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INTER-STORY POUNDING AND TORSIONAL EFFECT DUE TO INTERACTION BETWEEN ADJACENT MULTISTORY RC BUILDINGS

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Abstract. *The influence of the structural pounding on the seismic behaviour of reinforced concrete structures designed to EC2 and EC8 with non-equal story heights is investigated. In these cases the slabs of the diaphragms of the short stiffer structure hit the columns of the other adjacent structure at points within their deformable heights. Further it is quite usual seismically induced oscillations of a structure in a block of buildings in city center to be partly restrained in lateral displacements and therefore torsional behaviour to be introduced during an earthquake excitation. In this work the case of an 8-story reinforced concrete building that suffers inter-story pounding in a non-symmetric way is studied. Pounding occurs only in one (case 1) or in two (case 2) columns of the structure whereas the other columns are free to move without restrictions and therefore a torsional behavior is produced. The slabs of the short stiff structure hit the columns of an 8-story frame structure at a height equal to 2/3 of their deformable length. Nonlinear dynamic step-by-step analysis and special purpose elements are employed for the needs of this study. Pounding cases with torsional effect between structures with non-equal story levels and different total heights for three excitations are studied and results in terms of displacements, torsional rotations, shear forces, ductility requirements are presented and commented. The results clearly show that high capacity requirements in terms of torsional moments and column shear strength are developed due to the asymmetric inter-story pounding. Furthermore from the results it can also be deduced that the columns that suffer the hit develop high shear requirements that exceed the available capacity during the step-by-step seismic response of the structures.*

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1 INTRODUCTION

Based on reports of field observations after numerous destructive earthquakes all over the world, it can be concluded that pounding is frequently observed when strong earthquakes strike big cities and densely populated urban areas [1],[2],[3]. Moreover the high cost of land in densely populated metropolitan cities and the small lot sizes make the seismic separation requirements not always easy to apply.

Karayannis and Fotopoulou (1998) [4] examined various cases of structural pounding between multistory reinforced concrete structures designed according to the Eurocodes 2 and 8. The work is based on non-linear dynamic step-by-step analysis and its purpose was to present initial results for the influence of some critical pounding parameters on the ductility requirements of the columns and to examine the possibility of taking into account the pounding effect during the design process according to EC2 to EC8.

Further in city centers with large blocks densely filled with buildings the land lots are mostly not equal nor alike in plan geometry henceforth it is very likely adjacent buildings in a block to be partly and in a non-symmetric way in contact to each other. Consequently it is quite usual seismically induced oscillations of a structure in a block to be partly restrained in lateral displacements and therefore a torsional movement to be introduced in the building during an earthquake excitation. This phenomenon can be referred to as asymmetric pounding.

Considering that (i) pounding is a frequent cause of structural damage that under certain conditions it can lead to collapse initiation, (ii) the problem has not yet been studied effectively especially for the case of colliding structures with non-equal inter-story heights, (iii) according to the new design codes (Eurocodes 2 and 8, ACI 318) flexible frame structures prone to structural pounding can be designed and (iv) seismically induced oscillations of a structure in a block of buildings in a city center is likely to be partly restrained in lateral displacements and therefore torsional behaviour to be introduced; in this paper an attempt to study the influence of the asymmetric structural pounding on the ductility and shear requirements for reinforced concrete structures with different story heights is presented. This phenomenon can be referred to as asymmetric inter-story pounding.

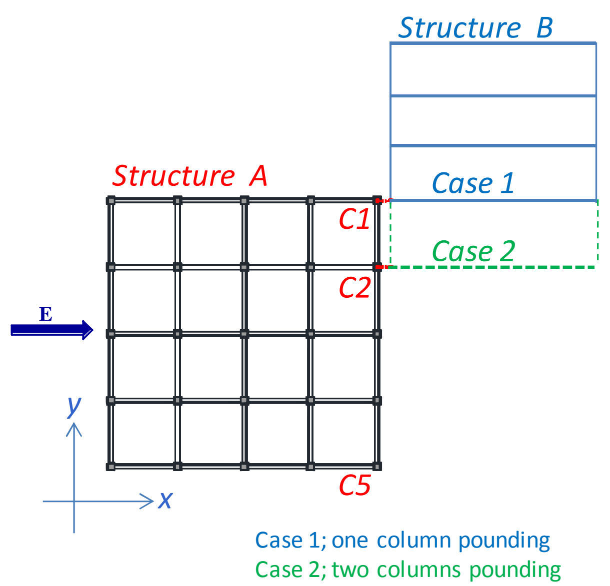
The examined structures are multistory reinforced concrete frames with unequal total heights and different story heights designed according to the codes EC2 and EC8. In these very common pounding cases the slabs of the diaphragms of the short stiffer structure hit the columns of the other structure at a point within the deformable height.

