# Influence of infill panels with and without openings on the pounding effect of RC structures

**M.J. Favvata, C.G. Karayannis**
*Democritus University of Thrace, Greece*

**V. Anagnostopoulou**
*Civil Engineer, MSc, Greece*

**SUMMARY:**
The structural pounding problem between adjacent multistory reinforced concrete structures with unequal total heights is investigated taking into account the influence of the infills. Two distinct types of structural pounding are considered namely: Type-A, where impacts between the adjacent structures may occur only between slabs and Type-B, the inter-story structural pounding, where the slabs of the one hit the columns of the other. In this study two different types of masonry panel are also considered: (a) solid infills and (b) infills with openings. The case of bare frame structure is also studied for comparison reasons. Results in terms of interstorey drifts, shear requirements and ductility requirements are presented. The most important issue in the inter-story pounding (Type-B) is the local response of the column of the tall structure that suffers the hit of the upper floor slab of the adjacent shorter and stiffer structure. This column appears to be in most of the times in a critical condition due to shear action. In the case of structural pounding Type-B the influence of the infill panels on the seismic performance of the critical column that suffers the hit led in all the examined cases to an increase of the demands for shear and ductility compared to the corresponding values in the cases that the RC structure is studied without considering the infills.

*Keywords: structural pounding, inter-story pounding, infills, infills with openings, non-linear seismic analysis*

## 1. INTRODUCTION

Masonry infills are usually used in RC frame structures as partition walls. Although the contribution of the infill panels has been recognised as substantial for the seismic response of the structures research results yielded controversial results for their influence on the capacity of the RC frames. Henceforth no code provisions or rational guidelines are still available for the design and safety assessment of such structures. The contribution of infills to lateral stiffness and strength of frames is usually neglected during the design of new buildings. Therefore, appropriate analytical tools for elastic and inelastic analysis of reinforced concrete frames with masonry infills need to be developed. Furthermore in the common case of structures with infilled masonry panels with openings the need of the appropriate analytical tools becomes very complex.

On the other hand an important cause of structural damage that under certain conditions can lead to collapse initiation is that of pounding between adjacent structures. Many analytical works on structural ounding have been reported during the last three decades.

The influence of structural pounding on the seismic response of multistory structures based on inelastic time-history (dynamic) has recently been studied.

Karayannis and Favvata (2005a) for the first time, examined the influence of the structural pounding problem on the ductility requirements and the overall seismic response of reinforced concrete structures with unequal heights designed according to the Eurocodes 2(EC2) and 8 (EC8). Results of seventy two pounding cases between structures with equal inter-story heights and each one for two different seismic excitations were presented and used in order to quantify the pounding effect.

Moreover, initial results for the case of pounding between adjacent structures where the slabs of the one structure hit the columns of the other one were included. This phenomenon is referred by the authors as inter-story pounding.
Furthermore, Karayannis and Favvata (2005b) have presented an extensive investigation on the inter-story pounding problem between adjacent multistory reinforced concrete frames with unequal total heights and different story heights designed according to the codes EC2 and EC8. Fifty two pounding cases each one for two different seismic excitations were examined. In these cases the slabs of the short stiffer structure hit the columns of the multistory structure at a point within the deformable height and this phenomenon was referred to as inter-story pounding. The effect of the number of stories on the response of the multistory frame structures that suffers the pounding effect was investigated. The results of this study yielded the conclusion that the most important problem in the case of inter-story pounding of reinforced concrete structures is the developing critical shear state at the columns that suffer the hit, since in these cases the demands of flexural ductility can more or less safely satisfied. It is noted that the local damage of the critical column that suffers the impact as a result of seismic pounding had not been investigated until then.
Recently, Favvata and Karayannis (2011) presented an effort to take into account the influence of the infills on the pounding problem, too. Damages in reinforced concrete buildings during the recent earthquakes indicated that the interaction between masonry infilled frames and bare frame can lead to unexpected effects on the seismic response of the RC building such as shear failure in columns, damage to joint region and soft storey mechanism. Considering that brittle failures can be occurred by the concentration of high stresses transferred from the infills to the columns the interaction between masonry infill and bare frame should also be considered in the seismic analysis of structures. The influence of the infill panels on the earthquake inter-story pounding between adjacent structures is studied in this work (Favvata and Karayannis, 2011). Two types of masonry infilled structures were considered: (a) infilled frame and (b) infilled frame without infills at the base story (pilotis type).
In the present work the pounding problem is examined for the case of multistory structures with masonry that have openings (windows) centrically located.

