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Numerical investigation of potential mitigation measures for poundings of seismically isolated buildings

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Abstract. During very strong earthquakes, seismically isolated buildings may experience large horizontal relative displacements, which may lead to poundings if an insufficiently wide clearance is provided around the building. This paper investigates, through numerical simulations, the effectiveness of using rubber bumpers, which could be attached at locations where it is likely to have impacts, in order to act as shock-absorbers. For the simulation of the dynamic behavior of such rubber bumpers during impacts, a nonlinear force-based impact model, which takes into account the finite thickness of the rubber bumpers, has been developed. Subsequently, a series of parametric analyses are performed to assess the effect of the gap size, the earthquake characteristics and the thickness, compressive capacity and damping of the bumpers. The stiffness of the moat wall is also parametrically considered during poundings of a seismically isolated building, as another potential mitigation measure for poundings of seismically isolated buildings.

Keywords: poundings; seismic isolation; shock-absorbers; bumpers; rubber; damping.

1. Introduction

1.1 Description of the problem

Seismically isolated buildings unavoidably experience large horizontal relative displacements during strong earthquakes due to the increased flexibility that is provided at the isolation level. Therefore, a sufficient clearance must be provided around a seismically isolated building in order to avoid poundings, either with the surrounding moat wall or with adjacent buildings. However, there are often several practical limitations to the size of the seismic gap that can be provided around a building, especially in densely built areas or in some rehabilitation cases. In addition, there are uncertainties regarding the characteristics of the design earthquake and the expected maximum horizontal relative displacement of a seismically isolated building, which is the determinant factor for the estimation of the required seismic gap. Therefore, during a very strong earthquake, there is a possibility of pounding occurrences of a seismically isolated building with adjacent structures.

The results from numerical simulations and parametric studies that have been conducted in previous studies (Komodromos *et al.* 2007, Polycarpou and Komodromos 2009) demonstrated the

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detrimental effects of potential poundings on the effectiveness of seismic isolation. In particular, both floor accelerations and interstory deflections of a seismically isolated building increase due to impact, either with the surrounding moat wall or with adjacent buildings. 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.

1.2 Overview of potential impact mitigation measures

Undoubtedly, the best mitigation measure for earthquake-induced poundings of buildings would be the prevention of impact by providing a sufficiently wide seismic gap between the structures in order to avoid any impact incidences. Due to practical constraints, the size of the clearance between buildings in series cannot be unlimited, especially in metropolitan areas, where neighboring buildings are often constructed with very small or without any clearance around them. In such cases, some other impact mitigation measures have been proposed by several researchers, mostly for pounding between adjacent fixed-supported buildings or among bridge decks (Warnotte *et al.* 2007).

Specifically, Anagnostopoulos and Karamaneas (2008), based on the observation that for very small or no seismic gap the effect of impacts are reduced, proposed the use of collision shear walls to minimize seismic separation and to protect adjacent fixed-supported buildings from collapse due to earthquake-induced pounding. Some other researchers proposed the linkage between two adjacent buildings with the incorporation of viscoelastic dampers (Zhang and Xu 1999, Matsagar and Jangid 2005).

Although the above two solutions seem quite effective and promising for mitigating poundings for conventional fixed-supported buildings, they are not suitable for seismically isolated buildings for the following reasons: Potential usage of collision walls would reduce the available clearance and, therefore, increase the possibility of poundings to occur. Moreover, although shear walls may reduce the deformations of the superstructure, the expected high spikes in floor accelerations will affect sensitive equipment that may be housed in a seismically isolated building. Furthermore, the construction of shear walls within the superstructure of a seismically isolated building is against the basic design principles of seismic isolation. Finally, potential linkage between a seismically isolated building and an adjacent structure would restrain the unobstructed horizontal oscillation of the superstructure rendering the seismic isolation system ineffective.

Another proposed measure for reducing the effects of pounding is the attachment of layers of soft material, such as rubber, on certain locations, where impact is likely to happen, in order to act as shock-absorbers. Anagnostopoulos (1988) numerically examined the case of filling the seismic gap with a soft material to act as a shock-absorber by simply considering a decreased impact stiffness value for the linear viscoelastic impact model that he used for the simulation of poundings of buildings in series. He concluded that the use of bumpers may reduce, in some cases, the response due to poundings. Nevertheless, the maximum response values remain higher than the corresponding values without poundings. Jankowski *et al.* (2000) simulated the use of several devices to mitigate structural pounding among bridge segments during earthquakes. Specifically, they examined the potential usage of dampers and stiffeners as connectors of segments in series or rubber bumpers to absorb impact energy between girders. The rubber bumpers in that case were simulated using a

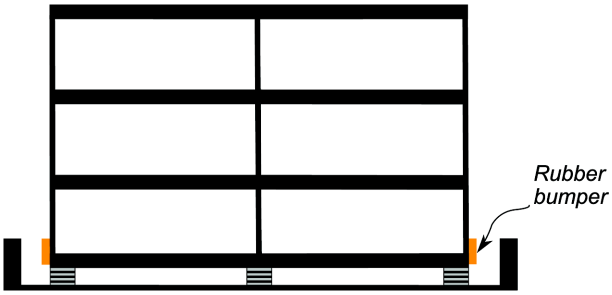


Fig. 1 Pieces of rubber can be attached at potential impact locations around a seismically isolated building, as an impact mitigation measure

linear spring-dashpot element and the results showed that the incorporation of such devices may substantially reduce the overall response due to poundings.

In the case of seismically isolated buildings, the incorporation of a layer of flexible material, such as a soft elastomeric compound, between the building and adjacent structures that acts as a collision bumper (Fig. 1) can be expected to be an effective measure to minimize the damaging effects of impacts. Nevertheless, there is a need for a thorough investigation of this approach, since the introduction of such material, with a certain thickness, reduces accordingly the width of the available seismic gap. In addition, there is a question about the modeling of the behavior of such a rubber bumper under impact loadings.

In this paper, a new nonlinear impact model with hysteretic damping is developed in an attempt to model the behavior of rubber bumpers, based on relevant experiments conducted by other researchers. Subsequently, the proposed impact model is used to parametrically examine the effectiveness of such an impact mitigation measure for a seismically isolated building that experiences poundings.

2. Modeling of structural poundings

In numerically simulated dynamic systems, such as multistory buildings under earthquake excitations, structural impact is typically considered using force-based methods, also known as penalty methods. These methods allow some interpenetration between the colliding rigid structures, which is justified by their deformability at the vicinity of the impact. Contact springs are automatically formed when an impact is detected, kept as long as the colliding bodies remain in contact and removed as soon as the bodies are detached from each other. The interpenetration depth is used together with the stiffness of the contact spring to estimate, according to the impact model, the contact forces that are applied to the colliding structures.

The linear viscoelastic impact model, also known as Kelvin-Voigt model, is a widely used impact model for simulating structural poundings. It consists of a linear impact spring and a viscous impact dashpot that act in parallel. The impact force at each time step is computed by the following expression

$$F_{imp}(t+\Delta t) = k_{imp} \cdot \delta(t) + c_{imp} \cdot \dot{\delta}(t) \tag{1}$$

where $\delta(t)$, is the interpenetration depth, $\dot{\delta}(t)$ is the relative velocity between the colliding bodies,

k_{imp} is the stiffness of the impact spring and c_{imp} is the impact damping coefficient. The later can be computed according to the following formulas, provided by Anagnostopoulos (1988)

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

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

In the above formulas, m_1 and m_2 are the masses of the two rigid bodies and COR is the coefficient of restitution, which is defined as the ratio of relative velocities after and before impact ($0 < COR \leq 1$).

3. Simulation of rubber bumpers

3.1 Behavior of rubber bumpers under impact

Relevant experimental studies reveal that such layers of rubber under static and dynamic compressive loading exhibit a nonlinear behavior (Kajita *et al.* 2001, Kawashima *et al.* 2002, Shim *et al.* 2004, Kajita *et al.* 2006). In particular, it has been observed that the compressive stress-strain curve, obtained from experiments, such as those conducted by Kajita *et al.* (2006), exhibit an exponential trend (see Fig. 2).

Beside static tests, Kajita *et al.* (2006) also conducted impact tests between two steel rods of about 300 kg each that were forced to collide with each other at a certain speed. Layers of rubber, with dimensions 40 mm × 40 mm and with varying thicknesses, were attached at the contact area. Fig. 3 presents the corresponding experimental results for the case of using a rubber bumper with a thickness of 10 mm with three different impact velocities. The force-displacement curve obtained

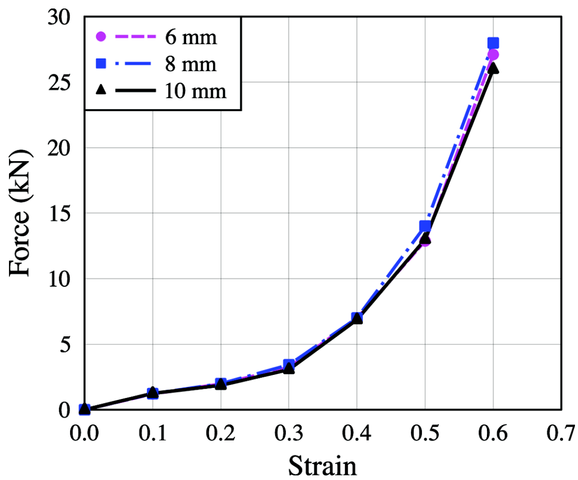


Fig. 2 Load-strain curves obtained from static compressive loading of rubber shock-absorbers of 6, 8 and 10 mm thick (Kajita *et al.* 2006)