In this work more than fifty pounding cases for three different seismic excitations each are examined. The examined cases include pounding cases between an 8-story reinforced structure designed to EC2 and EC8 and a shorter structure with n_s stories where n_s=1,2,3,4,5,6,7 and 8. The heights of the story levels of the multistory structures are not the same with the ones of the second structure. These cases are sorted into two series based on the level of the asymmetry introduced in an 8-story building due to pounding. In series 1 pounding cases with high asymmetry are included since pounding takes place between only one external column of the 8-story building and one column of the adjacent shorter structure. In series 2 pounding takes place between two columns of the 8-story building and two columns of the adjacent shorter structure. Each pounding case first is examined considering that the interacting structures are in contact from the beginning (gap distance d_g=0) and further it is examined considering that there is a gap distance equal to 1 or 2 cm (d_g=1 and 2 cm) between the structures. Nonlinear dynamic step-by-step analysis and special purpose elements are employed for the needs of this study.

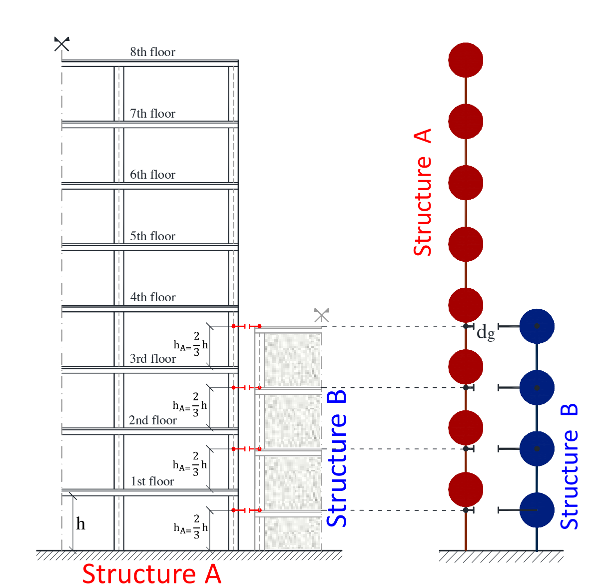
The results clearly show that high capacity requirements in terms of torsional moments and column shear strength are developed due to the asymmetric inter-story pounding. Furthermore from the results it can also be deduced that the columns that suffer the hit develop high shear requirements that exceed the available capacity during the step-by-step seismic response of the structures.

2 MODEL IDEALIZATION OF POUNDING

The pounding between adjacent structures with different total heights that are partly in contact to each other in a non-symmetric way is studied (fig. 1a). This configuration implies that the seismic oscillations of the tall building is laterally only partly restrained by the other structure and therefore a torsional movement is introduced in the building during an earthquake excitation. Henceforth in the examined cases pounding between adjacent structures introduces significant plan asymmetry in the building in terms of lateral stiffness distribution.



(a) Plan view of structures in contact in a non-symmetric way. Asymmetric pounding.



(b) Actual condition and model idealization of the pounding problem. Inter-story pounding.

Figure 1: Plan view of structures in contact in a non-symmetric way and model idealization of the pounding between buildings with different story heights. Asymmetric inter-story pounding.

It is considered that one flexible multistory building (Structure A in fig. 1) is in contact or in close proximity to one less flexible shorter structure (Structure B in fig. 1). If there is a gap distance between these structures collisions can only occur when the lateral displacements of the structures exceed the pre-defined gap distance (d_g). The influence of the gap size on the pounding effects is also investigated.

As it can be shown in fig. 1a two cases of asymmetric pounding are examined. In case 1 the lateral displacement of one column (column C1) of the 8-story building (structure A) is restrained in the x-direction only towards the adjacent structure (structure B); whereas in case 2 the lateral displacements of two columns (columns C1 and C2) are restraint. In both cases torsional movement is introduced in the structure under consideration (structure A) due to the plan asymmetry caused by the restraints imposed by the pounding between the adjacent structures.

The heights of the storey levels of the two structures are not equal (figure 1b). In this very common case the slabs of the diaphragms of each structure hit the columns of the other structure at a point within their deformable height. This phenomenon is especially intense at the contact point of the upper storey level of the short stiffer structure with the corresponding column of the tall building. The actual condition and the model idealization of this pounding case are shown in fig. 1b. Contact points are taken into account at the levels of the floor slabs of the short structure. Analyses have been performed using time steps of the order of 1=1000 to 1=10000 in order to achieve numerical stability and to adequately reproduce higher mode response excited by the short-duration impacts. Contact points are taking into account at the levels of the floor slabs of the short structure (fig. 1b). Nevertheless, from the analyses of the examined pounding cases it has been found that the response of the interacting structures is mainly influenced by the position and the characteristics of the contact point at the short structure's top floor. The influence of the other contact points on the results proved to be negligible in the examined cases. The same conclusion also holds, more or less, for the examined cases with non-zero initial distance gap.

Nevertheless, in the following analyses and results, the influence of the pounding effect through all floor contact point on the behaviour of the structures and on the response and ductility requirements of the columns is examined.

3 CONTACT ELEMENT

Collisions are simulated using special purpose contact elements that become active when the corresponding nodes come into contact.

