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TORSION EFFECT DUE TO ASYMMETRIC POUNDING BETWEEN MULTISTORY RC BUILDINGS

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Abstract. *Earthquake induced collisions between adjacent structures have been repeatedly reported in the literature as a frequent case of damage. It is quite usual seismic induced oscillations of a structure in a block of buildings to be partly restrained in lateral displacements and therefore a torsional movement to be introduced in the building during an earthquake excitation. Further it has been repeatedly observed that torsion is a critical factor leading in many occasions to major structural damage or even complete collapse during strong ground motions. Seismic damage surveys and relevant analyses conducted on modes of failure of building structures during past severe earthquakes have concluded that among the most damage susceptible structures are those that exhibit torsional behavior. In this work the case of reinforced concrete multistory buildings that suffer pounding in a non-symmetric way is studied. Pounding occurs only in one (case 1) or two (case 2) columns of the structure whereas the other columns are free to move without restrictions. This way torsional oscillations are introduced in the structural system during a seismic excitation. Nonlinear dynamic step-by-step analysis and special purpose elements are employed for the needs of this study. More than fifty pounding cases with torsional effect between structures with different total height for three excitations are studied and results in terms of displacements, torsional rotations, ductility requirements are presented and commented. The influence of the size of the gap distance between the adjacent structures on the torsion effect is also investigated. The results clearly show that high capacity requirements in terms of torsional moments, column shear strength and ductility are developed due to the asymmetric pounding.*

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1 INTRODUCTION

The earthquake induced collisions between structural systems that are in contact or in close proximity to each other is commonly referred to as structural pounding. 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]. Further false code application lead sometimes to building separations that are inadequate and inconsistent with the philosophy of modern codes that imply large deformations can occur during major earthquakes due to inelastic response. 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) examined various cases of structural pounding [4] 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.

Furthermore 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 seismic 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. Therefore it can be concluded that in these cases pounding between adjacent structures may introduce significant plan asymmetry in the building in terms of lateral stiffness distribution.

On the other hand it is well known that buildings due to inherent asymmetries may exhibit torsional behavior during seismic excitations. Further it has been repeatedly observed that torsion is a critical factor leading frequently to major structural damage or even complete collapse during strong ground motions.

In this work forty eight pounding cases each one for three earthquake excitations have been studied. 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 short and stiff structure. In series 2 pounding takes place between two columns of the 8-story building and two columns of the adjacent short and stiff structure. Both series include asymmetric pounding cases between the 8-story and an adjacent structure with n_s =1, 2, 3, 4, 5, 6, 7 and 8 stories. 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.

2 MODEL IDEALIZATION OF POUNDING

In this work 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. 1). This configuration implies that the seismic induced oscillations of the tall building is laterally partly restrained by the other structure and therefore a torsional movement is introduced in the building during an earthquake excitation. Therefore in the examined cases pounding between adjacent structures introduces significant plan asymmetry in the building in terms of lateral stiffness distribution.

