A methodology for an efficient three-dimensional (3D) numerical simulation of earthquake-induced pounding of buildings

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LISBOA 2012

SUMMARY:
This paper presents a methodology for simulating numerically in three dimensions the case of pounding between adjacent buildings during strong earthquakes. In particular a new approach to the numerical problem of impact modelling is presented that does not require the 'a priori' determination of contact points, taking also into account the geometry at the vicinity of impact. In addition, the proposed method can be applied also in the case of slab-to-column pounding. In the current study, the buildings are simulated as linear multi degree of freedom systems, but the methodology can be easily extended to consider also non-linear behaviour. The methodology is implemented in a specially developed software application, using modern object oriented programming.

Keywords: pounding, impact, seismic gap, three dimensions, numerical analysis

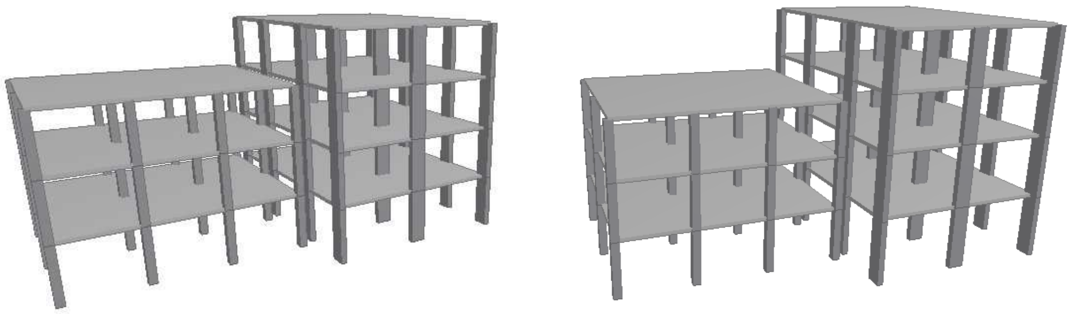
1. INTRODUCTION

Very often, especially in densely-resided areas and city centres, neighbouring buildings are constructed very close to each other, or even without any clearance between them. Thus, structural pounding may occur, during strong earthquakes, between adjacent buildings due to deformations of their stories. Consequences of such pounding incidences, ranging from local light damage to severe structural damage or even collapse, have been observed and reported in past strong earthquakes (Bertero, 1986; Anagnostopoulos, 1995; Kasai and Maison, 1997; Cole et al, 2011). Pounding may also occur in cases of seismically isolated buildings when the available width of the provided seismic gap around them is limited, while larger than expected horizontal relative displacements occur at the isolation level during very strong seismic excitations (Polycarpou and Komodromos, 2010; Masroor and Mosqueda).

Several studies have been performed during the last decades in order to investigate the effects of earthquake induced pounding of buildings, with the majority simulating the problem in two dimensions (2D). Although some basic effects of pounding on the dynamic response of buildings can be identified using 2D simulations, some also important factors that are directly related to the spatial movement of the structures are excluded due to this simplification. Specifically, 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 three-dimensional (3D) analysis may significantly affect the torsional vibration of the buildings (Liolios, 2000). Furthermore, any irregularities of the buildings 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 while using 3D analysis.

Papadrakakis et al (1996) simulated the problem in three dimensions, using MDOF systems and the Lagrange multiplier approach to simulate contacts, while any sliding between the neighbouring buildings was not taken into account. Few years later, Mouzakis and Papadrakakis (2004) simulated spatial pounding involving friction, based on the impulse-momentum relationship to calculate post-impact velocities, using the coefficient of restitution and the ratio of tangential to normal impulses, which corresponds to the coefficient of friction under certain conditions. The contact points were determined geometrically from the displacements of the diaphragms' centre of mass. However, the considered approach does not take into account cases of more than one contact occurring simultaneously at the same floor. Jankowski (2008) performed 3D non-linear dynamic analyses and parametric studies to investigate the case of earthquake-induced poundings between two 3-storey equal height buildings with substantially different dynamic properties. However, his methodology included only double-symmetric buildings, omitting the case of any torsional vibrations. Later on, the same researcher simulated a real case of earthquake-induced pounding using a detailed FEM analysis (Jankowski 2009), which is practically very difficult to be used for parametric studies due to its excessive computational cost.