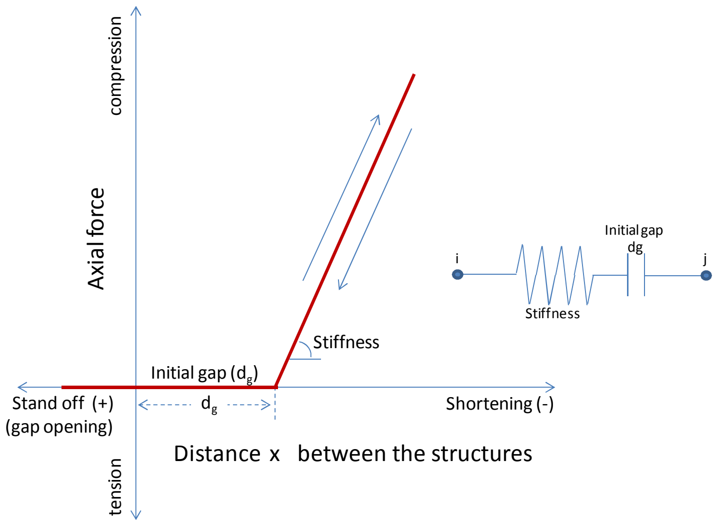


Figure 2: Contact elements

The response of the contact elements is shown in fig.2. The negative direction of the X-axis represents the condition that the buildings move away from each other. In the positive direction of the X-axis there are two parts in order to simulate the actual behaviour of the structures in case there is an initial small gap distance (d_g) between them. It is possible that the structures move one towards the other but the displacements are small and the existing gap is not covered. In this case the contact element remains non-active and the buildings continue to vibrate independently. In the case that the structures move one towards the other and the sum of the displacements of the two structures bridge the existing gap or the structures are in contact from the beginning (d_g=0) then the contact element responds as a spring with large stiffness.

4 ANALYSIS MODEL OF STRUCTURES

The frame structural system of the tall structure consists of beams and columns. Each structure is modeled as a 3D assemblage of non-linear elements connected at nodes. Each node has six degrees of freedom. The mass is lumped at the mass center of each floor. Each structure responds dynamically and vibrates independently. In the cases the interacting structures have equal story heights collisions occur when the lateral displacements of the structures at the floor levels exceed the predefined gap distance (d_g) between the two structures. In the cases that the heights of the interacting structures are not equal (inter-story pounding) the slabs of the shorter structure hit the corresponding columns of the 8-story building at points within their deformable length (fig. 1).

The computer program used in this work is the program package ETABS2000. The finite element mesh used here for the modeling of each structure utilizes an one-dimensional element for each structural member. The element is a common lumped plasticity beam-column model that considers the inelastic behaviour concentrated in zero-length "plastic hinges" at the element's ends. An interaction 3D surface N-M_x-M_y is employed for the check of the elastic or plastic response of the zero-length plastic hinges.

5 POUNDING CASES

More than fifty pounding cases have been studied for the needs of this work. Each one is subjected to three different natural seismic excitations having been selected so that their spectra fit properly with the design spectrum used for the design of the 8-story building.

In the inter-story pounding cases it is considered that the pounding takes place at points of the deformable height of the columns of the more flexible 8-storey frame structure. It is expected that the important problem in the case of inter-floor pounding of reinforced concrete structures is the development of critical shear state, since in these cases the demands of flexural ductility can more safely be satisfied. Furthermore, the fact that the failure of reinforced concrete members due to shear is brittle led the investigation of inter-floor pounding to the examination of the developing shear forces and their comparisons to the corresponding shear strength. Pounding at the mid-height of the column produces two column parts with equal flexural moments that may be flexurally critical parts. Further in any case the two parts of the column (the upper and the down part) suffer the same shear force which is equal to half of the impact force. Thus pounding cases at points of the column different to the mid-height creates a long part that may be flexurally critical and leads to a short shear critical column part. Therefore the contact points of the two structures in the examined cases lie at 2/3 of the height of the columns of the 8-story building; thus $h_A = 2/3$ h in Fig. 1b.

The examined cases are sorted into two series based on the level of the asymmetry that is induced in the 8-story building due to the pounding.

Series 1 includes pounding cases with high asymmetry (case 1 in fig. 1a) where pounding takes place between only one column of the 8-story building (column C1 in fig. 1a) and one column of the adjacent short and stiff structure. In series 2 (case 2 in fig. 1a) pounding takes place between two columns of the 8-story building (columns C1 and C2 in fig. 1a) and two columns of the adjacent short and stiff structure.

Thus both series include asymmetric pounding cases between the 8-story and an adjacent very stiff structure which has n_s story levels; where n_s =1, 2, 3, 4, 5, 6, 7 and 8 stories.

Each one of the pounding cases of both series first is examined considering that the interacting structures are in contact from the beginning (gap distance d_g=0); further each pounding case is examined considering that between the interacting structures there is a gap distance equal to 1 and 2 cm (d_g=1 and 2 cm).

6 RESULTS AND COMMENTS

The results and the conclusions deduced from the analyses of each series include the observed overall response of the multistory frame in terms of the induced torsional behavior and its repercussions on the developing capacity requirements of the columns. Therefore results for the shear demands and shear capacity of the columns are also presented and commented upon. Special attention has been given to the response of the columns of the story of the multistory frame where the pounding takes place.

