therefore, it would be more appropriate to simulate the incorporation of rubber-bumpers by using a non-linear impact model. Furthermore, since a rubber shock-absorber has a finite thickness, there is a possibility to reach its ultimate compressive strain during severe impacts, whereas the impact stiffness should represent the material behind the rubber (e.g. concrete) and not the rubber bumper, since the ultimate strain of the rubber is exceeded.

In a relevant research work [16, 17], regarding the usage of rubber bumpers as an impact mitigation measure for earthquake-induced poundings of seismically isolated buildings, a non-linear impact model with hysteretic damping has been proposed and verified. That simple and efficient impact model is also used in the simulations performed in the present research work. The impact force during the approaching phase is provided by the formula:

$$F_{imp}^{A} = \left\{ \begin{array}{ll} k_{imp} \cdot \delta^{n} & for \quad \delta < \delta_{u} \\ k_{imp} \cdot \delta_{u}^{n} + k_{imp\_PY} \cdot \left(\delta - \delta_{u}\right) & for \quad \delta > \delta_{u} \end{array} \right\} \text{ when } \dot{\delta} > 0 \tag{4}$$

While during the restitution phase the impact force is computed by the expression:

$$F_{imp}^{R} = k_{imp} \cdot \delta^{n} \cdot \left(1 + C_{imp} \cdot \dot{\delta}\right) \qquad for \quad \dot{\delta} < 0 \tag{5}$$

In Eq. (4), k_{imp} is the impact stiffness, δ is the indentation and n is the impact exponent ($n>1$). The impact stiffness is given by the following expression:

$$k_{imp} = \alpha \cdot k_{st} = \alpha \cdot \frac{A \cdot K_{r}}{d^{n}} \tag{6}$$

where k_{st} is the bumper's static stiffness and $\alpha > 1$ is a multiplier that ranges usually between the values of 2 to 2.5 as it was found from relevant experiments [15]. A is the contact area of the bumper, d is the bumper's thickness and K_r expresses the material stiffness. The unknown parameters that have to be determined in Eq. (6) is the material stiffness K_r and the exponent n. The values of both parameters depend on the material characteristics and, therefore, their evaluation can be done experimentally. In the current study, those values have been estimated [16-17], based on relevant experiments from the literature [15].

Eq. (4) takes into account the case of exceeding the ultimate compressive strain of the material, during the approach phase, as it is assumed that after a certain indentation, δ_u, which corresponds to the ultimate compressive capacity of the rubber bumper, the exponential trend becomes a linear trend with a linear post-yield stiffness, k_{imp_PY}.

The damping term C_{imp} in Eq. (5) is given by the formula:

$$C_{imp} = 1.55 \cdot \frac{1 - COR^{2}}{COR^{0.7076} \cdot \left(\dfrac{m_1 \cdot m_2}{m_1 + m_2}\right)^{0.0025} \cdot v_{imp}^{0.9755}} \tag{7}$$

where v_{imp} is the impact velocity, which is the relative velocity of the two bodies just before impact.

The force-time and force-displacement diagrams of the proposed non-linear model for simulating the response of rubber bumpers under impact loading are shown in Figure 2. Figure 3 demonstrates the same diagrams in the case of exceeding the ultimate compressive capacity of the bumper for three different values of the coefficient of restitution.

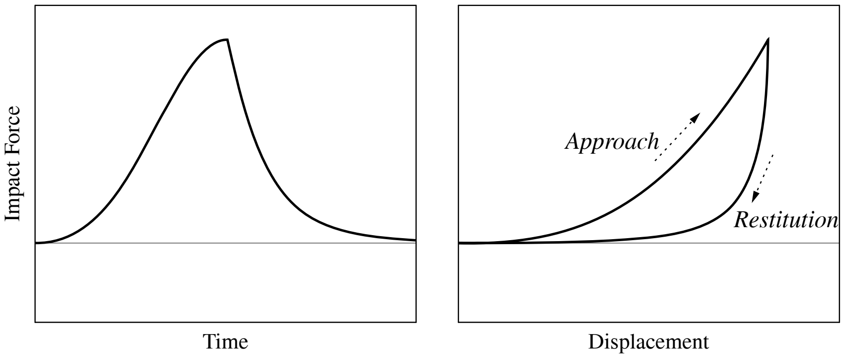

Figure 2. Force-displacement diagram of the non-linear impact model with hysteretic damping.

