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ASSESSMENT OF MULTISTORY RC BUILDINGS SUFFERING INTER-STORY POUNDING

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Abstract. *The pounding of adjacent RC frames with different heights is studied. The main issue behind this investigation is the influence of the local behaviour of the columns that suffer the hit from the slabs of the adjacent building during the seismic excitation. This column's requirements for ductility and shear capacity have been proven to be the critical parameters for the behaviour and final performance of the whole structure. These parameters can be designed in order the obtained performances to satisfy the seismic demands of the Eurocodes. In this study the critical column's requirements for ductility and shear capacity are evaluated for three seismic demands based on Eurocode 8-part3: (a) demand for Damage Limitation limit state that corresponds to ground motions with return periods of 225 years (b) demand for Significant Damage limit state that corresponds to ground motions with return periods of 475 years and (c) demand for Near Collapse limit state that corresponds to ground motions with return periods of 2475 years. The evaluated requirements are for seven different seismic excitations that have been properly scaled to fit the Eurocode's three seismic demands of low zone of seismic hazard. Afterwards, the minimum required gap distances between the adjacent structures are evaluated taking into account the local capacities of the columns that suffer the inter-story pounding effect. These results are compared with the corresponding limitations for adequate gap distances that are provided by the Eurocode 8. The results show that even in the case of Damage limitation seismic demand special measures have to be taken for the column of the multistory RC frame that suffers the hit. The seismic performance of the columns at a specific limit state of the assessment should be considered for the estimation of an adequate gap distance between the adjacent structures. Thus, the minimum gap distance that is required in order to eliminate the possibility for interaction between adjacent structures depends on the limit state of the assessment. Eurocode's provisions for adequate gap separation do not depend on the seismic demand (limit state) but in any case based on the results of this study these provisions seem to be conservative.*

1 INTRODUCTION

An important issue in the field of the structural engineering is the assessment of the seismic performance of the structures under strong ground motions while the inter-story pounding between adjacent structures has been recognized as the most crucial case of interaction for the integrity of the structural stability. The problem of earthquake induced pounding between adjacent buildings has received substantial attention over the last two to three decades [1–23]. However, most of the studies have been focused on modeling the floor to floor collision. Most of these studies have yielded conclusions not directly applicable for the design or the assessment of multistory buildings potentially under pounding. It has to be stressed (see also Cole *et al* [9]) that the majority of the inter-story (floor to column) pounding research has been undertaken by Karayannis and Favvata [1-6]. In these studies the influence of the structural pounding on the seismic behaviour of adjacent multistory 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 to column joints damage effect, the infills effect with and without openings, the case of open ground story (pilotis type building) and the seismic excitations. The most important problem in the case of inter-story pounding 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 was investigated for the first time in 2005 by Karayannis & Favvata [1], [2].

2 SCOPE OF THIS STUDY

The main issue behind the inter-story pounding between adjacent structures is the local behaviour of the columns that suffer the hit during the seismic excitation. This column's requirements for ductility and shear capacity have been proven to be the critical parameters for the behaviour and final performance of the whole structure. These parameters can be designed so that performances that could satisfy the seismic demands of the Eurocodes to be obtained. Nevertheless, in the modern seismic design codes there are no provisions to ensure the column that may be suffer the impact effect from critical increase of the flexural and shear capacity requirements.

A key parameter for the elimination of the interaction is the initial gap distance between the adjacent structures. About this issue Eurocode 8 provides gap separation limits between the structures in order to prevent possible pounding problems during strong motion earthquakes. However, none of these limits is directly associated with the seismic demand and the seismic hazard design code approaches for the structures. Furthermore, the new design philosophy of the codes leads to flexible frame structures while the adequate seismic separation that is required by the codes is not always easy to apply.

Based on these thoughts in this study, the minimum required gap distance between the adjacent structures at different seismic demands of the Eurocode 8 is also evaluated taking into account the local capacities of the columns that suffer the inter-story pounding effect. These results are compared with the corresponding limitations that are provided by the Eurocode 8.

