The 9th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2024
3 – 7 June 2024, Lisbon, Portugal

An Experimental Study for the Assessment of Numerical Impact Models for Simulating Earthquake Induced Pounding

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Key Words: *seismic pounding, impact modelling, adjacent structures, SDOF, free vibration, rubber bumper, impact mitigation*

Summary: *This paper presents the results of a simple experimental study involving two adjacent single degree of freedom systems that are interacting between each other though pounding when subjected to free vibration. The experimental results are compared with the corresponding numerical results that are computed considering the most common impact models to simulate pounding. The purpose of this study is, through this simple experimental setup, to assess the effectiveness of these widely used force-based impact models and provide a better understanding on the effects of the impact parameters values, i.e. the impact stiffness and the coefficient of restitution. The displacement and acceleration time-histories are compared for various values of impact parameters and it is observed that the coefficient of restitution value affects significantly the accuracy of the impact model, while the effect of the impact stiffness value is limited on the amplitude of the high spikes of the computed acceleration.*

1 INTRODUCTION

In most of the developed cities, as the result of dense multifunctional mixed planning and high prices of land, high and medium-rise buildings are constructed in close proximity to each other. This, however, in combination of the occurrence of strong earthquakes in the region, may result to collisions between the adjacent buildings which may cause light or severe damage that can even lead to collapse [1-3]. The phenomenon is known as earthquake-induced pounding and has been observed, not only between conventional adjacent buildings, but also in other types of structures, such as bridge decks and seismically isolated buildings.

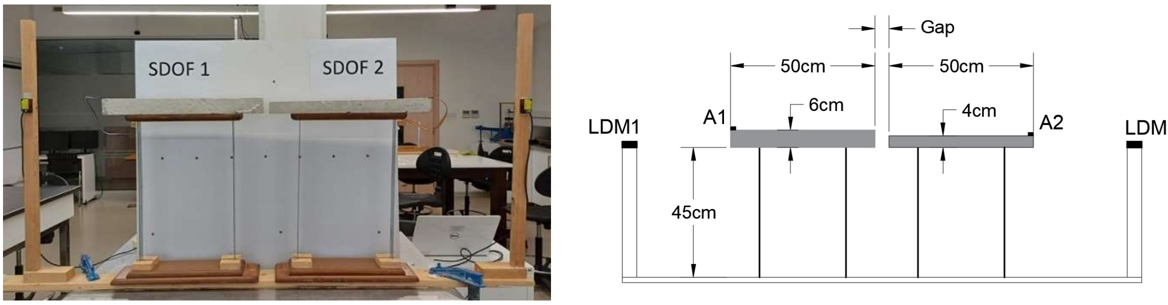
The problem of pounding between adjacent structures during strong earthquakes is being investigated in various ways for the last few decades. Several numerical studies were conducted and various impact models were developed, aiming to model efficiently and effectively the complex dynamic problem of seismic pounding between adjacent structures [4, 5]. In most of the cases, the problem is numerically simulated considering plane (2D) structural models and the interaction between structures is modelled using one-dimensional force-based impact models. In these impact models the 'penalty method' is implemented, where the magnitude of the impact force is estimated based on an impact stiffness value and the overlapping distance (indentation) between the colliding objects.

The studies have shown that the type of the impact model and the corresponding impact parameters, of which the values are difficult to be determined, may affect significantly the computed results. Nevertheless, very limited experimental studies were performed to verify the accuracy of the various numerical impact models or to provide a safe guidance for the estimation of the impact parameters, such as the impact stiffness coefficient and the coefficient of restitution [6-9]. Moreover, the majority, if not all, of such experimental studies were performed on a shake table, subjecting the models to seismic excitations, which complicate the response, making the identification of the effects of impact forces difficult.

In the current study, a simple experimental setup is constructed, consisting of two single-degree-of-freedom (SDOF) systems that are let to collide freely between each other, without base excitation. The retrieved data is compared with numerical results that are obtained considering the most common types of force-based impact models. The purpose of this paper is to provide a better understanding on the effect of selecting different impact models and impact parameters on the computed responses when numerically simulating structural pounding.

2 EXPERIMENTAL SETUP

Two Single Degree of Freedom (SDOF) systems (frames) have been constructed, using thin galvanised steel columns with negligible mass and concrete beams as colliding masses. The columns are connected in such a way to behave as double-fixed members, while the concrete beams can be assumed rigid compared to the flexibility of columns. Therefore, the two models could be considered as frames with shear-type behaviour. The dynamic response of each system is recorded using high-definition digital instruments that record simultaneously the displacement and the acceleration with a time-step of 0.001sec. Specifically, two Laser Distance Meters (LDM1 and LDM1) with an accuracy of 0.001mm and two Accelerometers (A1 & A2) with a range of ±3g where arranged as shown in Figure 1.



