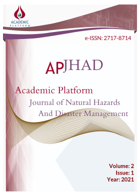

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Seismic Pounding Between Adjacent Buildings: A Review

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Abstract

The collision between adjacent buildings with an insufficient seismic separation distance has been reported after earthquakes. This collision between adjacent buildings, commonly referred to as earthquake-induced pounding, entails huge damages to the involved buildings. The main cause of damage was interpreted to the developed impact forces between colliding buildings. The intensity of the impact force relies on many factors, therefore, a significant research effort was found to address this issue from different perspectives. This paper presents a summary of the main research conducted in the context of structural pounding namely, field observations, experimental and numerical studies. The main recommendations and results of each category have been highlighted and insights for future research are provided.

Keywords: Pounding, impact force, RC buildings, separation distance

1. Introduction

Limited inhabitable land in highly populated countries is a typical problem around the globe. As such, for the optimum use of the available land, most of the existing buildings in these regions were found with no separation distance even in highly earthquake-prone regions [1]. During earthquakes, these buildings undergo lateral displacement, and, therefore, potential collisions between adjacent buildings are inevitable. The collision between adjacent structures, also known as earthquake-induced pounding, introduces waves of stress due to the impact between the adjacent buildings. These waves of stress, which are not considered during the design stage, significantly change the global response of the colliding buildings namely the loading path and, therefore, the failure mechanisms.

Based on the post-event survey after major earthquakes, adjacent buildings showed a vulnerable performance with excessive damages compared to the individual buildings [2-4]. The observed damage varies from local damages at the contact surface to more severe damages namely shear failure at beam or columns and even the global collapse. Devastating earthquake events entail huge life and economical losses particularly for those structures with inherited seismic vulnerability. Earthquakes, however, keep deepening the knowledge of the scientific community and keep raising the awareness of the scientific, technical and political community to the need of identifying assets at risk (i.e., such adjacent buildings) and developing more

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effective risk mitigation strategies. Based on the provided lessons from major earthquakes, a vast body of literature addressing the pounding effects on the structural response of adjacent structures during earthquakes have been found over the past five decades (e.g., see [5-19] among others). The research on earthquake-induced pounding was found in different scales; from studying the impact phenomena to the global performance of the adjacent structures. Also, the critical pounding configurations, these with a high probability of experiencing severe damage due to earthquakes, have closely been studied. This paper categorises the literature on earthquake-induced pounding into three main groups; studies related to the post-earthquake field observations, experimental studies, and numerical studies. An overall summary of each type of these categories has been provided with an emphasis on the points which need to be covered in future studies.

2. Problem statement and paper organization

The separation distance that mitigates the collisions between adjacent buildings is required by several design regulations [13], however, most existing buildings are found either with no separation distance or with insufficient separation [10]. As such, a collision between the adjacent buildings is expected during earthquakes. Depending on the relative dynamic characteristics of the adjacent buildings (e.g., fundamental period, mass, height, stiffness, orientation, geometry, etc.), the intensity of the collision can be classified into two scenarios as shown in Figure 1. In which for buildings with similar dynamic characteristics, the developed later displacement of the adjacent buildings will be synchronized (in-phase), therefore, no collision is expected. However, given the building-to-building variability, the adjacent buildings most likely develop different lateral responses (out-of-phase), as such, collisions between adjacent buildings with insufficient separation distance are inevitable. This collision between adjacent buildings results in different damage levels which vary from local damage at the contact locations during moderate seismic excitation or significant damage or even global collapse for more severe earthquakes as shown in Figure 2.