6.1 Torsional behavior

Torsional oscillation is observed in the 8-story building due to the asymmetric inter-story pounding that occurs between it and the adjacent shorter and stiff structure. The time histories of the developing torsional moment at the base floor of the 8-story building during the seismic excitation due to asymmetric inter-story pounding (fig. 1) with a single-story very stiff structure for pounding cases 1 and 2 are presented in fig. 3. Similarly the time histories of the developing torsional moment at the base floor of the 8-story building due to asymmetric inter-story pounding with a 3-story very stiff structure for pounding cases 1 and 2 are presented in fig. 4.

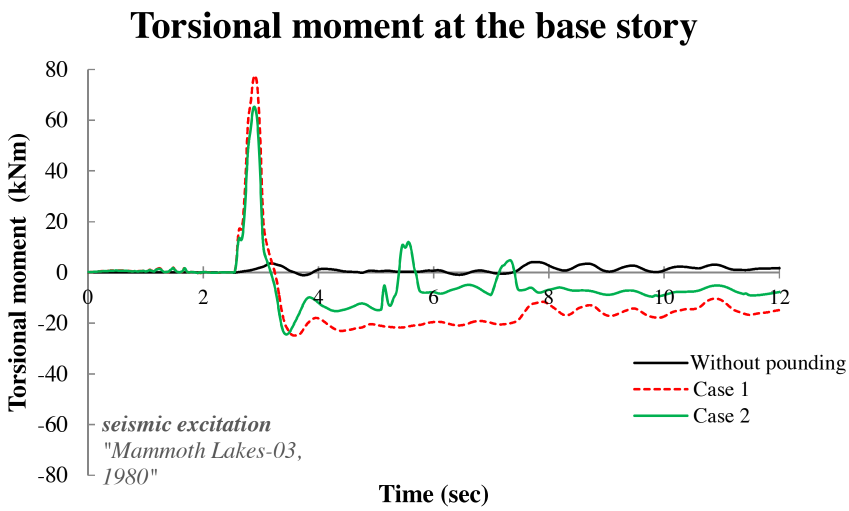


Figure 3: Time history of the torsional moment at the base floor due to asymmetric inter-story pounding for cases 1 and 2 between the 8-story building and a single story stiff structure.

Further in figs. 3 and 4 the time history of the corresponding torsional moment at the base floor of the 8-story building during the same seismic excitation without pounding is also included for comparison reasons. From this figures (fig. 3 and 4) it can clearly be deduced that asymmetric type inter-story pounding causes significant torsional movement and high value torsional moments in the 8-story building although its plan view is symmetric and in the cases it vibrates without the pounding effect it presents insignificant torsional moment and consequently no torsional movement.

From the results it is also deduced that the torsional movement which is induced due to the asymmetric pounding highly influences the distribution of the developing shear forces in the columns [5]. High shear forces are developed in the columns in the direction normal to the earthquake direction although the plan view of the building is symmetric in both directions.

In fig. 5 the observed maximum torsional rotations of all stories of the 8-story building (8RC) due to asymmetric pounding cases 1 and 2 are presented.

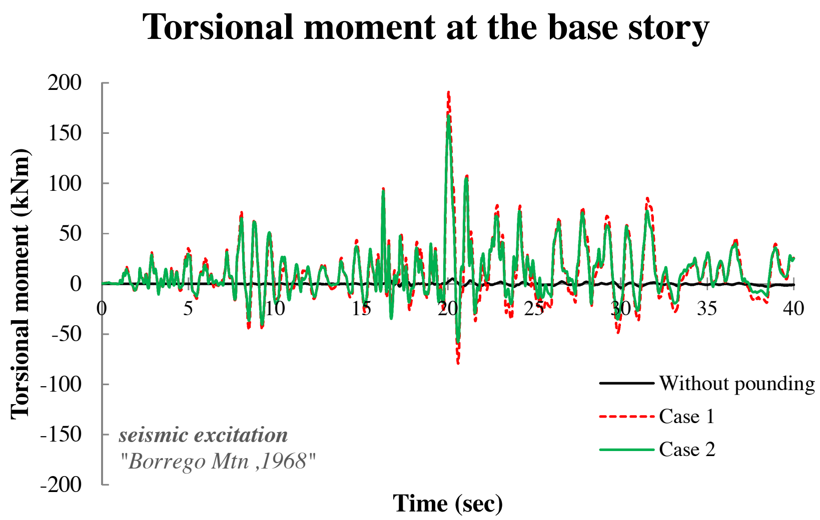


Figure 4: Time history of the torsional moment at the base floor due to asymmetric inter-story pounding for cases 1 and 2 between the 8-story building and a 3-story stiff structure.