(a) *(b)*

Figure 1. Experimental setup. (a) Photo, (b) Diagram, instruments and dimensions

At first, the two systems were let to free vibrate individually, without pounding, and the response was recorded (Figure 2). The dynamic properties of the two systems were determined after measuring the mass and processing the free vibration data of each frame (see Table 1).

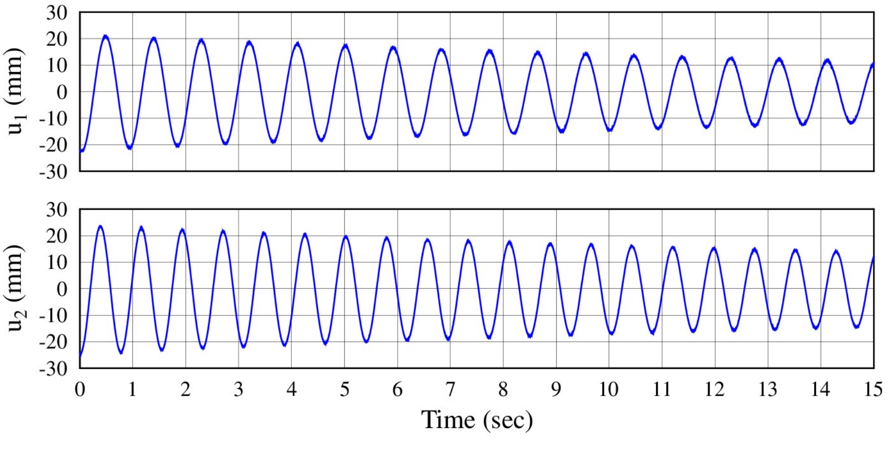


Figure 2. Free vibration response of the two SDOF systems

Table1. Dynamic properties of the two SDOF systems

Property	SDOF 1	SDOF 2
ass, m (kg)	6.0239	4.9871
Natural Period, T_n (sec)	0.909	0.772
Damping ratio, ζ	0.006	0.0046
Stiffness, k (N/m)	287.91	330.278

Then, the frames were aligned next to each other with a finite separation distance (initial gap), such as to allow pounding between the two concrete masses when the SDOF systems are vibrating. Since the purpose of the current study was to focus on the simulation of impact, the simplest form of vibration was chosen, i.e. the free vibration. Specifically, an initial displacement is induced at the first frame, while the second one is at rest. By releasing the first frame, pounding occurs between the concrete masses that initiates the vibration of the second frame as well. Since the length of the current paper is limited, in the following the results of such a test are presented where the initial gap was measured to be 23mm and the initial displacement of the SDOF1 was $u_1(0)$=-40mm. Figure 3 and 4 present the displacement and acceleration response of the two systems.

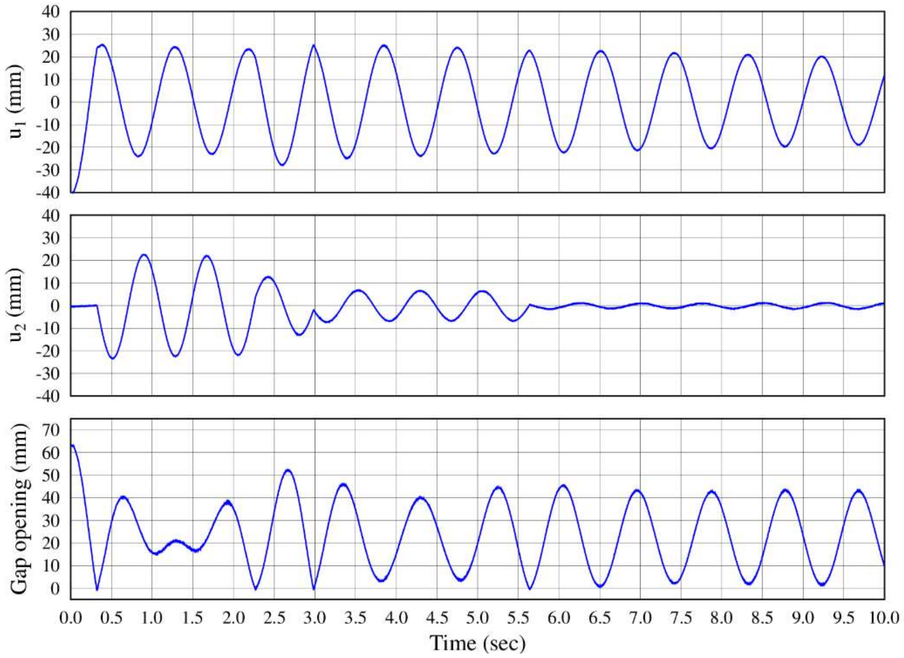


Figure 3. Displacement time-history of the two systems after inducing free-vibration with initial displacement of the SDOF1 (u(0)1=-40mm)

