Interaction of adjacent multi-storey RC frames at significant damage and near collapse limit states

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Abstract

The interaction problem between adjacent multi-storey reinforced concrete structures with unequal storey levels and different total heights at different limit states for three intensity levels of seismic hazard is evaluated. The seismic performance of the external column of the tall building that suffers the impact from the upper floor slab of the adjacent shorter structure is under consideration. The critical column's local requirements are checked at three different seismic demands according to the Eurocode 8 – part 3: (a) demand for damage limitation limit state (b) demand for significant damage limit state and (c) demand for near collapse limit state. More than 252 nonlinear dynamic step by step analyses have been performed. The results indicate that the column that suffers the impact appears to be in a critical condition due to high ductility demands when the limit state for the assessment is increased from damage limitation to significant damage and to near collapse state. As expected, the column that suffers the hit is always in a critical condition due to shear action. The limit state that is adopted for the evaluation of the pounding effect on the maximum shear requirements of the column slightly altered the results. However, the level of the seismic intensity influences the number of times the shear demands of the column exceed the available strength during the analysis. An increase of the developing requirements for inter-storey drift is also observed in all the cases where the seismic intensity is increased and the limit state becomes more exigent. The minimum gap distance between the adjacent structures that is required in order to eliminate the shear demands of the column seems to be depended on the limit state and the level of the seismic hazard that is used for the evaluation.

1 Introduction

Modern seismic design codes recognize that an important cause of structural damage that under certain conditions can lead to collapse initiation is that of the interaction of adjacent structures. For this reason the codes provide general gap separation limits between structures in order to prevent pounding problems during strong motion earthquakes. However, none of these limits is directly associated with the seismic demand and seismic hazard design code approaches for the structures. Moreover, the earthquake-induced inter-storey pounding between adjacent structures is also recognized by the modern seismic codes (including Eurocode-8) as the most crucial case of interaction for the integrity of the structural stability. However, although the problem of earthquake induced pounding between adjacent buildings has received substantial attention over the last two to three decades [1–18] most of the studies have been focused on modeling the floor to floor collision. Furthermore, the majority of the studies have yielded conclusions not directly applicable for the design or the assessment of multi-storey buildings potentially under pounding. It has to be stressed (see also Cole *et al.* [9]) that the majority of the inter-storey (floor to column) pounding research has been undertaken by Karayannis and Favvata [1, 2], Favvata and Karayannis [4], Favvata *et al.* [3, 5, 6]. In these studies the influence of the structural pounding on the seismic behavior 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 was investigated for the first time in 2005 by Karayannis and Favvata [1, 2]. 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. Also, the code's limits for adequate gap distances between the structures are not directly incorporated with the seismic hazard level and the local capacities of the columns that suffer the inter-storey pounding effect.

2 Structural modeling assumptions

The inter-storey pounding problem of adjacent structures at different limit states for three level of seismic hazard is studied. In the inter-storey pounding the slabs of the diaphragms of each structure hit the columns of the other structure at a

point within the deformable height (fig. 1). Collisions are simulated using special purpose contact elements that become active when the corresponding nodes come into contact. Emphasis has been given on modeling the actual behavior of the critical column that suffers the hit. For this reason, eight control cross-sections at the critical points along the height of the column have been used. More details on the structural modeling assumptions that are used can be found in previous works by Karayannis and Favvata [1, 2].
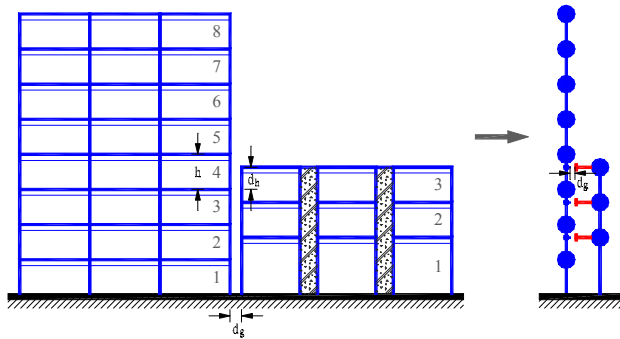

Figure 1:   Actual condition and model idealization of inter-storey pounding.