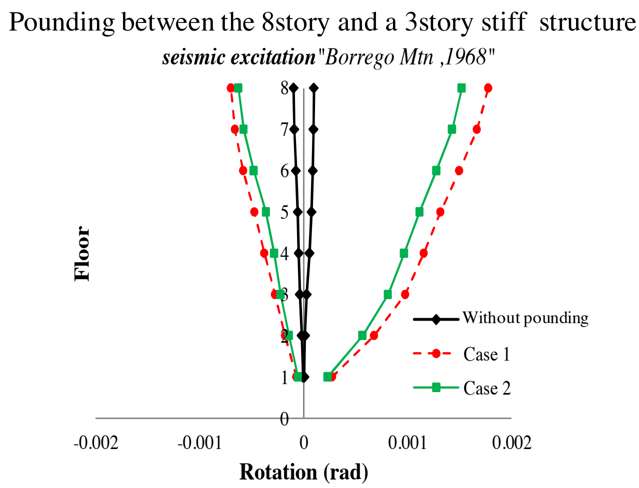


Figure 5: Maximum Torsional rotations of all stories of the 8-story building (8RC) due to asymmetric pounding (*cases 1 and 2*).

6.2 Columns that suffer the pounding - Shear force time histories

Time history for the developing shear force of the column C1 that suffers the pounding hit at the base floor of the 8-story building for pounding case 1 between the 8-story and a single story very stiff structure is presented in fig. 6 and is compared to the shear force time history of the same column for the response of the building without pounding. It can easily be concluded from fig. 6 that the developing shear forces in the case of inter-story pounding are significantly higher than the corresponding ones in the case that the building responds without pounding problems.

The ratio p_v of the maximum shear force $V_{x,max,ip}$ developing in the x-direction in the case of asymmetric inter-story pounding (ip) to the maximum shear force $V_{x,max}$ in the case that the building responds without pounding effect may point out the significance of problem. Thus the ratio p_{v1} for the case 1 and the ratio p_{v2} for the case 2 are 8.8 and 5.7, respectively.

Based on these values it can easily be obtained that when inter-story pounding occurs the developing shears are very high compared to the expected ones without the pounding problem.

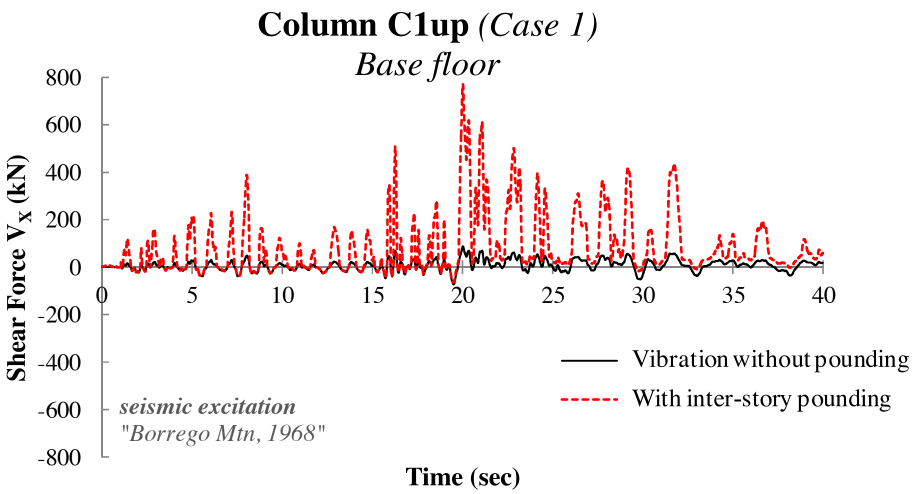


Figure 6: Time history of the shear force of Column C1 that suffers the hit (upper part) at the base floor due to asymmetric inter-story pounding for case 1 between the 8-story building and a single story stiff structure.

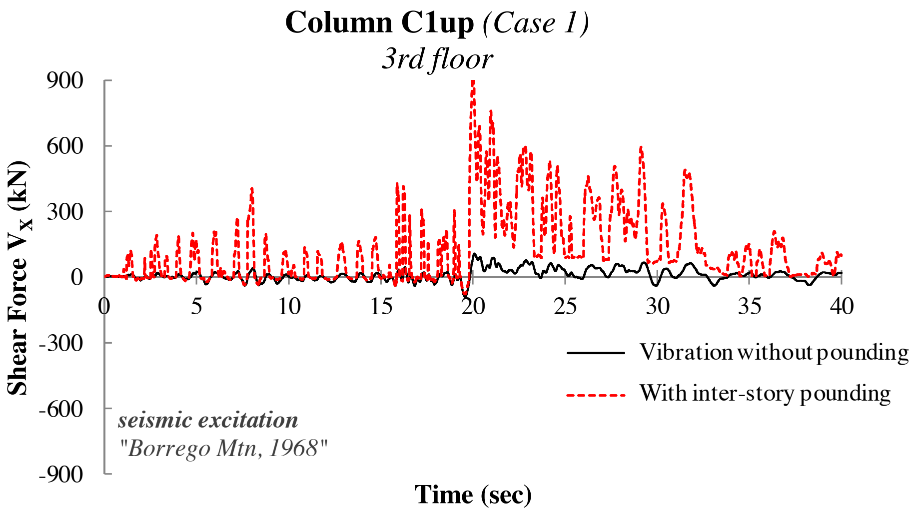


Figure 7: Time history of the shear force of Column C1 that suffers the hit (upper part) at the 3rd floor due to asymmetric inter-story pounding for case 1 between the 8-story building and a 3- story stiff structure.