3 EXAMINED CASES

The seismic assessment of the 8-storey RC frame structure that suffers the inter-story pounding effect from an adjacent 3-storey structure with unequal interstory heights is investigated. Considering that the level of the seismic hazard for the examined interaction problem is low the seismic performance of the external column that suffers the impact from

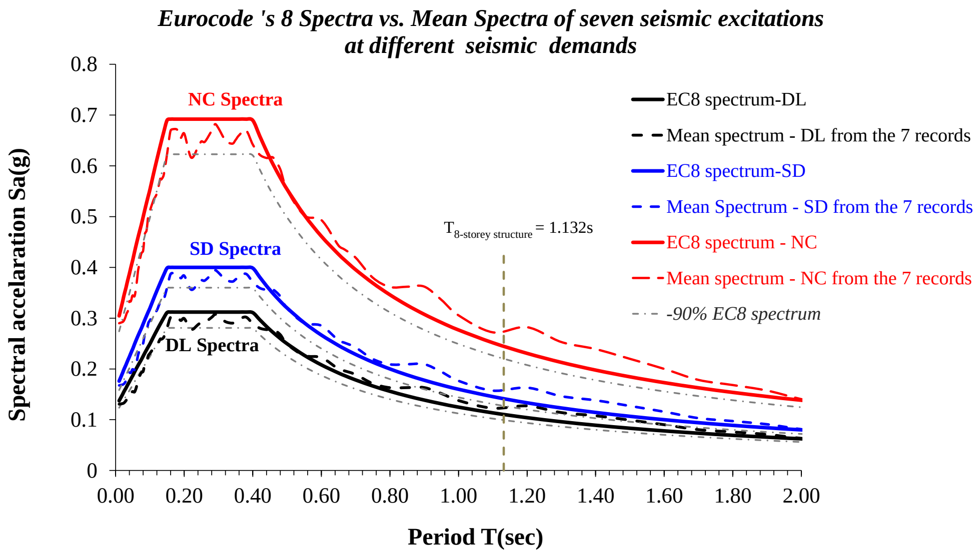
the upper floor slab of the adjacent shorter and stiffer structure is evaluated for three different seismic demands according to the Eurocode 8 - Part3:
(a) seismic demand for Damage Limitation (DL) limit state that corresponds to ground motions with return periods of 225 years and peak ground acceleration 0.13g
(b) seismic demand for Significant Damage (SD) limit state that corresponds to ground motions with return periods of 475 years and peak ground acceleration 0.16g
(c) seismic demand for Near Collapse (NC) limit state that corresponds to ground motions with return periods of 2475 years and peak ground acceleration 0.28g.

For this purpose, both components of seven different seismic excitations extracted from the PEER's database are taken into account. The selected ground motions are scaled to fit Eurocode's 8 elastic spectrum of low zone of seismic hazard at three different seismic demands and ground type A (Fig. 1).

The two adjacent structures are considered to be in contact from the beginning (d_g =0) while the highest contact point of the two structures lies between the levels of the 3rd and the 4th floor of the 8-storey frame at the 1/3 of the height of the column of the 4th floor.

Beams, columns, and walls of the examined structural systems were designed according to Eurocodes 2 and 8, meeting the Ductility Capacity Medium (DCM) criteria of the codes. The structure geometry and reinforcement of the columns of the 8-storey frame are shown in Figure 2. The well known nonlinear dynamic structural analysis program Drain-2dx is used. Non-linear dynamic step-by-step analysis and special purpose elements are employed for the needs of this study. More details about the design of the structures and the structural modelling assumptions can be found in a previous work by Karayannis and Favvata [1].

Results concerning the flexural and the shear demands of the critical external column of the 8-storey frame structure that suffer the impact are presented and compared with the corresponding available capacities at different limit states for low intensity level of seismic hazard. Of course, results in terms of displacements and interstory drift requirements due to pounding effect are presented and compared with the Eurocode's 8 limitations.



<u>Records</u>: *San Fernando, 1971 (EQ59), Italy Auletta, 1980(EQ284), Italy Arienzo, 1980(EQ283), Loma Prieta, 1989 (EQ804), Chi-Chi Taiwan-06, 1999 (EQ3479), Chi-Chi Taiwan-04,1999 (EQ2805), Denali-Alaska, 2002 (EQ2107)*

Figure 1: Eurocode's 8 elastic spectra for three different seismic demands of low seismic hazard in comparison to the corresponding Mean spectra of seven seismic excitations.