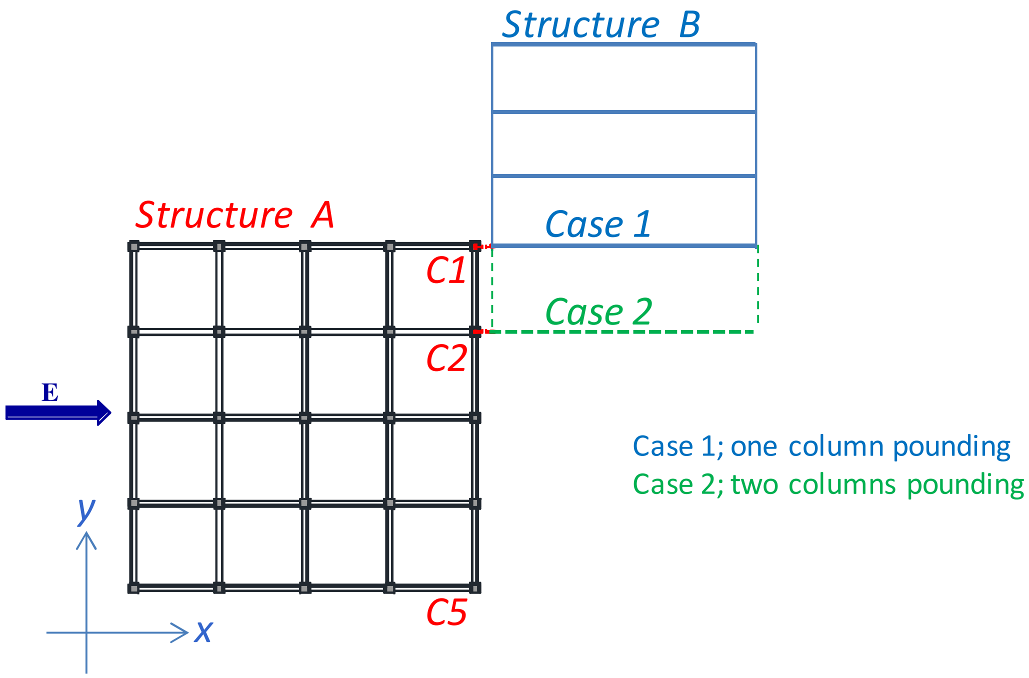

Figure 1: Plan view. Asymmetric pounding.

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. 1 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 story levels of the two structures are equal (Fig. 2). Actual condition and the model idealization of this pounding case are shown in Fig. 2.

Contact points are taking into account at the levels of the floor slabs of the short structure (Fig. 2). 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.

Seismic analyses have been performed using time steps in the range of 1/1000 sec to 1/10000 sec in order to maintain equilibrium during the integration.

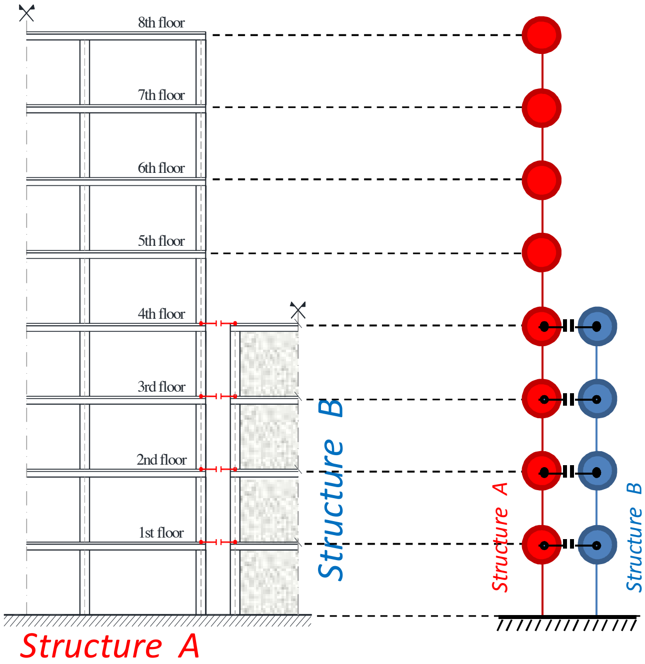

Figure 2: Pounding between buildings with different total heights. The heights of the stories of the two structures are alike.

3 CONTACT ELEMENT

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

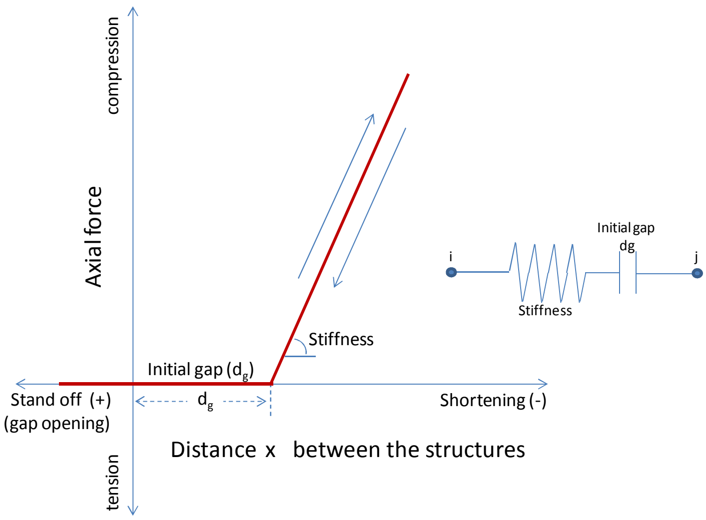

Figure 3: Contact elements

The response of the contact elements is shown in Fig.3. 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. Collision occurs when the lateral displacements of the structures at the floor levels exceed the predefined gap distance (d_g) between the two structures.