## 2. MODELLING ASSUMPTIONS

### 2.1 Idealization of inter-story structural pounding

The earthquake-induced interaction between adjacent structures with different total heights is studied taking into account the local response of masonry infilled panels. The actual condition and the model idealization of this interaction case are shown in Fig.1.
In the case of the inter-story pounding the slabs of the diaphragms of each structure hit the columns of the other structure at a point within the deformable height. Contact points are taking into account at the levels of the floor slabs of the short structure, since it has been found (Karayannis and Favvata, 2005a) that the response of the interacting structures is influenced only 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 for such types of structural pounding.
Collisions are simulated using special purpose contact elements that become active when the corresponding nodes come into contact. This idealization is consistent with the building model used and adequate for studying the effects of pounding on the overall structural response for the pounding cases under examination. In the case that the structures move one towards the other but the displacements are small and the existing gap is not covered 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 displacements bridge the existing gap or the structures are in contact from the beginning then the contact element responds as a spring with almost infinite stiffness. More details on the characteristics and response of the contact element can be found in previous works by Karayannis and Favvata 2005a, b.
Seismic analyses have been performed using the well known computer program Drain-2Dx (Prakash et al 1993).

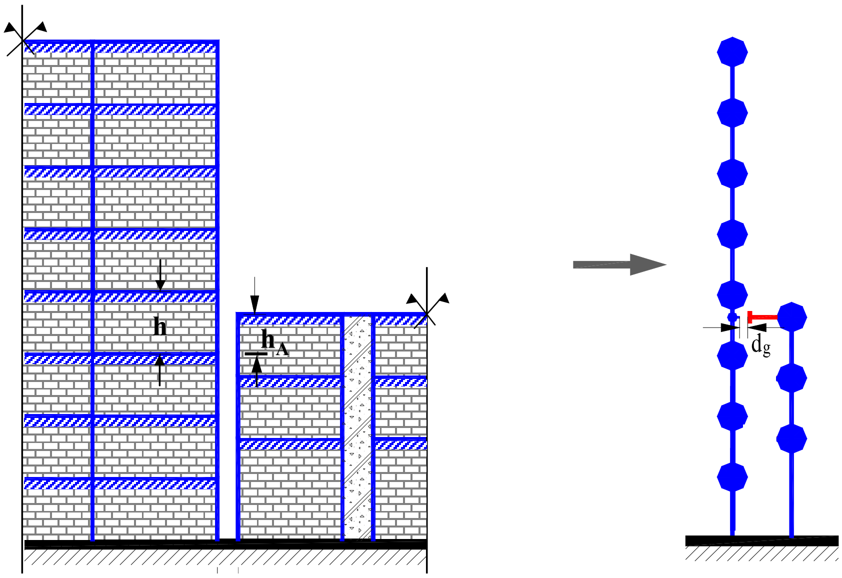


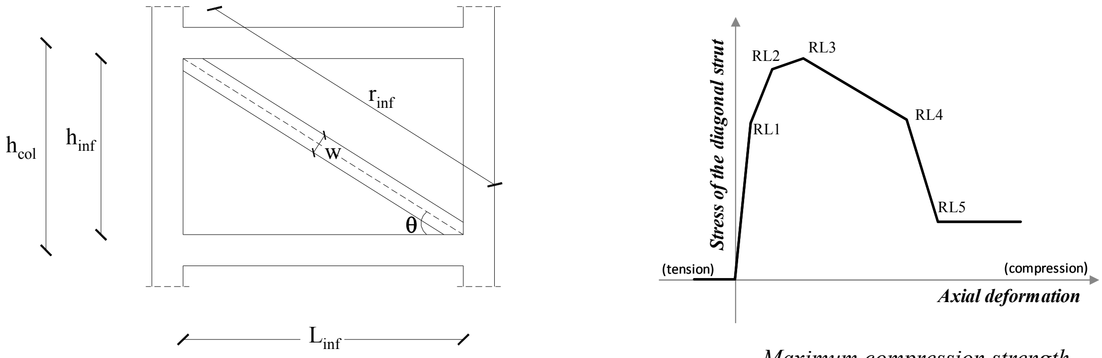

**Figure 1.** Actual condition and model idealization of inter-story pounding problem that includes infills panel local response.