Generally, in the case of earthquake induced pounding between adjacent buildings two distinct cases are identified in the common practice: (a) the case of impact between slabs of adjacent stories of equal heights and (b) the case of impact between a slab and the columns of the adjacent building (Fig. 1.1). The former case has been systematically examined in the majority of the previous research studies, considering, in most of the cases, 2D analysis and central impacts with no frictional or torsional phenomena. Beside the case of pounding of buildings, the case of simulating plate-to-plate impact has also found great use in the investigation of pounding of bridges' segments. The second case (plate-to-column impact) is obviously the most dangerous scenario in practice, regarding the potential damage that the building may suffer during an earthquake, which in some cases may lead to collapse. However, due to the complexity of the problem very few researchers have examined this scenario through numerical simulations. The aim of the current research study is to numerically and parametrically investigate both above cases of structural pounding, as well as the case of pounding of seismically isolated buildings.



(a) (b)

Figure 1.1. (a) Floor-to-floor pounding case; (b) Mid-column pounding case.

All the above indicate the need for the development of a specialized software application that will implement an efficient and simple methodology, able to take into account all the determinant factors regarding the 3D dynamic response of buildings, subjected to pounding during earthquake excitations. In addition, the developed software must provide the ability of performing parametric studies, where large numbers of simulations could be executed automatically, while varying certain parameters, within a user-specified range of values, in order to assess their influence on the computed response. This paper presents a simple but efficient methodology for simulating almost any case of pounding between neighbouring buildings that is implemented in a specially developed software application, using Object-Oriented Programming.

2. MODELLING OF STRUCTURES

The methodology that is followed to accomplish the targets of the current project is based on the simulation of buildings as three-dimensional multi-degree-of-freedom (MDOF) systems with shear-type behaviour for their stories in the horizontal direction. The slab at each floor level is represented by a rigid diaphragm that is defined 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. 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. Both linear elastic and non-linear inelastic behaviour can be considered for the columns of the simulated buildings, while, in the case of seismically isolated buildings, a bilinear inelastic behaviour is used for the seismic isolation system.

In the case of a linear elastic system, the global stiffness matrix is composed, based on the 3×3 stiffness matrices of the floors, which are, in turn, composed by superposing the 3×3 stiffness matrices of the floor's columns. In particular, the whole procedure of computing the global stiffness matrix is presented in the following paragraphs.

2.1. Stiffness matrix

Let us consider a typical plan of a floor *i* (i=1...N) and a column *j* (j=1...n), where *n* is the total number of columns at the floor *i* and *N* is the total number of storeys of the simulated building (Fig. 2.1).

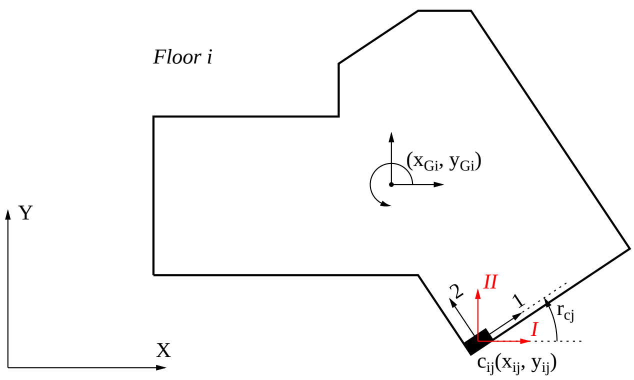


Figure 2.1. Representation of a typical floor diaphragm as polygon, with the dynamic degrees of freedom at the centre of mass and the location and orientation of a typical column.

