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AN EFFICIENT NUMERICAL APPROACH FOR THE PARAMETRIC INVESTIGATION OF THE EFFECTS OF POUNDING ON THE 3D DYNAMIC RESPONSE OF BUILDINGS DURING EARTHQUAKES

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Abstract. *This paper presents a new methodology that is used to numerically simulate buildings in three-dimensions, which are subjected to pounding during strong earthquakes. The structures are modeled as 3D MDOF dynamic systems, while an innovative, simple and efficient approach is used to model impacts, taking into account the geometry at the vicinity of impact and without the use of any contact elements that require the "a priori" determination of the impact location. A simple example of two adjacent buildings that are subjected to pounding is also presented, along with some parametric investigation of the effects of certain factors on the 3D dynamic response of the buildings during pounding incidences.*

1 INTRODUCTION

The problem of structural pounding of adjacent buildings during strong earthquakes has shown great interest in the last decades, since significant numbers of pounding occurrences have been recorded during past seismic events worldwide [1-4]. An example of such pounding incident is shown in Figure 1 as has been identified by the EERI/PEER reconnaissance team after the L'Aquila Earthquake, which hit Central Italy on April 2009 [5]. Several numerical studies have been performed in order to investigate the effects of earthquake induced pounding of buildings, with the majority of researchers simulating the problem in two dimensions (2D) [6-8]. The results from the various 2D parametric studies have demonstrated the detrimental effects of pounding on the dynamic response of multistory buildings and showed the importance of this problem regarding the safety and functionality of these structures. Studies have also revealed the consequences of structural pounding on the dynamic response of seismically isolated buildings, which exhibit quite different dynamic characteristics from fixed-supported buildings [9-11]. Actually in the case of seismically isolated buildings the problem of the amplification of the response due to pounding is considered to be more serious since it is more likely to have more demanding performance requirements and higher expectations than for conventionally fixed-supported buildings. However, as mentioned above, the great majority of past numerical studies involved only 2D simulations of buildings, especially in the case of seismically isolated buildings, while almost no parametric investigation of pounding effect has been conducted using three-dimensional (3D) simulations.

Figure 1: Damage of a four-story conventional building due to pounding with its adjacent two-story building, during the L'Aquila earthquake in Italy, in April 2009 [5].

Although some basic effects of pounding on the dynamic response of buildings can be identified using 2D simulations, other factors that are directly related to the spatial movement of the structures are excluded due to this simplification. Specifically, the fact of using both orthogonal seismic components of the excitation in the case of 3D simulations has a significant effect on the overall response of the building, compared to the corresponding unidirectional excitation in the 2D models. In addition, in 2D simulations involving structural pounding, the impacts are considered to be central, without any friction developed in the tangential direction. In a real case of pounding between adjacent buildings, friction phenomena occur during an impact, which in the case of a 3D analysis may significantly affect the torsional vibration of the buildings. Furthermore, any eccentricities, irregularities or asymmetries in plan, which may excite the torsional vibration of a building and increase the possibility of impacts during earthquakes, are essential parameters that can be considered only through a 3D analysis. The aim of the current research work is to present an efficient methodology that enables the parametric investigation of the effects of such factors on the 3D response of both conventional & seismically isolated buildings, utilizing a software application that has been specifically developed for this cause, using modern Object-Oriented Programming (OOP).

2 MODELING OF STRUCTURES

The proposed methodology considers buildings as three-dimensional multi-degree-of-freedom (MDOF) systems with shear-type behavior for their stories in the horizontal direction. The slab at each floor level is represented by a rigid diaphragm that is mathematically simulated as a convex polygon, while the masses are considered to be lumped at the floor levels, having three dynamic degrees of freedom (DOFs), i.e. two translational, parallel to the horizontal global axes, and one rotational along the vertical axis (Figure 2). Therefore, considering ground excitations only in the horizontal directions, which is the most important in the current case, no displacement occurs in the vertical direction, since the translational dynamic DOF of the structure refer only to horizontal planes. Accordingly, it is assumed that the impact forces occur only in horizontal planes.

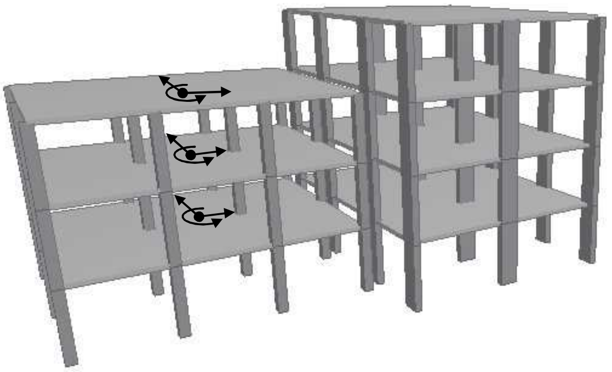


Figure 2: Three-dimensional modeling of adjacent buildings.