### 2.2 Simulation of the beams and columns

The structural system consists of beams and columns. The structure is modeled as a 2D assemblage of non-linear elements connected at nodes. The mass is lumped at the nodes and each node has three degrees of freedom. The finite element mesh utilizes a one-dimensional element for each structural member. Two types of one-dimensional beam-column elements were used. The first one is the common lumped plasticity beam - column element and it was used for the modeling of the beams. With this element-model the inelastic behaviour is concentrated in zero-length "plastic hinges" at the element's ends. For the modeling of the columns a different type of element is adopted. That was the "distributed plasticity" special purpose element. This type of element is accounting for the spread of inelastic behaviour both over the cross-sections and along the deformable region of the member length. Moreover, this element performs numerical integration of the virtual work along the length of the member using data deduced from cross-section analysis at pre-selected locations. Thus, the deformable part of the element is divided into a number of segments and the behaviour of each segment is monitored at the centre cross-section (control section) of it. The cross-section analysis that is performed at the control sections is based on the fibre model. This fibre model accounts rationally for axial – moment (P-M) interaction.

### 2.3 Simulation of the infill panels

For the simulation of the local response of the masonry infill panel the equivalent diagonal strut model is used. For this purpose a special purpose beam-column element is used for the modeling of the infills (Karayannis et al 2005). This element accounts for more accurate definition of the response properties of infilled masonry since it includes degrading branch (Fig. 2). Special attention has been given in the implementation of this element for the simulation of the infill panel in order to exhibit axial response only and not flexural one. An important problem in modeling the infill panel is the determination of the response characteristics of the diagonal strut model, taking into account the actual conditions of the effective lateral confinement of the masonry by the reinforced concrete frame. The actual properties of the infill panel have been approached using the experimental results by Karayannis et al (2005) and Kakaletsis & Karayannis (2009). After the assessment of the lateral resistance of the infill panel the characteristics needed for the diagonal strut model were determined. The effective width of the diagonal element was determined according to FEMA 273 (1997) & FEMA 306 (1999) recommendations that are mainly based on the Mainstone's formula (1971) (see also Fig. 2). Based on these results the influence of an opening (window) on the compression strut characteristics has also been taken into account (see also Kakaletsis et al, 2006).




*w : width of equivalent diagonal compression strut*

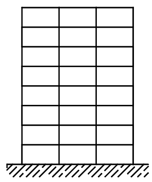
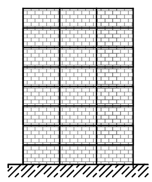
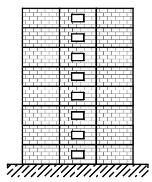
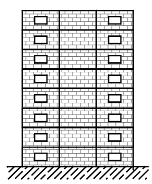
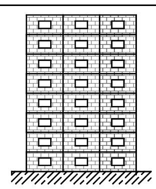
*Maximum compression strength*
*without opening $f'_m \approx 5{,}05$ MPa*
*with opening $f'_m \approx 3{,}44$MPa*

a. Characteristics of the equivalent diagonal strut

b. Response of the equivalent strut

**Figure 2.** Simulation of the infill panel based on the diagonal strut model

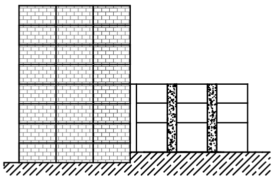
**Table 1.** Fundamental periods of 8-story structures

| | | 1st mode period T1(sec) |
|---|---|---|
| **bare frame** |  | 1.132 |
| **fully infilled frame** |  | 0.460 |
| **infilled frame - infills of the central bay have openings** |  | 0.557 |
| **infilled frame - infills of the two external bays have openings** |  | 0.632 |
| **infilled frame – all infills with openings** |  | 0.827 |

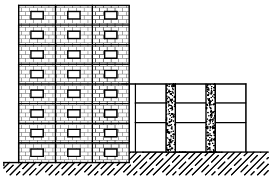
## 3. EXAMINED CASES

The structural pounding problem between adjacent multistory reinforced concrete structures with unequal total heights is investigated taking into account the local response of the infills. Two, well known, distinct types of structural pounding are considered, namely: Type-A, where impacts between the adjacent structures may occur only between slabs and Type-B; the inter-story structural pounding, where the slabs of the one building hit the columns of the other.
Two different types of masonry panel are considered: (a) fully infilled panel and (b) infill panel with openings, while four different interstory stiffness distributions are taken into account (based on these two types of masonry). This way, the examined multistory infilled structure that suffers the earthquake pounding effect is studied as: (a) fully masonry infilled structure (b) fully masonry infilled structure with openings and (c) masonry infilled structure with openings at specific positions. The case of bare frame RC structure is also studied for comparison reasons. These examined cases are presented in Fig.3.