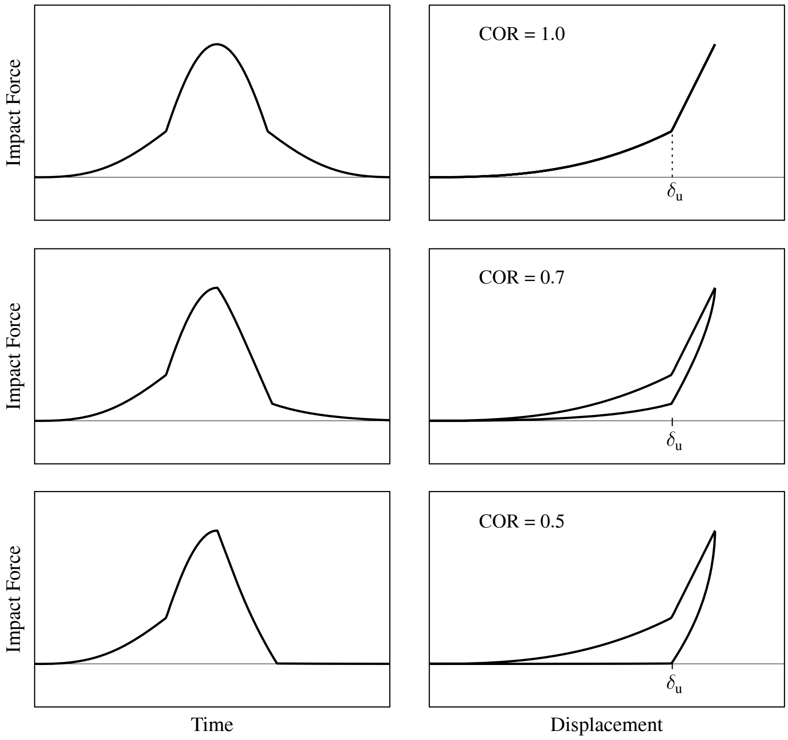

Figure 3: Impact force in terms of time and displacement in the case of exceeding the ultimate compressive strain capacity of the rubber bumper

3 NUMERICAL EXAMPLE CONSIDERING TWO RIGID BODIES

In order to examine the effect of using a rubber shock-absorber on the computed responses after impact, a simple numerical example of two free rigid bodies of equal masses that collide with a constant relative velocity has been performed. Two different circumstances were considered regarding the area of contact. In the first case, concrete-to-concrete impact was considered and the modified linear viscoelastic impact model was used (Eq. 1). In the second case a rubber bumper 5 cm thick was assumed to be incorporated at the area of contact, which is simulated using the non-linear impact model with hysteretic damping (Eq. 4 and 5). The impact parameters, used in both cases, are provided in Table 1. The masses of the two colliding rigid structures are assumed to be 320 tons each, while two different values of impact velocity were used, specifically 0.5 and 1.0 m/sec.

Property	**No Bumper**	**With Bumper**
Impact model	Linear	Non-linear
Exponent (n)	1.0	2.65
Impact stiffness (k_{imp})	2500 kN/mm	0.36 kN/mm$^{2.65}$
Coefficient of Restitution (COR)	0.6	0.5
Bumper thickness (d)	-	5 cm
Bumper's max strain (δ_u/d)	-	0.8
Post-yield impact stiffness (k_{imp_PY})	-	2500 kN/mm

Table 1: Impact parameters for the cases without and with rubber bumper.

Figure 4 demonstrates the load-displacement diagrams for the two cases of the impact velocity and for both cases of with and without the use of the rubber bumper. The results show that the indentation, which represents the local deformation at the vicinity of impact, is much larger in the case of having the rubber shock-absorber due to the reduced impact stiffness. Furthermore, in the case of the relatively high impact velocity of 1.0 m/sec, the deformation exceeds the maximum compressive capacity of the 5 cm thick rubber bumper and the impact force begins to rise rapidly, since the post-yield linear impact stiffness is used.