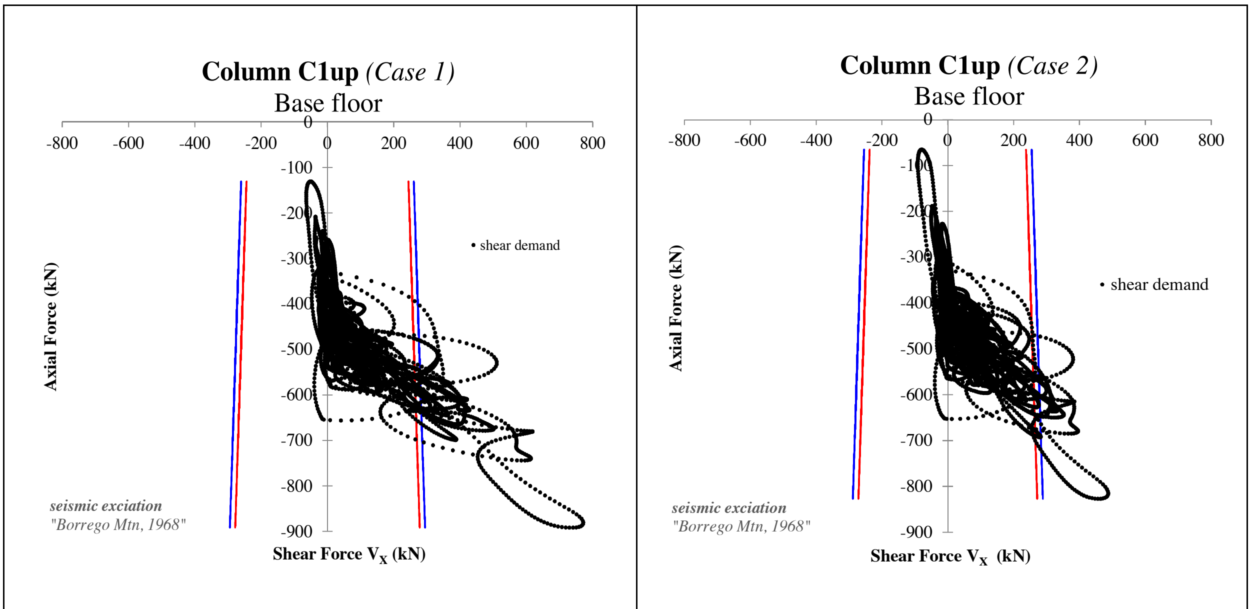
Furthermore in fig. 7 time history for the developing shear force of the column C1 that suffers the pounding hit at the 3rd floor of the 8-story building for pounding case 1 between the 8-story and a 3-story stiff structure is presented in fig. 7 and is compared to the shear force time history of the same column for the response of the building without pounding. It can easily be concluded from fig. 7 that the developing shear forces in the case of inter-story pounding are significantly higher than the corresponding ones in the case that the building responds without pounding problems.

The ratio p_{v1} for the case 1 and p_{v2} for the case 2 are 9.2 and 3.5, respectively. Based on these values it can easily be obtained that when inter-story pounding occurs the developing shears are very high compared to the expected ones without the pounding problem.

6.3 Columns that suffer the pounding - Shear force capacity

In figs. 8a and b the developing shear force values at the upper part of the column C1 at the base floor of the 8-story building for pounding with a single story stiff structure and for cases 1 and 2, respectively, are presented and compared to the ones of the available shear strength. In these figures the pairs of the observed shear force V - axial force N for all the time steps of the performed dynamic step-by-step analysis are presented and compared to the limits of the available strength. The red line represents the strength limits for each pair of V - N for the limit state of Significant Damage (SD) whereas the blue line the strength limits for the Near Collapse (NC) limit state.

It can be observed that in both asymmetric pounding cases (case 1 and case 2) there are pairs V - N values that lie outside the line limit of the available strength. It means that there are time periods during the seismic response of the building within which the developing shear forces exceed the available shear capacity and therefore a potential of a local shear brittle failure can be expected.



(a) Asymmetric pounding case 1 (b) Asymmetric pounding case 2

Figure 8: Asymmetric inter-story pounding between the 8-story building and a single story very stiff structure. Shear force V - axial force N pairs of observed values for all the time steps of the performed dynamic step-by-step analysis are presented and compared to the limits of the available strength.

Similarly in figs. 9a and b the developing shear force values at the upper part of the column C1 that suffers the hit at the 3rd floor of the 8-story building for pounding with a 3-story stiff structure for the cases 1 and 2, respectively, are presented and compared to the ones of the available shear strength.

It can be observed that in both asymmetric pounding cases (case 1 and case 2) there are pairs V - N values that lie outside the line limit of the available strength. It means that there are time periods during the seismic response of the building within which the developing shear forces exceed the available shear capacity and therefore a potential of a local shear brittle failure can be expected.