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.

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

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

Pounding cases of the 8-story building with an adjacent single story structure with different period values (not very stiff) are also examined and results are presented herein.

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 movement is observed in the 8-story building due to the asymmetric pounding that occurs between it and the adjacent shorter and stiff structure. The time history of the developing torsional moment at the base floor of the 8-story building during the seismic excitation due to case 1 asymmetric pounding (fig. 1) with a 3-story very stiff structure is presented in figure 4.

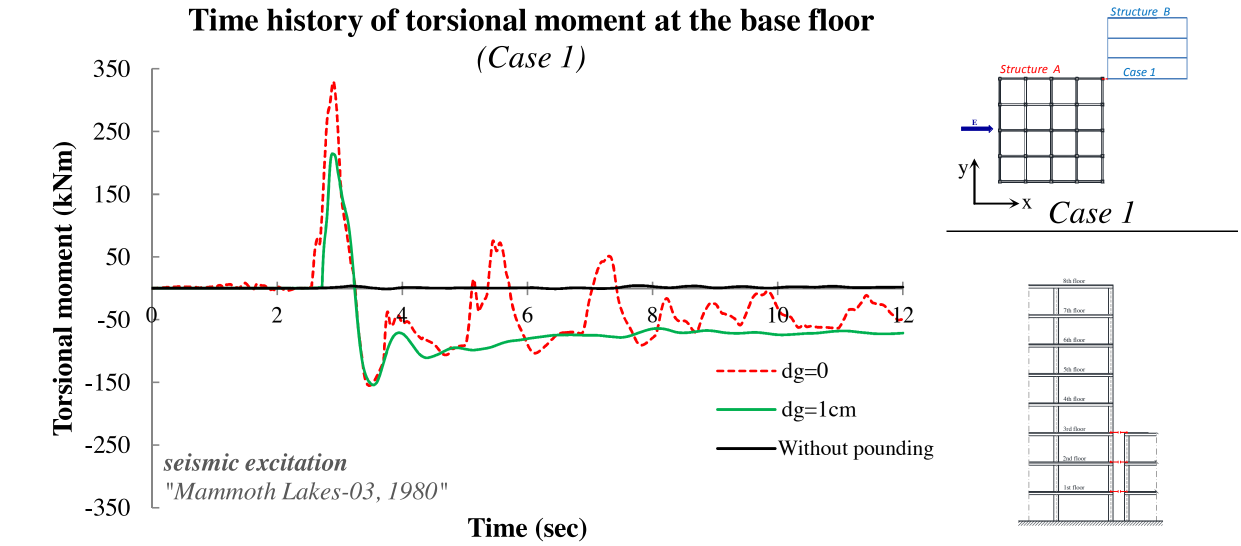

Figure 4: Time history of the torsional moment at the base floor due to asymmetric pounding case 1 between the 8-story building and a 3-story stiff structure.