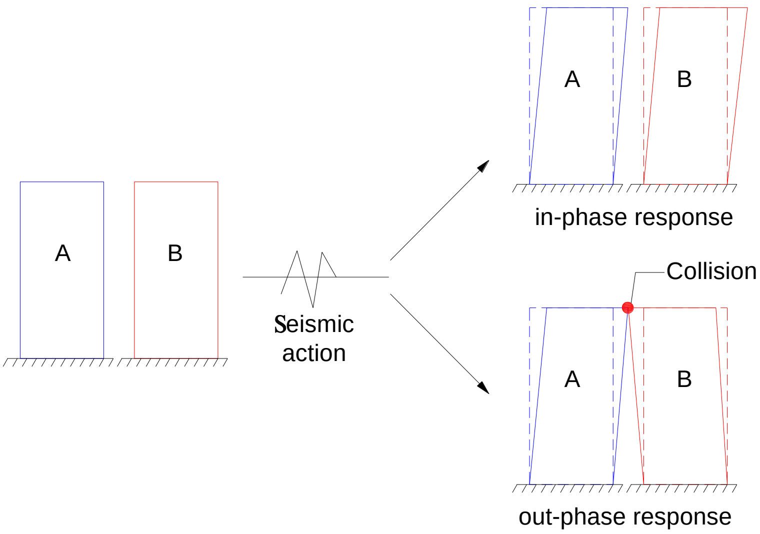

Figure 1. A Schematic sketch for the potential responses of two adjacent buildings

a) damage at contact [20] *b) damage at infill walls [20]* *c) global collapse [21]*

Figure 2. Damage pattern due to pounding effect

Field observation studies of the damage patterns of the adjacent buildings after recent major earthquakes come as the first approach for a better understanding of the seismic pounding. However, the limited available data promotes researchers to define other alternatives to closely study the earthquake-induced poundings. As typical approaches for studying similar problems, experimental and numerical studies were found in the literature to address the seismic pounding. A limited number of experimental studies were found in the literature due to the associated resources. In contrast, promoted by the limited required resources compared to experimental investigations, several numerical studies have been conducted in different scales. This paper presents first the studies related to the observed damages after recent major earthquakes. Based on these field observations, the critical configurations of pounding between adjacent buildings are presented. Thereafter, the experimental and numerical studies are presented, highlighting the main aspects of these studies and their main conclusions.

3. Field observation investigations

The great Alaskan earthquake in 1964 provided the first piece of evidence on the vulnerability of adjacent buildings with insufficient separation distance [22, 23]. Since then, structural pounding was identified as the cause of several damage patterns and mechanisms that lead to the global collapse of the inadequately separated buildings [22, 23]. Thereafter, several field observations correlated damage patterns and collapse mechanisms with structural poundings. For example, the collapse of the external stairway of Olive View hospital, after the San Fernando earthquake in 1971 showed the vulnerability of buildings at the end of a row of buildings and those with significant differences in their dynamic characteristics [24]. Also, it was observed after the Mexico City earthquake in 1985 that pounding affected over 40% of the 330 affected buildings. The pounding was the primary cause of collapse at least 15% of the pounding-affected buildings [21]. In the same context, in the survey database after the 1989 Loma Prieta earthquake over 200 out of 500 inspected buildings were found pounding-affected [20]. Whereas the pounding of adjacent unreinforced masonry (URM) buildings entailed shear failure of the brickwork leading to the partial collapse of the wall. The structural pounding was also observed in many adjacent buildings after the 1999 Chi-Chi earthquake struck centre of Taiwan. However, schools that have been expanded by new adjacent structure experienced a higher probability of damages. Whereas the old and new classrooms have a difference in height, stiffness, and mass due to the different construction times. Thus, these structures developed an out-of-response, leading to the high level of damages [25]. Similar observations were drawn after Kocaeli earthquake and North Athens for the same years [26].

The Kaliningrad earthquake in 2004 emphasised that pounding configuration plays a fundamental role in the overall behaviour of adjacent buildings. Whereas, buildings with eccentric pounding configurations exhibited local damages (plaster spalling) due to the excessive torsion strain along the contact area [27]. More recently, the observations after the Christchurch earthquake, 2011, showed that 6% of the 376 surveyed buildings in the central business district damaged by the pounding [2]. Given that unreinforced masonry (URM) buildings are the most common structures in that central district, most of the observed are located at this type of buildings. These damages are interpreted to brittle behaviour of the URM which cannot sustain the large demand of the pounding in a short period. Recently similar observations have been reported after the 2020 Sivrice-Elazığ, Turkey earthquake [28], emphasising the fragile behaviour of adjacent buildings with unaligned slabs which jeopardize the safety of the buildings due to the shear failure of the impact columns.