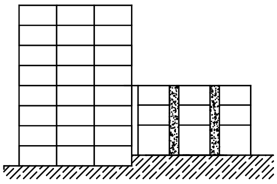
**Structural Pounding Type-A**



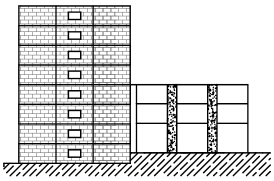
*(a) fully masonry infilled structure*

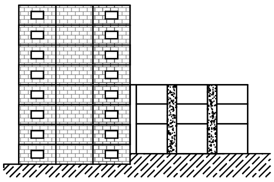


*(b) fully masonry infilled structure with openings*



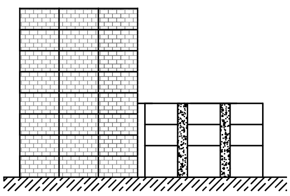
*(d) bare frame structure*



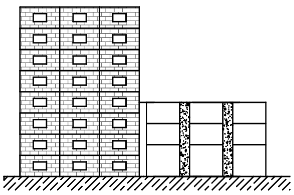


*(c) masonry infilled RC structure with openings on specific positions*

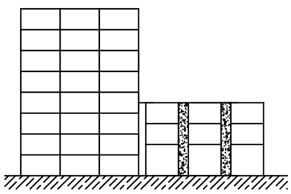
**Structural Pounding Type-B**



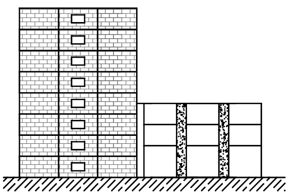
*(a) fully masonry infilled structure*

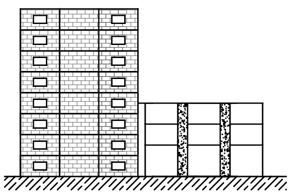


*(b) fully masonry infilled structure with openings*



*(d) bare frame structure*





*(c) masonry infilled RC structure with openings on specific positions*

**Figure 3.** Examined interaction cases

The examined RC structure is an 8-story frame building structure designed according to the Eurocodes 2 & 8. The mass of the structure is taken equal to M = (G+0.3Q) (where, G gravity loads and Q live loads). The design base shear force of the examined 8-story structure was equal to V = (0.3g/q)M where, q is the behaviour factor of the structure that equals to 3.75. Reduced values of member moments of inertia ($I_{ef}$) were considered in the design to account for the cracking; for beams $I_{ef}=0.5I_g$ (where $I_g$ the moment of inertia of the gross section) and for the columns $I_{ef}=0.9I_g$ . Critical for the dimensioning of the columns proved to be in most of the cases the code provision regarding the axial load ratio limitation $v_d \leq 0.65$ and in a few cases the code requirements for minimum dimensions.

## 4. RESULTS

The excitation of El Centro 1940 has been used for the performed seismic analyses. The displacement time histories of the 4th story of the 8-story structure for the interaction cases of Type-A and Type-B are presented and compared to each other in Figs. 4, 5 & 6 for the cases of (a) bare 8-story frame, (b) infilled 8-story frame with solid infills and (c) infilled 8-story frame with infills that have openings (in the interior bay), respectively.

