Structural pounding between adjacent buildings: The effects of different structures configurations and multiple earthquakes

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SUMMARY:
This paper examines the collision between adjacent reinforced concrete (RC) buildings under multiple earthquakes. Furthermore, the effect of the different structures configurations is also investigated. Two five-storey and two eight-storey frames are examined, which have been combined together to produce 9 different pairs of adjacent RC structures. These pairs of buildings are subjected to numerous single and multiple strong ground motions. Various parameters are investigated as the maximum displacements, permanent displacements, interstorey drift ratios etc. It is concluded that the effect of collision of adjacent frames seems to be unfavourable for the most of the cases and, therefore, the structural pounding phenomenon is rather detrimental than beneficial. Furthermore, it is found that the seismic sequences appear to be detrimental in comparison with the corresponding single seismic events.

Keywords: Structural pounding; different building configurations; multiple earthquakes

1. INTRODUCTION

Because of insufficient separations, structural pounding can occur between adjacent buildings during strong ground motions. Modern seismic codes propose a large enough separation, which appears to be ineffective in many cases. Although the majority of modern seismic design codes, as for example EC8 (2005), examining the nonlinear behaviour of structures, the structural pounding, a phenomenon with strong nonlinearities is not considered. Pounding between adjacent structures is a very complex phenomenon, which makes the analysis of the corresponding problem complicated. Various impact analytical models have been developed to define the structural response of adjacent structures during an earthquake. One can mention here the pioneering works of Anagnostopoulos (1988, 1995, 1996, 2004) and the contribution of Papadrakakis et al. (1995, 1996), Jankowski (2005, 2006, 2008), Liolios (2000) and Karayannis and Favvata (2005a,b). In spite of the extensive research done on the seismic collision of buildings during the last two decades, which has been mainly reported in the previous paragraph, the findings of many works have been refuted by other pertinent studies. According to Cole et al. (2010), this discrepancy has to do with the high level of complexity inherent in the problem.

This study examines four reinforced concrete (RC) framed structures, i.e., two five-storey and two eight-storey planar frames, which have been combined together to produce nine different pairs of adjacent RC structures. These pairs of buildings are initially subjected to six strong ground motions, which are absolutely compatible with the design process. The inelastic time-history responses of these RC frames are evaluated by means of the Ruaumoko software (Carr 2008). Comprehensive analysis of the created response databank is employed in order to derive significant conclusions, i.e., to evaluate the beneficial to detrimental proportion of structural pounding examining many critical structural parameters. Furthermore, the paper presents an extensive parametric study on the inelastic response of adjacent RC planar frames under real seismic sequences which are recorded by the same station, in the same direction and in a short period of time, up to three days. In such cases, there is a significant damage accumulation as a result of multiplicity of earthquakes and the collision of structures, and due to lack of time of successive seismic events, any rehabilitation action is impractical (Hatzigeorgiou 2010a,b,c, Hatzigeorgiou and Beskos 2009, Hatzigeorgiou and Liolios 2010, and Loulelis et al. 2012). Examining the results of this study, it is found that seismic sequences and the collision of the adjacent structures have significant effect on the response and, hence, on the design of RC frames.

2. DESCRIPTION OF STRUCTURES AND MODELING ASSUMPTIONS

In this paper, 4 planar frames (F1-F4) are considered with the first two of them (F1, F2) having 5 storeys and the other two (F3, F4) have 8 storeys. Both the examined 5- and 8-storey buildings have 3 equal bays with total length equal to 18 m. Typical floor-to-floor height is equal to 3.0 m, while for the first floor of the 8-storey buildings the height is equal to 4.0 m. The total height of the 5-storey buildings is 15m and all their beams and columns are 30x50cm and 40x40cm, respectively. The 8-storey frames are 25m tall with square columns of 40cm side for typical floors, and 50cm side for the ground floor. The beams of a typical floor are equal to 30x50cm while those for the ground floor are 30x60cm. Since all beams represent the concrete slabs at each floor, they are assumed not to be able to deform along their axis, in order to simulate the diaphragm action of slabs. The frames are considered to be fixed on the ground. Pounding between the frames in every case took place between one 5-storey and one 8-storey frame to examine closely its effects to collision of structures with different floor levels. Material properties are assumed to be 20 MPa for the concrete compressive strength and 500 MPa for the yield strength of steel reinforcements. These structures have been designed for earthquake loads with PGA=0.24g and soil class B according to EC8 (2005), and dead and live loads G=20kN/m and Q=10kN/m, respectively, directly applied to beams. The equation of motion of these structures can be expressed as (Anagnostopoulos 1988)