Both linear elastic and non-linear inelastic behavior can be considered for the columns of the simulated buildings, while, in the case of seismically isolated buildings, a bilinear inelastic behavior is used for the seismic isolation system. In the case of a linear elastic system, the $3N\times3N$ global stiffness matrix is composed based on the 3×3 stiffness matrices of the N floors of the building, which are, in turn, composed by superposing the 3×3 stiffness matrices of the floor's columns. The corresponding $3N\times3N$ damping matrix of the system is computed using the Rayleigh method, based on providing two damping ratios ζ_i and ζ_j for two eigenfrequencies of the system ω_i and ω_j [12]. All matrices are transposed to global coordinates.

The equations of motion of the system can be expressed in matrix form as follows:

$$\bar{M}\cdot\underline{\ddot{U}}(t)+\bar{C}\cdot\underline{\dot{U}}(t)+\bar{K}\cdot\underline{U}(t)+\bar{F}_{imp}=-\bar{M}\cdot\left[\bar{I}_L\cdot\ddot{u}_g^L(t)+\bar{I}_T\cdot\ddot{u}_g^T(t)\right] \qquad (1)$$

where $\underline{U}(t)$ is the vector of displacements in global coordinates at time *t*, $\overline{F}_{imp}$ is the vector of the computed impact forces, acting on each DOF, $\overline{I}_L$ and $\overline{I}_T$ are the influence vectors coupling the DOFs of the structure to the two ground motion components $\ddot{u}_g^L(t)$ and $\ddot{u}_g^T(t)$ in the longitudinal and transverse directions, respectively. In particular, the influence vectors for the two horizontal components are provided by the following expressions:

$$\begin{aligned}\overline{I}_L &= I_X \cdot \cos\theta + I_Y \cdot \sin\theta \\ \overline{I}_T &= -I_X \cdot \sin\theta + I_Y \cdot \cos\theta\end{aligned} \quad \text{, where} \quad I_X = \begin{bmatrix}1 & 0 & 0\end{bmatrix}^T \quad \text{and} \quad I_Y = \begin{bmatrix}0 & 1 & 0\end{bmatrix}^T \qquad (2)$$

θ is the excitation angle in respect to the system's principle axes.

The differential equations are directly integrated using the Central Difference Method (CDM), computing the displacements at time $t+\Delta t$. At each time-step of the analysis the algorithm performs a check for detecting potential impacts, based on the deformed position of each floor diaphragm in space. For this reason the time-step size, Δt, is selected to be small enough (usually in the range of *1* to 2×10^{-5} sec) to ensure the stability and maximize the accuracy of the method. When an impact is detected, the resulting impact forces are computed according to the impact model and the methodology that is presented in the next section.

3 EXISTING KNOWLEDGE ON IMPACT MODELLING

The numerical modeling of impact and the estimation of the impact forces acting on the colliding bodies is an essential topic, not only for the cases of structural poundings, but also for other research purposes involving numerical simulation of contact and impact problems. In most cases, impacts involve local plastic deformations, friction, thermal, acoustic and other complex phenomena that render their detailed modeling very difficult, if not impossible. However, in the case of structural poundings, a simple impact model that can be used to estimate with sufficient accuracy the impact forces acting on the colliding structures is only needed. Usually, in numerically simulated dynamic systems, such as multistory buildings under earthquake excitations, structural impact is considered using force-based methods, also known as "penalty" methods. These methods allow relatively small interpenetration between the colliding structures, which can be justified by the local deformability at the point of impact. The interpenetration depth is used along with an impact-stiffness coefficient, representing an impact spring, to calculate the impact forces that act on the colliding structures, pushing them apart.

In 2D simulations involving structural pounding, the impacts are considered to be central, i.e. without frictional forces developed in the tangential direction. However, as mentioned above, in a real case of poundings between adjacent buildings, frictional phenomena occur during an impact, which may significantly affect the torsional response of the simulated buildings. Therefore, in the case of simulating impacts in 3D, a quite different approach should be followed, since during the overlapping of the two colliding bodies an area is formed instead of an indentation depth. In addition, the frictional forces in the tangential direction of the contact surface, which are omitted in the case of 2D analyses, must also be taken into account. Therefore, in the frame of the proposed methodology, an effective and efficient approach for modeling 3D impacts needs to be developed and implemented in the specially developed software application to simulate structural pounding.

In general, very limited numerical studies in the literature have considered pounding of fixed-supported structures in three dimensions (3D), mainly due to the involved complexities. A summary of the conducting research on 3D impact modeling, considering the advantageous 'penalty' method is presented in the following paragraphs.