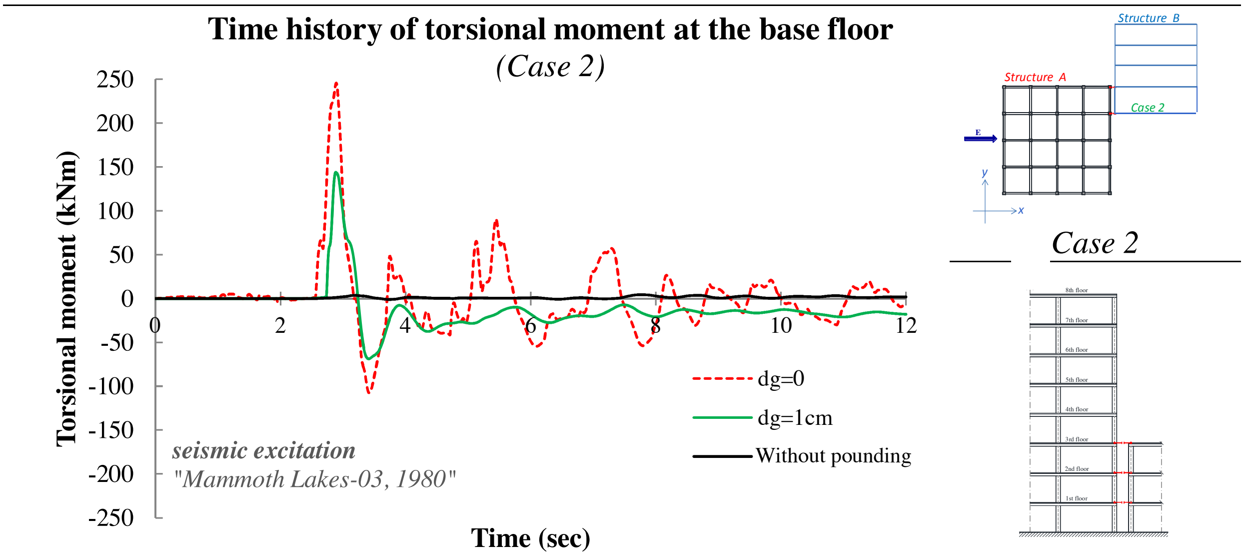

Figure 5: Time history of the torsional moment at the base floor due to asymmetric pounding case 2 between the 8-story building and a 3-story stiff structure.

Further the time history of the torsional moment at the base floor of the 8-story building during the seismic excitation due to case 2 asymmetric pounding (fig.1) with a 3-story very stiff structure is presented in figure 5. From these figures (figures 4 and 5) it can be deduced that asymmetric type of 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 no torsional moment and consequently no torsional movement.

From the results it can also be deduced that the developing torsion of the 8-story building also depends on the height of the adjacent stiff structure. In Fig. 6 the time histories of the developing torsional moment for the four cases of pounding are presented. In particular the pounding case between the 8-story building (8RC) and a single story building (1RC), a three story building (3RC), a five story building (5RC) and an eight story building (8RC) are included and compared to each other. From these comparisons it can be observed that in general the developing torsion increases as the height (the number of the stories) of the adjacent stiff structure increases.

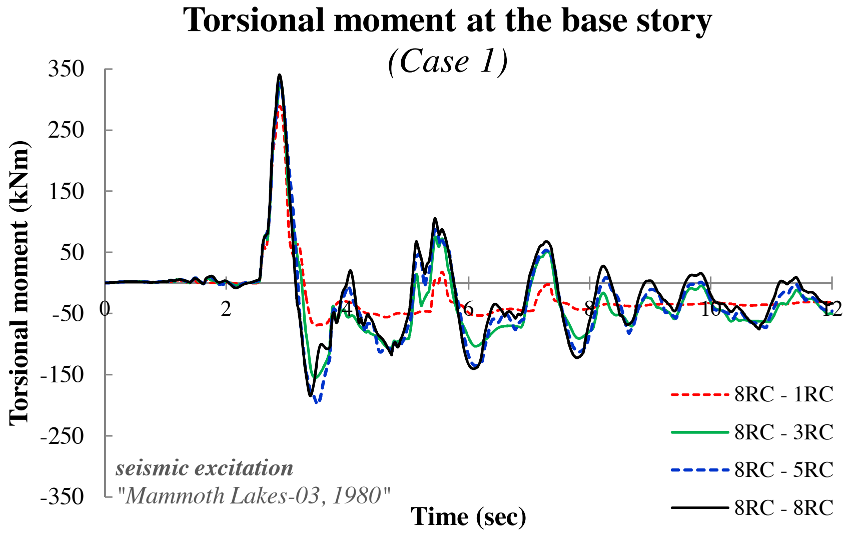

Figure 6: Influence of the number of stories (total height) of the adjacent structure on the developing torsional moment of the 8-story building (8RC) as observed at the base floor due to asymmetric pounding (case 1).