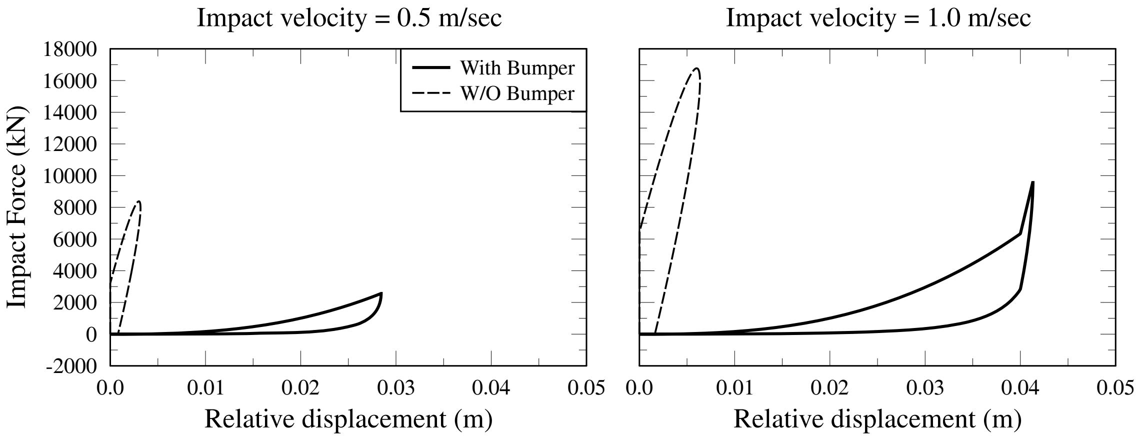

Figure 4: Impact force – displacement diagram for the cases of two impacting rigid bodies, with and without the incorporation of a rubber bumper and for two different values of the impact velocity.

The plots in Figure 5 show the impact force, relative velocity and acceleration time histories for the same cases. It is evident that the use of the rubber bumper elongates the duration of impact and reduces both the maximum impact force and the maximum acceleration. The ratio between the relative velocity after and before impact is equal to the coefficient of restitution used in the corresponding impact model, which verifies the correctness of the two impact models used in the simulations.