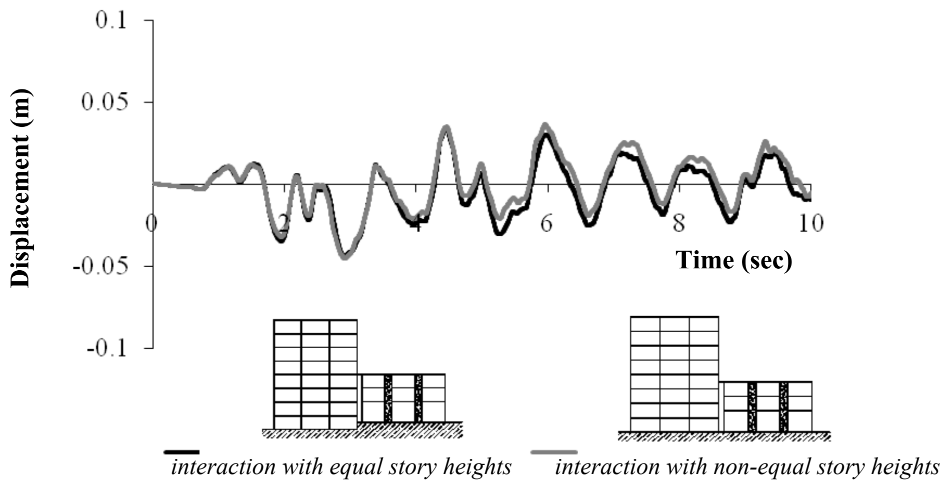



**Figure 4.** Displacement time histories of the 4th story of the 8-story bare frame for Type-A and Type-B pounding cases.

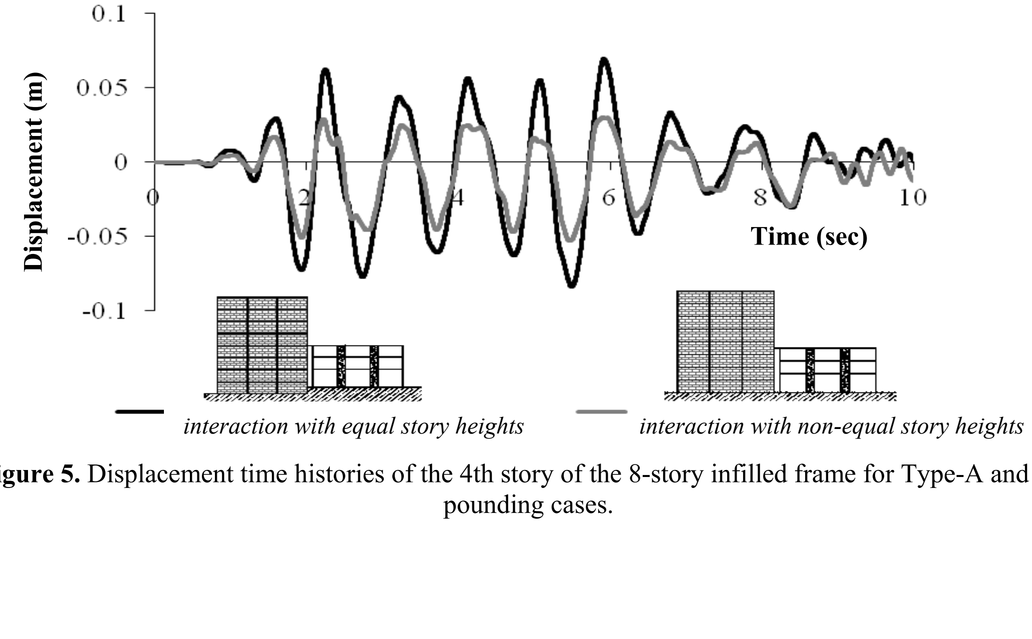



**Figure 5.** Displacement time histories of the 4th story of the 8-story infilled frame for Type-A and Type-B pounding cases.