It can be concluded that damage observed in adjacent buildings that pounded varied from local damage in infill walls to more severe damage such as shear failure of columns and even collapse. Moreover, five pounding configurations were identified to exhibit a high probability of damage during earthquakes, which are shown in Figure 3. These configurations include adjacent buildings exhibiting floor-to-column alignments, adjacent buildings with significant mass or height differences, buildings at the end of a row of buildings, and buildings likely to experience eccentric pounding [2, 3, 16, 29].

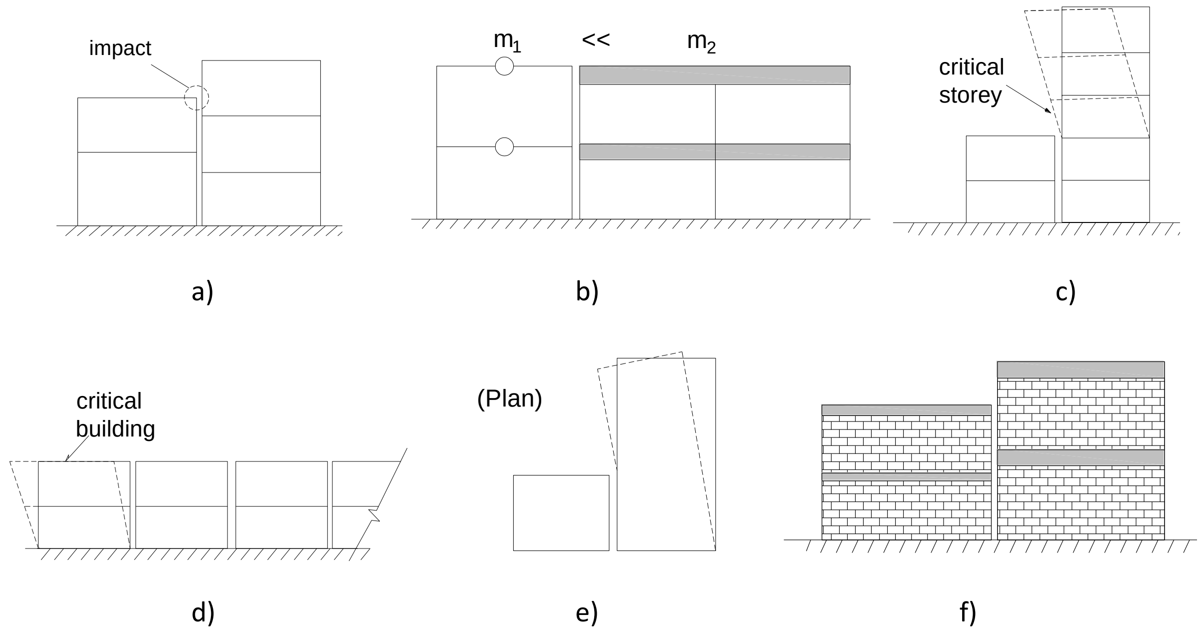

Figure 3. Critical pounding configurations after Cole, et al. [16]