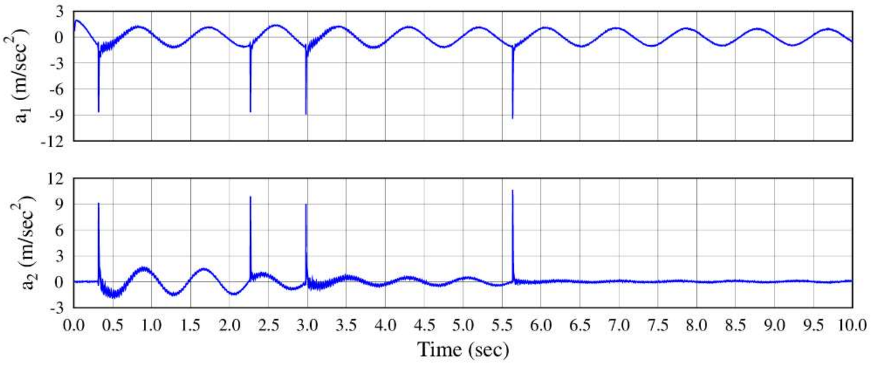


Figure 4. Acceleration time-history of the two systems after inducing free-vibration with initial displacement of the SDOF1 (u1(0) = -40 mm)

3 NUMERICAL SIMULATION

The two SDOF systems are simulated using custom code in Java language and the coupled dynamic problem is solved using the Central Difference Method, while pounding is considered using three common force-based impact models. According to the "penalty method", these impact models compute the impact force considering a linear or non-linear impact spring and an impact damper connected in parallel that are activated when a contact is detected [10]. Follows a brief description of the three impact models considered for this investigation.

3.1 Linear viscoelastic impact model

This impact model is also known as a Kelvin-Voigt model. Whenever there is impact, the impact force at time t is provided by the expression:

$$F_{imp}(t) = k_k \cdot \delta(t) + c_k \cdot \dot{\delta}(t) \tag{1}$$

where c_k is the impact viscous damping coefficient and $\dot{\delta}(t)$ is the relative velocity between the structures in contact at time t. Anagnostopoulos [11] has provided the following analytical expressions that associate the impact viscous damping coefficient with the coefficient of restitution (e) and the masses, m_1 and m_2, of the colliding bodies:

$$c_k = 2 \cdot \xi_k \sqrt{k_k \cdot \frac{m_1 \cdot m_2}{m_1 + m_2}}\ \text{, where}\ \xi_k = -\frac{ln\,\mathrm{e}}{\sqrt{\pi^2 + (ln\,\mathrm{e})^2}} \qquad \text{(2a), (2b)}$$

The coefficient of restitution is defined as the ratio of the relative velocity between the colliding bodies after and before impact. A value of the coefficient of restitution equal to zero corresponds to perfectly plastic impact, while a value equal to 1.0 corresponds to the case of no energy dissipation during impact, which means that the impact is perfectly elastic. In the current study, a minor modification of this impact model, proposed by Komodromos et al [12], is used to avoid the unrealistic tensile impact forces that emerge due to the damping term at the end of the restitution phase. The modification simply ignores those tensile impact forces.

3.2 Modified Linear viscoelastic impact model

Ye et al. [13] proposed a different modification to the Kelvin-Voigt impact model, noting that the Kelvin-Voigt model cannot reasonably reflect the physical nature of structural pounding. The proposed model preserves the convenience in determining the linear impact spring stiffness, while the damping coefficient $\hat{c}_k$ and the damping constant $\hat{\xi}_k$ are given by the following formulas:

$$\hat{c}_k(t) = \hat{\xi}_k \cdot \delta(t)\,, \qquad \hat{\xi}_k = \frac{3}{2} \cdot \frac{k_k \cdot (1-e)}{e \cdot (v_1 - v_2)} \qquad \text{(3a), (3b)}$$

3.3 Non-linear (Hertzian) viscoelastic impact model

Jankowski [14] proposed an improvement of the classical Hertz model [10] by incorporating a non-linear viscous damper parallel to the non-linear spring in order to include an energy dissipation mechanism. In this model, assumes that the kinetic energy is dissipated only during the approach phase, while during the restitution phase impact damping is neglected:

$$F_{imp}(t) = k_{imp} \cdot \delta(t)^{1.5} + c_{imp}(t) \cdot \dot{\delta}(t) \qquad for \quad \dot{\delta}(t) > 0 \tag{4a}$$

$$F_{imp}(t) = k_{imp} \cdot \delta(t)^{1.5} \qquad for \quad \dot{\delta}(t) < 0 \tag{4b}$$

where: $c_{imp}(t) = 2 \cdot \xi_{imp} \sqrt{k_{imp} \cdot \sqrt{\delta(t)} \cdot \frac{m_1 \cdot m_2}{m_1 + m_2}}$ and $\xi_{imp} = \frac{9\sqrt{5}}{2} \cdot \frac{1 - COR^2}{COR\left(COR(9\pi - 16) + 16\right)}$

4 RESULTS AND DISCUSSION

Considering the same structural properties and initial conditions for the SDOF systems, as recorded in the experiment, a set of numerical simulations was performed to assess the efficiency and accuracy of the above impact models, as well as to examine the sensitivity of the impact parameters on the computed response. The authors support that the simplicity of the chosen excitation (i.e. free vibration) makes it easier to emphasise on the impact modelling rather than having a base excitation that would complicate the response, making the interpretation of results more difficult and the conclusions more doubtable.