The horizontal stiffness values of a shear-type column c_{ij} in the two orthogonal directions (*I* and *II*) parallel to the horizontal global axes (*X* and *Y*) are given by the following expressions:

$$\begin{aligned} k_{cj}^{I} &= k_{1,cj} \cdot \cos^2 r_{cj} + k_{2,cj} \cdot \sin^2 r_{cj} \\ k_{cj}^{II} &= k_{1,cj} \cdot \sin^2 r_{cj} + k_{2,cj} \cdot \cos^2 r_{cj} \end{aligned} \quad \text{where} \quad \begin{aligned} k_{1,cj} &= 12EI_{22} / h_j^3 \\ k_{2,cj} &= 12EI_{11} / h_j^3 \end{aligned} \tag{2.1}$$

In the above equations, r_{cj} is the rotation angle of the principal axes (*1* and *2*) of the section of the column in respect to the global axes, $k_{1,cj}$ and $k_{2,cj}$ are the horizontal stiffness terms in the principal directions of the column *j*, *E* is the Young's modulus, I_{11} and I_{22} are the moments of inertia of the section, while h_j is the height of the column. The rotational (torsional) stiffness of the column is defined as:

$$k_{cj}^{\theta} = GJ_c / h_i \tag{2.2}$$

where *G* is the shear modulus and J_c is the polar moment of inertia of the column's section.

Accordingly, the local stiffness matrix of the column is:

$$\overline{k}'_{cj} = \begin{bmatrix} k_{cj}^{I} & 0 & 0 \\ 0 & k_{cj}^{II} & 0 \\ 0 & 0 & k_{cj}^{\theta} \end{bmatrix} \tag{2.3}$$

At a floor *i*, the horizontal displacements at the head of a column c_{ij} in the local coordinate system (axes *I* and *II*) can be expressed in terms of global coordinates (axes *X* and *Y*) using the following transformation:

$$\overline{d}_{ij}^{local} = \overline{T}_{ij} \cdot \overline{d}_{i}^{global} \Leftrightarrow \begin{bmatrix} u_{ij} \\ \upsilon_{ij} \\ \theta_{ij} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -y_{ij} \\ 0 & 1 & x_{ij} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} u_{i} \\ \upsilon_{i} \\ \theta_{i} \end{bmatrix} \tag{2.4}$$

where $\overline{T}_{ij}$ is the transformation matrix, which can be used to express the local stiffness matrix of the column *j* in global coordinates as follows:

$$\overline{k}_{cj} = \overline{T}_{ij}^{T} \cdot \overline{k}'_{cj} \cdot \overline{T}_{ij} = \begin{bmatrix} k_{cj}^{I} & 0 & -y_{ij} \cdot k_{cj}^{I} \\ 0 & k_{cj}^{II} & x_{ij} \cdot k_{cj}^{II} \\ -y_{ij} \cdot k_{cj}^{I} & x_{ij} \cdot k_{cj}^{II} & k_{cj}^{\theta\theta} \end{bmatrix}, \text{ where: } k_{cj}^{\theta\theta} = y_{ij}^{2} \cdot k_{cj}^{I} + x_{ij}^{2} \cdot k_{cj}^{II} + k_{cj}^{\theta} \tag{2.5}$$

Therefore, the *3×3* stiffness matrix of the whole storey is formed by summarizing the stiffness matrices of all of its columns that have been calculated using Eq. 2.5:

$$\overline{k}_{i} = \sum_{j=1}^{n} \overline{k}_{cj} \tag{2.6}$$

The composition of the *3N×3N* global stiffness matrix of the building is performed by superposing the *N* stiffness matrices of the storeys. In particular, the non-zero elements of the stiffness matrix are:

$$\begin{aligned} \overline{K}_{i,i} &= \overline{k}_{i} + \overline{k}_{i+1} \\ \overline{K}_{i+1,i} &= \overline{K}_{i,i+1} = -\overline{k}_{i+1} \end{aligned} \tag{2.7}$$