4. Experimental studies

Mier, et al. [30] conducted a series of tests to investigate the impact between two concrete elements. This test has been performed in form of a pendulum experiment where strikers (concrete blocks with various front shapes) were used to impact prestressed concrete piles. Several parameters were considered in this study such as the compressive strength of the concrete element, the size of the plastically deformed zone in a static test, etc. Based on this test, a proposal for the definition of the contact parameters based on a static test has been introduced. Papadrakakis and Mouzakis [31] tested one-bay-building adjacent frames with two storeys using a shaking table simulator. The structures were designed to maintain their elasticity under the imposed excitation with a design spectrum of 1.0 g. Furthermore, the dynamic characteristics of the tested frames were adjusted to simulate the scenario of a stiff building adjacent to a flexible building with no gap distance. The structures were subjected to a ramped sinusoidal displacement signal having a peak displacement of 0.13 cm and at resonance with the fundamental frequency of the flexible structure (f = 4.1 Hz). Based on the experimental measurements, they concluded that acceleration responses for the tested frames were dramatically increased (six-fold increase) due to the pounding effect. Due to the tested frames were well-designed and the low level of excitation, this test did not provide further information regarding the damage pattern. Chau, et al. [32] carried out a series of shaking table tests to estimate the pounding responses between two steel towers with different natural frequencies, damp ratios, and separations. The structures were subjected to sinusoidal waves of various magnitudes and frequencies, as well as the ground acceleration of the 1940 El Centro earthquake. It was found that pounding generates a significant amplification in the response of the stiffer structures and reduces the flexible structure's response. It was found that the maximum relative impact velocity occurred at an excitation frequency between the natural frequencies of the two structures. Rezavandi and Moghadam [17] conducted shaking table experiments on reduced-scale moment-resisting one-bay steel frames subjected to harmonic excitation and real seismic ground motion. Series of tests were performed to investigate the effect of the distance between the buildings, impact-absorbing material, and the case when adjacent frames are connected. Experiments and numerical analyses have revealed both the effectiveness and drawbacks of each method for reducing pounding effects. However, impact-absorbing materials were found to be more effective in reducing the pounding effect. Furthermore, they concluded that frame responses were highly sensitive to the gap between them. More recently, Jankowski, et al. [14] performed a shaking table test on pounding using three reduced-scale steel frames with various configurations and different gap separation distances between them. In addition to the obvious conclusions drawn by previous researchers, this test referred to that the increase or decrease of the gap distance may lead to the increase or decrease in the response under different earthquakes with no specific trend.

In a general sense, these studies emphasised that structural pounding has a great contribution to the dynamic response of adjacent buildings and this contribution should not be discarded. However, as can be seen, a limited number of experimental tests were found. In addition, most of the experimental tests were performed using a single degree of freedom or reduced scale steel frames. Furthermore, most studies emphasised the difficulty of obtaining precise measurements; some studies suggest that accelerometers be supplemented with acoustic signal sensors and video recorders. Given the scarcity of experimental results in full-scale buildings, numerical modelling, in particular detail micro-model, can be used as a proxy for the experimental tests.

5. Numerical studies

Modelling earthquake-induced pounding between buildings requires using an accurate numerical model, particularly that simulates the impact between the colliding bodies. In this context, existing numerical studies can be divided into two types: element-level studies that focused on modelling and developing the collision model between adjacent buildings, and the structure-level studies which focused on structures' response considering the collisions by using predefined impact element. The main objective of the former-mentioned studies is to define a reliable numerical model to simulate impact phenomena. On the other hand, using the recommendations of element-level studies, the structure-level studies aim to define the effect of the pounding on the overall behaviour of adjacent buildings in a more comprehensive way. The next sections will briefly address these numerical studies, highlighting their main objectives and findings.

5.1 Numerical studies in element-level (impact modelling)

As referred before, the vast majority of the research that tackled pounding relied on numerical simulation due to its feasibility compared to the experimental tests. Whereas the reliability of the model that simulates the impact phenomena is the key element for realistic numerical simulations, several numerical studies have been developed to address this issue (e.g., see [33-36] among others). These studies highlighted that adequate modelling of the impact between adjacent buildings is fundamental. The general idea of modelling the impact between two adjacent buildings is to define the interaction between the two bodies during and after the impact using predefined mathematical rules. Two approaches with different theoretical-based were found in the literature to model the impact between colliding bodies: *stereo mechanics approach and force-based approach*. Depending on the impact stag, these approaches provided different mathematical formulations for the impact. To recognize these stages, Figure 4 shows two spherical bodies at different stages of impact. As can be seen, the two bodies with mass m_1 and m_2 are approaching each other with velocity v_1 *and* v_2 (at left) and getting closer until the penetration displacement δ equals zero, in which the impact is imminent. Thenceforth, the two bodies are called in the *approach phase*. At that stage, the penetration distance δ and relative velocity *dv* are larger than zero. This phase ends when penetration distance δ reaches to δ_{max} value and *dv* equals zero. From that point, the two bodies start to separate which is called the *restitution phase*. The restitution phase lasts until δ reaches zero again with final velocities v'_1 *and* v'_2 for m_1 and m_2, respectively. The main idea behind the impact numerical model is to modify the dynamic response of the colliding bodies according to their impact stage. The next sections present the referred approaches (i.e., stereo mechanics approach and force-based approach), highlighting their privileges and drawbacks.