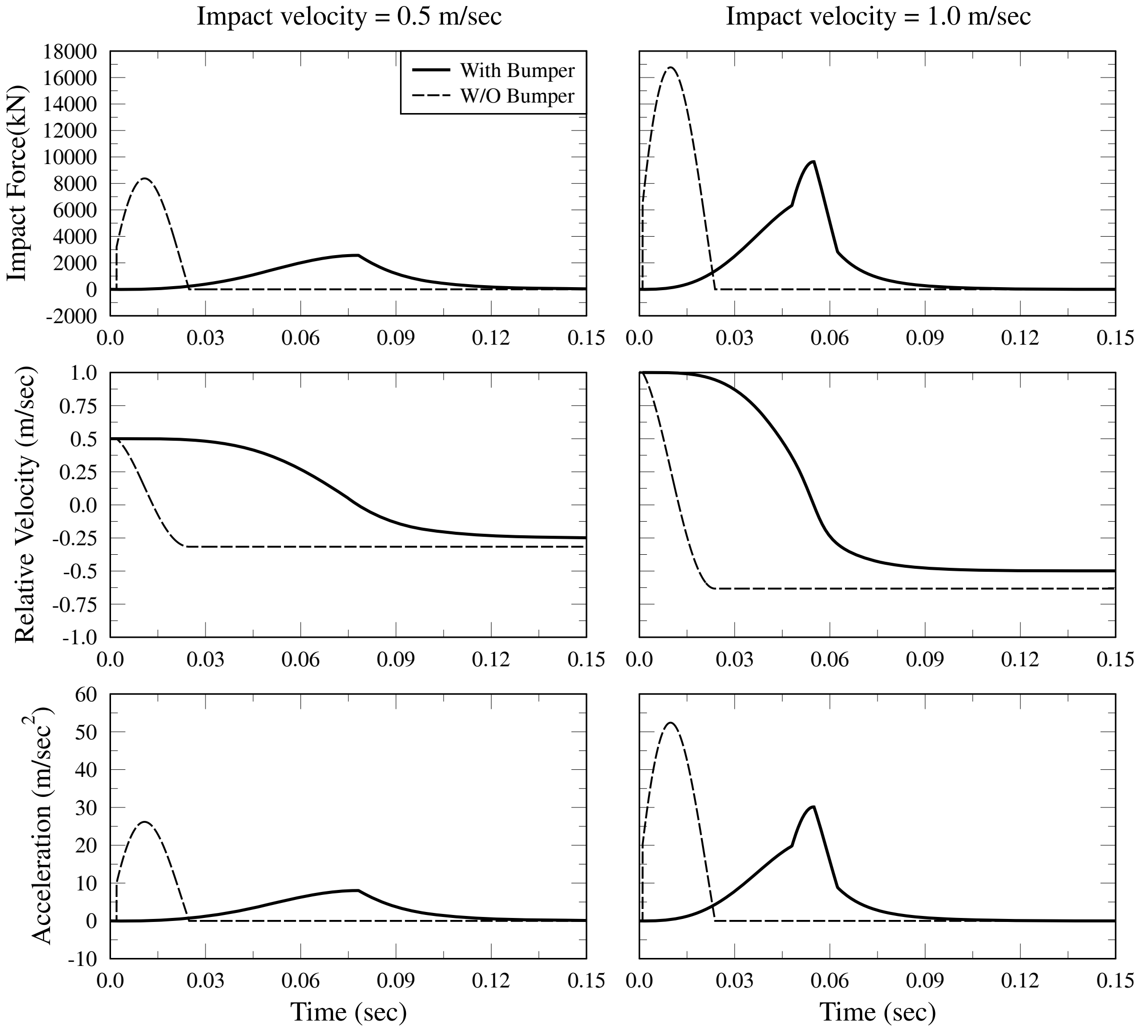

Figure 5: Impact force, relative velocity and acceleration time histories for the case of two impacting rigid bodies, with and without the incorporation of a rubber bumper and for two different cases of the impact velocity.

4 APPLICATION EXAMPLE AND PARAMETRIC ANALYSES

Next, a practical example is presented in order to assess the effectiveness of using rubber shock absorbers as an impact mitigation measure for cases of narrow seismic gap sizes between adjacent multistory buildings. For the numerical simulations, a specialized software application has been specifically developed using modern object-oriented programming in order to efficiently perform dynamic analyses of multistory buildings in two dimensions, modeling the consideration of potential structural pounding. The simulated buildings are modeled as multi-degree of freedom (MDOF) systems, with shear-beam behavior and the masses lumped at the floor levels, assuming linear elastic behavior during earthquake excitations.

A 4-story and a 6-story fixed-supported buildings were considered in series for the performed simulations, as shown in Figure 6. Each floor has a lamped mass of 320 tons, except of the top floor where a mass of 250 tons is considered. Each story has a horizontal stiffness of 600 MN, while a constant viscous damping ratio of 5% has been considered for both buildings. The floors of the neighboring buildings are assumed to be at the same levels.

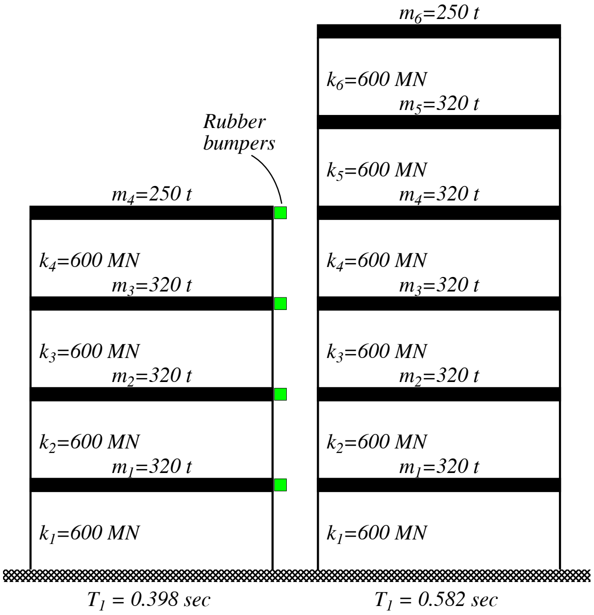

Figure 6: The two multistory buildings considered in the simulations and their structural properties.

For the particular structural system, the performed analysis examined whether the incorporation of rubber bumpers at the locations of potential impacts, which reduces the available seismic gap width, would be beneficial for the colliding buildings or not. For the performed simulations, 5 cm thick bumpers were assumed to be installed at all floor levels, as shown in Figure 6. Therefore, by applying the rubber shock-absorbers at the side of the one of the two buildings, the existing seismic gap size reduces by 5 cm, when compared with the case without the bumper. Consequently, the results obtained from the simulations considering the use of the rubber bumpers are compared with the corresponding results from the case without the bumpers but with a clearance that is 5 cm wider. In the performed parametric analyses, the available seismic gap was varied in the range of 5 to 25 cm, which corresponds to a clearance width of 0 to 20 cm in the case of incorporating rubber bumpers.