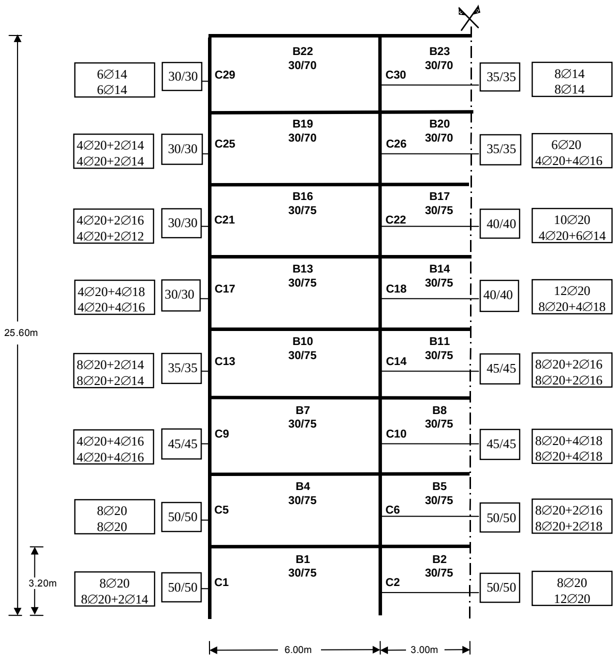


Figure 2: Structural system and column reinforcement of the 8-storey frame structure.

4 RESULTS

The seismic assessment of the 8-storey RC frame structure that suffers the inter-story pounding effect from the adjacent 3-storey structure is investigated. In this study the adjacent structures are considered in contact from the beginning (d_g=0). Based on the provisions of the Eurocode 8, the minimum gap distance that the 8-storey frame structure should have in order to prevent inter-story pounding problems with the adjacent structure is defined and discussed. According to the Eurocode 8 the gap distance between adjacent structures can be considered adequate when it is greater than the maximum plastic design displacement of the structure at the level of pounding. The maximum plastic design displacement ($\delta_{EC8,plastic}$) that can be developed by the structure is the corresponding maximum elastic design displacement ($\delta_{EC8,elastic}$) multiplied by the seismic behavior factor q.

The maximum elastic ($\delta_{EC8,elastic}$) and plastic ($\delta_{EC8,plastic}$) design displacements that can be developed by the 8-storey frame structure at all the story levels are presented in Figure 3a and are compared in the same figure with the maximum displacements (at the pounding side) of the 8-storey frame without and with the inter-story pounding effects at limit states of Damage Limitation (DL) and Near Collapse (NC). It can be observed that in the examined cases the maximum displacements of the 8-storey frame are less than the capacity of the structure for inelastic response. Also, as it was expected the demands for displacement of the structure are depended on the limit state that is used for the evaluation. However, the code’s provisions for the minimum gap distance separation do not depend on the limit state. Based on the Eurocode 8 a minimum gap distance of 9.0cm should be adopted in order to prevent the interaction between the 8-storey frame structure and the 3-storey structure at the 4th floor level (Fig. 3a). The maximum displacements of the 8-storey frame at the pounding side are decreased due to the pounding effect.

The maximum interstory drifts at three limit states for low level of seismic hazard due to the interaction of the 8-storey frame with the 3-storey structure are presented in Figures 3b, 3c, 3d and are compared with the ones of the 8-storey frame vibrating without pounding effects. As it was expected the maximum interstory drifts of the 8-storey frame are increased in the floors above the upper floor level of contact (4th floor level) in comparison with the corresponding ones without pounding effect. It can also be observed that the developing requirements for interstory drift are increased when the limit state for the evaluation of the seismic performance becomes more exigent.

Further, in Figures 3b, 3c and 3d the maximum interstory drifts that can be developed by the 8-storey frame structure without suffering the pounding effect are also presented. These drifts are deduced from the maximum plastic design displacement ($\delta_{EC8,plastic}$) of the frame structure. It can be observed that in the case of evaluating the pounding effect at the Near Collapse limit state the capacity of the structure for interstory drift is exceeded at the last two floor levels (7th and 8th) (Fig. 3d). In Figure 3, each value of drift or displacement requirement is the mean value of fourteen maximum interstory drifts or displacements as resulted from both components of the seven seismic excitations that are used in this study.

