Earthquake induced interaction between RC frame and steel frame structures

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Abstract

Dynamic step by step analyses are performed for the study of the structural pounding between a reinforced concrete (RC) frame structure and a steel (ST) frame structure. The examined RC frame is designed to Eurocodes EC2 and EC8 and the ST frame to EC3 and EC8. Both structural systems have ten (10) floor levels. The adjacent structures have non-equal inter-storey height at the base floor and therefore an inter-storey pounding problem takes place. The slabs of the ST structure hit the columns of the RC frame structure and the slabs of the RC frame hit the columns of the ST frame. The seismic response of the structures without the pounding effect is also studied and compared to the corresponding demands that are developed due to the interaction problem. Results in terms of displacements, ductility requirements, flexural demands and shear demands, have shown that in situations where pounding may occur, the potential effects may lead to non-safe building design or evaluation for both structures. Thus, in cases where inter-storey pounding takes place and, especially for the columns of both RC and ST frames that suffer the hit critical increase of the shear and ductility demands, are observed due to the interaction effect.
Keywords: steel structure, reinforced concrete structure, structural pounding, inter-storey pounding, shear demands, ductility requirements, seismic analysis.

1 Introduction

The problem of earthquake induced pounding between adjacent buildings has received substantial attention over the last two decades. Naserkhaki *et al.* [1] presented a numerical study on the pounding between the adjacent buildings. Analyses results for the pounding case between the Olive View Hospital main

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building and one of its independently standing stairway towers were presented by Jankowski [2, 3]. Assessment approaches and various parametric studies for the study of the pounding between adjacent buildings have also been reported in literature [4–9]. Further the influence of the structural pounding on the seismic performance of base-isolated building was the subject of recent research [10, 11]. Experimental studies [12, 13] have also been reported in literature.

Nevertheless all the above works have been focused on modelling the floor to floor collision. It is stressed (see also Cole *et al.* [14]) that the majority of the inter-storey (floor to column) pounding research has been undertaken by Karayannis and Favvata [15–19]. In these studies the influence of the structural pounding on the seismic behaviour of adjacent multi-storey RC structures was investigated taking into account several parameters such as: the height variations between the adjacent structures, the positions of the contact points, the separation gap distances, the beam-column joints damage effect, the infills' effect with and without openings, the case of open ground storey (pilotis type building) and the seismic excitations. The most important problem in the case of inter-storey pounding of reinforced concrete structures is the developing critical shear state at the columns that suffer the hit. The local damage of the critical column that suffers the impact as a result of the seismic pounding has been investigated for the first time in 2005 by Karayannis and Favvata [15, 16]

In 2008 Anagnostopoulos and Karamaneas [20] also underlined the significant effect of the inter-storey pounding on the seismic response of the buildings in order to study the effectiveness of collision shear walls to help the colliding buildings avoid major damage due to interaction effect.

2 Key parameters for the structural pounding idealization

2.1 Inter-storey pounding

The inter-storey pounding between a 10-storey steel (ST) frame structure and a 10-storey reinforced concrete (RC) frame structure is studied. The two adjacent structures have non-equal base floor story height and thus the slabs of the ST structure hit the external columns of the RC frame structure and the slabs of the RC frame hit the external columns of the ST frame. It is considered that from the beginning the flexible ST building is in contact to the less flexible RC structure. The actual condition and the model idealization of the examined structural inter-storey pounding are shown in fig. 1.

In recent works by Karayannis and Favvata [15, 16], it has been proved that in the case of pounding between adjacent structures with significant total height difference the whole response of the interacting buildings and the local requirements of the members is influenced only by the position and the characteristics of the contact point at the short structure's top floor.

In this study the examined pounding cases are between frame structures with almost equal total height (10-storey frames) and the contact points are considered at the levels of all the floor slabs of both structures (see fig. 1).