2.2. Mass matrix

As mentioned above, the mass of each floor is considered to be concentrated at its centre of gravity that has the coordinates in plan x_{Gi} and y_{Gi}. If we consider that the mass matrix of the floor *i*, in respect to its centre of gravity is:

$$\overline{m}_{i}^{G} = \begin{bmatrix} m_{i} & 0 & 0 \\ 0 & m_{i} & 0 \\ 0 & 0 & m_{i} \cdot J_{G} \end{bmatrix} \tag{2.8}$$

where m_i is the total mass of the storey and J_G is the polar moment of inertia of the polygon representing the floor’s slab, the corresponding mass matrix of the floor in respect to the global coordinate system is:

$$\bar{m}_i = \bar{T}_{ij}^T \cdot \bar{m}_i^G \cdot \bar{T}_{ij} = \begin{bmatrix} m_i & 0 & -y_{ij} \cdot m_i \\ 0 & m_i & x_{ij} \cdot m_i \\ -y_{ij} \cdot m_i & x_{ij} \cdot m_i & m_i \cdot J_m \end{bmatrix}, \quad \text{where: } J_m = J_G + x_{ij}^2 + y_{ij}^2 \tag{2.9}$$

So the $3N \times 3N$ global mass matrix of the building has the diagonal form:

$$\bar{M} = \begin{bmatrix} \bar{m}_1 & 0 & \cdots & 0 \\ 0 & \bar{m}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \bar{m}_N \end{bmatrix} \tag{2.10}$$

2.3. Damping matrix

The corresponding $3N \times 3N$ 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:

$$\underline{C} = \alpha \cdot \underline{M} + \beta \cdot \underline{K} \quad , \quad \text{where:} \quad \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 1/(2 \cdot \omega_i) & \omega_i / 2 \\ 1/(2 \cdot \omega_j) & \omega_j / 2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \zeta_i \\ \zeta_j \end{bmatrix} \tag{2.11}$$

2.4. Equations of motion

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

$$\bar{M} \cdot \ddot{\underline{U}}(t) + \bar{C} \cdot \dot{\underline{U}}(t) + \bar{K} \cdot \underline{U}(t) + \bar{F}_{imp} = -\bar{M} \cdot \left[\bar{I}_L \cdot \ddot{u}_g^L(t) + \bar{I}_T \cdot \ddot{u}_g^T(t) \right] \tag{2.12}$$

where $\underline{U}(t)$ is the vector of displacements in global coordinates at time t, $\bar{F}_{imp}$ is the vector of the computed impact forces, acting on each DOF, $\bar{I}_L$ and $\bar{I}_T$ 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. The differential equations are directly integrated using the Central Difference Method (CDM), computing the displacements at time $t+\Delta t$.

3. IMPACT MODELLING

The numerical modelling 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 modelling 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.

Structural impact is usually considered in the relevant scientific literature using methods that are based either on 'stereomechanical' or 'forced-based' approaches (Goldsmith, 1960). The stereomechanical, also known as impulse-based, approach assume that the duration of an impact is zero and compute instantaneous changes of the velocities based on the preservation of momentum, taking also into account the coefficient of restitution, which is defined as the ratio of the relative velocity between the colliding bodies after and before impact. However, this approach cannot handle multiple impact incidences at any time instance. Furthermore, this method does not provide the impact forces acting on the colliding bodies at the time of impact.

Force-based, also known as ‘penalty’, methods allow interpenetration between the colliding structures, which is justified by their deformability at the vicinity of the contact. Contact springs are automatically formed when an impact is detected, kept as long as the bodies remain in contact and removed as soon as the structures detach from each other. In contrast with the impulse-based approach, these methods allow the efficient simulation of multiple deformable bodies with the possibility of multiple impacts occurring at the same time, due to the fact that the computed impact forces are superimposed in the corresponding equations of motion. This considerable advantage of the force-based impact models renders them more suitable for simulating pounding of buildings in series and, therefore, the methodology that is presented herein follows this approach.