Fujino et al [13] have presented a 3D impact model that they have used in simulations of earthquake induced pounding of bridges' segments [14] and which is quite similar to that used by Goyal et al [15] who simulated the contact between distinct rigid bodies. In particular, Fujino et al considered the case of a point of the impacting body hitting against the target surface. The impact model is constituted by an impact spring in the direction of impact and two dashpots in the normal and tangential directions of the target surface. The direction of impact is defined by two nodes, which are the contactor node and the initial point of impact, respectively. The impact force, which is calculated, based on the spring's stiffness and the interpenetration depth (distance between the two nodes) is analyzed in normal and tangential components to the target surface, with the tangential force representing the friction following the Coulomb's friction law.

Following a similar approach, Guo et al [16] have examined, both experimentally and analytically the problem of earthquake induced pounding in bridges, considering also the case of point-to-surface pounding, which was represented in the simulations by using a modified contact-friction element. In particular, based on the rotation and displacements of the centre of masses of each of the colliding rigid bodies, the point of impact is located when overlapping occurs and the impact force, which is composed by the normal and tangential (frictional) force components, is calculated as a function of the relative displacements in the normal and tangential directions. The impact parameters (stiffness and damping) used in the performed analyses were defined through experiments.

A similar methodology has been followed by Wei et al [17] to represent the case of a single mass tower, pounding against a rigid barrier under sinusoidal excitations. However in that case, no tangential or frictional forces were taken into account. The same practice of omitting the tangential contact forces was followed by Gong and Hao [18] when they parametrically examined the lateral-torsional-pounding responses of two single-storey systems due to an earthquake excitation.

4 PROPOSED IMPACT MODEL

As described in previous paragraphs, the majority of the force-based impact models calculate the impact force as a function of the interpenetration depth between the colliding bodies. However, this approach has a significant drawback in the case of 3D impact modeling. Specifically, this approach assumes that the calculated impact force depends only on the indentation and not the geometry at the contact region. This would be true if the later was taken into account for the calculation of impact stiffness at each time-step based on the deformed position of the colliding structures, but at least for the presented studies that was not the case. Therefore, based on this observation, it is crucial and more appropriate to take into account the area of the overlapping region instead of the interpenetration depth in the calculation of the impact force, since it is widely accepted that the impact stiffness depends on the geometry at the contact region [19].

Figure 3 describes schematically how the proposed impact model works. In particular, when two polygons, representing the buildings' slabs, come in contact they form an overlapping region which in the most of the cases is either a triangle (Case A) or a quadrilateral (Case B). The algorithm uses the geometry of the overlapping region at each time-step in order to determine: (i) the location of the action point of the impact forces, (ii) the direction of the impact forces and (iii) the magnitude of the impact forces.

4.1 Location of the action point of the impact force

As will be shown later in this paper, the location of the action point of the impact forces is a very important issue in the case of simulating poundings of buildings in 3D. While in the case of 1D impact models the location of the resultant force vector clearly is at the point of contact, in the case where contact conditions exist over a finite surface area on both bodies, the exact point where the contact force should be applied is not so obvious. For the specific problem of modeling impact between rigid diaphragms, the contact forces in the normal and tangential directions are assumed to act on the centroid of the overlapping region, and applied at the corresponding position of the bodies in contact.

4.2 Direction of the impact forces (contact plane)

For the proposed impact model, it is also necessary to determine the normal and tangential contact directions in order to be able to properly apply the corresponding normal and tangential impact forces as well as the Coulomb's Law of Friction. Taking into account the assumptions of the current problem and specifically the considered case of colliding diaphragms (rigid plates) of constant thickness the contact plane is actually a line. So, the contact plane is assumed to pass through the centroid *C* of the overlapping region and to be parallel to the line that is determined by the two nodes *P1* and *P2* of intersection between the boundaries of the two colliding bodies (Figure 3). The methodology that is used defines a normal and a tangential direction in such a way to assure that no directional jump occurs, between two sequential time-steps of the analysis. Specifically, the contact plane smoothly changes direction, while the overlapping contact area changes from triangular to quadrilateral and vice-versa.