In order to investigate the effect of the earthquake characteristics, three different seismic records (Table 2) from relatively strong and widely-known earthquakes were selected as ground excitations.

Earthquake	**M_w**	**Station**	**PGA (g)**
Kobe, Japan 1995	6.9	0 KJMA	0.821
Northridge, USA 1994	6.7	74 Sylmar - Converter Station	0.897
San Fernando, USA 1971	6.6	Pacoima Dam, S16	1.170

Table 2: Earthquake records that were used in the simulations.

Plots in Figure 7 demonstrate the effect of using rubber bumpers on the computed response of the 4-story and the 6-story buildings, in terms of the size of the seismic gap for the Kobe earthquake record. In particular, the plots present the amplification of the peak floor accelerations and peak interstory deflections due to the implementation of the rubber shock-absorbers with a thickness of 5 cm, between the two buildings. The amplification of the response is defined as the ratio of the response obtained after the incorporation of rubber bumpers, which unavoidably reduce the available clearance, to the corresponding response, without the usage of bumpers. Therefore, the usage of rubber bumpers has beneficial effects on the corresponding response quantity when the amplification ratio value is smaller than 1.0.

The results indicate that the size of the seismic gap affects the effectiveness of the rubber bumper in a different manner on each floor and for each building. For example, the peak floor acceleration at the 4th floor of the 4-story building is reduced after the incorporation of the bumper almost for all seismic gap sizes, while at the same time the peak acceleration at the 2nd floor of the 6-story building amplifies up to 30%. Moreover, the maximum interstory deflections are not affected in the same way with the floor accelerations, since the later may be amplified after the use of the rubber bumper, while the former are reduced for a certain gap size. Nevertheless, peak floor accelerations seem to be more sensitive to the use of bumpers than interstory deflections, since the variations of the curves in the plots of Figure 7 are more pronounced in the former case.