In 2D simulations involving structural pounding, the impacts are considered to be central, i.e. without frictional forces developed in the tangential direction and for the calculation of the impact force, the interpenetration depth between the colliding rigid bodies is used along with an impact spring. 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 modelling 3D impacts needs to be developed and implemented in the specially developed software application to simulate structural pounding.

3.1. Common practices on 3D impact modelling

As mentioned in a previous section, very limited research works have been conducted considering pounding of fixed-supported structures in three dimensions (3D), mainly due to the involved complexities. A summary of the conducting research on 3D impact modelling, considering the advantageous ‘penalty’ method is presented in the following paragraphs.

Fujino et al (2000) have presented a 3D impact model that they have used in simulations of earthquake induced pounding of bridges’ segments (Zhu et al, 2002). In particular, they 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 *k* and *p*, which are the contactor node and the initial point of impact, respectively. The impact force 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 (2011) 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 (2009) 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 (2005) when they parametrically examined the lateral-torsional-pounding responses of two single-storey systems due to an earthquake excitation.

3.2. Proposed methodology

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 modelling. 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, but at least for the presented studies (Section 3.1) that was not the case. For example, consider the two cases of impact between the two rigid plates presented in Figure 3.1. Considering a constant impact stiffness parameter and taking into account only the interpenetration depth, the impact force would be the same for the two cases. However, in reality, someone would expect that the impact force in the first case (Case A) would be greater than in the second case, since the overlapping *area*[1] is greater. Therefore, based on this observation, it is crucial to take into account the area of the overlapping region in the calculation of the impact force, since it is widely accepted that the impact stiffness depends on the geometry at the contact region (Goldsmith, 1960). The current proposed methodology of impact modelling is based on a similar research work that numerically simulates interactions between discrete rigid bodies (Komodromos et al, 2007, Papaloizou, 2009).

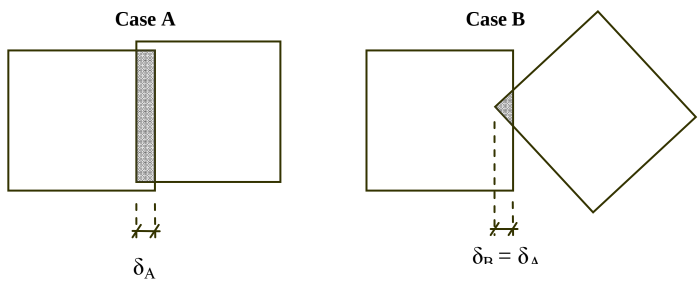


Figure 3.1. Two different cases of impact geometry between two rigid plates.

3.2.1. Location of the action point of the impact force

The location of the action point of the impact forces is an important factor that must also be taken into account. 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 (Figure 3.1), the exact point where the contact force should be applied is not so obvious. For the specific problem of modelling impact between rigid diaphragms, the contact forces in the normal and tangential contact planes are assumed to act on the centroid of the overlapping region, and applied at the corresponding position of the bodies in contact.

3.2.2. Contact plane

In addition to the determination of the contact area of the bodies in contact, it is necessary to determine the normal and tangential contact directions in order to be able to apply the corresponding normal and tangential impact forces as well as the Coulomb's Law of Friction. For the current problem and the considered case of colliding diaphragms (rigid plates) of constant thickness the contact plane is actually a line. The contact plane is assumed to be parallel to the line that is

[1] Note that the term 'area' which is used here is based on the assumption of having two colliding plates of constant thickness, without any out of plane displacements. Otherwise, in the general case, there would be an overlapping volume instead of an area

determined by the two nodes *P1* and *P2* of intersection between the boundaries of the two colliding bodies. Figure 3.2 illustrates two different cases of contact geometry between two polygons with the corresponding contact planes. In Case A, a corner of the first polygon indents to a side of the second polygon and the overlapping region is a triangle. In Case B, we have the overlapping between two corners of the rigid bodies and therefore the area of indentation is a quadrilateral. Since the impact forces will be applied at the centroid *C* of the overlapping region, the contact plane is passing through that point. The methodology that is used defines a normal and a tangential plane in such a way that no directional jump occurs, at any case. Specifically, the two contact planes smoothly change direction, while the overlapping contact area changes from triangular to quadrilateral.