Figure 4 presents the maximum curvature ductility requirements that are developed at the critical part of the column of the 4th floor level of the 8-storey frame that suffers the inter-story pounding effect from the slab of the adjacent 3-storey structure. The developed requirements are compared with the corresponding available capacity of the column. Based on these results it can be observed that for the same level of seismic hazard (low) the evaluation of the pounding effect on the column's maximum ductility requirements is influenced by the seismic demand (limit state) under consideration. In fact, the column that suffers the impact appears to be in critical condition due to high ductility demands when the limit state for the assessment is enhanced from Damage Limitation to Significant Damage and to Near Collapse.

The maximum shear requirements of the critical column of the 4th floor level of the 8-storey frame due to the pounding effect at the limit states of Damage Limitation, Significant Damage and Near Collapse are also evaluated for all the seismic excitations. In all the examined cases the requirements for shear exceed the available shear strength of the column, indicating this way that the column that suffers the hit is always in a critical condition due to shear action (Table 1).

Nevertheless, shear failure of the column due to the pounding effect cannot be concluded based only on the number of times that the shear force is exceeding the available strength during the analyses. A parameter that could be used in order to identify possible shear failure is the sequence of the impacts that cause high values for shear strength. In other words, the number of critical demands for shear that are developing at a time or/and at successive times during the seismic analysis at the column that suffers the inter-story pounding problem. Thus, in Figure 5 the time history of the shear requirements that are developing due to the inter-story pounding effect on the critical part of the column of the 4th floor level of the 8-storey frame are presented and compared with the corresponding available shear strength during the analysis. The exact time the demand exceeds the available strength is also depicted in the same figure. Based on these results, it can be observed that different seismic demand (limit state) for the evaluation of the pounding effect on the shear requirements of the column altered the times and the successive times that the column is in critical condition of shear failure. It is noted that the column's behaviour is elastic in flexure and in shear in all the examined cases of this study without the pounding effect.

Also, the adjacent structures suffered the inter-story pounding effect almost from the beginning of both seismic excitations EQ59 and EQ804 and for the three limit states (Fig. 5).

From the beginning of the seismic excitation EQ59 the critical column of the 8-storey frame structure developed high demands for shear that restrict the development of high ductility requirements (see also Fig. 4). However, in the case of the seismic excitation EQ804 that column is in critical condition due to high demands for both shear and flexure strength at all the limit states.