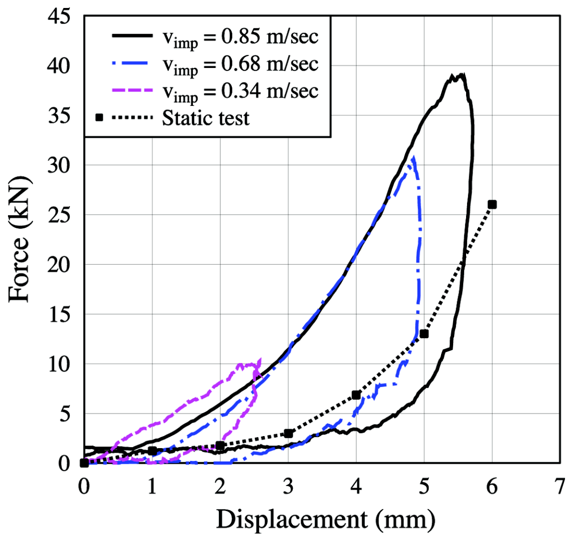


Fig. 3 Force-displacement curves obtained from impact tests (Kajita *et al.* 2006), involving a 10 mm thick rubber shock-absorber

from the corresponding static test is also included in the graph. It is observed that the curves obtained from impact tests do not follow the same path with the corresponding static test. Specifically, during dynamic loading, higher values of the impact force are developed for a certain deformation, compared to the corresponding values obtained from the static test. In particular, the impact stiffness in the cases studied by Kajita *et al.* (2006), was found to be approximately 2.25 times higher than the corresponding static stiffness. Similar behavior was observed in other relevant experimental studies, whereas dynamic tests showed that the behavior of rubber under static and dynamic loading differs significantly. Through experiments, Shim *et al.* (2004) found that the behavior of rubber under compression and tension is rate-dependent. Also, Ishikawa *et al.* (2006) observed that the values of the impact loading curve were about 2.5 times larger than the load values of the corresponding static loading test. Moreover, the experimental results demonstrated an immediate drop of the impact force at the beginning of the restitution phase, which returns to zero also with an exponential trend, indicating an inelastic behavior of the bumper. Test measurements also showed that the residual strain in specimens after unloading was negligible (Shim *et al.* 2004).

3.2 Proposed impact model for rubber shock-absorbers

A simple and efficient method is required for the modeling of the behavior of rubber shock-absorbers, in order to be properly considered in a numerical simulation involving poundings of structures, such as seismically isolated buildings. Considering the above observations and, specifically, the trends of the stress-strain curves obtained from experiments, the use of linear impact models for simulating the response of rubber during impact loading does not seem to be the most suitable approach. On the contrary, the use of a nonlinear impact model would be much more appropriate for the simulation of rubber bumpers, according to the available experimental data.

The two most commonly used nonlinear force-based impact models for the numerical simulation of structural pounding are the so called "*Nonlinear viscoelastic*" (Jankowski 2005) and the "*Hertzdamp*" (Muthukumar and DesRoches 2006) impact models, where the impact force is exponentially increasing with the interpenetration depth. Nevertheless, both impact models are characterized by a quite different force-displacement curve than those of rubber bumpers (Fig. 4). In addition, the formulas that provide the impact damping coefficient refer only to the case of using an exponent of 1.5, which is relatively low to represent the nonlinear behavior of rubber. Therefore, based on the above observations, a simple nonlinear impact model with hysteretic damping, able to simulate the behavior of rubber in a more appropriate manner is proposed in the current study. The proposed impact model is described in the following paragraphs.

Firstly, it is assumed that the impact force exponentially increases with the indentation, according to the Mayer's law (Goldsmith 1960). Fig. 5 displays the shape of the force-displacement graph of the proposed impact model. Impact is separated in two stages: the approach phase and the restitution phase. The enclosed area A_h is the area of the hysteresis loop and expresses the dissipated energy during impact, while no impact dashpots are employed with the proposed approach. The impact force, during the approach phase, can be expressed by the Mayer's law, as noted above (where $n > 1$)

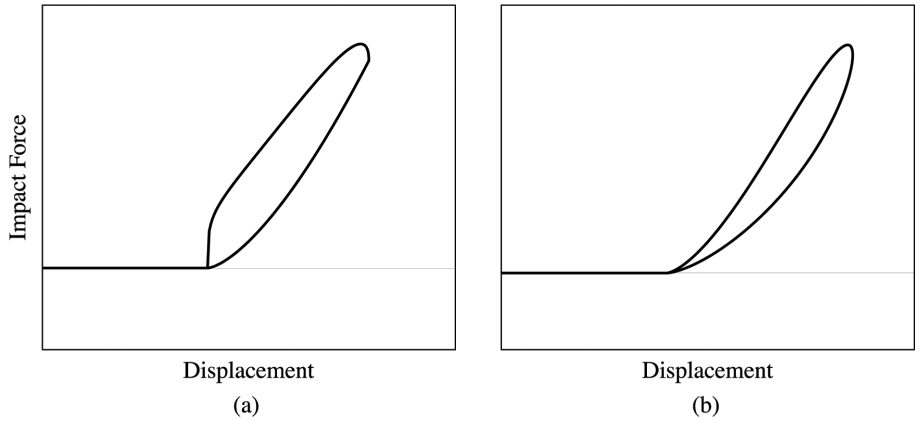


Fig. 4 (a) Nonlinear viscoelastic impact model (Jankowski 2005), (b) Hertzdamp impact model (Muthukumar and DesRoches 2006)

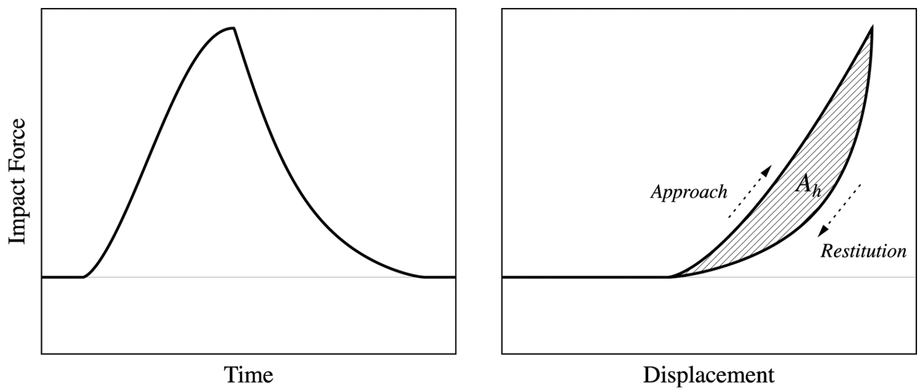


Fig. 5 The proposed nonlinear impact model with hysteretic damping

$$F_{imp}^{A} = k_{imp} \cdot \delta^{n} \qquad for \qquad \dot{\delta} > 0 \tag{4}$$

For the determination of the trend of the curve during the restitution phase, the corresponding equation must fulfill the equilibrium of the kinetic energy loss with the dissipated energy due to impact, which is represented by the area A_h of the hysteresis loop. When two rigid bodies collide, the kinetic energy loss due to impact is described by the following expression (Goldsmith 1960)

$$\Delta E = \frac{1}{2} \cdot \frac{m_1 \cdot m_2}{m_1 + m_2} \cdot (1 - COR^2) \cdot v_{imp}^2 \tag{5}$$

where v_{imp} is the impact velocity, which is the relative velocity of the two bodies just before impact. During the restitution phase, the impact force can be described by the following expression, which is similar to the one that provides the impact force for the *Hertzdamp* model (Muthukumar and DesRoches 2006)

$$F_{imp}^{R} = k_{imp} \cdot \delta^{n} \cdot (1 + C_{imp} \cdot \dot{\delta}) \qquad for \qquad \dot{\delta} < 0 \tag{6}$$

Since the relative velocity during the restitution phase is always negative, the second part of the equation expresses the reduction of the impact force due to damping, forming, in this way, a hysteresis loop. The only remaining unknown parameter is the term C_{imp}, which can be called as the "*impact damping coefficient*". It is assumed that the impact damping coefficient depends on the same parameters that determine the kinetic energy loss (Eq. 5), as in the following formula

$$C_{imp} = f\left(COR, m_{eff} = \frac{m_1 \cdot m_2}{m_1 + m_2}, v_{imp} \right) \tag{7}$$

For the derivation of the formula, a single condition that must be fulfilled is taken into account. In particular, for a coefficient of restitution equal to 1, no energy must be dissipated during impact, which corresponds to perfectly elastic impact, meaning that the impact damping coefficient must be equal to zero. Therefore, the solution may have the following simple form

$$C_{imp} = a_1 \cdot (1 - COR^2) \tag{8}$$

where a_1 is a constant that contains all three determinant factors (COR, m_{eff}, v_{imp}) and, for a given system and coefficient of restitution, should have such value so that the kinetic energy loss Eq. (5) is equal to the area A_h of the hysteresis loop. In order to achieve that, an iterative procedure is followed, solving numerically the equations of motion for a given problem and varying each time the constant a_1 explicitly, until the aforementioned equilibrium is fulfilled.

For this reason, a software module has been specifically developed to simulate the impact of two rigid bodies and solve numerically, using the Central Difference Method, the equation of motion. Considering various systems and following iterative procedures, while changing in turn each parameter so as to fulfill the energy equilibrium and eliminate the error, the following expression has been derived for the evaluation of the appropriate value for the impact damping coefficient

$$C_{imp} = 1.55 \cdot \frac{1 - COR^2}{COR^{0.7076} \cdot \left(\frac{m_1 \cdot m_2}{m_1 + m_2}\right)^{0.0025} \cdot v_{imp}^{0.9755}} \tag{9}$$

3.3 Evaluation of the impact stiffness

The impact stiffness value that is used in the numerical simulations should correspond to the dimensions and material properties of the specific bumper. Jankowski *et al.* (2000) used a linear spring to simulate rubber bumpers between bridge segments, with a stiffness value equal to

$$k_b = \frac{A \cdot E_r}{t} \tag{10}$$

where A is the contact area, E_r is the Young's Modulus for rubber and t is the thickness of the bumper. However, as seen from experimental results, a linear model is not appropriate for simulating the behavior of rubber under compressive loadings.