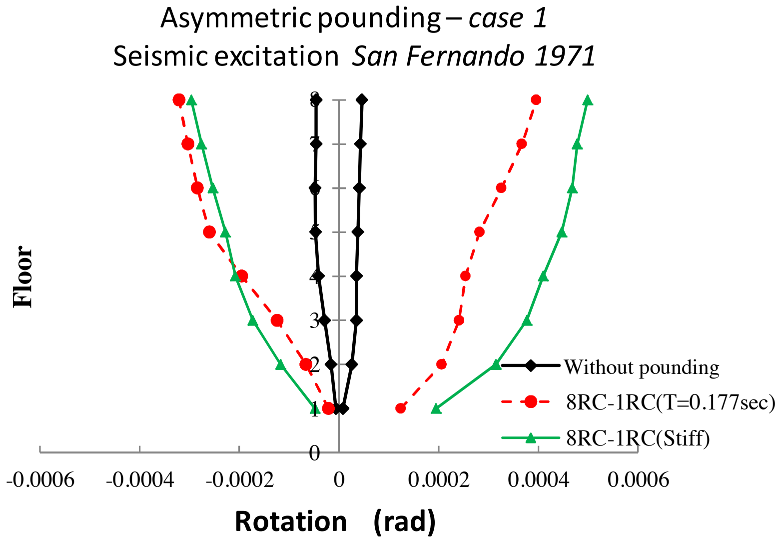

Figure 7: Influence of the period of the adjacent single story structure (1RC) on the developing torsional oscillations (maximum observed rotations of all stories) of the 8-story building (8RC) due to asymmetric pounding (*case 1*).

Furthermore the developing torsion of the 8-story building is also influenced by the period of the adjacent structure. In Fig. 7 the maximum observed rotations of the all floors of the 8-story structure are presented for the cases (a) free vibration without pounding, (b) pounding case 1 with a single story structure exhibiting period in the direction of the seismic excitation equal to T=1.77s and (c) pounding case 1 with single story very stiff structure.

From Fig. 7 it can be observed that the period of the adjacent single story structure influences the pounding of the buildings and it seems that the stiffer single story structure induces higher values of rotation in the 8-story building.

6.2 Column shear forces

As expected the torsional movement of the examined building highly influences the distribution of the developing shear forces in the columns. In Fig. 8 the time history of the developing shear forces of column C1 of the 3rd floor is for the pounding case 1 between the 8-story building and a 3-story stiff structure.