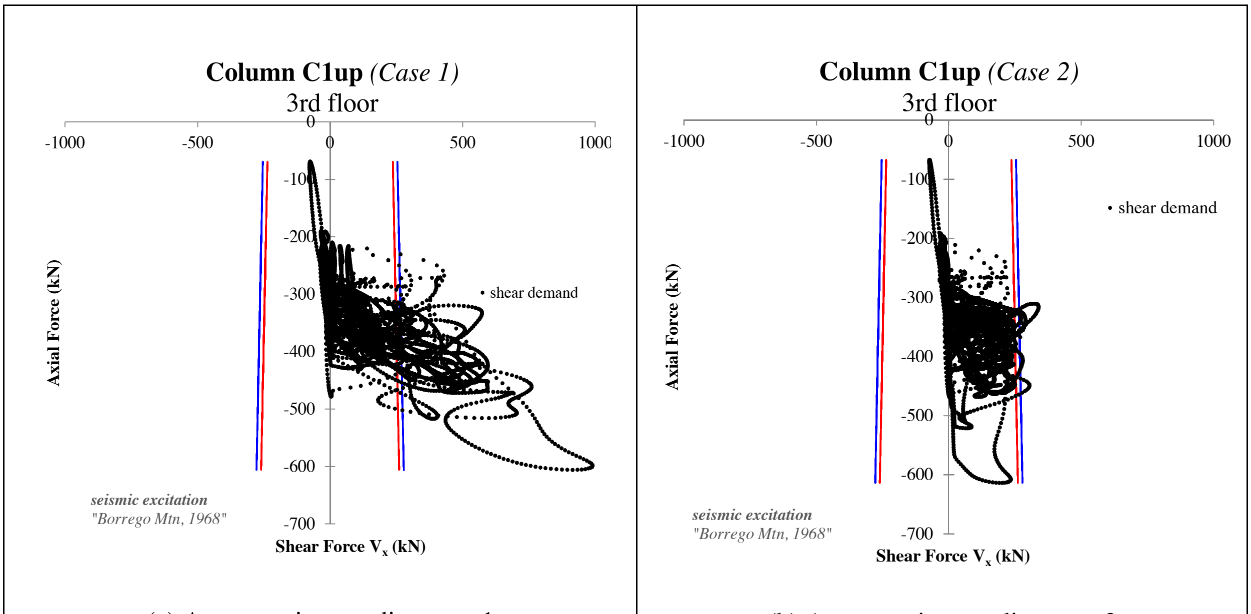


Figure 9: Asymmetric inter-story pounding between the 8-story building and a 3-story story very stiff structure. Shear force V - axial force N pairs of observed values for all the time steps of the performed dynamic step-by-step analysis are presented and compared to the limits of the available strength.

6.4 Ductility requirements

Pounding induced torsional vibration changes the ductility requirements of the columns and significantly increases the ductility requirements of the column that experiences the hit due to the inter-story pounding between the adjacent structures.

The ductility requirements of column C1 of the 8-story building in all floor levels for inter-story pounding with a single story stiff structure are presented in fig. 10. The presented results are for pounding cases 1 and 2 and the structures are in contact (d_g=0) from the beginning of the excitation.

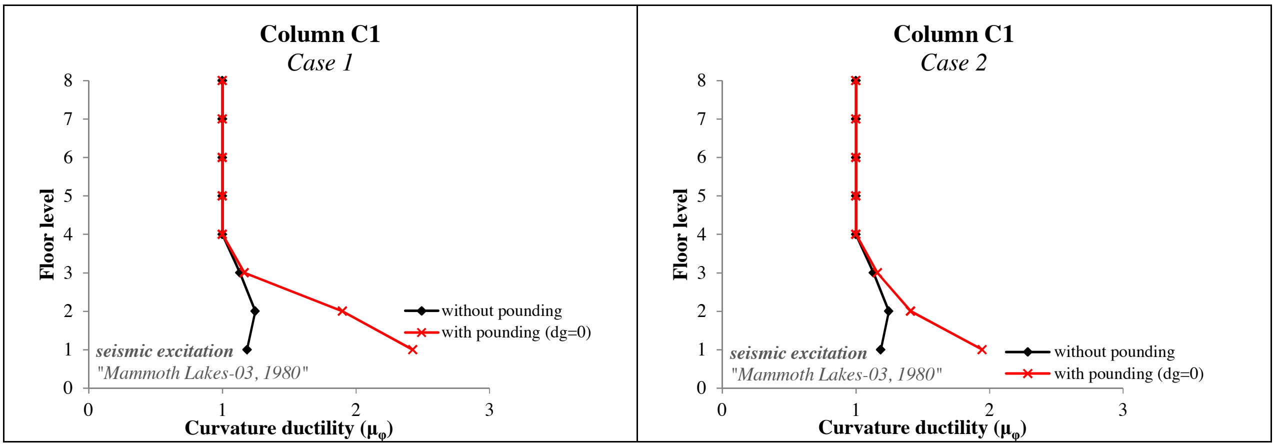


Figure 10: Maximum ductility requirements of column C1 in all floor levels. Comparisons of ductility requirements between pounding (case1) of the 8-story building with a single story structure and the free vibration of the 8-story building (without pounding effect).