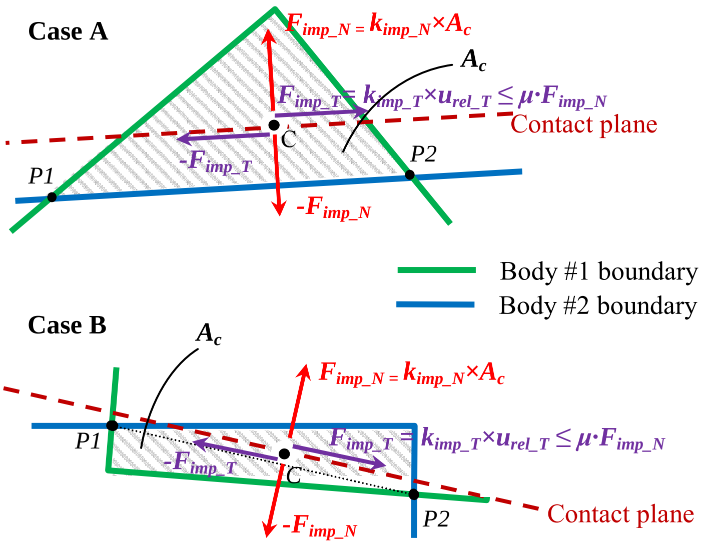


Figure 3: Schematic representation of the proposed impact model

4.3 Calculation of the impact forces

As mentioned in previous, in the proposed impact model the stiffness of the impact spring is used along with the area (A_c) of the overlapping region to calculate the elastic impact force. Since the impact response differs between the normal and tangential directions, two different equations are needed to calculate the normal and tangential elastic impact forces, respectively, at each iteration time step:

$$^{(t+\Delta t)}F_{imp,N} = {}^{(t)}A_c \cdot k_{imp,N} \tag{3}$$

$$^{(t+\Delta t)}F_{imp,T} = {}^{(t)}F_{imp,T} + {}^{(t)}u_{rel,T} \cdot k_{imp,T} \tag{4}$$

The indices *N* and *T* in the above equations indicate the normal and the tangential directions, respectively, as indicated in Figure 2. $k_{imp,N}$ (in *kN/m*^{2}) and $k_{imp,T}$ (in *kN/m*) are the impact stiffness coefficients in the normal and tangential directions, respectively. A_c is the area of the contact region and $u_{rel,T}$ is the relative displacement along the tangential direction. The time instance ($t+\Delta t$) represents the current time-step, since the Central Difference integration method is used, while (t) represents the previous time-step.

The Coulomb friction law is used to limit the tangential impact force below a certain magnitude taking into account the magnitude of the normal impact force and the static and kinetic friction coefficients of the contact surface:

$$\begin{aligned} &\text{If } \left|{}^{(t+\Delta t)}F_{imp,T}\right| \le \left|{}^{(t+\Delta t)}F_{imp,N} \cdot \mu_s\right| \quad \rightarrow \quad \text{use Equation (4)} \\ &\text{If } \left|{}^{(t+\Delta t)}F_{imp,T}\right| > \left|{}^{(t+\Delta t)}F_{imp,N} \cdot \mu_s\right| \quad \rightarrow \quad {}^{(t+\Delta t)}F_{imp,T} = {}^{(t+\Delta t)}F_{imp,N} \cdot \mu_k \end{aligned} \tag{5}$$

where μ_s and μ_k are the static and kinetic friction coefficients, which are applied in the 'stick' and 'slide' mode of contact, respectively.

As in the case of 1D impact models, a viscous dashpot can be used, in parallel with the impact spring to represent the dissipation of energy during impact (e.g. thermal and acoustic energy) and along with the relative velocity of the bodies in contact can provide the damping impact force. However, for simplicity, in the frames of the current paper only the elastic impact forces are considered in the performed simulations, saving the details for the description of the corresponding viscoelastic impact model and the methods of determining the damping coefficients for future publications.

4.4 Impact stiffness coefficients

The estimation of the impact parameters, i.e. the impact stiffness and impact damping coefficients is a common difficulty when using forced-based impact models and it is often considered one of the major disadvantages of this method. Nevertheless, several numerical studies in 2D showed that in the case of simulating the problem of earthquake induced pounding of adjacent buildings, the values of the impact parameters slightly affect the overall structural response, besides of the acceleration at the impacting floor [9]. In the frames of the current study, a simple approximation is followed in order to determine a reasonable value for the impact stiffness and impact damping in both normal and tangential directions of the contact plane.

As it is well known the impact stiffness value depends mainly on the material characteristics of the colliding structures and the geometry at the vicinity of contact. If we assume that the contact geometry is taken into account with the use of the area of the overlapping region instead of the indentation depth, then the impact stiffness should be directly related to the moduli of elasticity of the colliding bodies. Based on fundamental theories of contact mechanics [19, 20], it is assumed that the normal impact stiffness value can be approximated as follows:

$$k_{imp,N} = \left[\frac{1-\nu_1^2}{E_{Dyn,1}} + \frac{1-\nu_2^2}{E_{Dyn,2}}\right]^{-1} \tag{6}$$

where
$$E_{Dyn,i} = 5.82 \cdot \left(E_{St,i}\right)^{0.63}, \text{ in } GPa \tag{7}$$

is the dynamic elastic modulus for normal strength concrete as has been determined through relevant experiments [21], expressed in terms of the static elastic modulus E_{st} and v_i is the Poisson's ratio for the material of body *i*. In a similar manner, the tangential impact stiffness is approximated using the shear moduli of the materials of the colliding bodies:

$$k_{imp,T} = \left[\frac{2-\nu_1}{G_{Dyn,2}} + \frac{1-\nu_2}{G_{Dyn,2}}\right]^{-1} \tag{8}$$