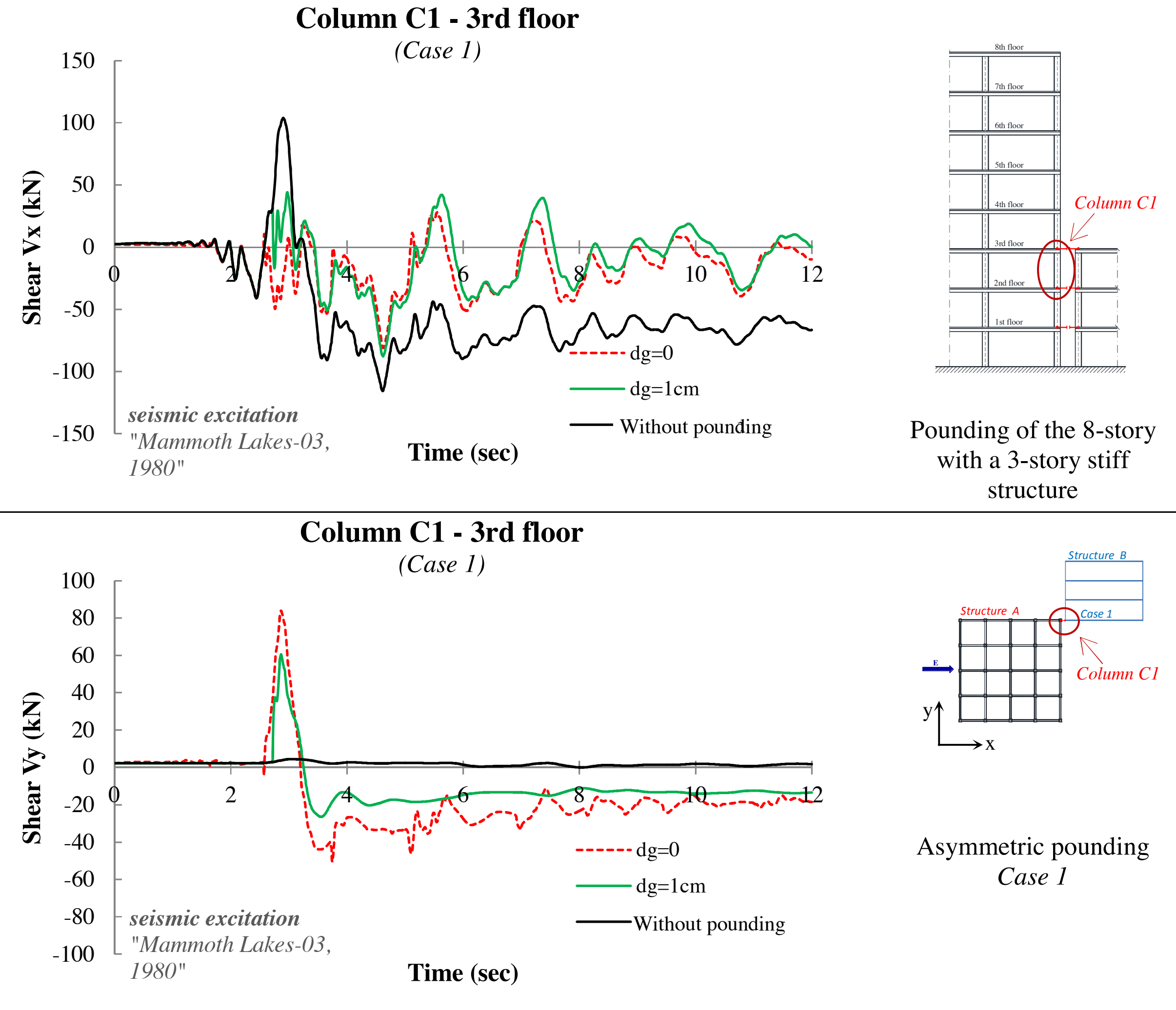

Figure 8: Shear time history for column C1 of the 3rd floor in the two directions for seismic excitation acting in the x-direction. It is stressed that high shear is developed in the normal direction (y-direction) due to the torsional movement induced by the asymmetric pounding.

It can be seen the shear forces of the column C1 in the direction of the earthquake excitation (x-direction) decrease due to the movement restraint provided by the adjacent 3-story structure at this point of the building whereas at the same time significant shear forces are developed in the normal direction (y-direction).

The ratios r_v of the maximum shear force ($maxV_y$) of column C1 at the base floor developing normal to the direction of the earthquake excitation to the maximum shear force ($maxV_x$) of the same column developing in the direction of the earthquake excitation for the pounding between the 8-story building and the single story stiff structure are presented in table 1 for pounding cases 1 and 2.

$r_v=maxV_y/maxV_x$ seismic excitation	*Case 1*	*Case 2*
Borego Mtn (4/9/1968)	0.98	0.56
San Fernando (2/9/1971)	0.76	0.63
Mammoth Lakes-03 (5/25/1980)	1.11	0.61

Table 1: Ratios r_v for column C1 at the base floor. Pounding between 8-story and single story structures.

The ratios r_v of the maximum shear force ($maxV_y$) of column C1 at the 3rd floor developing normal to the direction of the earthquake excitation to the maximum shear force ($maxV_x$) of the same column developing in the direction of the earthquake excitation (x-direction) for the pounding between the 8-story building and the 3-story stiff structure are presented in table 2 for pounding cases 1 and 2.

$r_v=maxV_y/maxV_x$	$d_g = 0$		$d_g = 1$ cm	
seismic excitation	*Case 1*	*Case 2*	*Case 1*	*Case 2*
Borego Mtn (4/9/1968)	0.85	0.66	0.46	0.37
San Fernando (2/9/1971)	0.71	0.70	0.41	0.31
Mammoth Lakes-03 (5/25/1980)	1.03	0.94	1.37	0.50

Table 2: Ratios r_v for column C1 at the 3rd floor. Pounding between 8-story and 3-story structures.