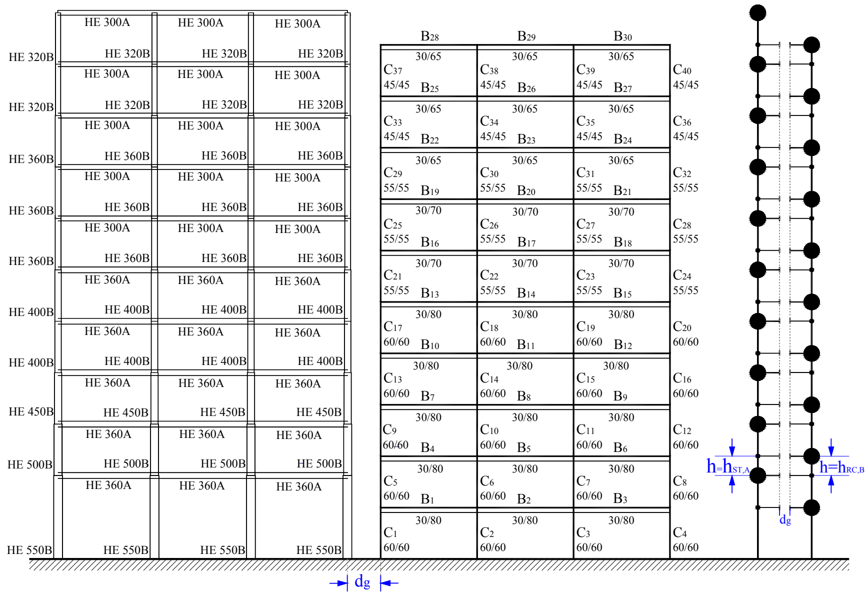

Figure 1: Actual condition and model idealization of pounding between a 10-storey steel (ST) frame and a 10-storey reinforced concrete (RC) frame.

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 the inter-storey pounding on the overall structural response. Further, the damage at the contact area is expected to be concentrated from the beginning at the column that suffers the impact. Thus, considering that the damage of the building materials and the damage of the slabs of the structure are not significant, an elastic contact element has been used. See also previous works by the authors [15, 16].

Analyses have been performed using time steps of the order of 1/10000 in order to achieve numerical stability and to adequately reproduce higher mode response excited by the short duration impacts. The well known nonlinear dynamic structural analysis program Drain-2dx is used for the purposes of this study.

2.2 Beam-column elements

The frame structural systems consist of beams and columns. Each structure is modelled as a 2D assemblage of non-linear elements connected at nodes and the mass is lumped at the nodes. The finite element mesh used here for the modelling of each structure utilizes a one-dimensional element for each structural member. Two types of beam-column elements were used: (a) a special purpose element of "distributed plasticity" type accounting for the spread of the inelastic behaviour both over the cross-sections and along the deformable region of the member length and it is employed for the modelling of the columns of the 10-storey RC structure and (b) a lumped plasticity beam-column model that considers the inelastic behaviour concentrated in zero-length "plastic hinges" at the element's ends and it is employed for the modelling for the beams of RC frame and for all the members of the ST frame structure.

In order to accurately model the actual behaviour of the columns of both ST and RC frame in the area that pounding takes place the deformable height of each column is divided into two elements the way it is shown in fig. 2. Further, for the columns of the RC frame each of the two special purpose elements of "distributed plasticity" type is divided in four unequal segments. Thus, there are eight control cross-sections along the height of the critical RC column. This partition of the column's deformable height can reasonably take into account the actual distribution of reinforcement and confinement degree of concrete and further it allows for the setting of the control cross-sections near the element's critical points. Similar simulation also holds for the columns of the ST frame. Two elements with lumped plasticity beam-column model are employed for the simulation of the columns of the ST frame that suffer the hit.

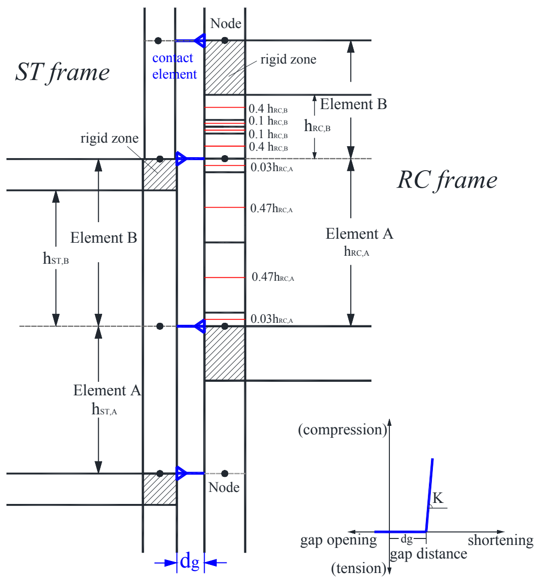

Figure 2: Analysis model idealization for the pounding area.