The problem is solved numerically, considering the three different impact models that are described above for different values of the impact stiffness coefficient and the coefficient of restitution. In this way, the effect of the values of those impact parameters on the computed responses can be evaluated and discussed. This is important since there is no safe methodology yet to determine their precise values or a way to associate them with a physical property.

4.1 Effect of the coefficient of restitution

The plots in Figures 5 and 6 present the comparison between experimental and numerically computed results, using the classical Kelvin-Voigt impact model for different values of the impact parameters. Specifically, for the three plots on the left column of Figure 5 three different values of the coefficient of restitution (*e*) are used: 0.35, 0.5 and 0.75. It is observed that the low value (*e*=0.35) slightly underestimates the displacement of the SDOF2, which was initially at rest before the 1st impact initiates its free vibration. On the other hand, a relatively high coefficient of restitution (*e*=0.75) overestimates the deflection of the frame. The value of 0.5 for the particular model and materials used seems to capture very well the response.

The effect of the coefficient of restitution on the acceleration response can be observed in the 3 plots of the left column of Figure 6. It is interesting to see that a relatively high value of *e* not only increases (slightly) the amplitude of the high spikes of acceleration that emerge at the time of impact, but also affects the overall response since a new impact incident occurs at time 8.3 sec that did not occur in the experiment.

Taking a look at the recorded gap-opening time-history from experimental results presented previously in Figure 3, a rough estimation of the coefficient of restitution can be made by simply dividing the second peak of the gap-opening (*t*=0.64s, after impact) over the first peak (at *t*=0, before impact). Specifically, in the particular case the $\max(gap)_{0.64}$=40.2mm and the $\max(gap)_0$=63mm, resulting to an *e*=0.64, which coincides with typically used values in the literature for concrete structures (0.5-0.7). The value is not too far from 0.5 and gives very similar results but due to limited space are not presented here.

4.2 Effect of the impact stiffness

The three plots on the right side of Figures 5 and 6 present the displacement and acceleration response, respectively, for three different values of the impact stiffness coefficient: 100, 200 and 20000 N/mm. So, totally there are four different cases of impact stiffness considering the middle plot on the left with a value of 2000 N/mm. For all four cases the coefficient of restitution is taken 0.5. It is obvious that the value of the impact stiffness has a negligible effect on the displacement response, while it affects significantly the amplitude of the spikes in the acceleration response. The higher the value of the impact stiffness, the higher the acceleration at the time of impact. Nevertheless, the rest of the acceleration response is not affected.