The ratios r_v of the maximum shear force ($maxV_y$) of column C1 at the 5th floor developing normal to the direction of the earthquake excitation to the maximum shear force ($maxV_x$) of the same column developing in the direction of the earthquake excitation (x-direction) for the pounding between the 8-story building and the 5-story stiff structure are presented in table 3 for pounding cases 1 and 2.

$r_v=maxV_y/maxV_x$	$d_g = 0$		$d_g = 1$ cm	
seismic excitation	*Case 1*	*Case 2*	*Case 1*	*Case 2*
Borego Mtn (4/9/1968)	1.00	0.54	0.83	0.74
San Fernando (2/9/1971)	0.99	1.25	0.88	0.84
Mammoth Lakes-03 (5/25/1980)	1.21	1.01	1.08	1.23

Table 3: Ratios r_v for column C1 at the 5th floor. Pounding between 8-story and 5-story structures.

From tables 1, 2 and 3 it can be seen that significant shear forces are developed in the direction normal to the direction of the seismic excitation. This conclusion holds for all seismic excitations used in this study. Thus for pounding case 1 and d_g=0 (structures in contact) for the pounding cases examined in this study ratio r_v shows that the shear force developed normal to the excitation direction is more or less equal to the shear force developed in the direction of the seismic excitation. Further though it can be observed that in cases an initial seismic gap (d_g=1cm) exists from the beginning between the interacting structures an essential mitigation of the phenomenon is observed.

6.3 Ductility requirements

Pounding induced torsional vibration changes significantly the ductility requirements of the columns and rather increases the ductility requirements of columns that experience high displacement due to the rotational movement of the structure and especially of column C5.

In Fig. 9 the ductility requirements of column C5 of the 8-story building (see Fig. 1) in all floor levels for pounding 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. It can be observed that column C5 in the levels above the contact level exhibits increased ductility requirements in comparison with the ones of the same column for the same excitation without pounding effect.

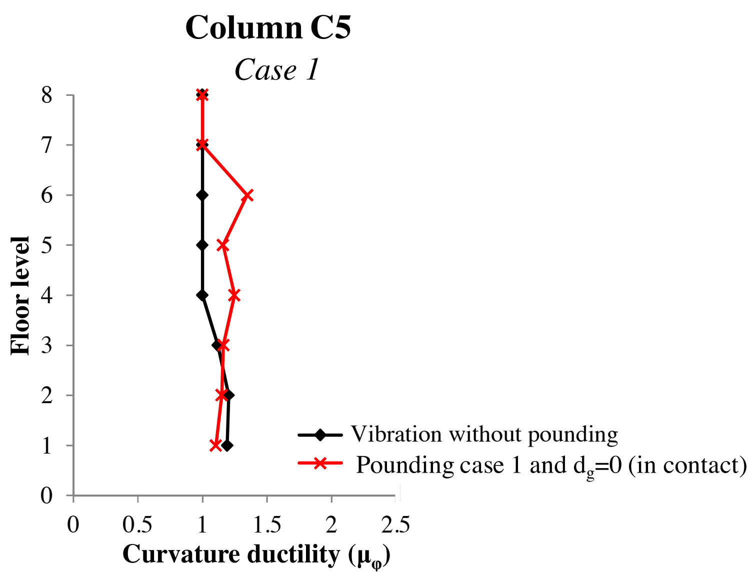

Figure 9: Maximum ductility requirements of column C5 in all floor levels. Comparisons of ductility requirements between pounding (case1) of the 8-story building with a single story structure and the free vibration of the 8-story building (without pounding effect).

7 CONCLUSIONS

- Seismic induced interaction between adjacent buildings that are partly and in a non-symmetric way in contact may introduce significant torsional oscillations. This type of structural interaction may be referred as asymmetric 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.

- The examined asymmetric type of pounding causes significant torsional movement and high value torsional moments in the 8-story building. The developing torsion increases as the height of the adjacent shorter structure increases.
- The period of the adjacent structure influences the severity of the pounding. In the case of pounding between the 8-story with a single story structure it seems the stiffer the single story structure is the higher values of rotation is induced in the 8-story building.
- 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. 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 significantly the ductility requirements of the columns and rather increases the ductility requirements of columns that experience high displacement due to the rotational movement of the structure.

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