3 Design of structures

Two multi-storey frame structures have been designed for the purposes of this work; one 10-storey reinforced concrete RC frame structure and one 10-storey steel ST frame structure. The 10-storey RC frame structure was designed

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according to the Eurocodes 2 and 8, meeting the Ductility Capacity Medium (DCM) design criteria. Its behaviour factor q was equal to 3.9. The height of all the story levels of the RC frame is the same and equal to 3.20m.

The 10-storey ST frame structure was designed according to the Eurocodes 3 and 8, meeting the Ductility Capacity Medium (DCM) design criteria. Its behaviour factor q was equal to 3.9. The height of the first story of the ST frame is 5.20m while the height of the other stories is 3.20m. The mass of both structures was taken equal to M=(G+0.3Q)/g (where G gravity loads and Q live loads) and the design base shear force was equal to V=(0.3g/q)M (where q the behaviour factor of the structure).

4 Examined cases

The structural inter-storey pounding between a 10-storey reinforced concrete (RC) frame structure and a 10-storey steel (ST) frame structure that are in contact from the beginning (d_g=0, see figs. 1 and 2) is herein investigated. The adjacent structures have non-equal interstorey height at the base and thus the slabs of the ST structure hit the columns of the RC frame structure and the slabs of the RC frame hit the columns of the ST frame. The contact points at the RC structure lie between 0.15 and 0.25 of the deformable interstorey height of the columns *(column part $h_{RC,B}$)*. The corresponding contact points for the ST frame (column parts $h_{ST,B}$) are located at 2/3 of the deformable height of the column at the base and at 2/5 of the deformable heights of the columns of the other storey levels.

The most important issue in the inter-storey pounding cases is the local response of the columns that suffer the impact from the floor slab of the adjacent structure. The consequences of the impact can be very severe for the integrity of the column and may be a primary cause for the initiation of the collapse of the structure. This is the most critical case of interaction between adjacent buildings [15, 16]. In this respect, for the examined interaction cases results concerning the flexural and the shear demands of the critical external columns of the RC and ST frame structures that suffer the impact are first presented and compared with the corresponding available flexural and shear capacities. Moreover results in terms of displacements and maximum ductility requirements are presented.

The inter-storey pounding problem is studied for three different seismic excitations (fig. 3); El Centro 1940 (Mexico), Bucharest NS 1977 and Bucharest EW 1977 (Romania). The maximum accelerations (α_{max}) of the selected earthquakes were scaled to be equal to the design acceleration of the examined structures (α_{max}=0.3g).

5 Results

In fig. 4, results of the dynamic analyses at the top contact point of the interacting adjacent structures are presented, for the seismic excitation of Bucharest NS. The top contact point is located at the 10th floor level of the RC

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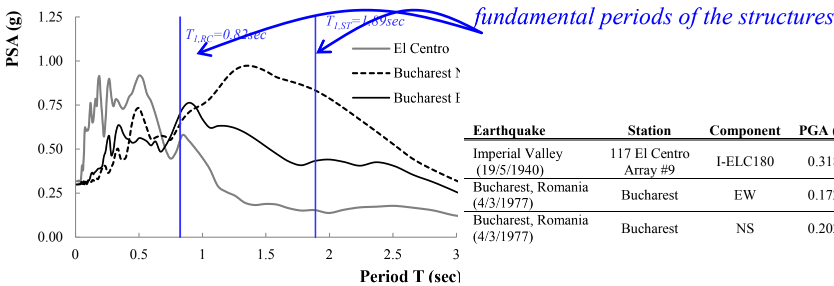


Earthquake	Station	Component	PGA (g)
Imperial Valley (19/5/1940)	117 El Centro Array #9	I-ELC180	0.318
Bucharest, Romania (4/3/1977)	Bucharest	EW	0.172
Bucharest, Romania (4/3/1977)	Bucharest	NS	0.202

Figure 3: Elastic response spectra of the selected earthquakes.