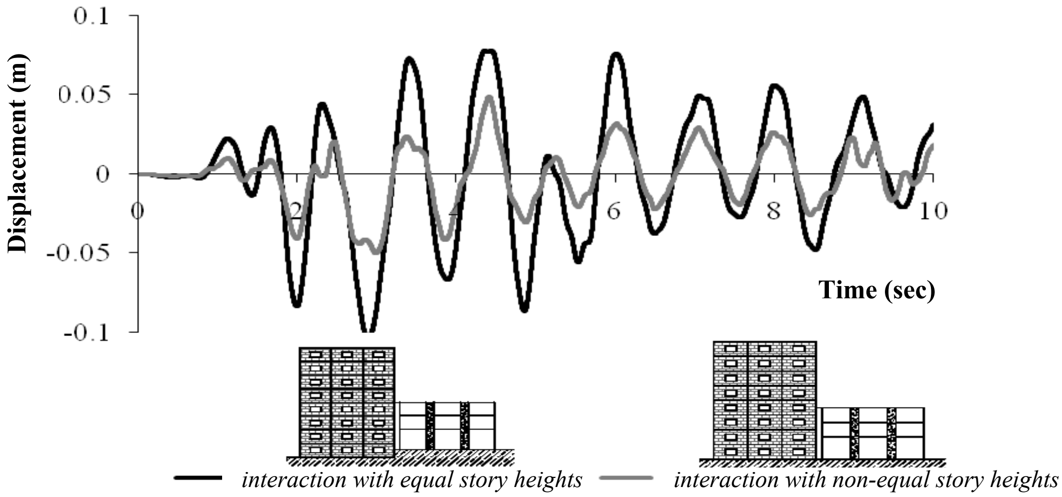



**Figure 6.** Displacement time histories of the 4th story of the 8-story infilled frame with infills that have openings for Type-A and Type-B pounding cases.

The ductility demands of the exterior columns of the 8-story frame structure are presented in Figs. 7, 8 & 9. In Fig. 7 the ductility demands of these columns are presented for the case without the pounding effect and compared to the available ductility values. In this case the available values of ductility are greater than the demanded values. In Fig. 8 the ductility demands for the cases of pounding Type-A are presented and compared with the corresponding available values. In this case the available values are also greater that the corresponding demands.
In Fig. 9 the ductility demands for the cases of pounding Type-B (inter-story pounding) are presented. In these cases the influence of the inter-story pounding effect on the seismic behavior of the critical column that suffers the hit has to be given special attention. In this respect, for the examined interaction cases results concerning the flexural and the shear demands of the critical external column of the 8-storey frame structure that suffers the inter-story pounding are presented and compared with the corresponding available flexural (Fig.9) and shear (Fig.10) capacities. The contribution of the infills on the seismic response of this critical column is presented in Fig. 9. From this figure it can be seen that in all cases the ductility demands of this column are greater that the available ones. Further it is pointed out that the most critical case is the case of the infilled 8-story frame with infills that have openings.

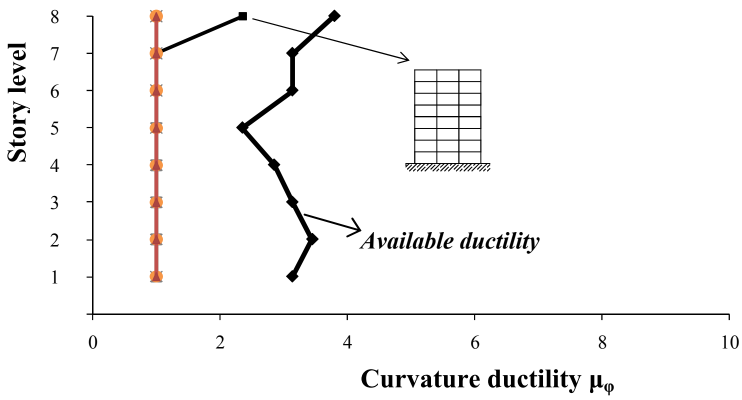



**Figure 7.** Ductility demands of the exterior columns of the 8-story frame and comparison with the available ductility values.

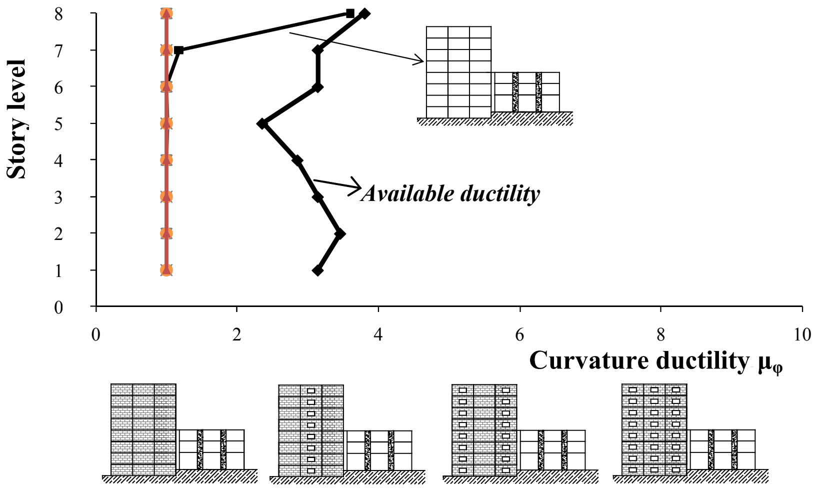



**Figure 8.** Influence of infills on the ductility demands of the exterior columns of the 8-story frame due to the pounding. Comparisons with the available ductility values. Type-A pounding.