In order to take a nonlinear behavior into account, it is assumed that the static stiffness of a bumper of constant thickness t is expressed as

$$k_{st} = \frac{A \cdot K_r}{t^n} \tag{11}$$

where K_r expresses the material stiffness and n is the exponent that characterizes the nonlinear behavior. As mentioned previously, the impact stiffness is found to be 2.0 to 2.5 times larger than the corresponding static stiffness of the bumper. Therefore, if the static stiffness is known, then the corresponding impact stiffness can be easily estimated, based on the above observation, as

$$k_{imp} = \alpha \cdot k_{st} = \alpha \cdot \frac{A \cdot K_r}{t^n} \tag{12}$$

where $\alpha > 1$ is a multiplier and ranges usually between the values of 2 to 2.5 as mentioned above. The unknown parameters that have to be determined in Eq. (12) 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 particular, a static test curve of a rubber specimen can be approximated with an exponential curve of the form

$$f(x) = c \cdot x^b \tag{13}$$

In this way, c would represent k_{st}, while b would represent the exponent n. Then, the material stiffness K_r can be calculated by substituting these values in Eq. (11). After obtaining the material properties K_r and n, the impact stiffness of any rubber bumper with the same material and different dimensions can be calculated using Eq. (12).

3.4 Validation of the proposed impact model

In order to validate the accuracy of the proposed nonlinear hysteretic impact model, the load-displacement curves obtained from the collision tests, conducted by Kajita *et al.* (2006), are compared with the corresponding results from numerical analyses, using the developed software that simulates the impact of two free bodies using the proposed impact model. The evaluation of the unknown values of the impact stiffness and the exponent for the impact modeling is based on the static test curve (Fig. 6(a)). In particular, the static test curve is approximated with an exponent equal to 2.65 and a static stiffness of 0.2 kN/mm$^{2.65}$. Consequently, considering the dimensions of the shock-absorber that was used in the experiments, the term K_r is found to be equal to 55,835 kN/m^2. The multiplier α is taken to be equal to 2.25 and, therefore, the impact stiffness for the dynamic response is calculated to be equal to 0.45 kN/mm$^{2.65}$. According to Kajita *et al.* (2001) the energy loss during impact was found to be around 40 to 50% when using the rubber shock-absorbers. Accordingly, the coefficient of restitution is assumed to be equal to 0.45 for the simulations. Nevertheless, the value of the coefficient of restitution, in the proposed impact model, does not affect the value of the maximum impact force, but only the trend of the restitution phase, determining the hysteretic energy loss.

Plots in Fig. 6(b)-6(d) present the force-displacement curves obtained from our analyses, together with the corresponding experimental curves of Kajita *et al.* (2006). The numerical results considering the *Hertzdamp* impact model (Muthukumar and DesRoches 2006), using the same values for the impact parameters, are also plotted for comparison. It is observed that, in general, the trends of the numerical analysis, using the proposed hysteretic impact model, are very similar to the experimental ones, with a small variation on the maximum value of the impact force, for two of the

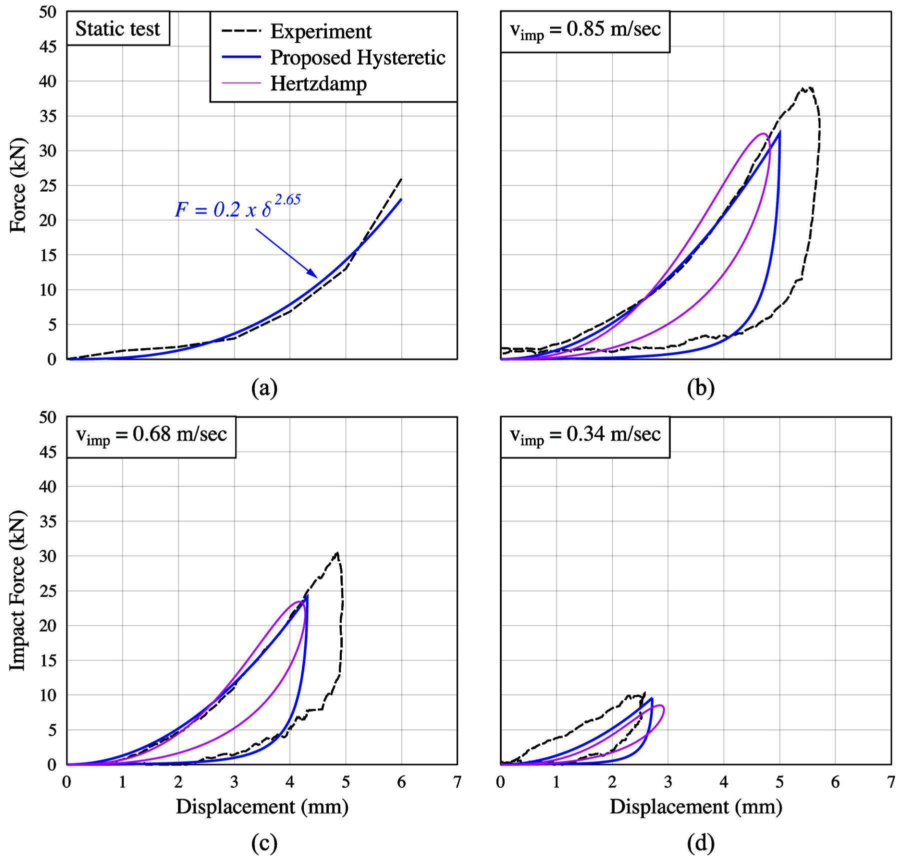


Fig. 6 Force-displacement curves for the case of incorporating a rubber shock-absorber of 10 mm thickness between two steel rods of 300 kg mass each

three cases. Furthermore, the most important advantage of this model is that the trend during the approach phase, which determines the acceleration response during impact, is roughly the same with the trend that was revealed from the experiments. In addition, the shape and size of the hysteresis loop of the proposed impact model is very close to the corresponding experimental results. On the contrary, the dynamic behavior obtained from the use of the *Hertzdamp* model differs significantly from the observations of the impact tests, especially regarding the area of the hysteresis loop that indicates the dissipation of energy by the shock-absorber.

3.5 Exceeding the ultimate compressive strain of rubber

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 be that of the colliding wall and not, anymore, that of the rubber bumper. In order to take into account such a case, the following assumption has been implemented in the developed software. During the approach phase, it is assumed that after a certain indentation, δ_u, which corresponds to the ultimate compressive strain capacity of the rubber bumper, the exponential trend alters to a linear trend with a linear post-yield stiffness, k_w

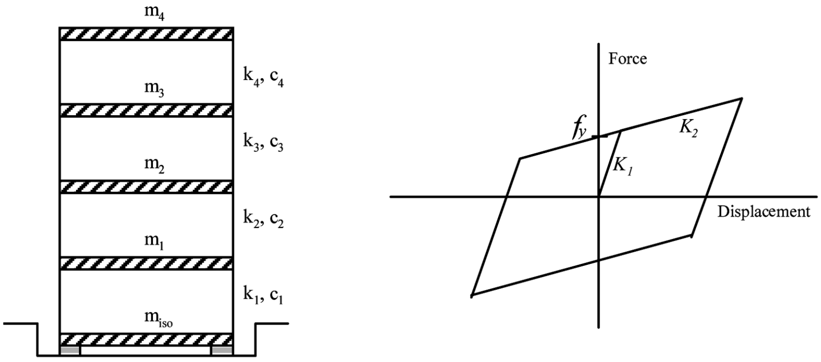
$$F_{imp} = \begin{Bmatrix} k_{imp} \cdot \delta^n & for \quad \delta < \delta_u \\ k_{imp} \cdot \delta_n^n + k_w \cdot (\delta - \delta_u) & for \quad (\delta > \delta_u) \end{Bmatrix} \quad \text{when } \dot{\delta} > 0 \tag{14}$$

The maximum indentation δ_u is expressed as a percentage of the bumper's thickness, with a typical value around 75-80% of the thickness, t, of the rubber bumper, according to relevant experiments (Kawashima *et al.* 2002, Kajita *et al.* 2006). It can be assumed that the linear impact stiffness, k_w, expresses the static stiffness of the moat wall. The effect of choosing different values for this parameter is examined later in this paper.

4. Practical example

A practical example is presented in order to demonstrate the effect of implementing a rubber shock-absorber as an impact mitigation measure for cases of narrow seismic gaps around a seismically isolated building. For the numerical simulations, a specialized object-oriented software application has been designed and developed in order to efficiently perform dynamic analyses of seismically isolated buildings in two dimensions, with impact capabilities. A 4-story seismically isolated building is considered under the Kobe, Japan 1995 (0.821 g) and the San Fernando, California 1971 (1.17 *g*) earthquake records, assuming a shear-beam behavior for the superstructure and bilinear inelastic behavior for the base isolation system (Fig. 7).