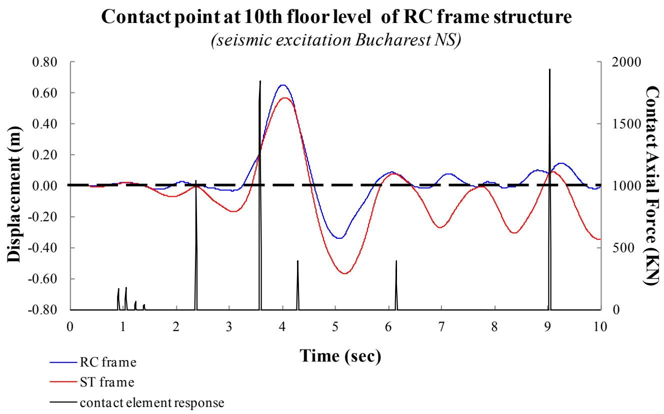
frame structure and thus the slab of the RC frame hit the column of the 10th storey of the ST frame.

In fig. 4(a) the displacement time history of the 10th floor (top) level of the RC frame is presented and compared with the corresponding displacements of the ST frame structure at the contact point. Moreover, in the same figure the response of the contact element during the seismic analysis is shown in terms of axial force time history. This way the times during the analysis and the displacement direction that the two structures suffer the pounding effect at the examined contact point are provided. Based on the results of fig. 4(a) it can be observed that the adjacent structures are interacting at the 10th storey level several times during the analysis.

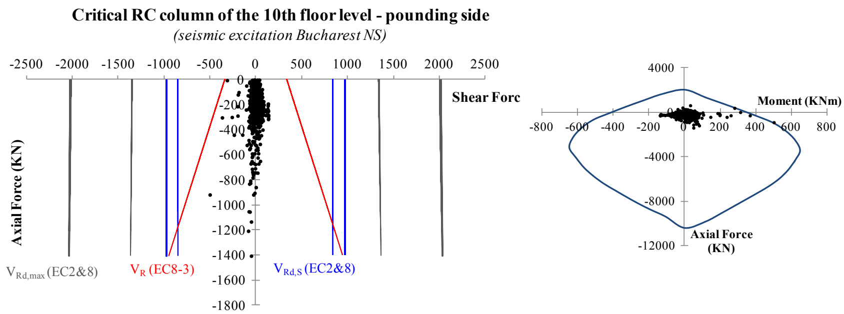
In figs. 4(b) and 4(c) the local responses of the critical columns of the 10th floor level of the RC frame and ST frame structure are presented. The results concerning the shear and the flexural demands of these columns are shown and compared with the corresponding available strengths (solid lines) for case of the Bucharest NS earthquake. It is mentioned that the available shear and flexural strengths were calculated taking into account the provisions of the Eurocodes EC2, EC3, EC8-part1 and EC8-part3 (solid lines).

Thus, in fig. 4(b) it can be observed that at the critical column of the RC frame (*column part* $h_{RC,B}$, see also figs. 1 and 2) the developing shear-axial interaction forces and the moment – axial interaction forces are not exceeding the available values during the excitation. However, the corresponding local requirements of the column of the ST frame at the 10th floor level (*column part* $h_{ST,A}$) are higher than the available strengths a few times during the analysis (fig. 4(c)). The seismic requirements of the same columns during the Bucharest EW and El Centro excitations are examined and compared with the available values. Similar results hold for these cases.