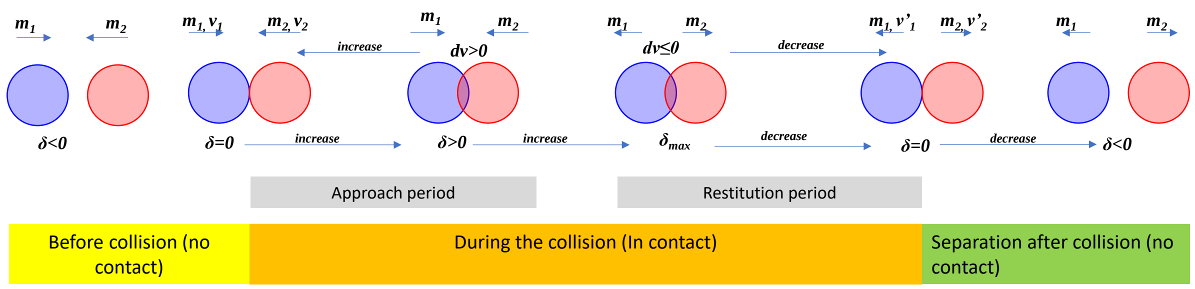

Figure 4. Schematic diagram of the impact between two spherical bodies at different impact stages

5.1.1 Stereo mechanics-based model

Despite being less common in use nowadays, the classical theory of impact (stereo mechanics) method still represents an important concept. In a general sense, stereo mechanics theory determines the post-collision velocity of colliding elements without tracing structural response by considering the conservation of momentum over the duration of impact [37]. Based on this theory, the final velocities of two bodies with m_1 and m_2 masses that impacted at initial velocities of v_1, v_2, respectively, can be determined as follows:

$$v'_1 = v_1 - (1 + e)\ \frac{m_2}{m_2+m_1}(v_1 - v_2) \tag{1a}$$

$$v'_2 = v_2 + (1 + e)\ \frac{m_1}{m_1 + m_2}\ (v_2 - v_1) \tag{1b}$$

Where v'_1, $v'_2$are the final velocities (i.e., after impact, see Figure 4) for the two bodies, respectively, and e is a coefficient of restitution. The coefficient of restitution (e) is defined as the ratio of the separation velocities of the bodies after impact to their approaching velocities before impact, which can be obtained from the equation:

$$e = \frac{v'_2 - v'_1}{v_1 - v_2} \tag{2}$$

The coefficient of restitution is a measure of plasticity in the collision. It depends on the relative shapes of the colliding structures, their material properties, and masses. The value of e = 1 corresponds to the case of a fully elastic collision, while the value of e = 0 deals with a fully plastic impact. Even though this approach has a rigorous theoretical base, its use is limited in the literature of the pounding between adjacent buildings due to the involved limitations regarding the tracing stresses transformation between the colliding bodies [37, 38]. These limitations due to the fact that the *Stereo mechanics*-based model focuses only on the determination of the velocity of colliding elements after the collision assuming that impact lasts for a negligibly short time therefore, this approach does not consider the transformation of stresses and deformations between the element of colliding bodies during impact. Furthermore, for multiple degrees of freedom system when several colliding expected at various time, the application of the Stereo-mechanics based model is seen as infeasible [34].