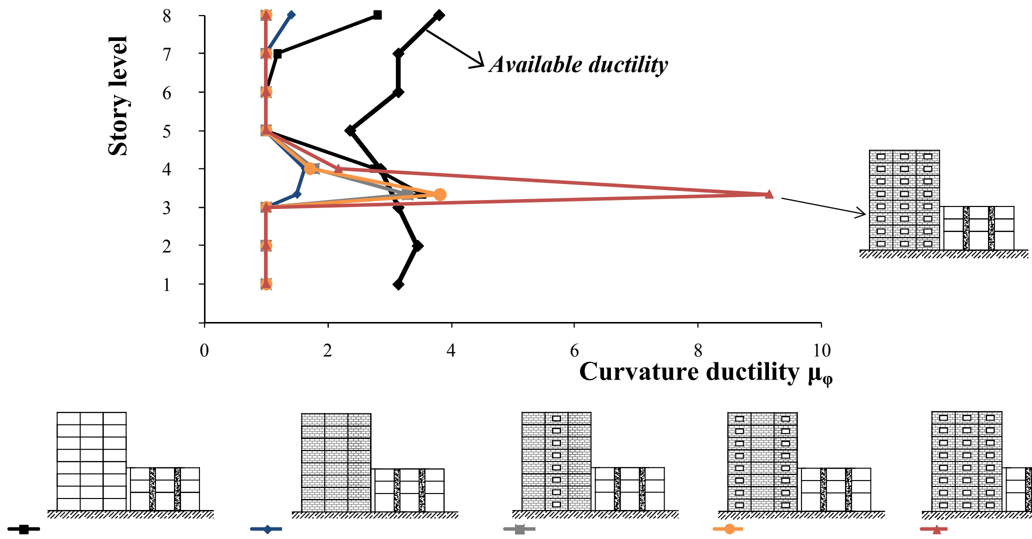



**Figure 9.** Influence of infills on the ductility demands of the exterior columns of the 8-story frame due to the pounding and comparisons with the available ductility values. The story heights of the two adjacent structures are non equal thus the slab of the top story of the 3-story building hits the column of the 4th floor of the tall building at the point of 1/3 of its height. Type-B pounding.

Fig. 10 presents the developing shear forces of the column of the 8-story structure that suffers the hit at the point $h_A$=1/3$h$ from the slab of the 3-story structure and the two structures are in contact from the beginning ($d_g$=0 see Fig.1) for the cases that the multistory structure is fully infilled frame structure. In this figure the points represent the pairs of the developing shear force, V, and the axial force, N, at every step of the seismic analysis, whereas the lateral solid lines show the available capacity of the reinforced concrete element for the combination of shear versus axial force (EC2 & 8). This way a direct comparison of the developing shear force at all the steps of the analysis with the available shear strength can be obtained. It can be observed that the inter-story pounding effect induces a critical shear state for the seismic performance of this column since the developing shear forces exceed the capacity for shear strength of the member many times during the excitation. It is noted that similar results hold for this column for all the examined cases of Type-B pounding.