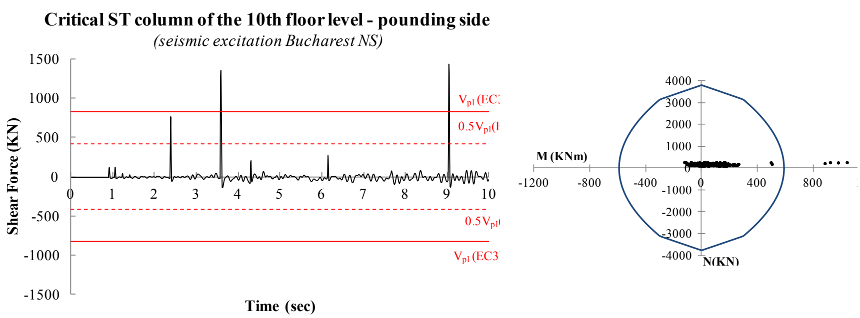
Similarly, the corresponding results at the first-bottom contact point of the interacting adjacent structures are also presented in figs. 5 and 6 for the seismic excitations of Bucharest. The first top contact point is located at the 1st floor level of the RC frame structure and thus the slab of the RC frame hit the column of the 1st storey (base) of the ST frame. Figs. 5(a)–6(a) show that the adjacent structures are interacting at the 1st storey level several times during the analysis. The pounding problem at the first-bottom contact point of the two frames is



(a) Displacement and contact force time histories.



(b) Shear and flexural demands and corresponding available strengths of the critical column C37 of the *RC frame structure*.



(c) Shear and flexural demands and corresponding available strengths of the critical column of the *ST frame structure.*

Figure 4: Seismic results of the inter-storey pounding effect at the top contact point of the interacting adjacent structures (10th floor level of RC frame structure-seismic excitation Bucharest NS).

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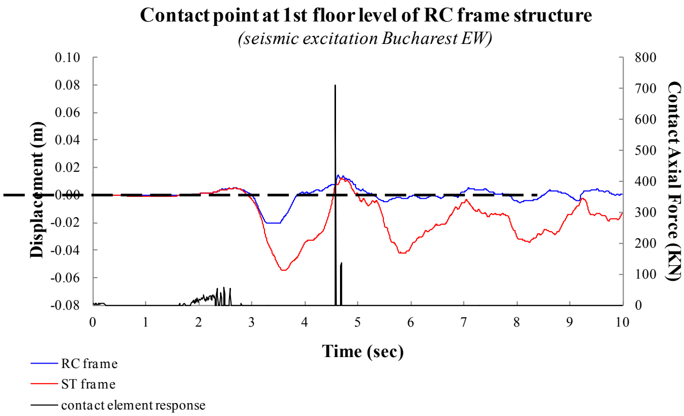
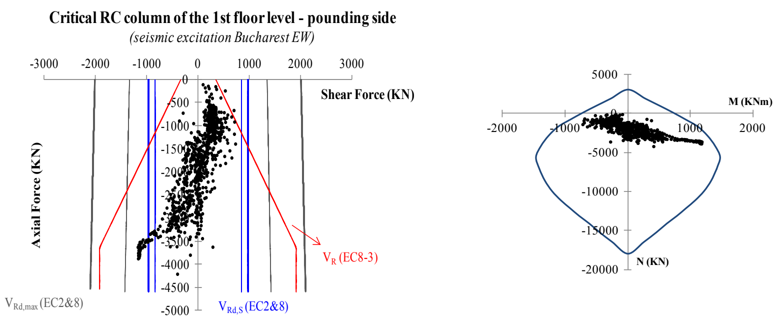
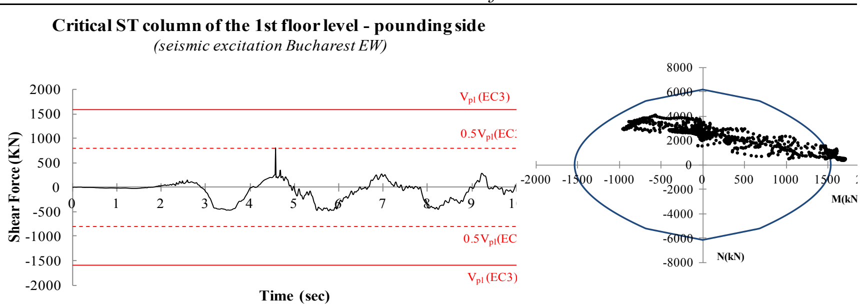


(a) Displacement and contact force time histories.