$$M\ddot{u}(t)+C\dot{u}(t)+K^{T}u(t)+F+R=-M\ddot{u}_{g}(t) \qquad (2)$$

where upper dots represent derivatives of time, C is the viscous damping matrix, M the matrix of mass, K^T the tangent stiffness matrix and $\ddot{u}_g(t)$ the ground acceleration. Furthermore, F and R are the vectors of impact forces and of restoring forces due to impact, respectively. The Ruaumoko program (Carr 2008) is used for the analysis, accounting for the material (inelastic behaviour) and geometrical (second-order effects through large displacements, contact/impact modelling) nonlinearities. According to Fardis (2007), the moment-curvature relation, M-ϕ, of an RC member can be suitably described by a hysteretic model without pinching. In this work, the Takeda et al. (1970) model is adopted. Pounding between adjacent frames was modelled by adopting the 'contact type members', whose parameters have been determined according to Anagnostopoulos (1988) and Jankowski (2005). Figure 1 shows the arrangement of a typical contact element and the modelling of contact interface.

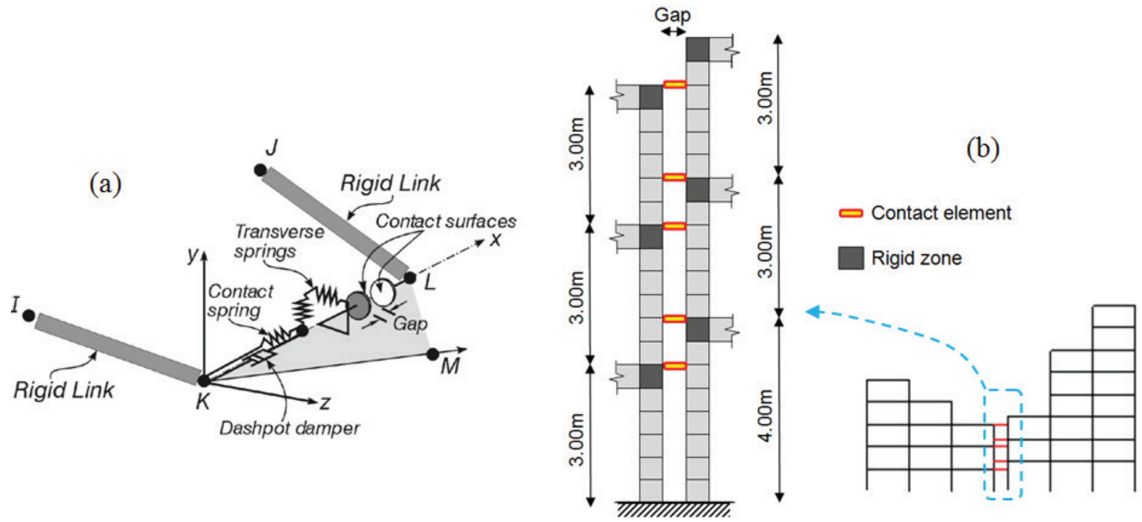

Figure 1. a) Ruaumoko contact element (Carr 2008), b) Modelling of structures interface

Nine different cases of structural pounding have been considered, as shown in Fig. 2. The investigation of the pounding of adjacent RC buildings, where one or both of them is irregular due to setbacks, is one of the objectives of this study. To the best of the authors' knowledge, although this is a frequent case in practice, it has not been investigated in the past in the pertinent literature.