3   Examined cases

The interaction problem between an 8-storey reinforced concrete frame structure and a 3-storey structure with unequal inter-storey heights is evaluated at different limit states. The influence of the seismic intensity level at different limit states on the pounding effects is also investigated. This work is focused on the evaluation of the seismic performance of the critical column that suffers the hit. Three seismic demands according to the EC8-part 3 are taken into account: (a) demand for damage limitation (DL) limit state that corresponds to ground motions with return periods of 225 years, (b) demand for significant damage (SD) limit state that corresponds to ground motions with return periods of 475 years and (c) demand for near collapse (NC) limit state that corresponds to ground motions with return periods of 2475 years. Both components of seven different seismic excitations extracted from the PEER's database are taken into account. The characteristics of the seismic excitations are presented in Table 1. The selected ground motions are scaled to fit the Eurocode's 8 (EC8) elastic spectrums for three different zones of seismic hazard namely Low (HL), Medium (HM) and High (HH) and ground type A. Thus, the inter-storey pounding problem is evaluated in accordance to the level of the seismic intensity for nine different values of peak ground accelerations of the selected records, as summarized in Table 2. The seismic response of the structure without the inter-storey pounding effect is also studied and compared to the corresponding demands that are developed due to the interaction effect. This way, two hundred fifty two nonlinear seismic step by step analyses are performed for the evaluation

of the inter-storey structural pounding effect on the seismic behavior of adjacent multi-storey reinforced concrete structures with different storey heights. In this study 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.

Table 1:   Main characteristics of the seismic excitations.

| Seismic record | Duration | Maximum acceleration α_{max} (m/sec^2) | | Mag |
		Component FN	*Component FP*	
Italy Arienzo, 1980	24s	0.268 (1)*	0.405 (2)	6.9
Italy Auletta, 1980	34s	0.615 (3)	0.655 (4)	6.9
Chi-Chi Taiwan-06, 1999	42s	0.073 (5)	0.070 (6)	6.3
Denali- Alaska, 2002	60s	0.869 (7)	0.975 (8)	7.9
Loma Prieta, 1989	25s	1.090 (9)	0.509 (10)	6.93
Chi-Chi Taiwan-04,1999	60s	0.096 (11)	0.075 (12)	6.2
San Fernando, 1971	14s	0.153 (13)	0.181 (14)	6.61

*numeration of seismic excitation.

Table 2:   Peak ground accelerations α_{max} (g) under consideration.

| Seismic hazard | Limit states | | |
	Damage Limitation (DL)	*Significant Damage (SD)*	*Near Collapse (NC)*
Low (HL)	0.13g	0.16g	0.28g
Medium (HM)	0.19g	0.24g	0.42g
High (HH)	0.28g	0.36g	0.63g

In this study the well-known nonlinear dynamic structural analysis program Drain-2dx is used. 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. More details about the design of the structures 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 different intensity levels of seismic hazard. Moreover, results in terms of inter-storey drift requirements due to pounding effect are presented and commented.

Another key parameter for the interaction of the structures is the initial gap distance between them. Thus, in this study the minimum gap distance between the adjacent structures that is required at different seismic demands for different intensity levels of seismic hazard is also examined.

4   Results

The maximum inter-storey drifts at three limit states for three levels of seismic hazard due to the interaction of the 8-storey frame with the 3-storey structure are presented in fig. 2 and are compared in the same figure with the ones of the 8-storey frame vibrating without pounding effects. Each value of drift in fig. 2 is the mean value from 14 maximum inter-storey drifts as resulted from the 14 seismic excitations that are used in this study. As it was expected the maximum inter-storey 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 in all the cases where the seismic intensity is increased the developing requirements for inter-storey drift are also increased. Of course, these demands are increased more when the limit state for the evaluation of the seismic performance becomes more exigent.