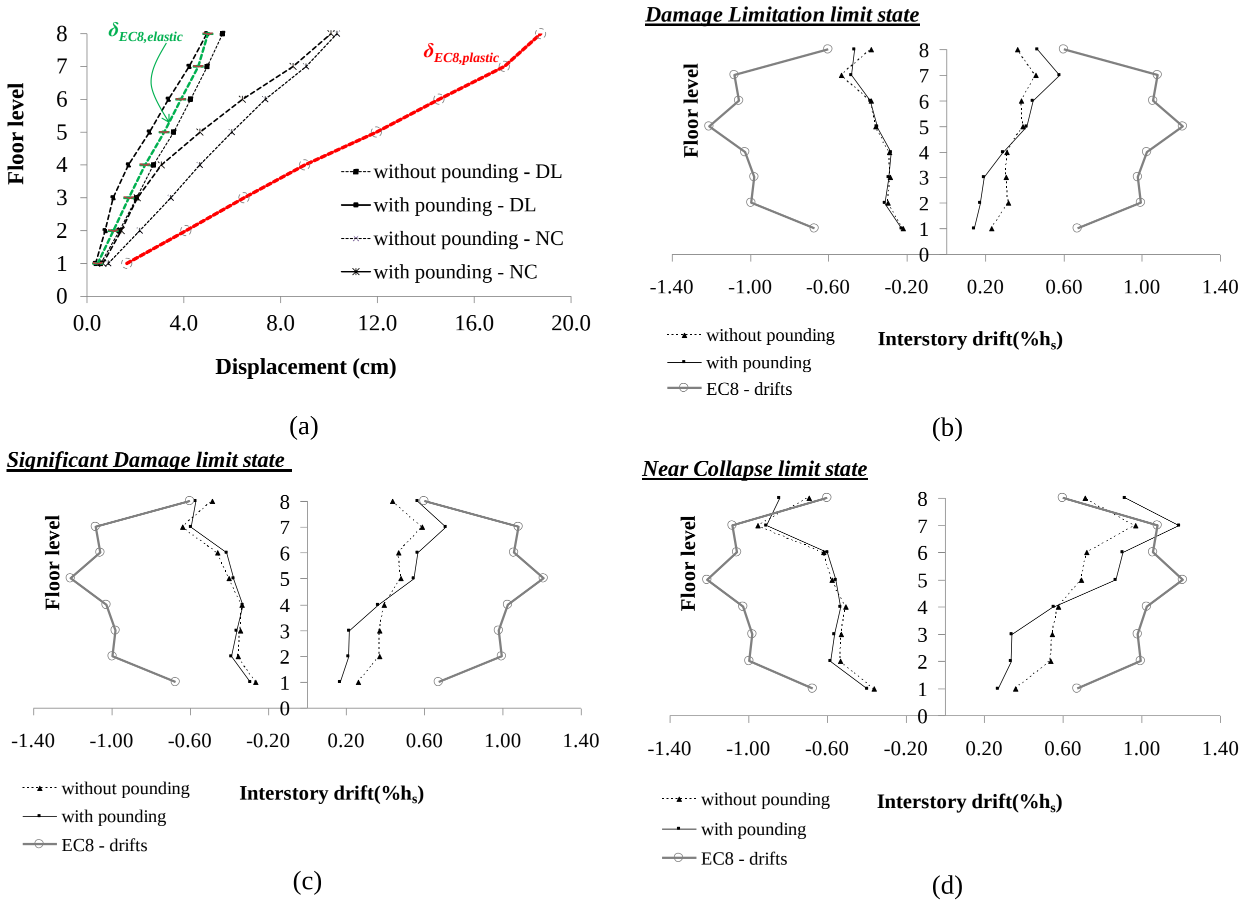


Figure 3: Maximun displacements and interstory drifts requirements of the 8-storey frame structure at three limit states in comparison to the Eurocode's 8 demands for the elimination of the pounding effect between the adjacent structures.

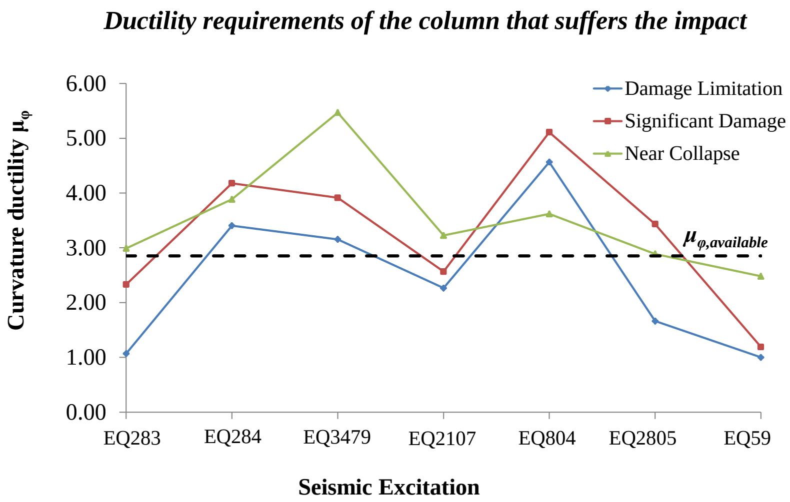


Figure 4: Maximun curvature ductility requirements of the column of the 8-storey frame structure that suffers the hit at three different limit states.