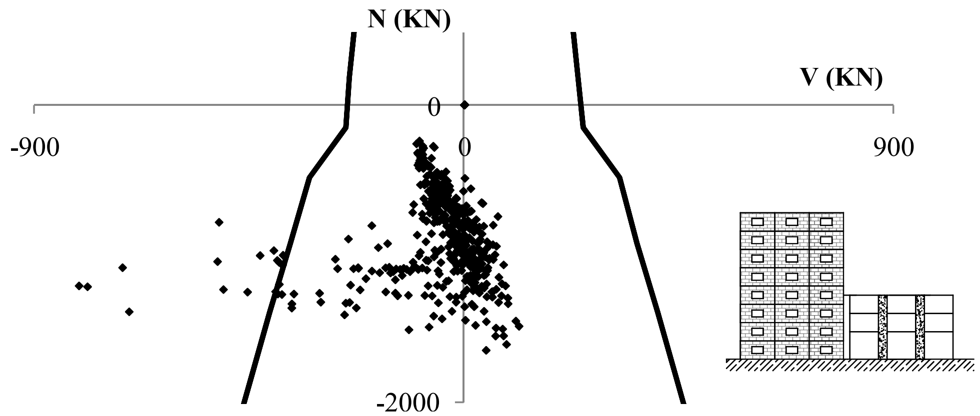



**Figure 10.** Developing shear forces of the column of the infilled 8-story structure that suffers the hit at the point $h_A$=1/3$h$ from the slab of the 3-story structure. It can be observed that the inter-story pounding effect induces a critical shear state for the seismic performance of this column since the developing shear forces exceed the capacity for shear strength of the member many times during the excitation.

## 4. CONCLUSIONS

The structural pounding problem between adjacent multistory reinforced concrete structures with unequal total heights has been investigated taking into account the influence of the infills. The most important issue in the inter-story pounding (Type-B) is the local response of the column of the tall structure that suffers the hit of the upper floor slab of the adjacent shorter and stiffer structure. This column appears to be in most of the times in a critical condition. In the case of structural pounding Type-B the influence of the infill panels on the seismic performance of the critical column that suffers the hit led in all the examined cases to an increase of the demands for shear and ductility compared to the corresponding values in the cases that the RC structure is studied without considering the infills. It is pointed out that the most critical case for this column in term of ductility demands is the case of the infilled 8-story frame with infills that have openings. Further it can be observed that the inter-story pounding effect induces a critical shear state for the seismic performance of this column since the developing shear forces exceed the capacity for shear strength of the member many times during the excitation. It is noted that similar results hold for this column for all the examined cases of Type-B pounding.

## REFERENCES


Federal Emergency Management Agency (1997). NEHRP Guidelines for Seismic Rehabilitation of Buildings (FEMA 273/274), Washington DC.

Federal Emergency Management Agency (1999). Evaluation of earthquake damaged Concrete and Masonry Wall Buildings. Infilled Frames (FEMA 306), Washington DC.

Federal Emergency Management Agency (2000). Pre-standard and Commentary for the Seismic Rehabilitation of Buildings (FEMA-356). Washington DC.

Mainstone, R. (1971). On the stiffness and strengths of infilled frames. *Institution of Civil Engineers supplement IV*, 57-90.

Karayannis, C. and Fotopoulou, M. (1998). Pounding of multistory RC structures designed to EC8 & EC2. *Eleventh European Conference on Earthquake Engineering.* ISBN 90 5410 982 3.

Karayannis, C. and Favvata, M. (2005a). Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights. *Earthquake Engineering and Structural Dynamics* **34:1**, 1-20.

Karayannis, C. and Favvata, M. (2005b). Inter-story pounding between multistory reinforced concrete structures. *Structural Engineering and Mechanics* **20:5**, 505-526.

Karayannis, C., Kakaletsis, D. and Favvata, M. (2005). Behaviour of bare and masonry infilled R/C frames under cyclic loading. Experiments and Analysis. *Fifth Conference on Earthquake Resistant Engineering Structures.*

Kakaletsis, D., Favvata, M. and Karayannis C. (2006). Behavior of infilled RC frames with openings under lateral loading. *Fifteenth Hellenic Conference on Concrete Structures*. **Vol D:** 328-339 (in Greek).

Favvata, M., Karayannis, C. and Liolios A. (2009). Influence of exterior joint effect on the inter-story pounding interaction of structures. *Structural Engineering and Mechanics* **33:2**, 113-136.

Kakaletsis, D. and Karayannis C. (2009). Experimental Investigation of Infilled reinforced Concrete Frames with Openings. *ACI Structural Journal*, **106:2**, 132-141.

Favvata, M. and Karayannis, C. (2011). The inter-story pounding effect on the seismic behavior of infilled and pilotis RC structures. *Sixth European Workshop on the Seismic Behaviour of Irregular and Complex Structures.*

Karayannis, C., Favvata, M. and Kakaletsis, D. (2011). Seismic behaviour of infilled and pilotis RC frame structures with beam–column joint degradation effect. *Journal of Engineering Structures* **33:10**, 2821-2831.