The contact points lie at 2/3 of the height of the columns of the 8-story building (inter-story pounding); thus $h_A = 2/3$ h in Fig. 1b. The results are compared with the corresponding ones of the same column for the same seismic excitation without pounding effect.

It can be observed that column C1 at the base floor where pounding takes place exhibits significantly increased ductility requirements in comparison with the ones of the same column for the same excitation without pounding effect.

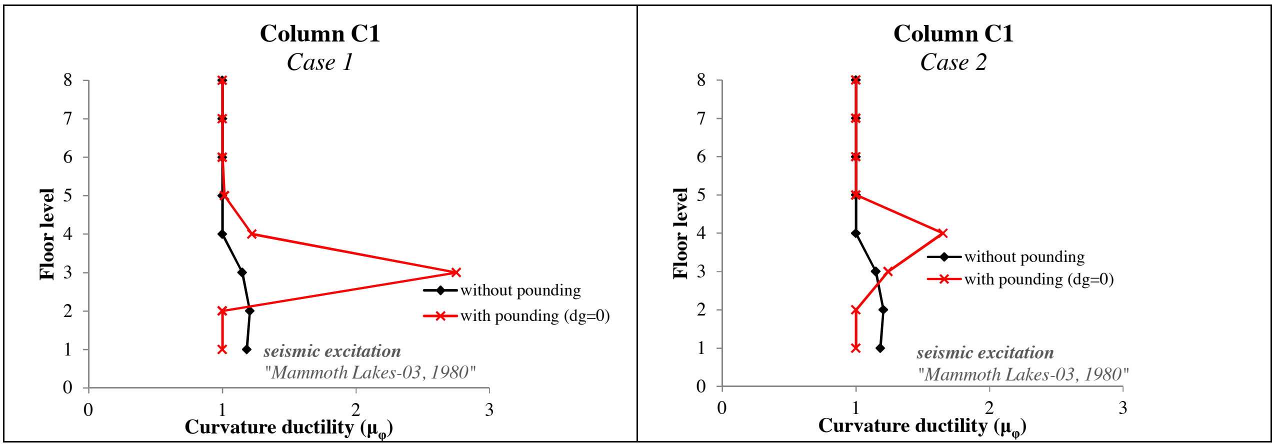


Figure 11: Maximum ductility requirements of column C1 in all floor levels. Comparisons of ductility requirements between pounding (case1) of the 8-story building with a 3-story structure and the free vibration of the 8-story building (without pounding effect).

Similarly in Fig. 11 the ductility requirements of column C1 of the 8-story building in all floor levels for inter-story pounding with a 3-story stiff structure, case 1 and d_g=0, are presented and compared with the corresponding ones of the same column for the same seismic excitation without pounding effect. Also in this case it can be observed that column C1 at the floor where pounding takes place exhibits significantly increased ductility requirements in comparison with the ones of the same column for the same excitation without pounding effect.

Furthermore it is observed that the column C1 at the 3rd level that suffers the hit exhibits higher ductility requirements in pounding cases where high asymmetric pounding (case 1) takes place in comparison with the ones in the cases where medium asymmetric pounding (case 2) occurs.

Nevertheless it has to be noted that the ductility requirements in the examined cases although substantially high in the cases that pounding takes place do not really exceed the usual available ductility capacity of reinforced concrete columns designed to Eurocodes 2 and 8.

7 CONCLUSIONS

- Seismically induced interaction between adjacent buildings that are partly and in a non-symmetric way in contact may introduce significant torsional oscillations. Furthermore in cases that the story heights of the interacting structures are not equal then the slabs of the diaphragms of the one structure hit the columns of the other structure at a point within their deformable height. This type of structural interaction may be referred to as asymmetric inter-story pounding.

- Asymmetric pounding between an 8-story reinforced concrete building with symmetric plan view and an adjacent shorter structure that has n_s floor levels is investigated for n_s=1,2,3,4,5,6,7 and 8 stories. Interaction cases with high (case 1) and medium (case 2) asymmetric pounding are included in the present study. It has been observed that in general the developing torsion increases as the height (the number of the stories) of the adjacent stiff structure increases.

- From the presented study it can be concluded that the torsional movement which is induced due to the asymmetric pounding highly influences the distribution of the developing shear forces in the columns. Furthermore high shear forces are developed in the columns in the direction normal to the earthquake direction although the plan view of the building is symmetric in both directions.
- Pounding induced torsional vibration changes the ductility requirements of the columns and significantly increases the ductility requirements of the column that experiences the hit due to the inter-story pounding between the adjacent structures.
- It is stressed that in all the examined inter-story asymmetric pounding cases during the step-by-step analyses a great number of time steps have been observed within which the pairs of the developing shear force - axial force (V - N) values lie well outside the line limit of the available strength. It means that there are time periods during the seismic response of the building within which the developing shear forces well exceed the available shear capacity and therefore a potential local shear brittle failure is expected.

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