Fig. 3(a) 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-storey pounding effect from the slab of the adjacent 3-storey structure. These ductility demands are evaluated at the limit state of "damage limitation" for the three levels of the seismic hazard: low, medium and high for each seismic excitation (it means 14 accelerations are used and totally 42 are analyzed). The developed requirements are compared with the corresponding available capacity of the column. It can be observed that when the seismic performance of the column is evaluated for the seismic demand of "damage limitation" the maximum requirement for flexural capacity due to the inter-storey pounding does not exceed the available one in most of the cases. Nevertheless, the intensity level of the seismic hazard seems to influence the requirements for curvature ductility that are developed in the critical part of the column. For example, in fig. 3(a) it can be observed that for the seismic excitation 6 (see Table 1 for numeration) in the case of seismic hazard high, the column develops maximum ductility of curvature that exceeds the available ductility of the column. Furthermore, this requirement is much greater than the corresponding ductility demands that are developed in the cases of low and medium level of intensity. Similarly, the seismic performances of the critical column that suffers the impact at "significant damage" and "near collapse" limit states are presented in figs 3(b) and (c). Based on these results it can be observed that for the same level of seismic hazard 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 (figs 3(b) and (c)) when the limit state for the assessment is enhanced from damage limitation to significant damage and to near collapse.

In the same concept, in fig. 4 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 presented considering all the seismic excitations. The effect of the pounding at
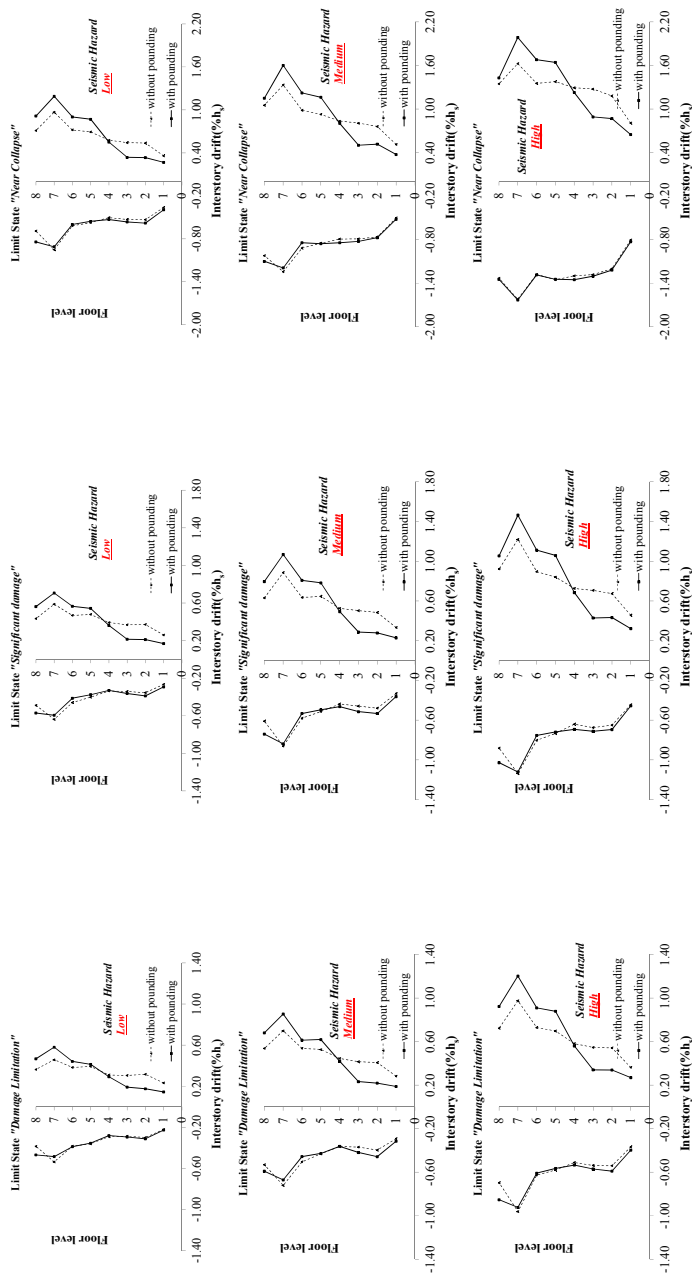
Figure 2:   Maximum inter-storey drifts requirements of the 8-storey RC frame structure at three different limit states for three intensity levels of seismic hazard. Influence of the structural pounding (*mean values of all the seismic excitations*).
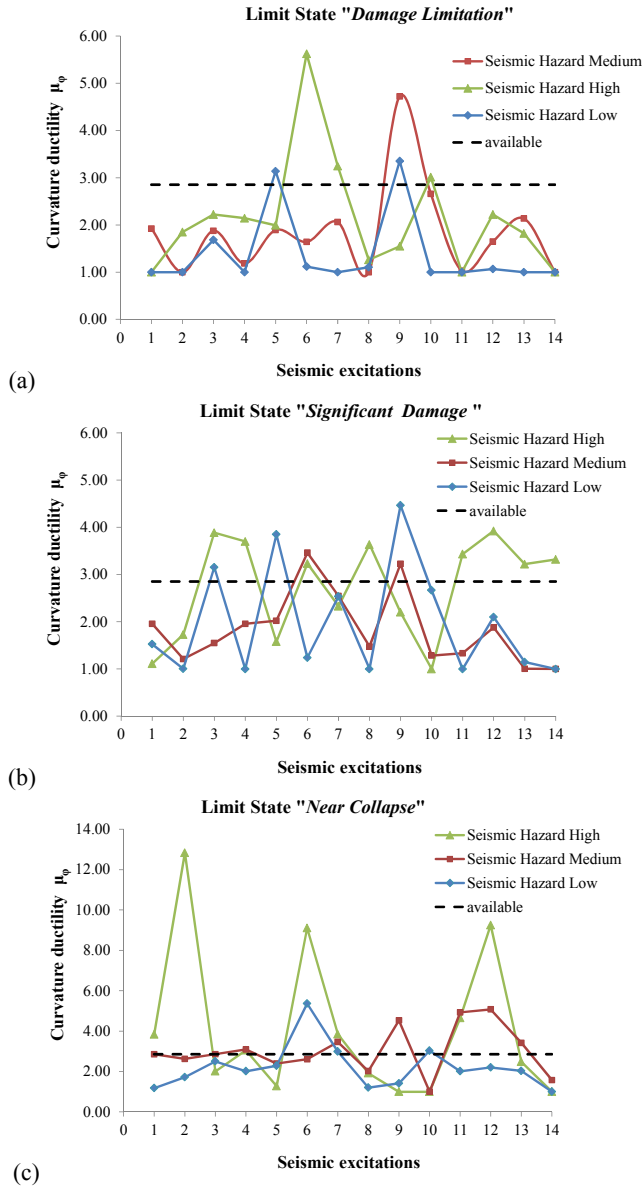
Figure 3:   Maximum ductility requirements of the column that suffers the hit at three different limit states for three intensity levels of seismic hazard.