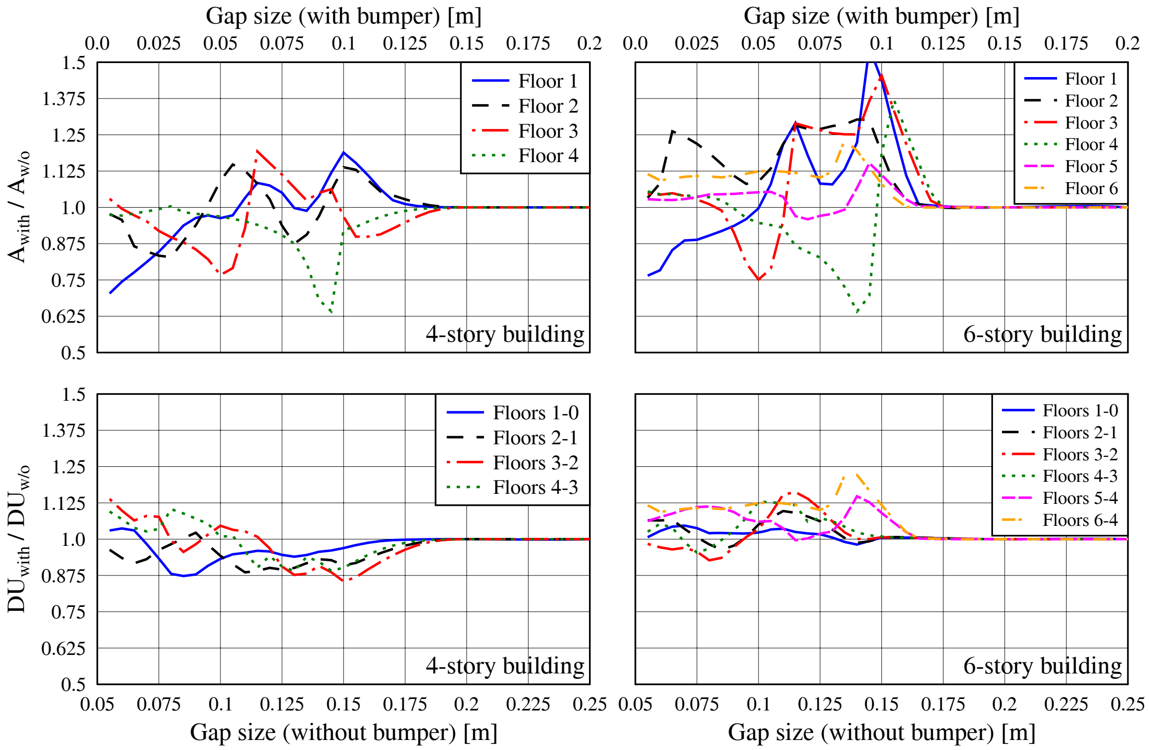

Figure 7: Amplification of the peak floor accelerations and interstory deflections of the 4-story and the 6-story buildings, due to the usage of rubber shock-absorbers, in terms of the width of the seismic gap, considering the Kobe earthquake record.

In order to be able to provide the computed results from all three earthquake records in the same plots, the mean peak responses among all floors of the buildings are computed and plotted in Figure 8. Specifically, these plots demonstrate, in a more general form, the effect of applying rubber bumpers of 5 cm thick inside the available gap on the overall seismic response of the two buildings. It is observed that the characteristics of the earthquake excitation affect the effectiveness of this kind of an impact mitigation measure, in combination with the size of the available clearance. It can be also observed that, under the considered circumstances, the incorporation of such a shock-absorber amplifies, in most of the times, the response, especially in the case of the 6-story building. However there are some cases of relatively narrow gap sizes in which the usage of rubber bumpers seems to be beneficial.

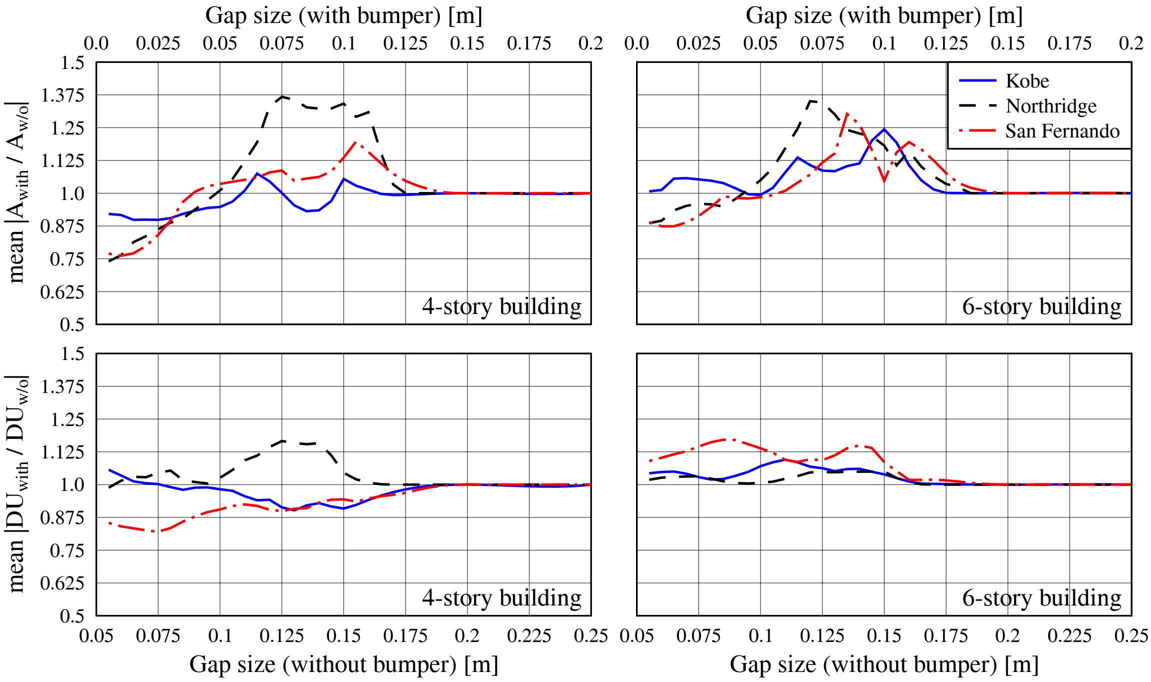

Figure 8: Mean values of the peak responses among all floors of the 4-story and the 6-story buildings, due to the usage of rubber shock-absorbers, in terms of the width of the seismic gap.