The initial seismic gap around the building is considered to be equal to 15 cm for the Kobe and 24 cm for the San Fernando earthquake, respectively. The selected widths of the seismic gaps are 10% smaller than the maximum unconstrained displacement at the isolation level (16.7 cm and 26.8 cm), under the corresponding excitation. This assumption is based on the uncertainties concerning the characteristics of the design-earthquake and the estimation of the maximum design displacement for a seismically isolated building. Two seismic records have been selected in order to



(a) (b)

Parameter	Value
- Superstructure's characteristics:	
Story stiffness (k_i)	600 MN/m
Story mass (m_i)	320 tons
Top story mass (mn)	250 tons
Superstructure's damping ratio (ξ_{sup})	2%
- Isolation system:	
Mass at isolation level (m_{iso})	320 tons
Viscous damping ratio (ξ_{iso})	5%
- Bilinear characteristics of the isolation system:	
Initial stiffness (K_1)	200 MN/m
Post yield stiffness (K_2)	25 MN/m
Characteristic strength (f_y)	$0.1\times W_{tot}{}^{*}$

* *W_{tot} = total weight of the building*

(c)

Fig. 7 (a) Model of a seismically isolated building, (b) Bilinear model of the isolation system behavior, (c) Characteristics of the considered seismically isolated building

demonstrate the effect of the earthquake characteristics on the effectiveness of the rubber bumpers as an impact mitigation measure. In the next section, series of parametric analyses are performed, including more earthquake records.

The same building is considered under a second configuration, where four 5 cm thick rubber shock-absorbers are attached at each side of the seismically isolated building at the isolation level (Fig. 8), with the clearance being reduced to 10 and 19 cm, respectively for the two seismic excitations. The bumpers are assumed to have a square plan section with 150 mm × 150 mm dimensions. The same material stiffness and impact exponent that have been derived from the experiments are used for the calculation of the impact stiffness, which is found to be 0.36 kN/mm$^{2.65}$. The post-yield linear impact stiffness is taken to be equal to 1500 kN/mm, while the ultimate compressive strain of the bumper is set to 0.8.

Fig. 9 presents the total acceleration time-histories at the base of the seismically isolated building, where poundings occur, for both cases, without and with bumpers, as well as for the case where no poundings occur, for the Kobe Earthquake record. It is observed that, in general, the value of the

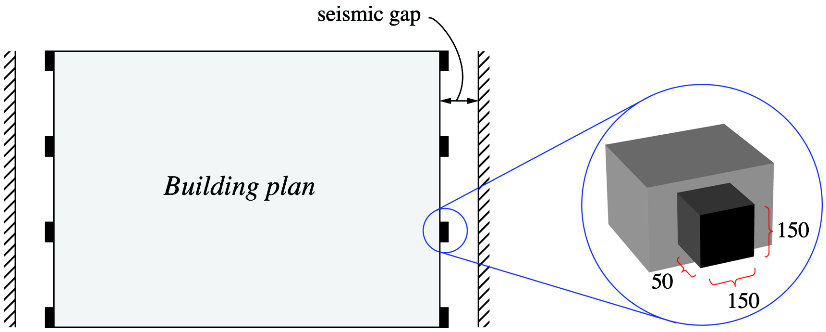


Fig. 8 Locations of rubber shock-absorbers in a plan view of the building

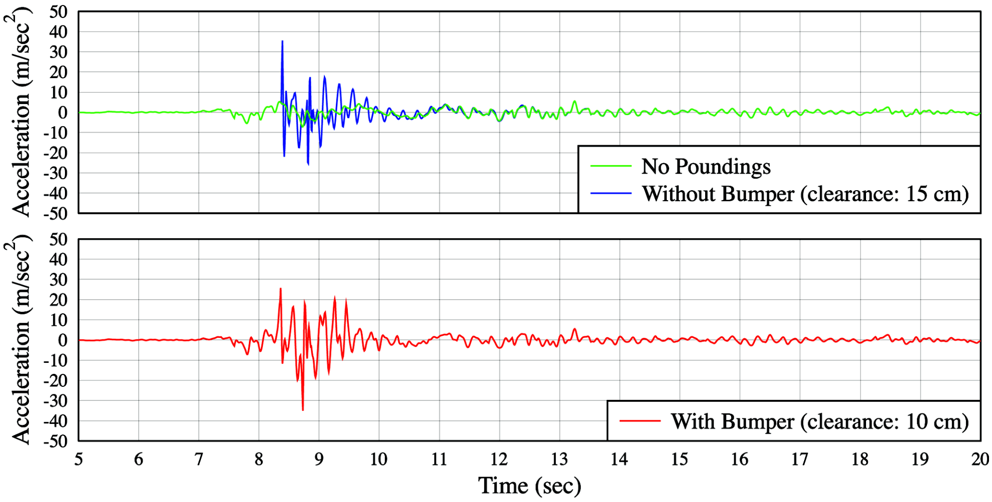


Fig. 9 Effect of the attachment of 5 cm thick rubber shock-absorbers on the total acceleration time-history response at the isolation level, during the Kobe Earthquake

peak floor acceleration remains almost the same after the implementation of the rubber shock-absorber. Therefore, potential use of such a measure in the particular case does not seem to be beneficial for the seismically isolated building, under the specific earthquake excitation.

On the contrary, when considering the San Fernando Earthquake record, the use of rubber bumpers seems to be quite effective. According to Fig. 10, although that the available clearance is reduced from 24 to 19 cm with the bumpers, the maximum acceleration response is much lower than the corresponding peak acceleration without bumpers. In particular, the high spikes in the acceleration response are eliminated due to the implementation of the rubber shock-absorbers. However, the peak acceleration values are still higher than the corresponding response of the seismically isolated building without poundings.

The reason of having such relatively high values of impact forces, when using the rubber bumpers, only in the case of the Kobe Earthquake, is because of the substantial exceeding of the maximum compressive capacity of the 5 cm thick bumpers, in contrast to the case of the San Fernando Earthquake, where a very small exceedance occurs. This can be seen in Fig. 11 where the impact forces are plotted in terms of the indentation for each of the two cases. It is observed that after exceeding the maximum compressive capacity, which in the current case corresponds to 4 cm

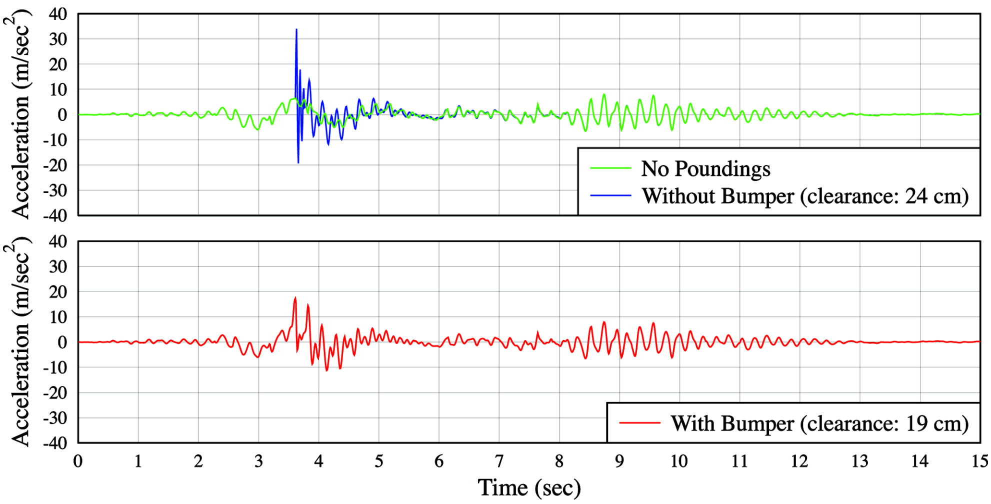


Fig. 10 Effect of the attachment of 5 cm thick rubber shock-absorbers on the total acceleration time-history response at the isolation level, during the San Fernando Earthquake

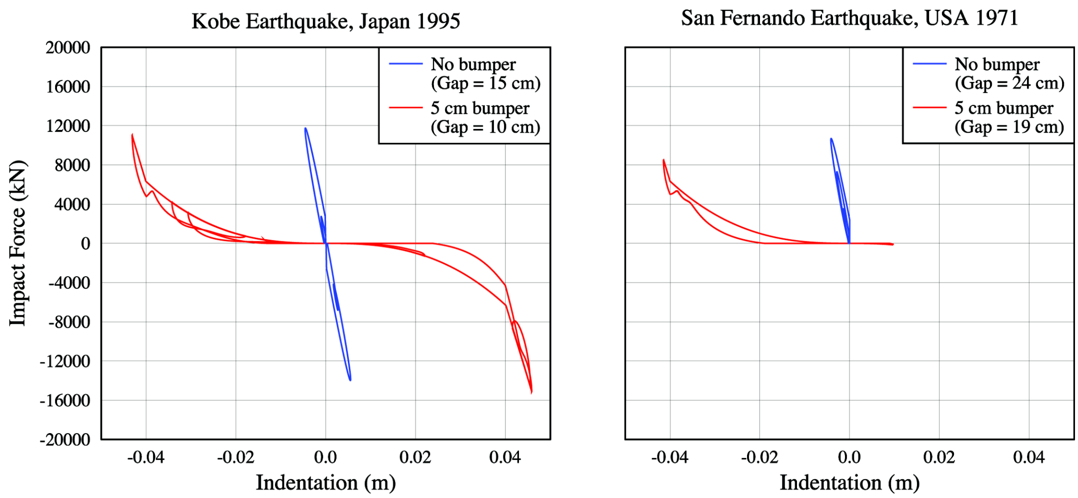


Fig. 11 Impact force in terms of the resulting indentation for the two cases of without and with bumpers

(80% of the bumper's thickness), the impact forces increase rapidly due to the increased impact stiffness. This sudden change, affects the acceleration response at the corresponding level, which increases drastically. This is mainly the reason for the ineffectiveness of the rubber bumpers as a mitigation measure for poundings under the Kobe Earthquake.

The overall peak response of the seismically isolated building under the Kobe earthquake is presented in Fig. 12, which provides the maximum responses at all floors of the building for the two configurations examined, i.e. with and without rubber bumpers, as well as for the case without poundings. An amplification of the interstory deflection is observed in the case of using the rubber bumpers, while the peak floor accelerations remain almost at the same levels as in the case without bumpers.