each limit state is evaluated and compared for the three intensity levels of seismic hazard: high, medium and low. It can be observed that in all the examined cases the requirements for shear exceed the available shear strength of

the column. These results show the column that suffers the hit is always in a critical condition due to shear action. However, the results in fig. 4 indicate that the level of the seismic demand that is adopted for the evaluation of the pounding effect on the maximum requirements for shear at the critical part of the column that suffers the hit slightly altered the results. Furthermore, there are many cases where this column develops almost equal maximum requirements for shear capacity due tothe interaction problem for the three zones of seismic hazard of the same seismic excitation. Based on the above observations further examination of the seismic performance of the critical part of the column that suffers the hit is performed for all the examined cases.

Thus, in fig. 5, the shear-axial interaction requirements of the column during the Chi-Chi Taiwan-04 excitation are presented and compared with the available strength (solid lines). The results are for three levels of seismic hazard at the "near collapse" limit state. As it can be observed in all the cases the developing requirements of the column are exceeding the available strength several times during the analysis. The level of the seismic intensity (low, medium or high level of seismic hazard) influences the number of times the shear demands of the column exceed the available strength during the analysis. As it is depicted in fig. 5, the demands for shear that are developed in the critical part of the column exceed the available strength 62 times in the case of low level of seismic hazard, 83 times in the case of medium level and 113 times for high level of seismic hazard during the Chi-Chi Taiwan-04 excitation.

Nevertheless, shear failure of the column due to the pounding effect cannot be concluded based only on these results. A reason for that is that the total number of steps in this analysis is 8,000 thus the above mentioned calculated number of times of exceeding the available strength during the analysis (e.g. 113 times for HH) cannot be considered great enough for causing shear failure at the column since each time the duration is only 10^{-3} sec. An additional important 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-storey pounding problem. In this direction, further investigation is needed.

It is noted that the column's behavior is elastic in flexure and in shear in all the examined cases of this study without the pounding effect.