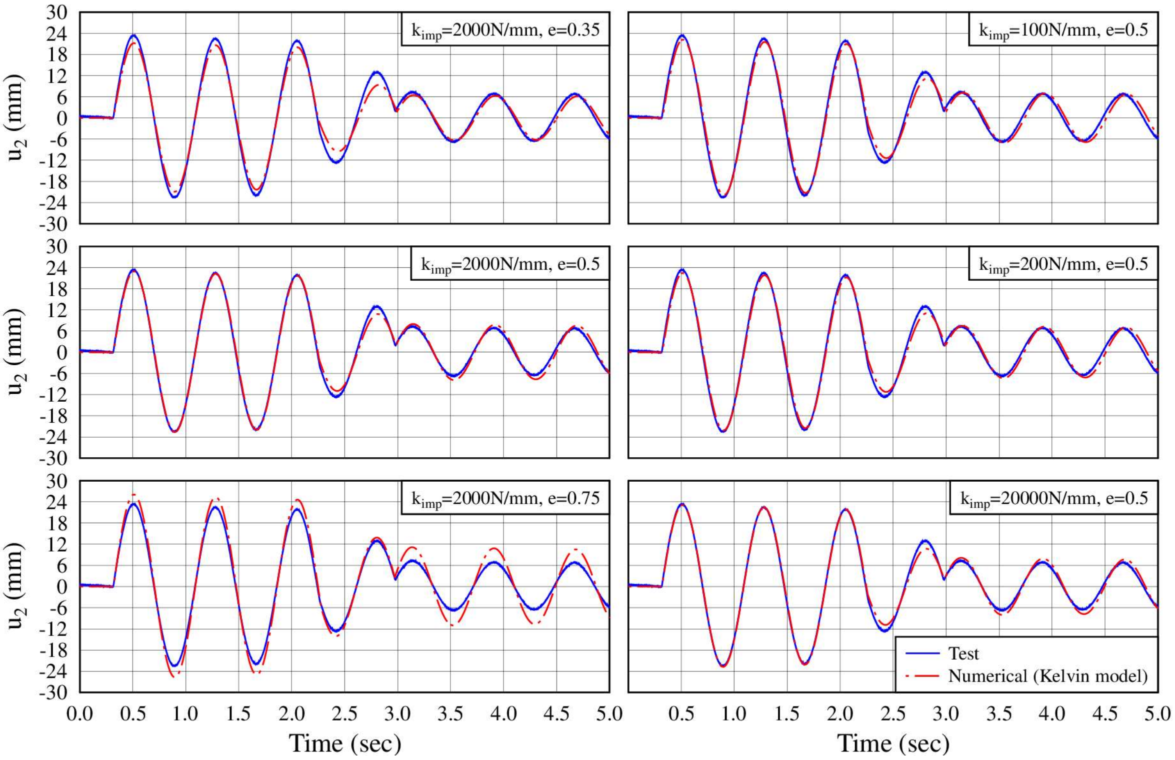


Figure 5. Displacement time-history of the SDOF2 system compared with the corresponding response computed using the Kelvin-Voigt model for different values of the impact parameters

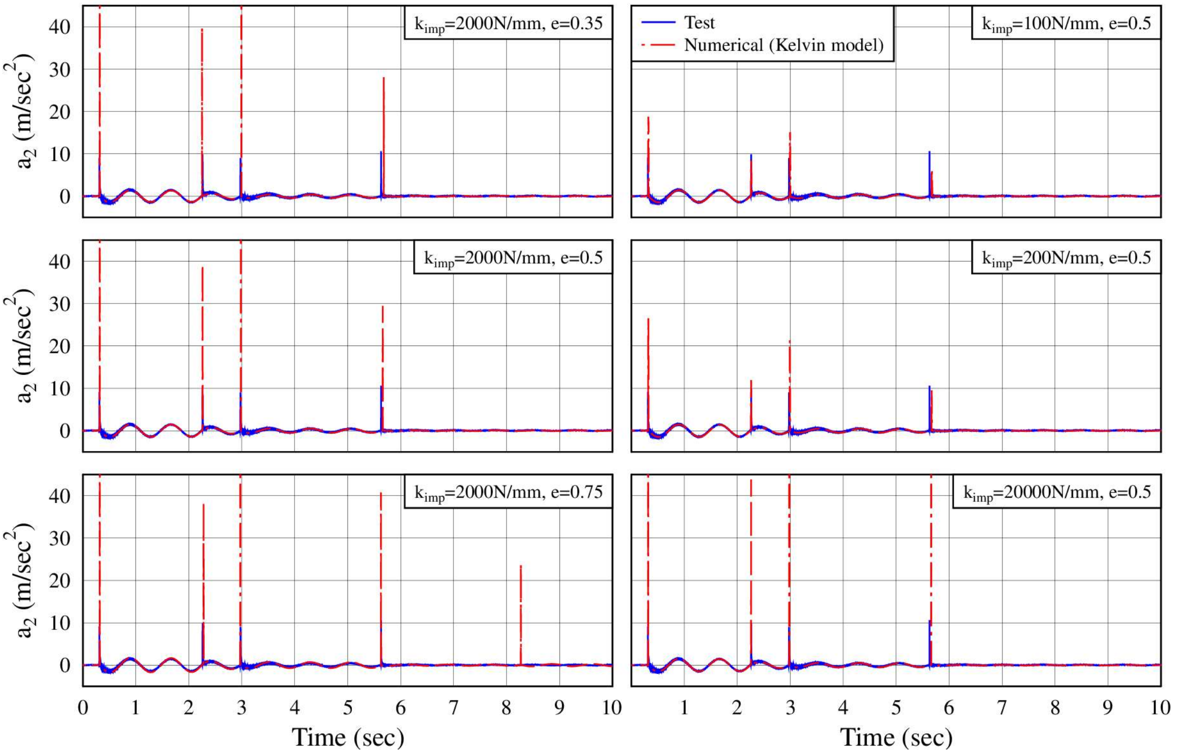


Figure 6. Acceleration time-history of the SDOF2 system compared with the corresponding response computed using the Kelvin-Voigt model for different values of the impact parameters

4.3 Effect of using different impact models

The same plots are produced performing the numerical simulations using the Modified Linear Viscoelastic impact model proposed by Ye et al. [13] and the Non-linear viscoelastic impact model proposed by Jankowski [14]. The plots are presented in Figures 7 and 8 for the former and Figures 9 and 10 for the latter. It is important to mention that the observations described above regarding the effects of the impact stiffness and coefficient of restitution apply for all impact models. In addition, it is observed that all three models can capture very well the response involving pounding.