Shear Demands of the critical column of the 4th floor level of the 8-storey frame structure that suffers the inter-story pounding effect at different limit states										
		Damage Limitation			Significant Damage			Near Collapse		
Earthquake		V (kN)		Total times[†] $V > V_{avail.}$	V (kN)		Total times[†] $V > V_{avail.}$	V(kN)		Total times[†] $V > V_{avail.}$
EQ283	FN	582	(1.6)*	56	684	(1.9)*	85	642	(1.7)*	101
	FP	615	(1.6)	94	698	(1.8)	65	791	(2.1)	108
EQ284	FN	705	(1.9)	68	721	(2.0)	76	771	(2.1)	142
	FP	545	(1.5)	75	683	(1.9)	89	769	(2.0)	123
EQ3479	FN	736	(1.9)	90	758	(2.0)	90	771	(2.0)	98
	FP	646	(1.9)	65	681	(1.9)	80	781	(2.1)	116
EQ2107	FN	647	(1.7)	24	777	(2.0)	22	802	(2.0)	38
	FP	675	(1.9)	21	614	(1.7)	31	695	(1.9)	75
EQ804	FN	823	(2.0)	91	829	(2.1)	97	772	(2.0)	98
	FP	677	(1.8)	58	785	(2.0)	56	795	(2.1)	67
EQ2805	FN	630	(1.7)	27	699	(1.8)	42	749	(2.0)	73
	FP	725	(1.9)	38	753	(2.0)	36	761	(2.0)	62
EQ59	FN	551	(1.5)	84	650	(1.7)	92	742	(2.0)	182
	FP	553	(1.4)	79	620	(1.6)	50	688	(1.8)	75
Maximum:		823	(2.0)	94	829	(2.1)	97	802	(2.1)	182
Average:		690	(1.8)	71	741	(1.9)	75	778	(2.0)	113

** Ratio of the maximum shear demand to the available shear strength*
[†] *Total times steps the shear demand exceeds the available shear strength during the analysis*

Table 1: Shear demands of the multistory RC frame external column that suffers the inter-story pounding at three different limit states for all the examined cases.

Further, as it can be observed in Figure 6a, in the case of the seismic excitation EQ804 at the limit state of Damage Limitation the minimum gap distance (d_g) that is required between the examined adjacent structures in order the critical developing shear forces and ductility demands due to the pounding effect to be minimized is 2cm.

However, for the same gap distance (d_g=2cm) at the limit state of Significant Damage the column is still in critical condition due to shear action (Fig. 6b) while at the limit state of Near Collapse the critical part of the column has increased demands for shear strength and ductility (Fig. 6c). Finally, the local performance of the column can be considered safe due to the inter-story pounding effect at the limit state of Near Collapse when a gap distance (d_g) equal to 4cm is provided (Fig. 6d). Thus, the seismic performance of the column that suffers the impact should also be taken into account for the evaluation of the minimum gap distance between adjacent structures so that the critical shear actions and ductility demands could be eliminated. Similar results also hold for all the examined cases of this study.

It is noted that according to the Eurocode 8 a minimum gap distance of 9cm is required in order to prevent the pounding between the 8-storey frame structure and the 3-storey structure at the 4th floor level (Fig. 3a). This code provision for the gap distance is independent of the seismic demand (limit state) under consideration.