In this study, the minimum gap distance between the adjacent structures that is required in order to eliminate the shear demands of the column and consequently the possibility for interaction is also evaluated at the limit states of "significant damage and "near collapse" for the case of seismic hazard high (see fig. 6). As it can be observed in fig. 6(a), at the limit state of "significant damage" the minimum gap distance (d_g) between the examined adjacent structures that is required in order the critical developing shear-axial interaction forces due to the pounding effect (see fig. 4(b)) to be minimized is 4cm. However, in the case of studying the pounding effect at the limit state of "near collapse" the corresponding gap distance (d_g) should greater than 11cm (fig. 6(b)).

Limit State "*Damage Limitation*"

(a)

Limit State "*Significant Damage*"
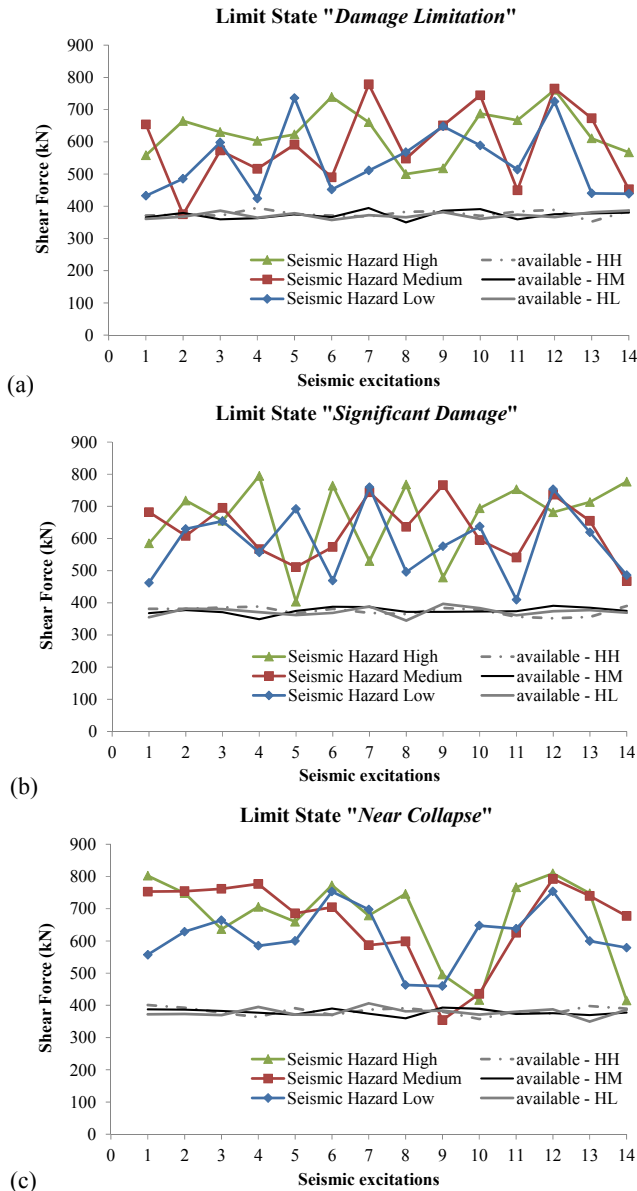

(b)

Limit State "*Near Collapse*"

(c)

Figure 4:   Maximum shear requirements of the column that suffers the hit at three different limit states for three intensity levels of seismic hazard.
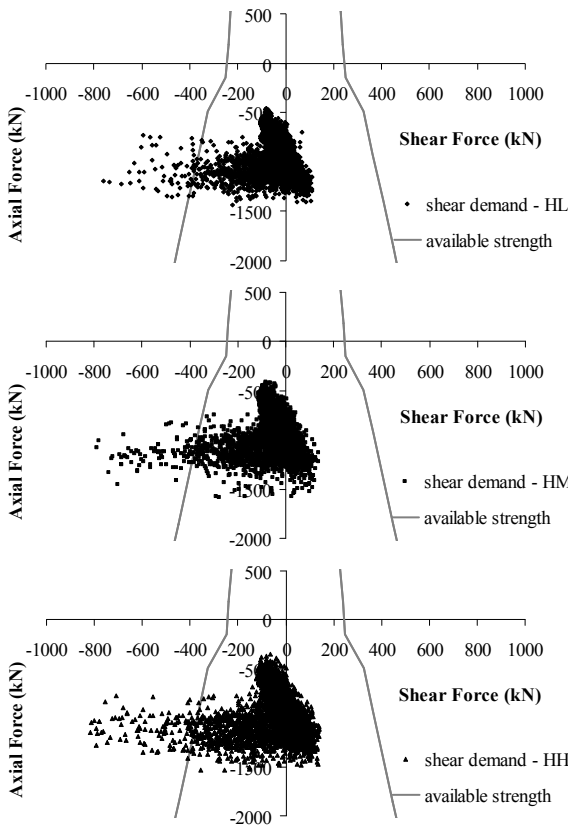
62 times of exceeding the available shear strength during the analysis