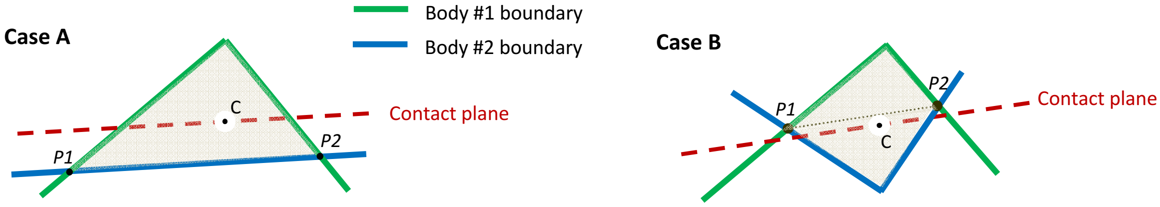


Figure 3.2. Determination of the contact plane, based on the geometry of the overlapping (shaded) region.

3.2.3 Calculation of contact forces

According to the basic concepts of the widely known 'penalty' method, contact springs are automatically formed when two rigid bodies are in contact in order to calculate the resulting impact force that pushes them apart. In the current case, the stiffness of the impact spring is used along with the area (A_c) of the overlapping region to calculate the elastic impact force. The area A_c and the coordinates of the centroid (C_x,C_y) of the overlapping contact region are given by the following equations:

$$A = \frac{1}{2}\sum_{i=0}^{n-1}\left(x_i \cdot y_{i+1} - x_{i+1} \cdot y_i\right) \tag{3.1}$$

$$C_x = \frac{1}{6 \cdot A}\sum_{i=0}^{n-1}\left(x_i + x_{i+1}\right)\left(x_i \cdot y_{i+1} - x_{i+1} \cdot y_i\right) \quad \text{and} \quad C_y = \frac{1}{6 \cdot A}\sum_{i=0}^{n-1}\left(y_i + y_{i+1}\right)\left(x_i \cdot y_{i+1} - x_{i+1} \cdot y_i\right) \tag{3.2}$$

where x_i, y_i are the coordinates of the node *i* from the total number of *n* nodes that determine the overlapping region.

Moreover, an impact 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. Since the impact response differs between the normal and tangential directions, two different equations are needed to calculate the normal and tangential impact forces, respectively, at each iteration time step:

$$^{(t+\Delta t)}F_{imp,N} = {}^{(t+\Delta t)}F^{elastic}_{imp,N} + {}^{(t+\Delta t)}F^{damp}_{imp,N} = \left({}^{(t)}A_c \cdot k_{imp,N}\right) + \left({}^{(t)}\dot{u}_{rel,N} \cdot c_{imp,N}\right) \tag{3.4}$$

$$^{(t+\Delta t)}F_{imp,T} = {}^{(t+\Delta t)}F^{elastic}_{imp,T} + {}^{(t+\Delta t)}F^{damp}_{imp,T} = \left({}^{(t)}F^{elastic}_{imp,T} + {}^{(t)}\dot{u}_{rel,T} \cdot \Delta t \cdot k_{imp,T}\right) + \left({}^{(t)}\dot{u}_{rel,T} \cdot c_{imp,T}\right) \tag{3.5}$$