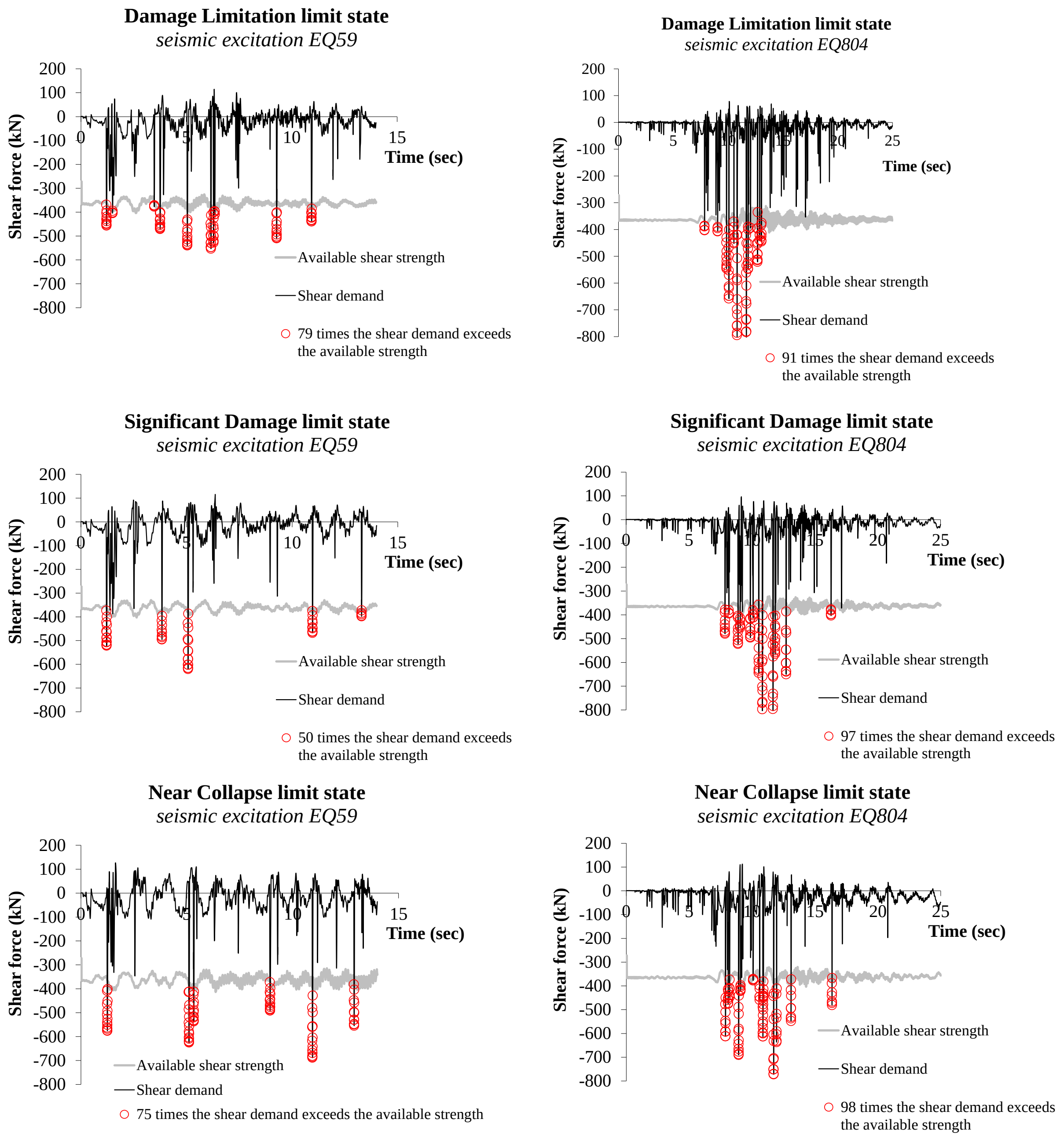


Figure 5: Time history shear requirements of the critical column of the 8-storey frame structure that suffers the hit at three different limit states. Comparison with the available shear strength.

5 CONCLUSIONS

In this study the seismic assessment of the inter-story pounding problem between adjacent structures is evaluated at different limit states for the case of low level of seismic hazard. Dynamic step by step analyses were performed and results in terms of displacement, interstory drifts, ductility requirements and shear requirements were presented. Further, the minimum required gap distance between the adjacent structures at different seismic demands of the Eurocode 8 was evaluated taking into account the local performances of the columns that suffer the inter-story pounding effect. These results are compared with the corresponding limitations that are provided by the Eurocode 8. The main conclusions of this study can be summarized as:

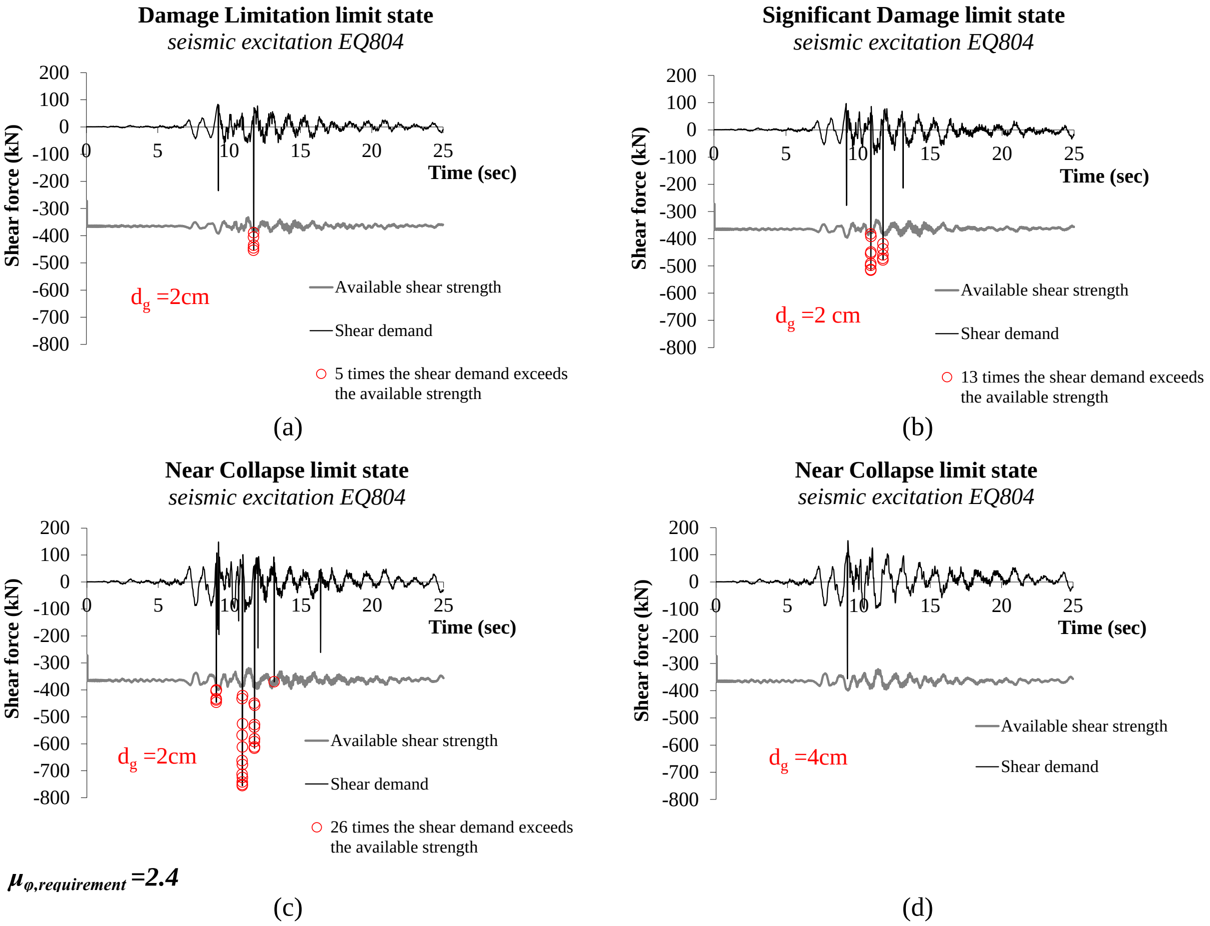


Figure 6: Estimated gap distances between the adjacent structures to prevent the critical shear demands of the critical column of the 8-storey frame structure that suffers the hit at three different limit states.

- The developing requirements for interstory drift are increased when the seismic demand for the assessment becomes more exigent.
- The column that suffers the hit is always in a critical condition due to shear action.
- The column that suffers the impact appears to be in critical condition due to high ductility demands when the limit state for the assessment is altered from Damage limitation to Significant damage and to Near collapse.
- Even in the case of Damage limitation limit state special measures have to be taken for the columns of the multistory RC frame that suffer the hit.
- The seismic performance of the columns that suffer the impact at a specific limit state of the assessment should be considered for the estimation of an adequate gap distance separation between adjacent structures.
- Thus, the minimum gap distance that is required in order to eliminate the possibility for pounding between adjacent structures depends on the limit state of the assessment.
- Eurocode's provisions for adequate gap separation do not depend on the seismic demand (limit state) but in any case based on the results of this study these provisions seem to be conservative.

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