The same values of the impact parameters are used for both linear models, but it seems that, for the particular impact parameters values, the Kelvin-Voight model matches better with the experimental results. It is though possible to achieve a better fit using the Modified linear model with a different combination of values.

In the case of the non-linear viscoelastic impact model, the impact stiffness takes different values, since the units are in N/mm$^{1.5}$ and usually an appropriate value is one order of magnitude lower than the corresponding linear models. In the particular case, a value of 500 N/mm$^{1.5}$ is taken as benchmark and seems to give satisfactory results, especially for the acceleration response. Specifically, the computed acceleration spikes are not so high as in the case of linear impact models, while the displacement response is well matching. Here, worths mentioning though that the true accelerations that the two masses experienced during the test may were much higher than those recorded by the instruments, due to various reasons. One such reason is the sensitivity and recording ability of the utilised acceleration sensors, which in this case is ± 3g according to the supplier. Another reason of false recording is the very short duration of impacts (2-4 milliseconds) in combination with the finite recording time-step (1 millisecond).

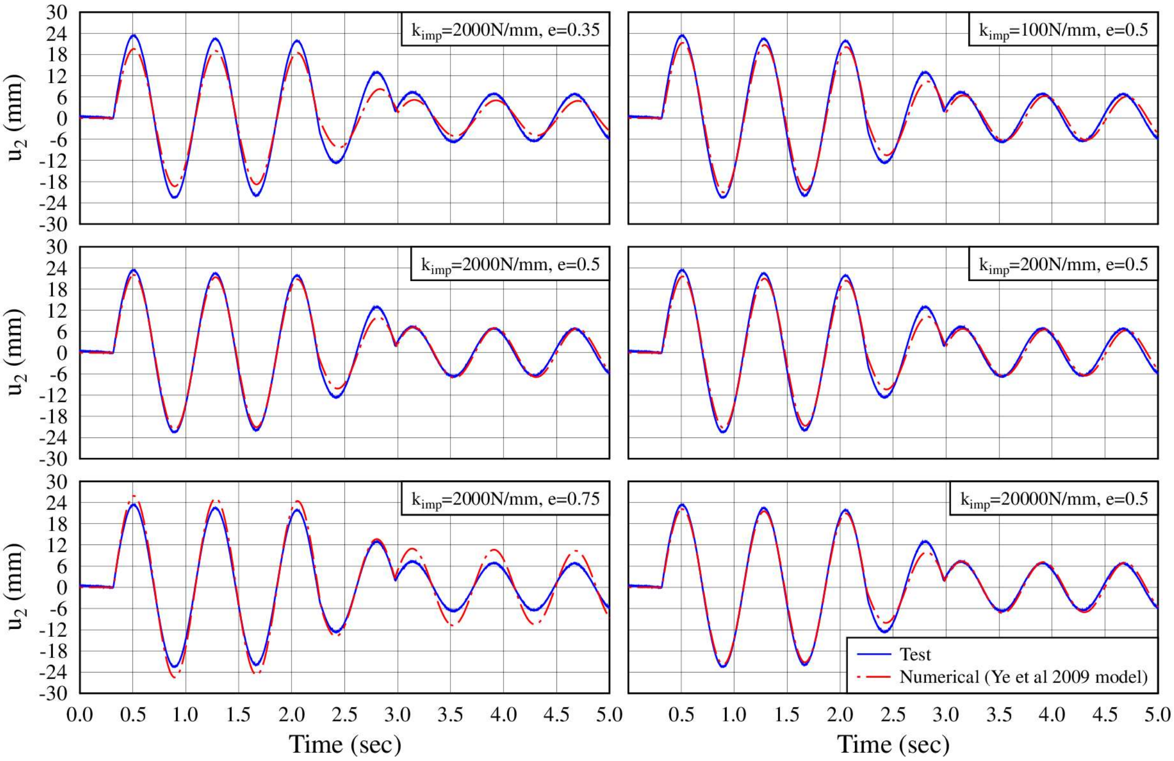


Figure 7. Comparison of the recorded displacement time-history of the SDOF2 system with the corresponding response computed using the Modified Viscoelastic Impact model [13] for different values of the impact parameters