83 times of exceeding the available shear strength during the analysis

113 times of exceeding the available shear strength during the analysis

Figure 5:   Shear requirements of the critical column that suffers the hit at the limit state of "near collapse" for three intensity levels of seismic hazard (seismic excitation *Chi-Chi Taiwan-04, 1999*).

Finally, it is worth noting that during the seismic excitation of the Chi-Chi Taiwan-04 at the limit state of damage limitation and for the three seismic hazards the maximum developing ductility requirements of the column do not exceed the available strength of it although the adjacent structures are considered in contact from the beginning (dg=0). However, a gap distance separation between the structures greater than 2cm has to be applied in order to avoid the shear failure of the column in the case of low seismic hazard.

5   Conclusions

In this study the inter-storey pounding problem between adjacent structures is evaluated at different limit states for three intensity levels of seismic hazard. Dynamic step by step analyses of 252 cases were performed and results in terms of inter-storey drifts, ductility requirements, shear requirements and

Limit State *"Significant Damage"*

(a)

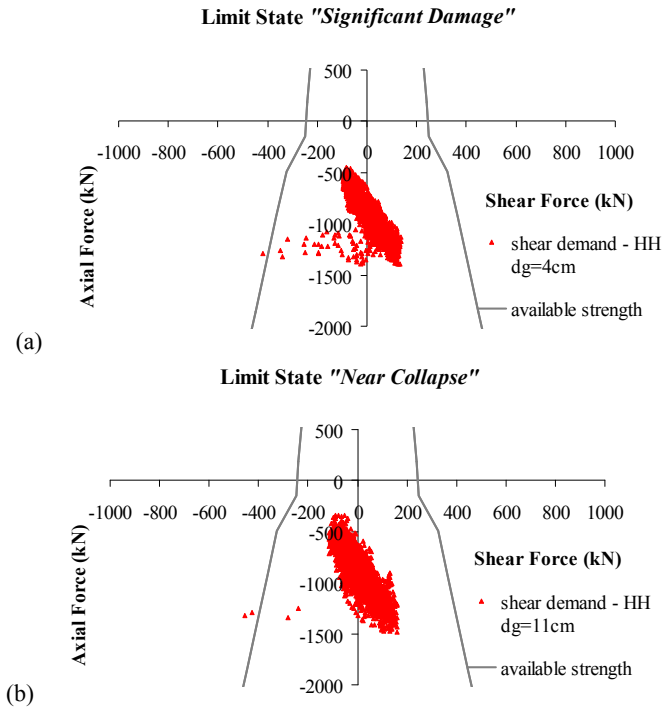**Limit State *"Near Collapse"***

(b)

Figure 6:   Estimated gap distances between the examined adjacent structures to prevent   the critical shear requirements that are developed at the column's part that suffers the hit (seismic excitation *Chi-Chi Taiwan-04, 1999*).

requirements for minimum initial gap distance between the structures were presented. The main conclusions of this study are:

•   In all the cases where the seismic intensity is increased the developing requirements for inter-storey drift are also increased. These demands are increased more when the limit state becomes more exigent.

•   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. Also, the intensity level of the seismic hazard seems to influence the requirements for curvature ductility that are developed in the critical part of the column.

The column that suffers the hit is always in a critical condition due to shear action. However, the limit state that is adopted for the evaluation of the pounding effect on the maximum shear requirements of the column slightly altered the results. Nevertheless, the level of the seismic intensity (low, medium or high level of seismic hazard) influences the number of times the shear demands of the column exceed the available strength during the analysis.

- Finally, the minimum gap distance between the adjacent structures that is required in order to eliminate the shear demands of the column and consequently the possibility for interaction seems to be depended on the limit state and the level of the seismic hazard that is used for the evaluation.

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