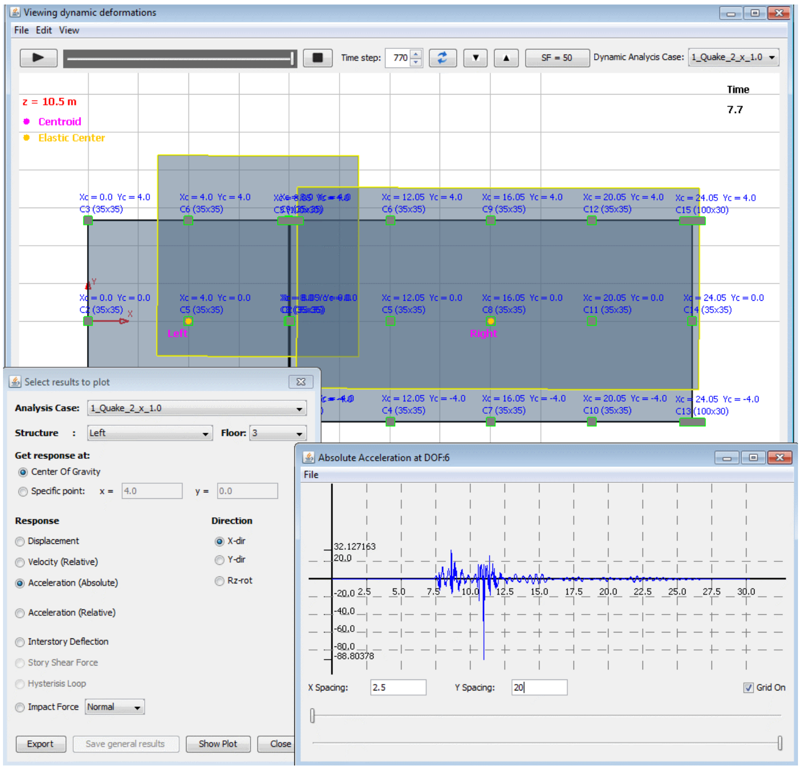
where
$$G_{i,Dyn} = \frac{E_{i,Dyn}}{2\left(1+\nu_i\right)} \tag{9}$$

The above methodology of predicting the impact stiffness coefficients is based on the assumption that the materials of the colliding bodies maintain an elastic behavior during impacts. However, during pounding the colliding structures, especially in the case of concrete structures, experience local damage, exhibiting highly non-elastic behavior at the vicinity of impact. Therefore, the impact stiffness is not actually constant but gradually decreases during impact due to the local plastic damage of the structures. Probably, it would be more appropriate to use a smaller equivalent impact stiffness value in order to take into account this local inelastic behavior of concrete. Having all that in mind, during this research study we will examine the effect of the magnitude of the impact stiffness value in order to evaluate how important is to predict a representative value for this parameter. The same approach has been followed in the case of studying the effects of pounding in 2D and was found that the specific parameter determines the magnitude of the impact force and affects mainly the acceleration response at the pounding floors.

5 DEVELOPED SOFTWARE

Considering the specific needs and demands of this numerical problem, as well as the limited flexibility and efficiency of the available general-purpose commercial software applications, the primary aim of the current research has been the development of a suitable software application in order to implement the presented methodology. In particular, the specially developed software application enables the effective and efficient performance of 3D numerical simulations and parametric analyses of both fixed-supported and seismically isolated buildings with contact detection capabilities, which allow the automatic consideration of structural poundings. Modern object-oriented design and programming approaches are utilized and the Java programming language and relevant technologies are employed in the development of the software application, taking into account the significant advantages that these technologies offer.

A significant advantage of the specially developed software is that it provides the desired flexibility, maintainability and extensibility in order to fulfill the needs of the proposed, while also facilitating extensions to accomplish future research plans. Moreover, a robust Graphical User Interface (GUI) with various capabilities has been designed and implemented, using the Java Swing API, to facilitate the effective performance of simulations and parametric analyses (Figure 4). The developed software allows the input data to be either imported from input files or specified using the GUI, while the computed results can be exported in output files or used to generate and store plots and animations in vector formats.