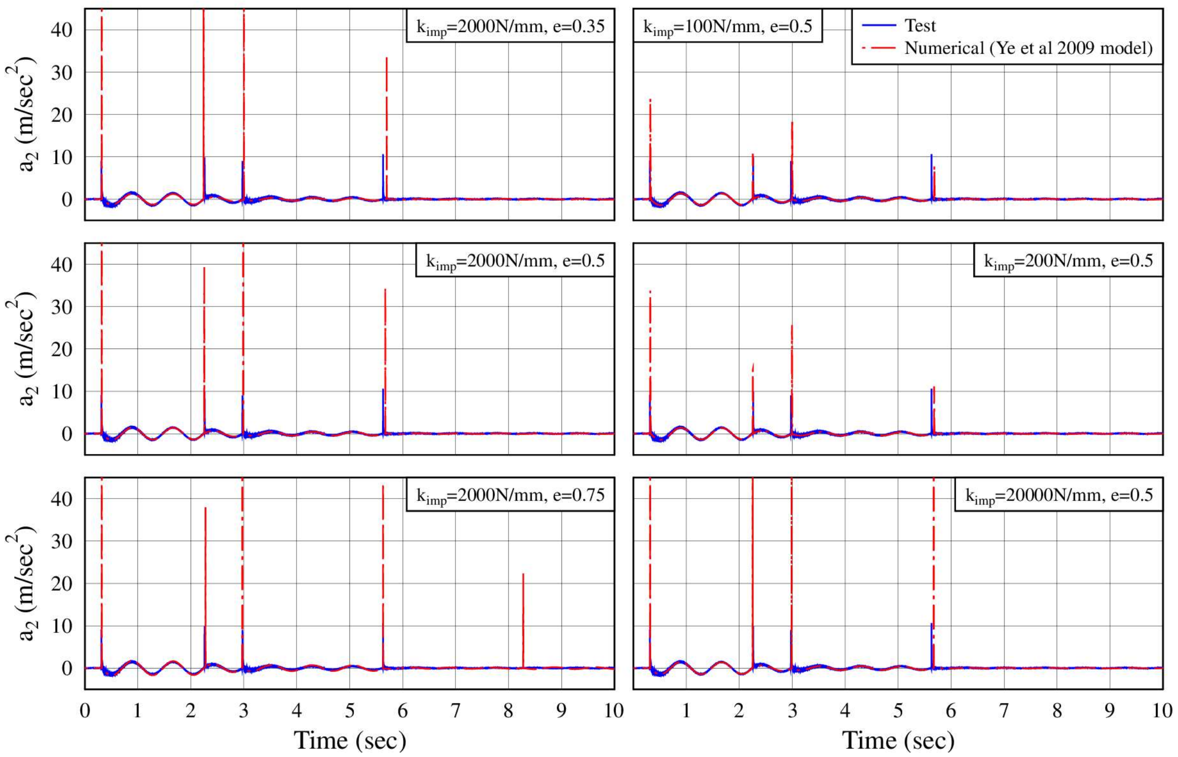


Figure 8. Comparison of the recorded acceleration time-history of the SDOF2 system with the corresponding response computed using the Modified Viscoelastic Impact model [13] for different values of the impact parameters