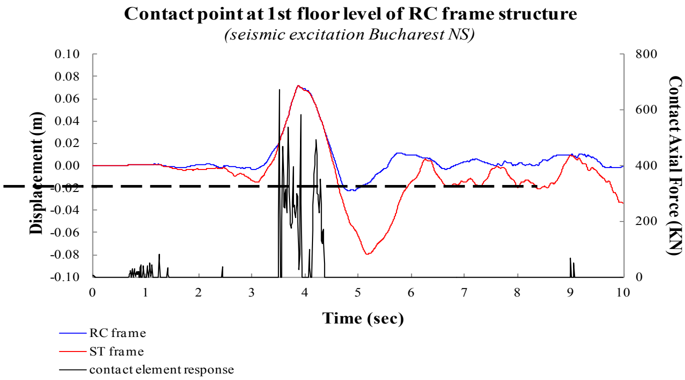


(b) Shear and flexural demands and corresponding available strengths of the critical column C1 of the *RC frame structure.*

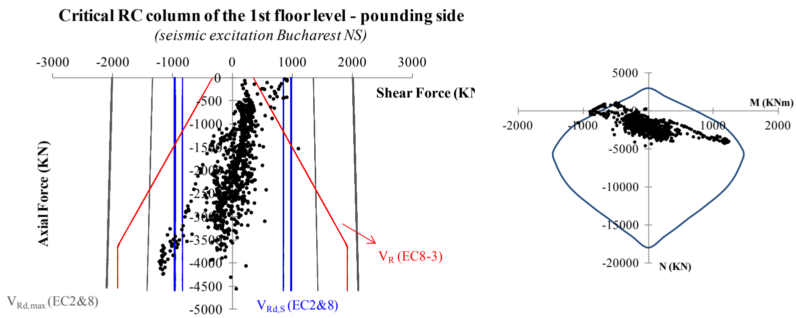


(c) Shear and flexural demands and corresponding available strengths of the critical column of the *ST frame structure.*

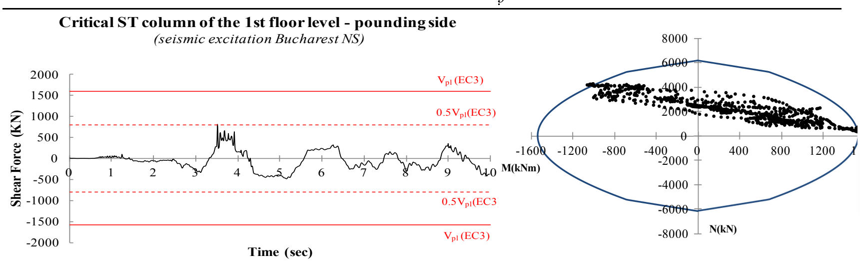
Figure 5: Seismic results of the inter-storey pounding effect at the first (bottom) contact point of the interacting adjacent structures (1st floor level of RC frame structure-seismic excitation Bucharest EW).



(a) Displacement and contact force time histories.



(b) Shear and flexural demands and corresponding available strengths of the critical column C1 of the *RC frame structure.*



(c) Shear and flexural demands and corresponding available strengths of the critical column of the *ST frame structure.*

Figure 6: Seismic results of the inter-storey pounding effect at the first (bottom) contact point of the interacting adjacent structures (1st floor level of RC frame structure-seismic excitation Bucharest NS).

occurred when the ST frame structure moves towards the RC frame. Nevertheless, in the case of the El Centro excitation the maximum contact force is developed when the RC frame structure moves towards the ST frame.

Considering the local responses of the critical columns of the 1st floor level of the RC frame and ST frame structure due to the pounding effect, the following observations are noted (figs. 5(b),(c) and 6(b),(c)):

(i) The external column of the RC frame at the base developed shear forces that exceed the available values ($V_{Rd,s}$) during the seismic excitations of Bucharest (figs. 5(b), 6(b)). Further, the seismic analysis of Bucharest NS yielded critical flexural requirements for the examined column.

(ii) Examining the corresponding local requirements of the critical column of the ST frame at the base critical are the flexural demands of the column since they are higher than the available strengths during the analyses (figs. 5(c), 6(c)).