Time step: 770

SF = 50

Dynamic Analycis Case: 1_Quake_2_x_1.0

z = 10.5 m

Analysis Case: 1_Quake_2_x_1.0

Structure : Left Floor: 3

Get response at:

● Center Of Gravity

○ Specific point: x = 4.0 y = 0.0

Response

○ Displacement

○ Velocity (Relative)

● Acceleration (Absolute)

○ Acceleration (Relative)

○ Interstory Deflection

○ Story Shear Force

○ Hysterisis Loop

○ Impact Force Normal

Direction

● X-dir

○ Y-dir

○ Rz-rot

X Spacing: 2.5 Y Spacing: 20

☑ Grid On

Figure 4. Typical view of Graphical User Interface of the developed software application

6 EXAMPLE APPLICATION

In order to demonstrate the capabilities of the methodology and the developed software application, as well as some of the basic effects of pounding on the 3D response of buildings, a representative example of colliding adjacent buildings is presented. In particular, two regular and symmetric reinforced concrete buildings of three and four stories, respectively, were selected for this example. Although the methodology supports the simulation of more complicate structures with irregularities both in plan and height, the selection of the particular buildings has been made in order to more easily identify the effects of the various parameters on the response during pounding.

The side view and the typical floor-plans of the simulated adjacent buildings are illustrated in Figure 5. All the columns sections have dimensions 35×35 *cm* except from the corner columns of the right 3-story building C1, C3, C13 and C15 which have dimensions 100×30 cm. The elastic modulus of concrete has been taken equal to 21 *GPa* with a Poisson’s ratio equal to 0.2. A uniformly distributed mass of 1000 kg/m^2 has been considered for all floors that resulted to a 64 *tons* concentrated floor mass for the left building and a 128 *tons* floor mass for the right building. A constant viscous damping ratio of 0.05 was considered for all modes for both buildings. The two horizontal components of the real seismic recording at the 0KJMA station during the 1995 Kobe earthquake were selected as excitation. The seismic gap *d* was taken to be equal to 5 *cm*. The normal impact stiffness was calculated using Eq. (6) and was found to be to be $k_{imp,N} = 2.06\times10^7\ kN/m^2$, while the corresponding tangential impact stiffness $k_{imp,T} = 4.59\times10^6\ kN/m$. The static and kinetic friction coefficients were taken to be $\mu_s = 0.8$ and $\mu_k = 0.6$, respectively.

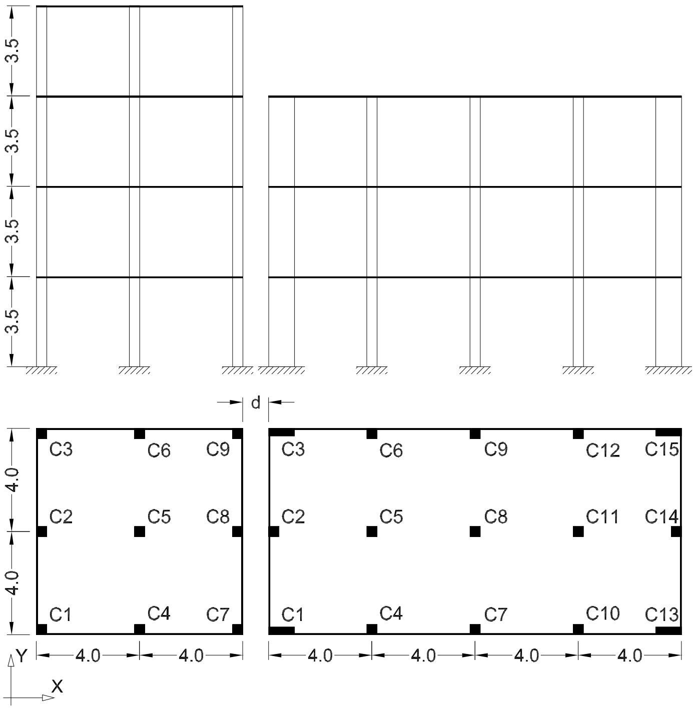


Figure 5. The side views and floor plans of the buildings considered in the presented example.

6.1 Effect of mass eccentricity

One of the parameters that can be examined through 3D simulations, in contrast to the case of modeling buildings as frames in 2D, is the accidental eccentricity of the floor mass. Many seismic codes demand the consideration of an accidental mass eccentricity when performing dynamic analysis of buildings. For example, Eurocode 8 suggests an eccentricity of the concentrated floor mass from its nominal location equal to 5% of the floor-dimension perpendicular to the direction of the seismic action. In order to examine the effects of this parameter on the response of the two above buildings during pounding, we simulated the structures using only the one of the two horizontal components of the Kobe seismic record (PGA=0.821*g*) and considering three cases regarding the position of the center of mass, with the possibility of pounding and two more cases without the consideration of any impacts. In particular, the following cases were considered:

- Case 1: the center of mass coincides with the floor's center of gravity for both buildings.
- Case 2: an eccentricity of 0.4 *m* is considered only for the left building.
- Case 3: both buildings have a 0.4 *m* eccentricity along Y axis but in opposite directions.
- Case 4: same as Case 1, but d = ∞ (no pounding).
- Case 5: same as Case 2, but d = ∞ (no pounding).