The corresponding results for the San Fernando earthquake are plotted in Fig. 13, which shows a quite different response compared to that for the Kobe earthquake. In particular, no significant

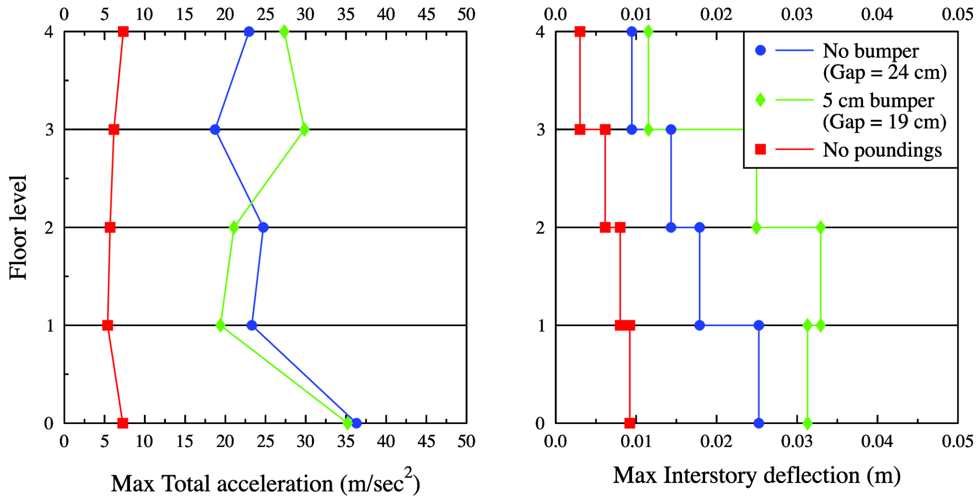


Fig. 12 Differences on the maximum responses of the seismically isolated building, under the Kobe Earthquake, due to the attachment of 5 cm thick rubber shock-absorbers at the potential impact locations

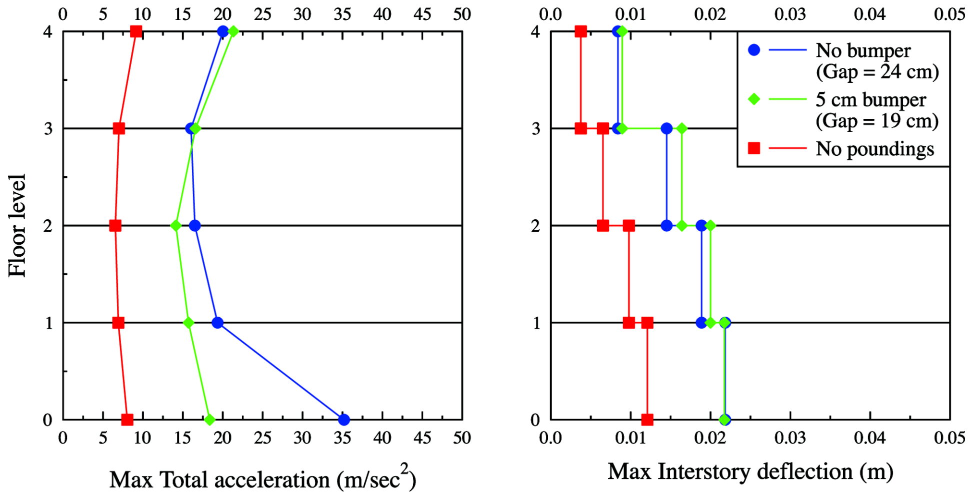


Fig. 13 Differences on the maximum responses of the seismically isolated building, under the San Fernando Earthquake, due to the attachment of 5 cm thick rubber shock-absorbers at potential impact locations

increases on the maximum interstory deflections or the maximum floor acceleration at the upper floors are observed, when rubber bumpers are used, due to the decreased gap size. On the contrary, the maximum interstory deflection at the first story, which is the largest among all stories, slightly decreases through the incorporation of the rubber bumpers. In addition, the peak absolute acceleration value at the base of the seismically isolated building, where the rubber shock-absorbers are attached, are considerably reduced, while at the upper floors of the superstructure the peak floor accelerations remain almost the same with the ones without bumpers.

The computed peak responses suggest that the employment of rubber bumpers within the seismic gap can sometimes mitigate, but, in some other cases, can even amplify the negative effects of poundings of a seismically isolated building with the surrounding moat wall. The earthquake characteristics seem to play a significant role on the effectiveness of the rubber bumpers. The effect of more parameters, while using a larger set of seismic excitations is examined in the following section.

5. Parametric studies

Large numbers of numerical simulations have been conducted, considering the 4-story seismically isolated building, in order to assess the overall effectiveness of rubber shock-absorbers, as an impact mitigation measure, for cases of narrow seismic gaps. Poundings are considered to occur only at the isolation level with the surrounding moat wall. Four different seismic records (Table 1) are used in the simulations of the current study in order to examine the effect of the characteristics of the seismic excitation on the response of the seismically isolated building during poundings. All selected earthquakes are characterized by low-frequency content, in order to induce large relative displacements to the seismically isolated building, since this is one of the most decisive factors for the occurrence of poundings in such structures.

5.1 Effect of the gap size and the earthquake characteristics

The width of the seismic gap, i.e. the distance of the surrounding moat wall from the base of the seismically isolated building, is varied between 15 and 45 cm. When rubber bumpers are used, the corresponding gap size on both sides of the seismically isolated building is reduced by 5 cm.

Fig. 14 and Fig. 15 demonstrate the effect of using rubber bumpers on the response of the 4-story seismically isolated building, in terms of the size of the seismic gap. In particular, the plots present the amplification of the peak floor accelerations and peak interstory deflections due to the implementation of four rubber shock-absorbers with the characteristics that have been used in the simulations of the previous section, on each side of the seismically isolated building. 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 any bumpers. Therefore, the usage of the bumper has beneficial effect on the corresponding response quantity when the amplification ratio value is smaller than one.

The computed responses indicate that for relatively wide seismic gaps the usage of rubber shock-absorbers increases the response instead of reducing it. In particular, this happens for seismic gaps, where poundings would not occur without the incorporation of the rubber bumpers, which decrease the available clearance from the moat wall. For some seismic actions the peak response with bumpers becomes two times greater than the corresponding cases without bumpers. For example, under the Kobe and Northridge Olive Station excitations, the maximum horizontal displacements are

Table 1 Earthquake records that were used in the simulations

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
Northridge, USA 1994	6.7	24514 Sylmar-Olive View Med FF	0.604
San Fernando, USA 1971	6.6	Pacoima Dam, S16	1.170

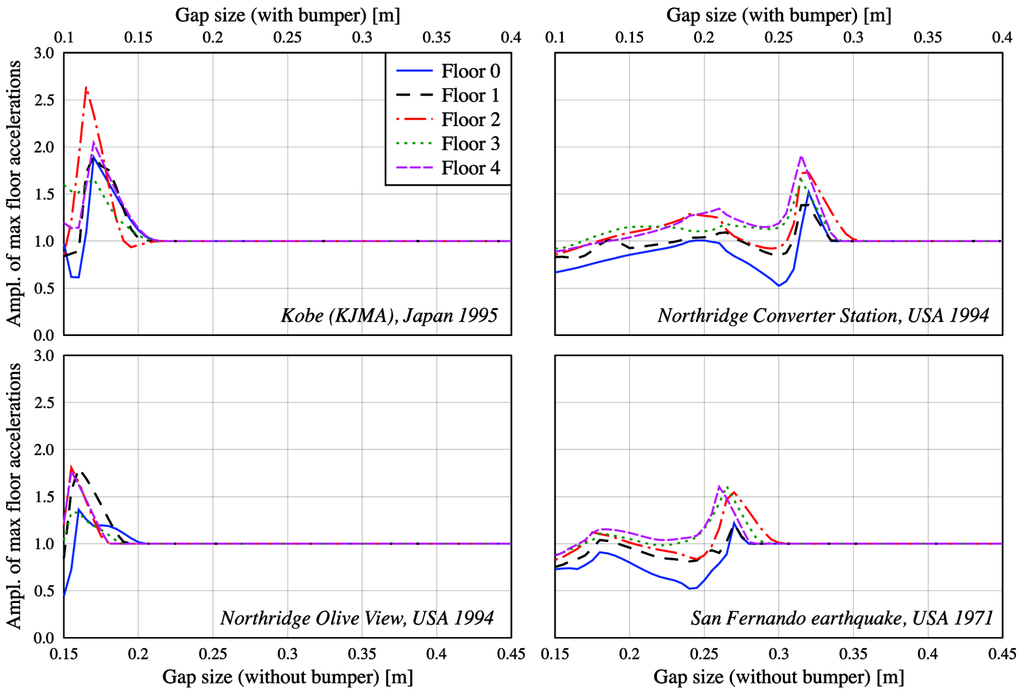


Fig. 14 Amplification of the peak floor accelerations, due to the usage of rubber shock-absorbers, in terms of the width of the seismic gap