5.1.2 Force-based models

The ability of the force-based approach to simulate the interaction between the colliding bodies in terms of stresses and deformation enables to overcome the limitations of the *Stereo mechanics*-based model. Moreover, their inherited simplicity and ability to be incorporated into time history analysis programs facilitated the widespread use of this approach [10, 36, 38]. The base of this approach is to impose a force during the impact between the colliding bodies which is known as impact force F. The impact force represents the measure to consider the interaction between the two bodies considering the relative dynamic characteristics of the colliding bodies. For clarity, the two structures 1 and 2 that are shown in Figure 5, are considered. The equation of motion of the two systems 1, 2 oscillating under an earthquake excitation $\ddot{u}_g$ can be expressed as:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix} + \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} + \begin{Bmatrix} F \\ -F \end{Bmatrix} = -\begin{bmatrix} m_1 & 0 \\ 0 & m_1 \end{bmatrix} \begin{Bmatrix} \ddot{u}_g \\ \ddot{u}_g \end{Bmatrix} \tag{3}$$

in which $u_i, \dot{u}_i$ and $\ddot{u}_i$ are the response in terms of displacement, velocity, and acceleration, respectively, of the ith system (1 or 2, according to the suffix) along the excitation direction, while m_i, c_i and k_i are the mass, damping and stiffness matrices, respectively, of the ith system (1 or 2, according to the suffix). The vector $\{\mathrm{F}, -\mathrm{F}\}$ contains the impact forces representing the interaction between the two systems during the collision otherwise, this vector will be null. Several proposals were found to express F as a function of the relative displacement between the colliding bodies, with linear or a nonlinear force relation and with/without viscous damper, [10, 34, 38]. Table 1 provides a brief description of these types along with their main modelling features. As can be noticed that the modelling of impact forces evolved from linear spring with no energy dissipation capabilities to these with full energy dissipation capabilities through nonlinear relation between the impact force and the penetration along with that dissipated in damping. Even though the latter is more accurate in terms of simulating the real behaviour, the former model (i.e., linear viscous model) was found to be more efficient for computationally-intense applications such as performance-based studies due to its balance between simplicity and accuracy [10, 36, 38].

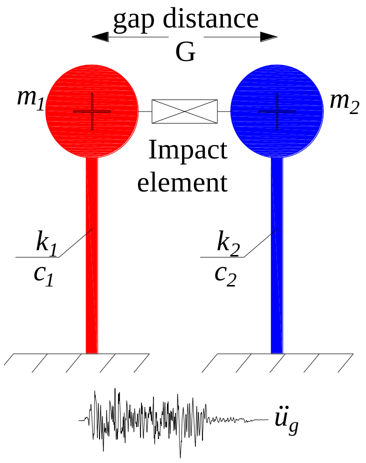

Figure 5. Representation of the force-based approach for two structural systems oscillating due to earthquake excitation

5.2 Numerical studies in structure-level

Based on the developed models in the previous section, several studies involved realistic building configurations were conducted to address the significance of the pounding effect on the global structural response during seismic actions (e.g., see [6, 8] among others). The manifold parameters involved result in multidirectional studies. Some of these studies were detected to quantify the safe separation distance between adjacent buildings, (e.g., see [44-48] among others). Other studies were conducted to investigate the effect of the dynamic characteristics of the involved structures either using a deterministic approach (e.g., [8, 49] among many others) or using a probabilistic approach [6, 50]. However, due to the high computational costs for the probabilistic approach particularly when the impact element is involved, the latter approach was found in a limited number of studies compared to the former approach. Moreover, others tackled the site and soil condition of the adjacent building [13, 51]. Eventually, the mitigation measures were presented in many studies as in [6, 52, 53].

As a general conclusion of all presented studies, the pounding effect reduces the displacement response of adjacent buildings on their impacted side and amplifies the displacement response on their unimpacted side [8, 13]. Additionally, pounding was also found to increase the acceleration response of the adjacent buildings during the impacts. However, the majority of these studies addressing the pounding phenomenon have limitations, i.e., none of them addressed the situation of the buildings at the end of a row of buildings also or these studies analysed the effect of pounding using a limited number of ground motion records. As such, results from previous research are not seen to be fully generalized [3, 6, 13, 16, 54]. Therefore, probabilistic studies should be carried out to analyse the significance of the pounding phenomena on the global response of structures.