The curvature ductility requirements for the external columns of the 10-storey RC frame that suffer the inter-storey pounding effect are presented in fig. 7 for the seismic excitations that are used in this study. The results of the analyses demonstrate that the ductility demands for the columns that suffer the most the pounding impact depend on the characteristic of the earthquake (as expected). In this view, it can be observed that the upper floor levels (7th–10th) are critical since the ductility demands of these columns appear to be almost equal or even higher than the available ductility values.

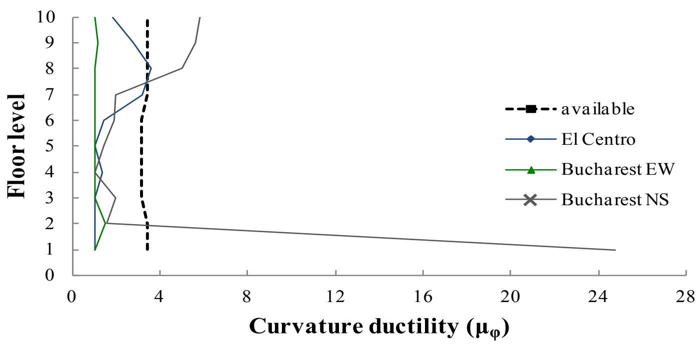


Figure 7: Maximun ductility requirements of the external columns of the RC frame that suffer the impact from the slabs of the adjacent ST frame.

It is worth noting here that although the flexural demands of the RC column of the 10th floor at the critical part $h_{RC,B}$ (figs. 2 and 4(b)) do not exceed the available values due to the pounding effect, this column is critical due to high ductility demands of the column part $h_{RC,A}$, during the Bucharest excitations.

Furthermore, in the case of Bucharest NS excitation the column at the base of the RC frame develops critical requirements for curvature ductility that are much higher than the available values.

Finally, from the results about the maximum interstorey displacements that are developed in both structures for the examined earthquake records it can be deduced that in the case where the ST frame is moving towards the RC frame structure the developed maximum displacements of the ST frame are decreased due to the pounding effect.

6 Conclusions

Dynamic step by step analyses were performed for the study of the structural pounding between a 10-storey reinforced concrete (RC) frame structure and a 10-storey steel (ST) frame structure. For the purpose of this work three different earthquake records were used. The observations and conclusions that follow are for the pounding case where the two buildings are in contact from the beginning (d_g=0). In this study the local shear and flexural demands of the critical columns at the 10th and 1st floor levels of the RC and ST frame structures due to the pounding effect were examined and compared with the corresponding available strength values for shear and flexure. Based on the results of this investigation the following conclusions were deduced:

- Critically increasing shear demands were developed due to the pounding problem in the exterior column of the RC frame at the base floor level. In this column the shear demands were higher than the available strength.
- The RC columns that suffer the most the pounding impact in terms of flexural demands were the ones at the upper floor levels of the RC frame. In these columns the ductility demands appear to be almost equal or even higher than the available ductility values. Furthermore, in the case of Bucharest NS excitation, the column at the base of the RC frame developed requirements for curvature ductility that were much higher than the available values.
- Examining the shear and flexural requirements of the external column at the base of the ST frame that suffers the impact from the slab of the adjacent RC frame critical were the flexural demands since these were higher than the available strengths.
- In situations where pounding may occur, the seismic response of the critical part of the ST column that suffers the hit at the 10th floor level is characterized as a critical one both in terms of shear and flexural demands.

References

[1] Naserkhaki, S., Daneshvar Ghorbani, S. and Tayyebi Tolloei, D., Heavier adjacent building pounding due to earthquake excitation. *Asian Journal of Civil Engineering,* **14(2)**, pp. 349-367, 2013.

[2] Jankowski, R., Non-linear FEM analysis of earthquake-induced pounding between the main building and the stairway tower of the Olive View Hospital. *Engineering Structures*, **31(8)**, pp. 1851-1864, 2009.