The horizontal interstory deflections at the corner-column C9 of the left building are compared for each case. The results, which are presented in the plots of Figure 6, indicate that by omitting the accidental mass eccentricity, following probably a 2D analysis (represented here by Case 1) leads to smaller deflections in the X-direction, while the deflections in the Y-direction and the torsion due to eccentricity are obviously omitted. In addition, it is observed that the deflections of the column in X-direction are reduced due to pounding for the first three stories, which are below the last impacting floor (3rd), but the corresponding deflection at the top floor is significantly increased due to impact with the adjacent 3-story building. Finally, the deflections in Y-direction and the torsion of the column are substantially increased due to pounding in the case of taking into account the accidental eccentricity.

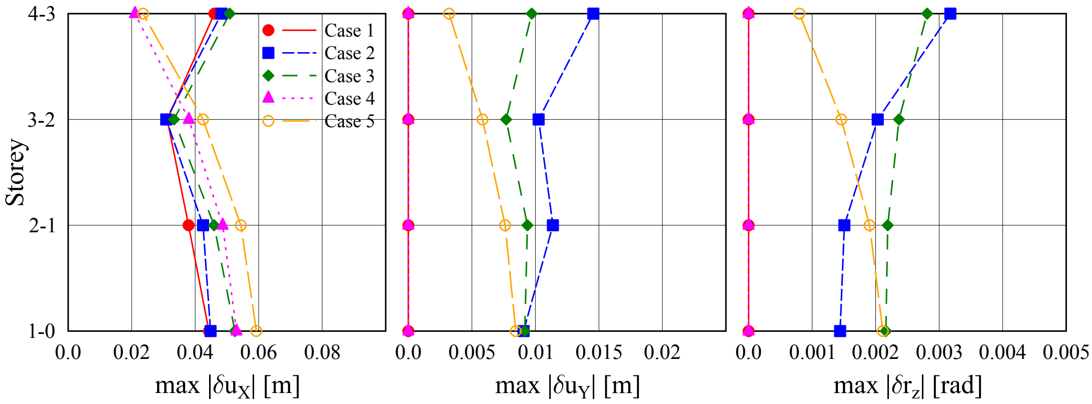


Figure 6. Peak absolute values of the deflections (two translational and one rotational) of the column C9 of the left building under the Kobe earthquake, for the five different cases regarding the mass eccentricity and the consideration of pounding.

6.2 Excitation with two orthogonal seismic components

Another aspect that cannot be examined in 2D simulations is the consideration of both horizontal components of the seismic action, which is obviously a more appropriate way to represent the real seismic event in numerical dynamic analyses of buildings. Therefore, the same buildings have been subjected to the longitudinal seismic record (PGA=0.821*g*) of Kobe 0KJMA along the X-axis and to the transversal seismic record (PGA=0.598*g*) along Y-axis. The results are compared with the two cases of having as excitation separately only one of the two components, which represents more or less the corresponding case of a 2D simulation. It is noted that in the case of the Y-only excitation no poundings occur. As previously, the deflections of column C9 of the left building are plotted for comparison in Figure 7 for the three cases. It is observed that the 2D simulations may provide a good approximation of the maximum deflections of the column in the two horizontal axes with negligible variations. However, the torsion that the column is subjected due to the rotational vibration of the building cannot be captured using single-component excitation and 2D analysis.

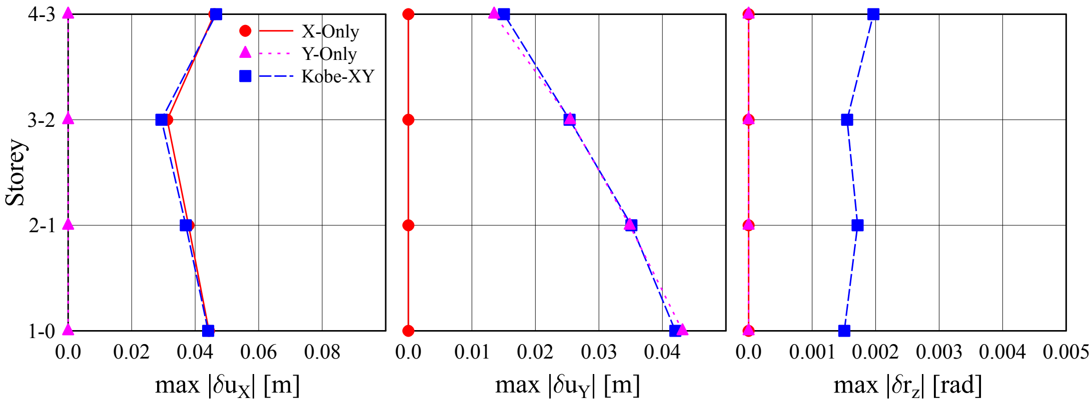


Figure 7. Peak absolute values of the deflections of the column C9 of the left building pounding against the right building under a single or both seismic components of the Kobe earthquake.