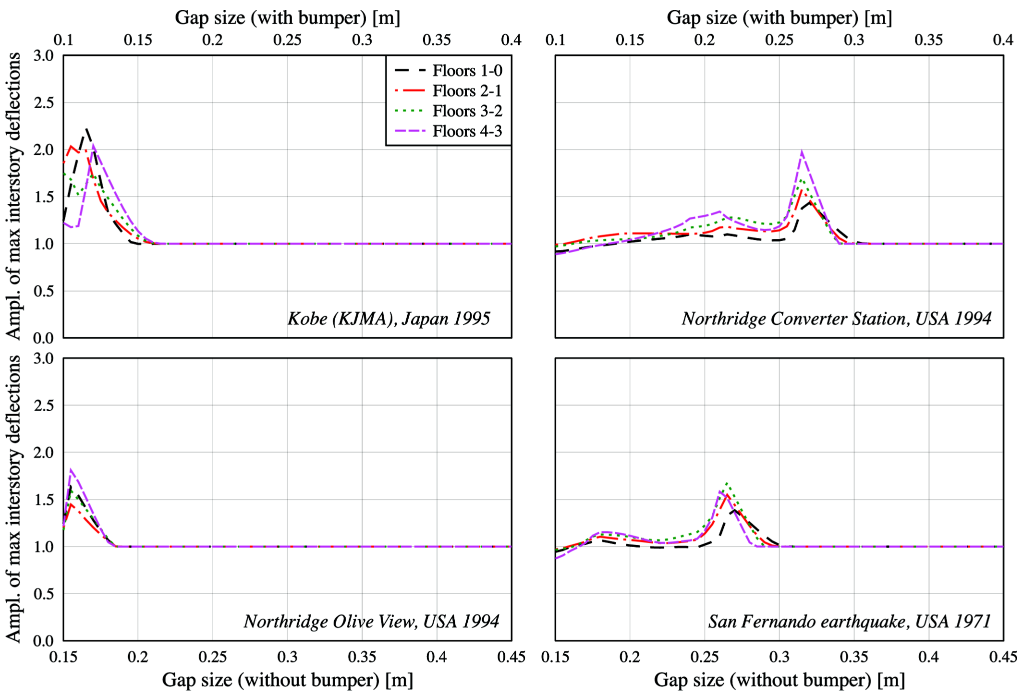


Fig. 15 Amplification of the peak interstory deflections, due to the usage of rubber shock-absorbers, in terms of the width of the seismic gap

16.74 and 15.63 cm, respectively, and, therefore, the attachment of 5 cm thick bumpers when the available clearance is over 15~16 cm wide is not beneficial for the building (Fig. 14). On the other hand, for the cases of the Northridge Converter Station and the San Fernando Earthquake records, where the induced displacements are quite large for the seismically isolated building, the usage of rubber bumpers can be beneficial for relatively narrow gap sizes. Nevertheless, this is not always true, especially concerning the interstory deflections (Fig. 15), which are in most of the examined cases amplified when rubber bumpers are used, due to the reduction of the corresponding gap size.

In general, it seems that the use of rubber bumpers is an effective measure in cases of relatively very strong earthquakes where the induced maximum relative displacements of the seismically isolated building are much larger than the available seismic gap. Also, the parametric analyses suggest that the incorporation of rubber bumpers is relatively more beneficial for the base floor of the building, where impacts occur with the moat wall than for the higher floors (Fig. 14).

5.2 Effect of the thickness of the rubber bumpers

Relevant experimental studies (Kim and Shafig 2001) found that the thickness of a viscoelastic material affects the response during impact loading. Specifically, the test results showed that the

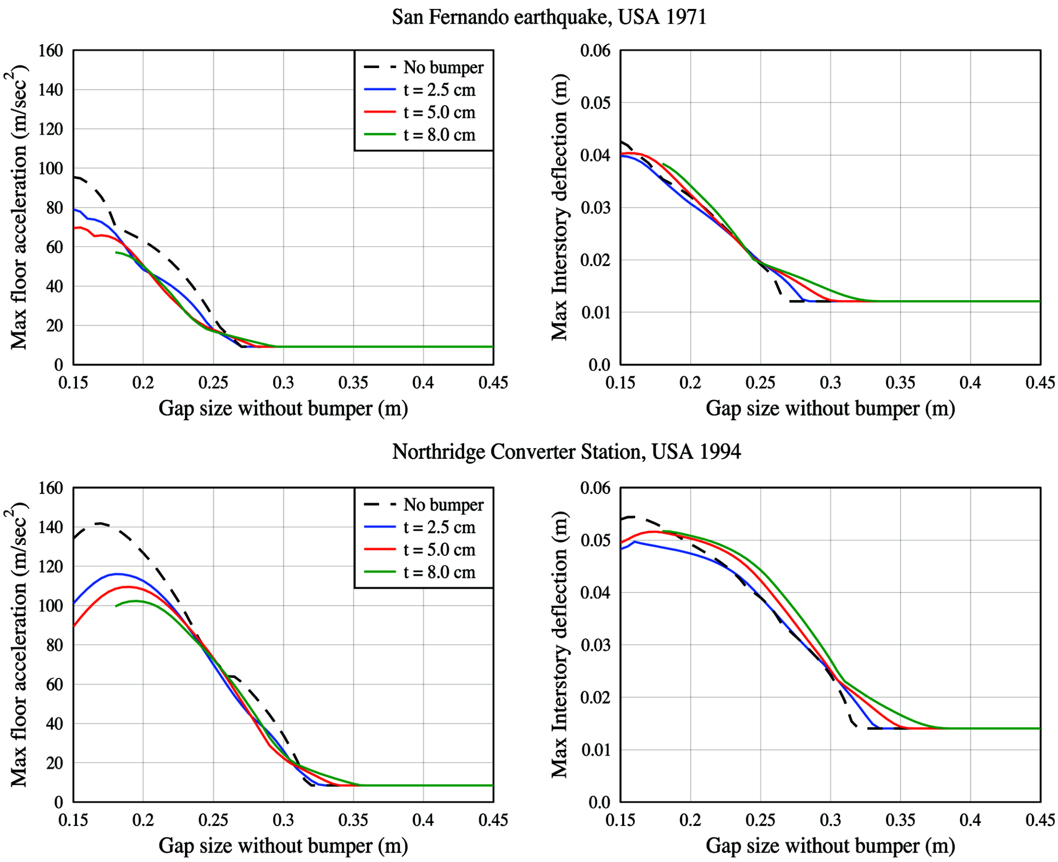


Fig. 16 Peak responses of the seismically isolated building in terms of the seismic gap width, assuming different thicknesses of the incorporated bumpers

impact force is reduced with the increase of the thickness of the material, while at the same time, the duration of the impact is elongated. However, in the current case of using layers of rubber to act as shock-absorbers, along with the increment of their thicknesses, the width of the seismic gap is, unavoidably, reduced. Therefore, conclusions cannot be safely derived regarding the actual effect of the rubber thickness without conducting a parametric investigation.

In order to examine the influence of the thickness of the rubber shock-absorber on the effectiveness of the latter, three cases of different thicknesses are considered. Four rubber bumpers are considered on each side of the seismically isolated building, while a post-yield linear impact stiffness of 1500 kN/mm is assumed. The plots in Fig. 16 present the maximum responses of the 4-story seismically isolated building in terms of the seismic gap width, considering different thicknesses for the rubber shock-absorbers. The maximum responses for the case without bumpers are also plotted with a dashed line in the figure. The Northridge Converter Station and San Fernando earthquake records are used as representative excitations, as they induce the largest relative displacements at the isolation level of the base-isolated building, among the five selected earthquakes.

The results show that an increased thickness of the bumpers reduces the amplification of the maximum floor acceleration values due to poundings, when the seismic gap is very narrow with respect to the maximum induced horizontal displacement. For medium to wide seismic gap sizes, the effect of the bumper thickness on the acceleration response is negligible. On the other hand, the maximum interstory deflections of the seismically isolated building seem to be increased with the thickness of rubber shock-absorbers. However, the thickness of the rubber bumpers does not seem to significantly affect the response, at least for the specific characteristics that have been assumed in this parametric analysis.

5.3 Effect of the maximum compressive capacity of the bumpers

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 moat wall, taking full advantage of the compressible width of the rubber, as shown in Fig. 17, without unnecessarily decrease further the width of the seismic gap. For example, if the thickness of a rubber bumper is 5 cm and its maximum compressive strain, ε_u, equals 0.8, then the compressible width of the bumper is 4 cm.