The indices *N* and *T* in the above equations indicate the normal and the tangential directions, respectively. $k_{imp,N}$ (in N/m^2) and $k_{imp,T}$ (in N/m) are the impact stiffness parameters in the normal and tangential directions, respectively. A_c is the area of the contact region, $\dot{u}_{rel,N}$, $\dot{u}_{rel,T}$, $c_{imp,N}$ and $c_{imp,T}$ are the relative velocities and the damping coefficients in the normal and tangential directions, respectively. Damping is velocity-proportional and the magnitude of the damping force is proportional to the corresponding relative velocity of the rigid plates that are in contact. 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:

$$\begin{aligned} &\text{If } \left|{}^{(t+\Delta t)}F_{imp,T}\right| \le \left|{}^{(t+\Delta t)}F_{imp,N} \cdot \mu_s\right| \quad \rightarrow \quad \text{use Equation 3.5} \\ &\text{If } \left|{}^{(t+\Delta t)}F_{imp,T}\right| > \left|{}^{(t+\Delta t)}F_{imp,N} \cdot \mu_s\right| \quad \rightarrow \quad {}^{(t+\Delta t)}F_{imp,T} = {}^{(t+\Delta t)}F_{imp,N} \cdot \mu_k \end{aligned} \tag{3.6}$$

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.

3.2.4 Impacts between slabs and columns

Similar approach to that of plate-to-plate impacts can be followed in the case of having slab-to-column impacts. Specifically, a slab will be again represented by a rigid polygon, while a polygon representing a column's cross section will be considered at the location of impact in the vertical direction of the column, in order to enable the computation of resulting impact forces according to the impact model (Figure 2.6). The computed impact forces shall then be transferred and applied at the centres of gravity of the two polygons. In the case of the column, the centre of gravity of the cross section is the location on the column element where the impact forces will be applied, inducing bending moments, shear and torsional forces at the column. The group of forces that will be applied on the diaphragms below and above the impacted column will be calculated at each time-step based on the assumption of having a double-fixed beam under concentrated static loading and computing the reactions on each of its ends.

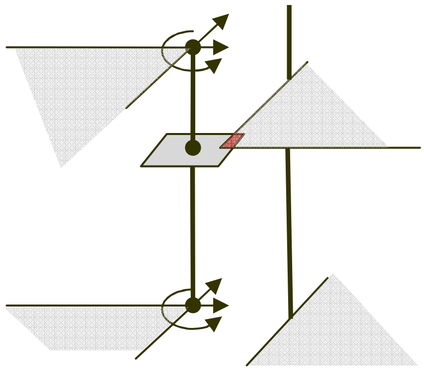


Figure 3.3. Model of a column subjected to mid-column pounding

4. SOFTWARE DEVELOPMENT

Since the specific needs and demands of this numerical problem cannot be fulfilled with any of the available general-purpose commercial software applications, the initial aim of the current research was the development of a suitable software application. The latter is specifically designed and developed to enable the effective and efficient performance of 3D numerical simulations and parametric analyses of both fixed-supported and seismically isolated buildings with contact capabilities, which will 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. The specially developed software provides the desired flexibility, maintainability and extensibility in order to fulfil the needs of the proposed, while also facilitating extensions to accomplish future research plans. Specifically, the Java programming language is used for the computational part, while the Java application programming interfaces (API) Java2D/Java3D and Java Swing are employed for the implementation of high quality 2D/3D Computer Graphics (CG) and an effective Graphical User Interface (GUI), respectively..

5. CONCLUDING REMARKS

This paper presents a methodology for simulating earthquake induced pounding of buildings that are modelled as 3D-MDOF systems. 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 modelling. 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 impact model is that the location of impact 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 direction of the impact forces since in their majority such contact elements have only one dimension. The presented methodology is being implemented in the algorithm of the specially developed software application that enables the 3D dynamic analysis of buildings under seismic excitations.

AKCNOWLEDGEMENT
This work was carried out in the frames of the project with protocol number 'ΔΙΔΑΚΤΩΡ/0609/39' (Website: http://www.eng.ucy.ac.cy/Archimedes/Projects/3DPound/), which is co-funded by the Republic of Cyprus through the Cyprus Research Promotion Foundation and the European Regional Development Fund.

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