[3] Jankowski, R., Assessment of damage due to earthquake-induced pounding between the main building and the stairway tower. *Key Engineering Materials*, **347**, pp. 339-344, 2007.

www.witpress.com, ISSN 1743-3509 (on-line)

[4] Tubaldi, E., Barbato, M. and Ghazizadeh, S., A probabilistic performance-based risk assessment approach for seismic pounding with efficient application to linear systems. *Structural Safety*, **36-37**, pp. 14-22, 2012.
[5] Tubaldi, E. and Barbato, M., Reliability-based assessment of seismic pounding risk between adjacent buildings. *Proc. of the 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, COMPDYN 2011, Corfu Greece, 2011.
[6] Lu, M. and Yang, Q., Maximum relative displacement between adjacent structures during ground motions. *Tumu Gongcheng Xuebao/China Civil Engineering Journal*, **45(3)**, pp. 74-78, 2012.
[7] Abdel-Mooty, M., Al-Atrpy, H. and Ghouneim, M., Modeling and analysis of factors affecting seismic pounding of adjacent multi-story buildings. *WIT Transactions on the Built Environment*, **104**, pp. 127-138, 2009.
[8] Abdel-Mooty, M., Ghouneim, M. and Eletrabi, H., Investigation of seismic pounding of adjacent multi-story reinforced concrete buildings. *Proc of the 9th US National and 10th Canadian Conference on Earthquake Engineering,* Canada, pp. 7270-7279, 2010.
[9] Cole, G.L., Dhakal, R.P. and Turner, F.M., Building pounding damage observed in the 2011 Christchurch earthquake. *Earthquake Engineering and Structural Dynamics*, **41(5)**, pp. 893-913, 2012.
[10] Pant, D.R. and Wijeyewickrema, A.C., Structural performance of a base-isolated reinforced concrete building subjected to seismic pounding**.** *Earthquake Engineering and Structural Dynamics*, **41(12)**, pp. 1709-1716, 2012.
[11] Abdel Raheem, S.E., Pounding mitigation and unseating prevention at expansion joints of isolated multi-span bridges. *Engineering Structures*, **31(10)**, pp. 2345-2356, 2009.
[12] Ma, Q., Yun, L., Ma, S. and Wang, H., Experimental study on dynamic collision characteristics of concrete. *Advanced Materials Research*, **150-151**, pp. 937-940, 2011.
[13] Chau, K.T., Wei, X.X., Guo, X. and Shen, C.Y., Experimental and theoretical simulations of seismic poundings between two adjacent structures. *Earthquake Engineering and Structural Dynamics,* **32**, pp. 537-544, 2003.
[14] Cole, G.L., Dhakal, R.P., Carr, A.J. and Bull, D.K., Building Pounding State of the Art: Identifying Structures Vulnerable to Pounding Damage, *New Zealand Society for Earthquake Engineering Annual Conference*, Wellington, New Zealand. p. paper P11., 2010.
[15] Karayannis, C.G. and Favvata, M.J., Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights. *Earthquake Engineering and Structural Dynamics,* **34**, pp. 1-20, 2005.
[16] Karayannis, C.G., and Favvata, M.J., Inter-story pounding between multistory reinforced concrete structures. *Structural Engineering and Mechanics*, **20(5),** pp. 505-526, 2005.

[17] Favvata, M.J., Karayannis, C.G. and Liolios, A.A., Influence of exterior joint effect on the inter-story pounding interaction of structures. *Structural Engineering and Mechanics,* **33(2)**, pp. 113-136, 2009.
[18] Favvata, M. and Karayannis, C., The inter-story pounding effect on the seismic behavior of infilled and pilotis RC structures. *Proc. of the 6th European Workshop on the Seismic Behaviour of Irregular and Complex Structures,* Haifa Israel, 2011.
[19] Favvata, M.J., Karayannis, C.G. and Anagnostopoulou, V., Influence of infill panels with and without openings on the pounding effect of RC structures. *Proc. of the 15th World on Earthquake Engineering,* Lisbon Portugal, pp. 24-28, 2012.
[20] Anagnostopoulos, S.A. and Karamaneas, C.E., Use of collision shear wall to minimize seismic separation and to protect adjacent buildings from collapse due to earthquake-induced pounding. *Earthquake Engineering and Structural Dynamics*, **37(12)**, pp. 1371-1388, 2008.