In the previously presented simulations, it has been assumed that, after the attachment of rubber bumpers on the side of the seismically isolated building, the reduction of the available clearance from the surrounding moat wall equals to the corresponding thickness of the bumpers. However, the rubber bumpers could be attached in small cavities on the buildings' walls, taking full advantage of the compressible width of the rubber, as shown in Figure 9, without unnecessarily decreasing further the width of the seismic gap. For example, if the thickness of a rubber bumper is 5 cm and its maximum compressive strain equals 0.8, then the compressible width δ_u of the bumper is 4 cm. Therefore, if the particular, 5 cm thick shock-absorber is attached in a cavity that is 1 cm deep, its effective width of 4 cm can be fully utilized, without unnecessarily decreasing further the width of the available seismic gap by 1 cm.

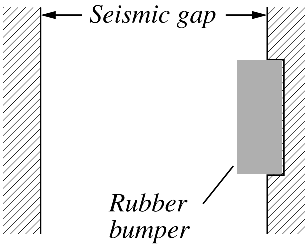

Figure 9: Attachment of a rubber shock-absorber in a cavity on the building's wall.

The above technique seems to be quite efficient since the corresponding amplification ratios due to the incorporation of the bumpers, shown in Figure 10, are substantially reduced in relation to those of Figure 8.

5 CONCLUSIONS

The performed simulations indicate that the incorporation of rubber shock-absorbers to an existing seismic clearance can reduce the peak responses of the pounding structures, under certain circumstances. The effectiveness of the bumpers depends on the existing gap size in combination with the earthquake characteristics and the structural properties (e.g number of stories). The attachment of the bumper in cavities on the building's wall, taking full advantage of the whole compressible width of the rubber, improves their efficiency.

Nevertheless, it has to be mentioned that the above observations concern only the specific earthquake excitations, structural properties and arrangement of buildings. There is a need for further investigation, performing numerous simulations considering different characteristics of the structures, more buildings and earthquake records, where the effectiveness of such impact mitigation measures will be more generally assessed.

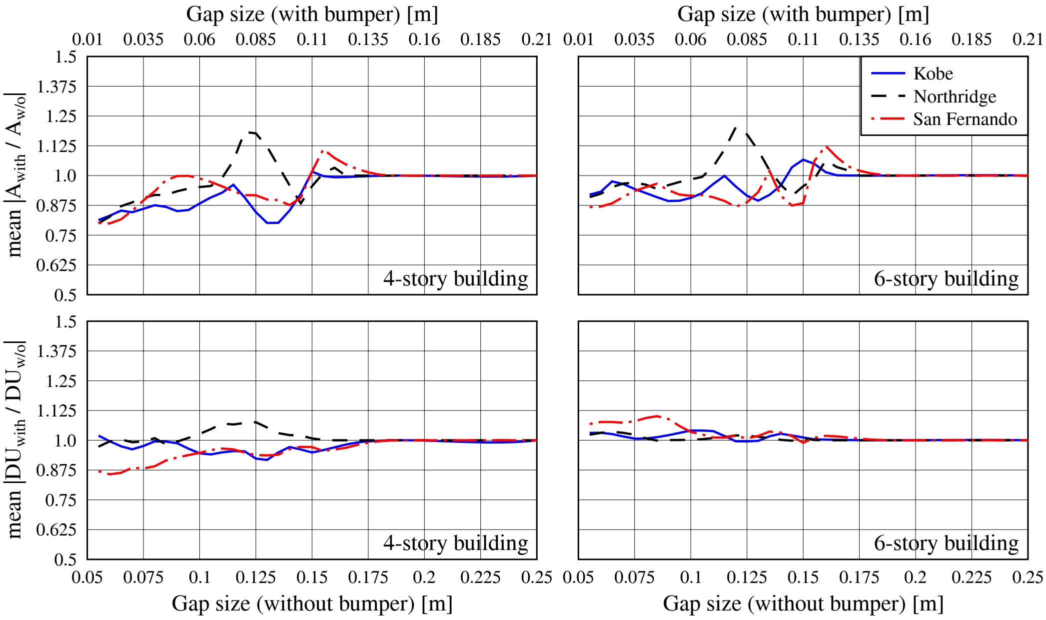

Figure 10: Mean values of the peak responses among all floors of the 4-story and the 6-story buildings, due to the usage of rubber shock-absorbers, in terms of the width of the seismic gap. with 1cm cavity (full advantage of bumper effective thickness, i.e. 4cm)

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