6.3 Effect of the excitation angle

Another ability that is provided through the presented methodology and the developed software application is the parametric investigation of the effect of the angle of the seismic excitation in respect to the global axes on the response of the adjacent buildings during pounding. The plots in Figure 8 present the maximum absolute values of the deflections of the column C9 of the left building during pounding, in terms of the excitation angle. For the analyses both seismic orthogonal components were used simultaneously. It becomes evident from the results that the direction of the excitation affects substantially the response during pounding and obviously is one important parameter that should be examine in more extent in future simulations and parametric studies in order to understand better the way it affects the response.

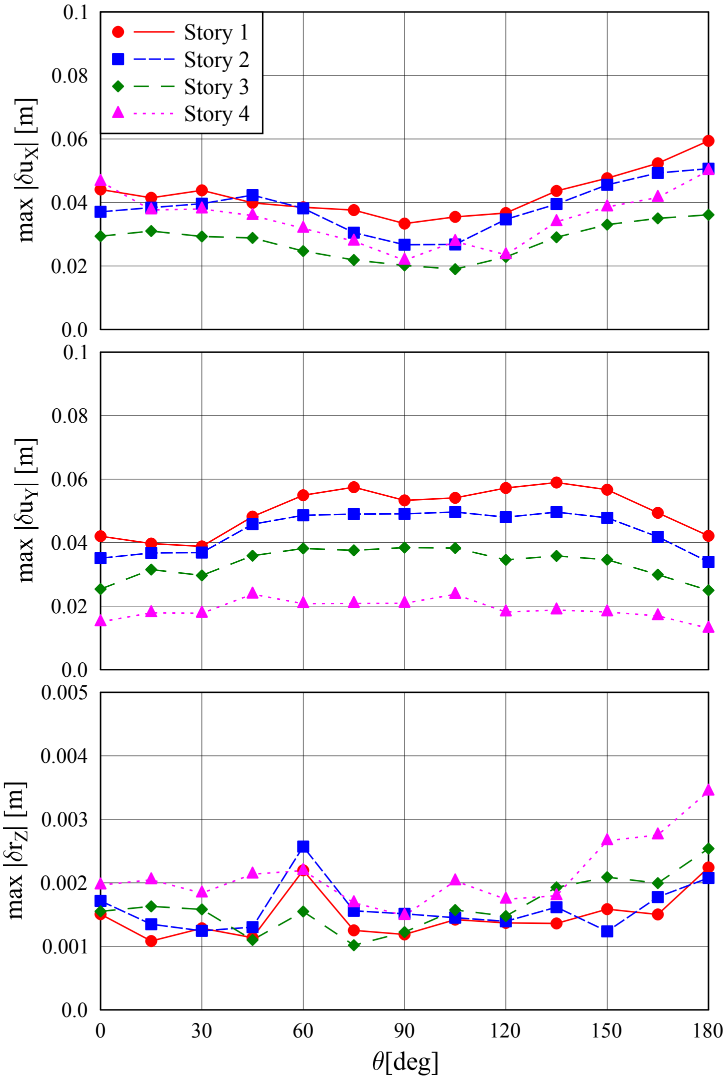


Figure 7. Peak absolute values of the deflections of the column C9 of the left building in terms of the excitation angle of the Kobe seismic record.

7 CONCLUSIONS

A new methodology for simulating earthquake induced pounding of buildings that are modeled as 3D-MDOF systems has been presented. Some significant disadvantages of the available impact models in the literature have led us to propose a new approach to the numerical problem of impact modeling. Specifically, following the ‘penalty’ method the impact forces are calculated based on the area of the overlapping region, instead of the overlapping depth that is usually used in previous similar studies. This assumption takes into account the geometry at the vicinity of impact, a factor that was omitted in the case of using only the indentation depth. Another advantage of the proposed methodology is that the location of impacts is not known ‘a priori’ since the impact detection is based on the spatially arbitrary location of each of the rigid diaphragms that are at the same level. Therefore, there is no need for contact elements applied at certain locations of each diaphragm, which actually omit the location and the direction of the impact forces since in their majority such contact elements have only one dimension.

The methodology has been implemented in a specially developed software application that enables us to efficiently perform 3D dynamic analysis of buildings considering the case of pounding. In particular, the total time that is needed for a dynamic analysis such as the one described in the above example, which includes two buildings of four and three stories respectively, is about 50 sec, which is extremely fast compared to many other commercial FEM software applications. This efficiency provides the ability to easily perform large number of simulations in order to parametrically examine the effect of certain factors on the 3D response of buildings during earthquake induced pounding. A small example of such parametric investigation has been presented in the current paper. Nevertheless, more extensive investigation has to be performed in the future, in order to take into account more kinds of structures, different building arrangement, more earthquakes, and, in general, more other influencing factors that can be examined through 3D analyses.

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