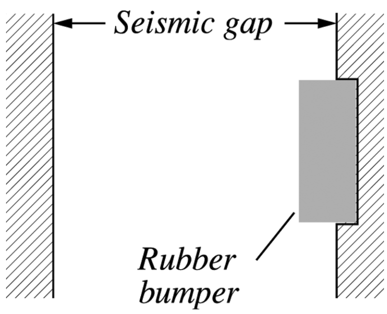


Fig. 17 Attachment of a rubber shock-absorber in a cavity on the wall

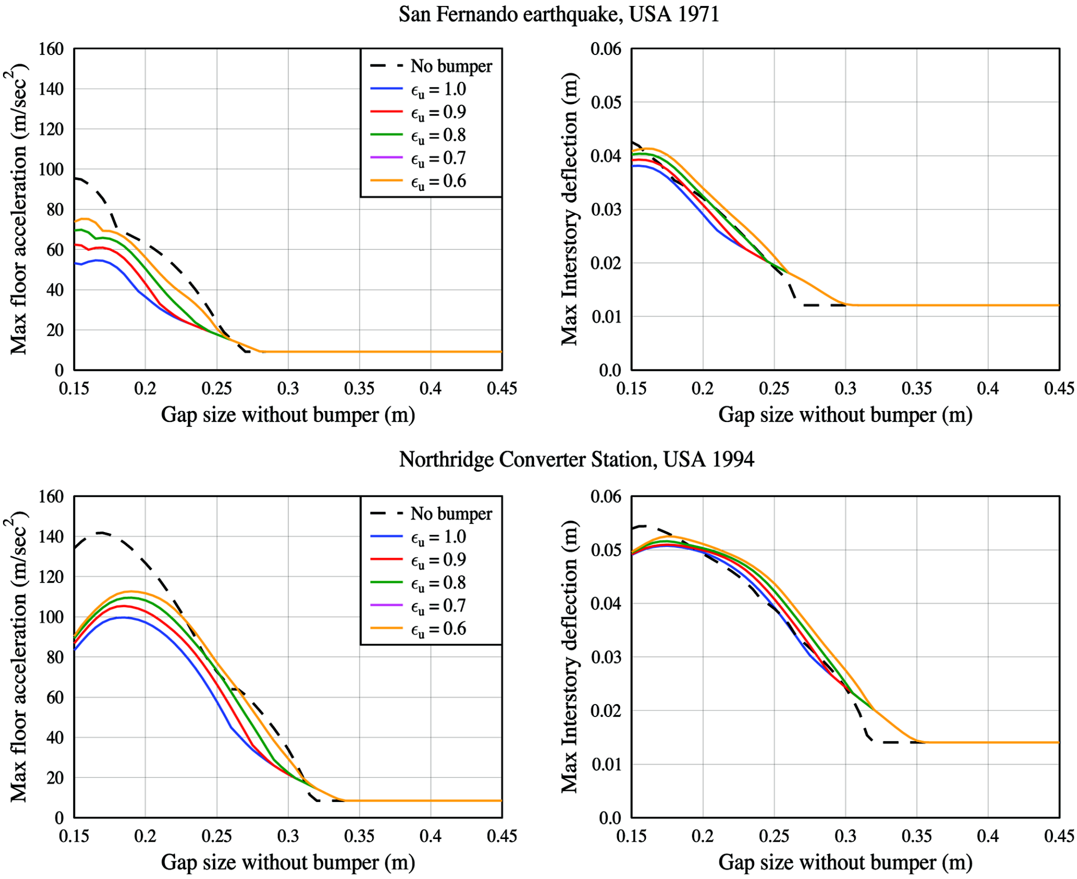


Fig. 18 Peak responses of the seismically isolated building in terms of the seismic gap width, assuming different values for the maximum compressive strain of the incorporated bumpers

Therefore, if the particular, 5 cm thick, shock-absorber is attached in a cavity of 1 cm deep, a width of 4 cm can be fully utilized with the maximum compressive strain of 1.0.

The plots in Fig. 18 demonstrate the effect of the value of the maximum compressive strain on the computed response, while the thickness of the rubber bumpers is assumed to be the same, i.e. 5 cm, for all cases. It is observed that both absolute floor accelerations and interstory deflections of the seismically isolated building decrease with the increase of the maximum compressive capacity of the rubber bumpers. Therefore, in order to make the use of rubber shock-absorbers more effective, a good practice would be the attachment of rubber bumpers in cavities, which are deep enough to take full advantage of the whole compressibility of the rubber, without unnecessarily reducing further the available width of the seismic gap.

5.4 Effect of the number of bumpers

The number of the rubber bumpers, which are attached on each side of the seismically isolated building, is also examined. Specifically, assuming the same characteristics of the bumpers, four different cases are considered with 4, 8, 16 and 32 bumpers with exponential stiffness values of

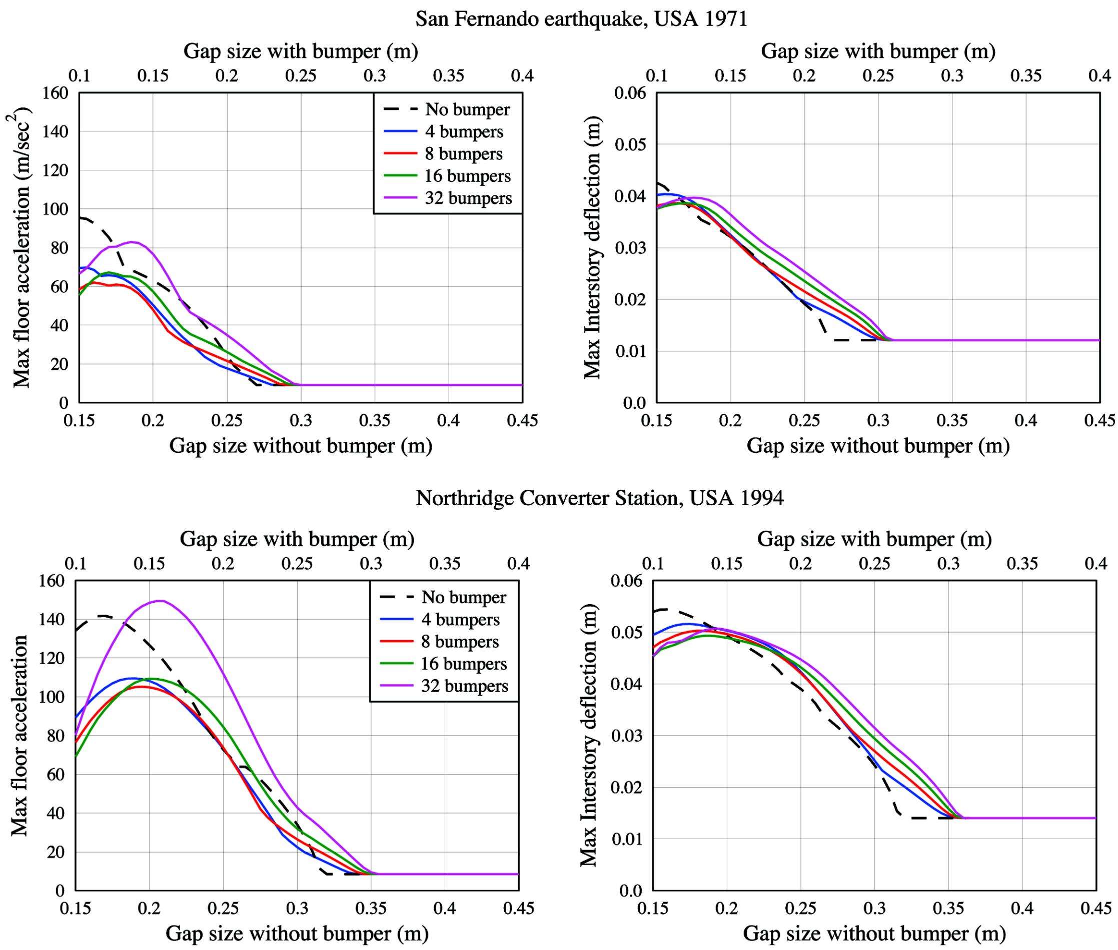


Fig. 19 Peak responses of the seismically isolated building in terms of the seismic gap width, for various numbers of rubber shock-absorbers.

0.36, 0.71, 1.42 and 2.85 kN/mm$^{2.65}$, respectively. It is assumed that the post-yield linear impact stiffness equals 1500 kN/mm and remains the same for all four cases, as it represents the static stiffness of the moat wall.

The results of the performed parametric analysis are presented in Fig. 19. It is observed that by increasing the number of bumpers, and, therefore, the exponential impact stiffness, the maximum responses of the seismically isolated building during poundings increase in almost all examined cases. However, for some very narrow gap sizes, the maximum responses are reduced when more bumpers are used. This is due to the fact that for the cases of very narrow gap sizes with a small number of bumpers, the maximum compressive strain of the bumpers is usually exceeded and, consequently, their effectiveness is reduced. Therefore, the usage of more rubber bumpers increases the exponential stiffness, avoiding the exceeding of the ultimate compressive capacity of the rubber.

Fig. 20 presents the maximum indentation in terms of the seismic gap width, for the four cases regarding the number of bumpers. As mentioned above, the maximum compressive capacity of the bumpers is 80% of the bumpers' thickness, i.e. 4 cm. It can be seen that by increasing the number

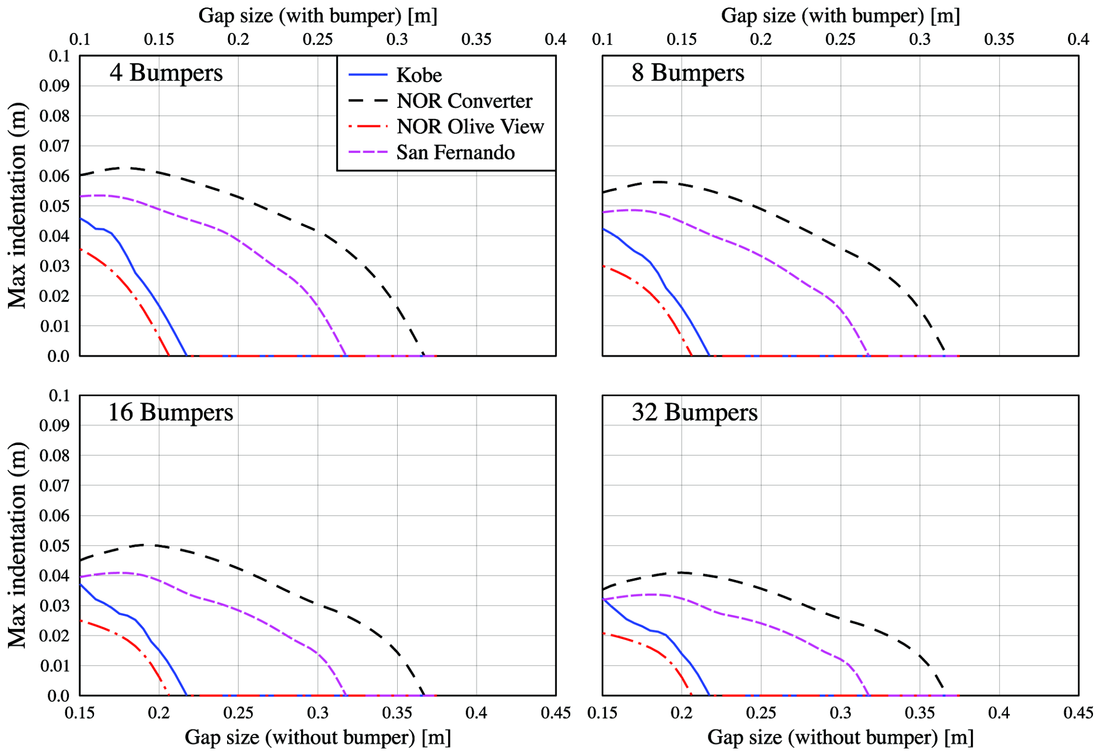


Fig. 20 Maximum indentation in terms of the seismic gap size, for the various excitations and four cases regarding the number of rubber shock-absorbers

of bumpers, the maximum indentation is reduced, while for the case of using 32 bumpers the indentation does not exceed the limit of 4 cm for all examined earthquake excitations.