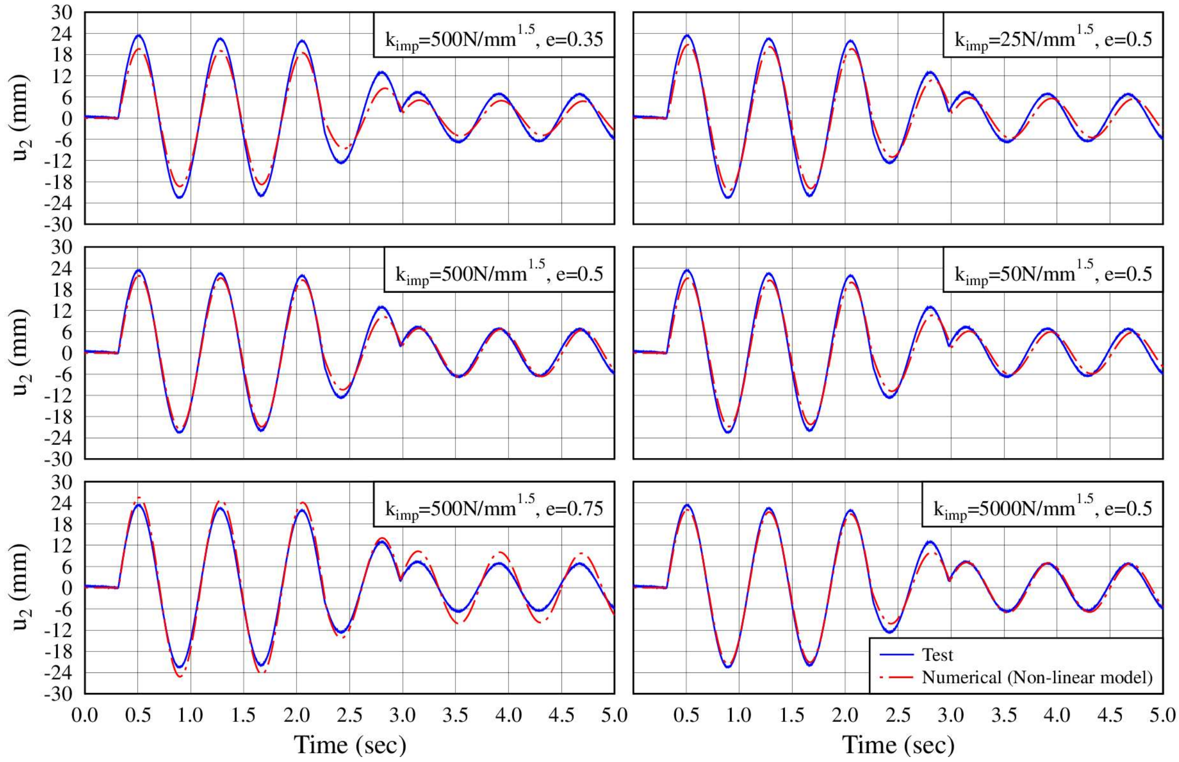


Figure 9. Comparison of the recorded displacement time-history of the SDOF2 system with the corresponding response computed using the Non-linear Viscoelastic Impact model for different values of the impact parameters

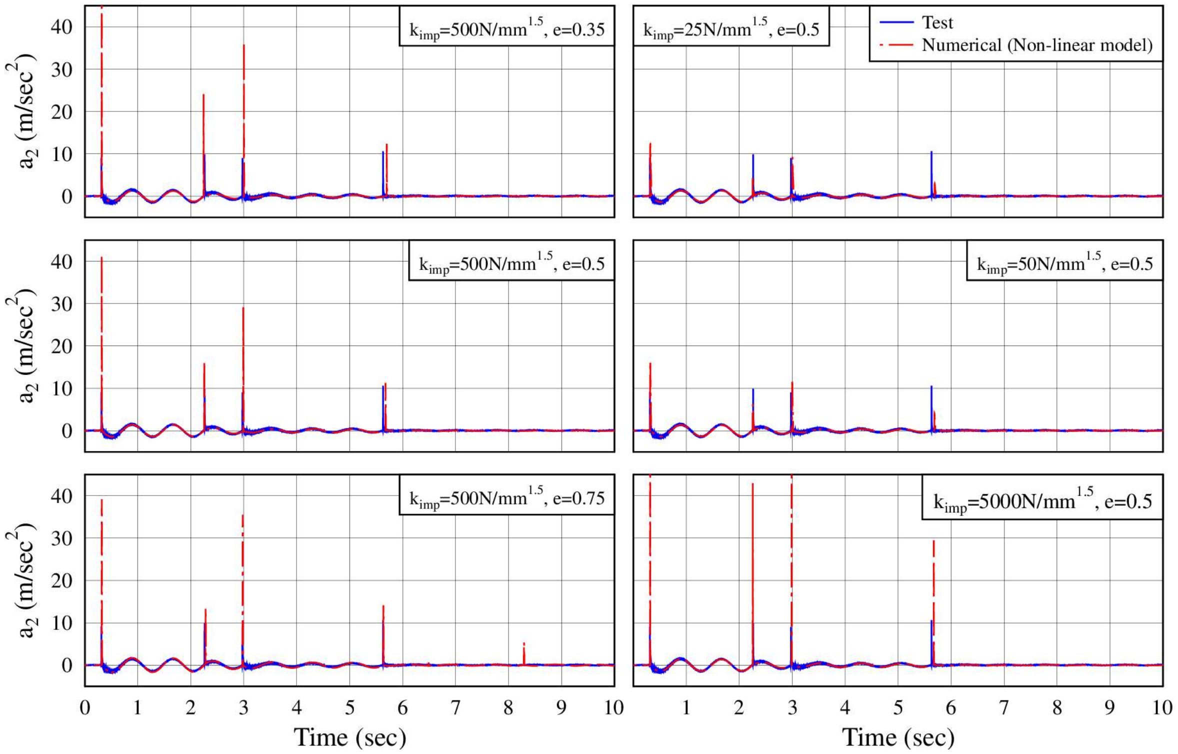


Figure 10. Comparison of the recorded acceleration time-history of the SDOF2 system with the corresponding response computed using the Non-linear Viscoelastic Impact model for different values of the impact parameters

5 CONCLUSIONS

When using a force-based impact model for simulating seismic pounding in adjacent structures, it is important to know its limitations and drawbacks, as well as the sensitivity of the involved impact parameters values, which are usually assumed. This study tries to provide information relevant to the above requirement, using a simple experimental setup and comparing the recorded data with the corresponding numerical results obtained considering three common impact models. The results indicate that all three impact models can capture with sufficient accuracy the response of the colliding systems, if appropriate values are chosen for the impact parameters. Unfortunately, there is not yet a safe method to determine the exact value of the impact stiffness. However, the above results indicate that the effect of the impact stiffness on the deflections is negligible, even in the case of varying its value by an order of magnitude. There is high dependency of the acceleration value during impact with the impact stiffness value, however the rest of the response is unaffected. In structural design, though, the deflection response is more important. Regarding the coefficient of restitution, it is observed that its value affects in greater degree the response, both deflections and accelerations. So, its value must be more carefully selected based on the type of materials in contact and their mechanical characteristics [9].

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