Table 1. Impact force F based on various force-based model

model [reference]	**Theoretical expression**			**Main feature**	**Damping ration expression**	**Notations**
	Approach phase $u_1 - u_2 > G$ & $\dot{u}_1 - \dot{u}_2 > 0$	Restitution phase $u_1 - u_2 > G$ & $\dot{u}_1 - \dot{u}_2 \leq 0$	#After /before impact			
Linear impact model (*Kelvin-Voigt model*) [33, 39, 40]	$F = K(u_1 - u_2 - G)$		0	Linear model Kelvin-Voigt model	None	K is the spring stiffness in form of *f/d* where *f* is in the force unit and *d* is in the displacement unit
Linear viscoelastic *Modified Kelvin-Voigt model*	$F = K(u_1 - u_2 - G) + C(\dot{u}_1 - \dot{u}_2)$		0	Count for the energy dissipation by considering the damping term	$^+C = 2\zeta\sqrt{K\left(\frac{m_1 m_2}{m_1 + m_1}\right)}$ where $\zeta = -\frac{\ln e}{\sqrt{\pi^2 + (\ln e)^2}}$	
Modified Linear viscoelastic model [35]	$F = K(u_1 - u_2 - G) + C(\dot{u}_1 - \dot{u}_2)$	$F = K(u_1 - u_2 - G)$	0	Eliminates the tensile force at the restitution phase	$\zeta = \frac{1 - e^2}{e(e(\pi - 2) + 2)}$	
Hertz model [37, 41]	$F = K_h(u_1 - u_2 - G)^{3/2}$		0	Introduce nonlinear form for the impact force which is a more effective way	None	
Hertzdamp model [36]	$F = (u_1 - u_2 - G)^{3/2}[K_h + \bar{\zeta}(\dot{u}_1 - \dot{u}_2)]$		0	Count for the energy dissipation by considering the damping term	$\bar{\zeta} = \frac{3K_h(1 - e^2)}{4(\dot{u}_1 - \dot{u}_2)}$	K_h is the impact stiffness in form of *$f/m^{3/2}$*
Modified nonlinear viscous model [34]	$F = K_h(u_1 - u_2 - G)^{3/2} + C_h(\dot{u}_1 - \dot{u}_2)$	$F = K_h(u_1 - u_2 - G)^{3/2}$	0	Eliminates the tensile force at the restitution phase	$* C_h = 2\check{\zeta}\sqrt{K_h\sqrt{(u_1 - u_1 - G)}\frac{m_1 m_2}{m_1 + m_2}}$ $\check{\zeta} = \frac{9\sqrt{5}}{2}\frac{1 - e^2}{e(e(9\pi - 16) + 16)}$ [42]	

⁎ modified versions of ζ have been proposed in
+Based on [43]
#$u_1 - u_2 \leq G$

Conclusions

This paper presents a review of the research that tackled the seismic pounding between buildings. These studies were categorized into three main groups: field observation studies, experimental studies, and numerical studies. As a general conclusion for all these studies, structural pounding changes the dynamic response of the adjacent structures and using mitigation measure are highly recommended. Also, for the numerical modelling of impact element, it can be concluded that, even though the nonlinear model is more accurate in terms of simulating the real behaviour, the linear model (i.e., linear viscous model) was found to be more efficient for computationally-intense applications such as performance-based studies due to its balance between simplicity and accuracy. Moreover, given the scarcity of fully reported experimental results, additional testing should be conducted. These tests should provide comprehensive information on the response of the building during impact, the damage pattern, and the mechanism that leads to the collapse. Eventually, this paper found that the majority of the presented studies were conducted for buildings with aligned slabs, therefore, more investigation should be carried to consider other configurations such as floor-to-column alignments, adjacent buildings with significant mass or height differences, buildings at the end of a row of buildings, and buildings likely to experience eccentric pounding.

Author Contribution

Mohamed, H., and Elyamany, G., collected, analysed the literature review and wrote the manuscript with input from all authors. Mohamed, H., and Khalil, E., contributed to the revision of the manuscript and supervising the research.

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