5.5 Effect of the stiffness of the moat wall

The influence of the post-yield linear impact stiffness, which essentially represents the static stiffness of the surrounding moat wall, is also examined. Three different values are considered: (i) 2500 kN/mm, which is equal to the impact stiffness that is used for the case without bumpers, using the linear viscoelastic impact model; (ii) 1500 kN/mm and (iii) 500 kN/mm, which is lower than the horizontal story stiffness of the superstructure (600 MN/m).

The plots in Fig. 21 indicate that the post-yield impact stiffness of the impact model for the rubber bumpers affects significantly the response during poundings. In particular, the maximum responses, and especially the maximum floor accelerations, of the seismically isolated building are significantly reduced when the linear post-yield stiffness takes relatively low values. Therefore, the design and construction of a relatively flexible moat wall may be an effective impact mitigation measure.

5.6 Effect of the impact damping

Finally, the influence of the impact damping on the computed structural response, when modeling

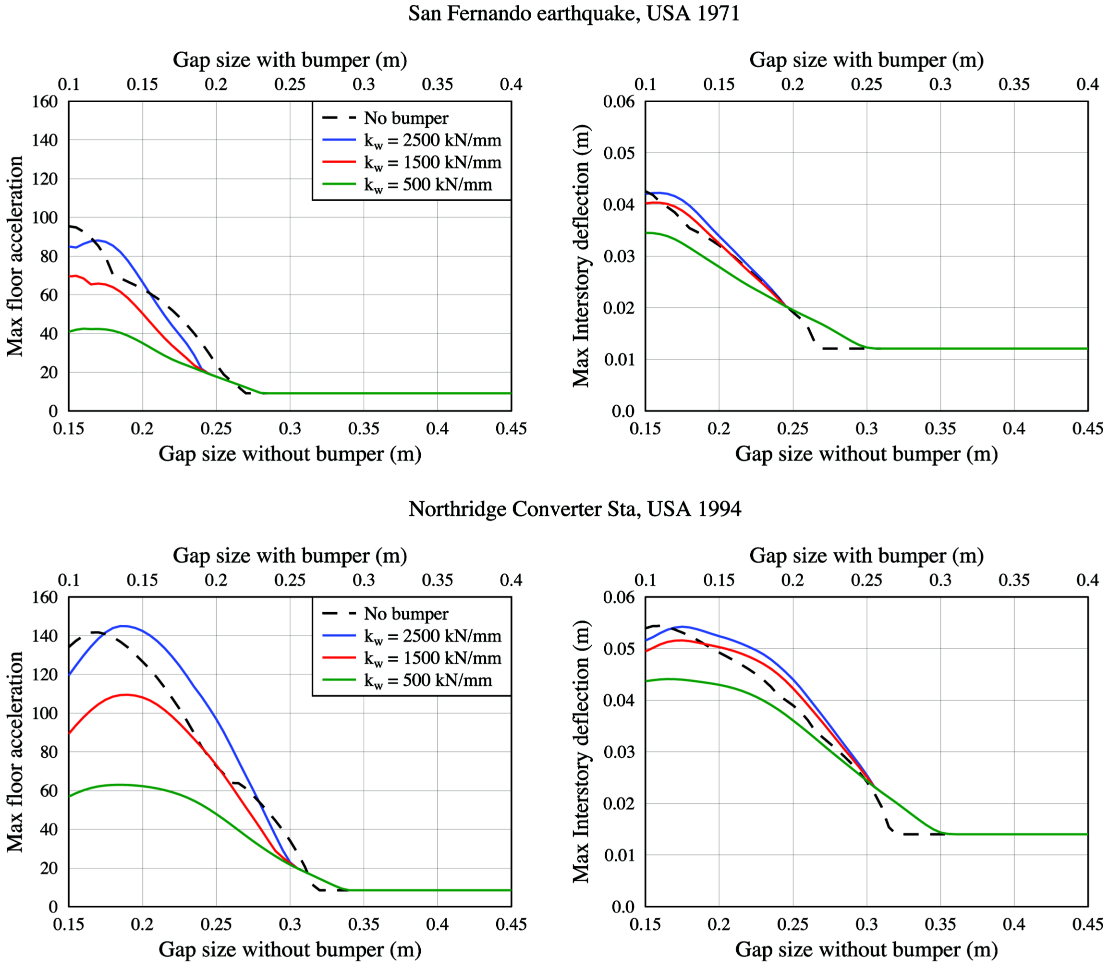


Fig. 21 Peak responses of the seismically isolated building in terms of the seismic gap width, assuming three different values for the stiffness of the moat wall

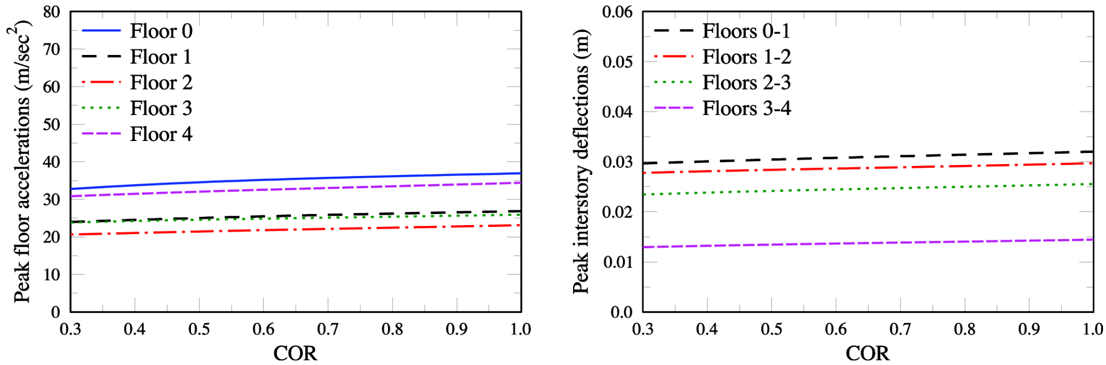


Fig. 22 Peak responses of the seismically isolated buildings under Northridge Converter Station seismic record, assuming a seismic gap 23.5 cm wide and 5 cm thick rubber bumpers

the incorporation of rubber bumpers, by using the proposed nonlinear hysteretic impact model, is parametrically investigated. In particular, the coefficient of restitution is varied between the values 0.3 and 1.0, considering the Northridge Converter Station earthquake record, a seismic gap size 28.5 cm wide and 5 cm thick rubber bumpers. Without the rubber bumpers, the seismic gap would be 10% smaller than the maximum horizontal unconstrained displacement at the isolation level under the same earthquake excitation.

The plots in Fig. 22 show that the coefficient of restitution does not affect the peak responses of the seismically isolated building. The approach phase of the nonlinear hysteretic impact model and the maximum impact force are not affected by the value of the coefficient of restitution, since the latter is used only during the restitution phase. Similar observations about the insensitivity of the response to the coefficient of restitution have been made also in previous research work (Komodromos *et al.* 2007), where the linear viscoelastic impact model was used to simulate poundings without considering any bumpers.

6. Conclusions

In this study, a nonlinear hysteretic impact model has been proposed for the simulation of the dynamic behavior of rubber bumpers under impact loadings. It has been shown that the proposed impact model can compute with sufficient accuracy relevant experimental results that are available in the literature. Then, a seismically isolated building with certain characteristics has been used to examine the effectiveness of incorporating rubber shock-absorbers as a mitigation measure for poundings with the surrounding moat wall.

In general, the results show that employing rubber shock-absorbers at impact locations may reduce the maximum impact force, as their presence elongates the duration of the impact and reduces the high spikes in the acceleration response. However, the usage of rubber bumpers unavoidably reduces the available clearance around a seismically isolated building and, in some cases, may prove detrimental, depending on various parameters.

Parametric studies have shown that for relatively wide seismic gap sizes the usage of rubber shock-absorbers may increase the response instead of reducing it. In particular, this may happen for seismic gap sizes where poundings would not occur without the incorporation of rubber bumpers, which reduce the width of the seismic gap. Rubber bumpers seem to be more effective for relatively narrow seismic gaps, compared to the maximum induced displacement of the seismically isolated building under very strong earthquake excitations.

The thickness of the rubber bumpers does not seem to affect significantly the response under the considered circumstances. Both floor accelerations and interstory deflections are reduced when the value of the maximum compressive strain of the rubber bumpers increases. This observation indicates that the use of rubber bumpers can be more effective when they are attached in cavities on the moat wall, taking full advantage of the whole compressible width of the rubber.

The flexibility of the moat wall, i.e. the value of the post-yield linear impact stiffness, affects significantly the effectiveness of the bumpers. In particular, when a relatively low value of the wall stiffness is considered, both floor accelerations and interstory deflections are reduced, compared to the case without rubber bumpers. Therefore, the construction of a relatively flexible moat wall around a seismically isolated building may be an effective measure to mitigate the detrimental effects of potential poundings during a larger than expected earthquake.

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