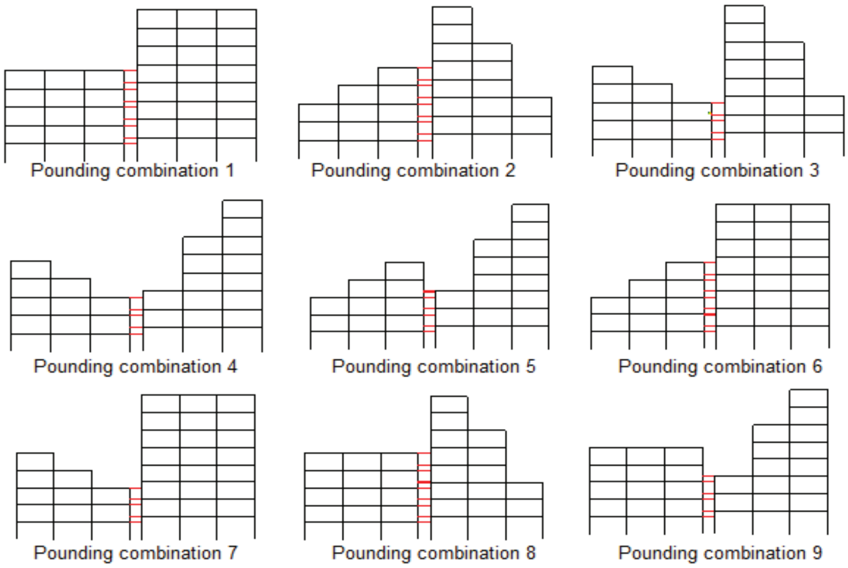

Figure 2. Examined pounding combinations

3. SEISMIC INPUT

The first strong ground motion database that has been used here comprises six artificial earthquakes which are absolutely compatible with the design procedure, i.e., the EC8 (2005) design spectrum with peak ground acceleration PGA=0.24g and soil class B. These earthquakes have been adopted in the analyses of the RC frames with and without pounding. They have been created using the specialized software SRP (1992) which creates time history seismic records matching user defined spectra. The generated artificial records, all of duration 20-25 sec, satisfy the provisions §3.2.3.1.2 of EC8 (2005) Taking into account the specific nature of the structural pounding problem, the selected time step is set to be much smaller than this critical value, i.e., $\Delta t=10^{-4}$sec for all records. Furthermore, the second database consists of five seismic sequences: Mammoth Lakes (May 1980), Chalfant Valley (July 1986), Coalinga (July 1983), Imperial Valley (October 1979) and Whittier Narrows (October 1987) earthquakes. The complete list of these earthquakes, which were downloaded from PEER (2012), appears in Table 1.

Table 1. Examined seismic events: 13 single earthquakes and 5 seismic sequences

No	Seismic sequence	Station	Comp.	Date (Time)	Period	Recorded PGA(g)	Normalized PGA(g)
1	Mammoth Lakes	54099 Convict Creek	N-S	1980/05/25 (16:34)	2 days	0.442	**0.240**
				1980/05/25 (16:49)		0.178	0.097
				1980/05/25 (19:44)		0.208	0.113
				1980/05/25 (20:35)		0.432	0.235
				1980/05/27 (14:51)		0.316	0.172
2	Chalfant Valley	54428 Zack Brothers Ranch	E-W	1986/07/20 (14:29)	1 day	0.285	0.153
				1986/07/21 (14:42)		0.447	**0.240**
3	Coalinga	46T04 CHP	N-S	1983/07/22 (02:39)	3 days	0.605	0.198
				1983/07/25 (22:31)		0.733	**0.240**
4	Imperial Valley	5055 Holtville P.O.	HPV315	1979/10/15 (23:16)	3 min.	0.221	**0.240**
				1979/10/15 (23:19)		0.211	0.229
5	Whittier Narrows	24401 San Marino	N-S	1987/10/01 (14:42)	3 days	0.204	0.231
				1987/10/04 (10:59)		0.212	**0.240**

The examined records are compatible with the soil class B, and therefore compatible with the design process used for the considered frames. Furthermore and for compatibility reasons with the design process, the seismic sequences are normalized to have maximum *PGA* equal to 0.24g. Every sequential ground motion record from the PEER database (2012) becomes a single ground motion record (serial array) by applying a time gap equal to 100 sec between two consecutive seismic events, as shown in Fig. 3. This gap has zero ground acceleration ordinates and is adequate to cease the motion of any structure due to damping before the action of the next event. Therefore, the analysis after the first, second, etc. event starts from the point where the structure has been left after the previous event, i.e., any residual deformations and the appropriate loading paths are correctly applied. Furthermore, the existing damage from the previous seismic events will be accumulated for any oncoming strong ground motion.

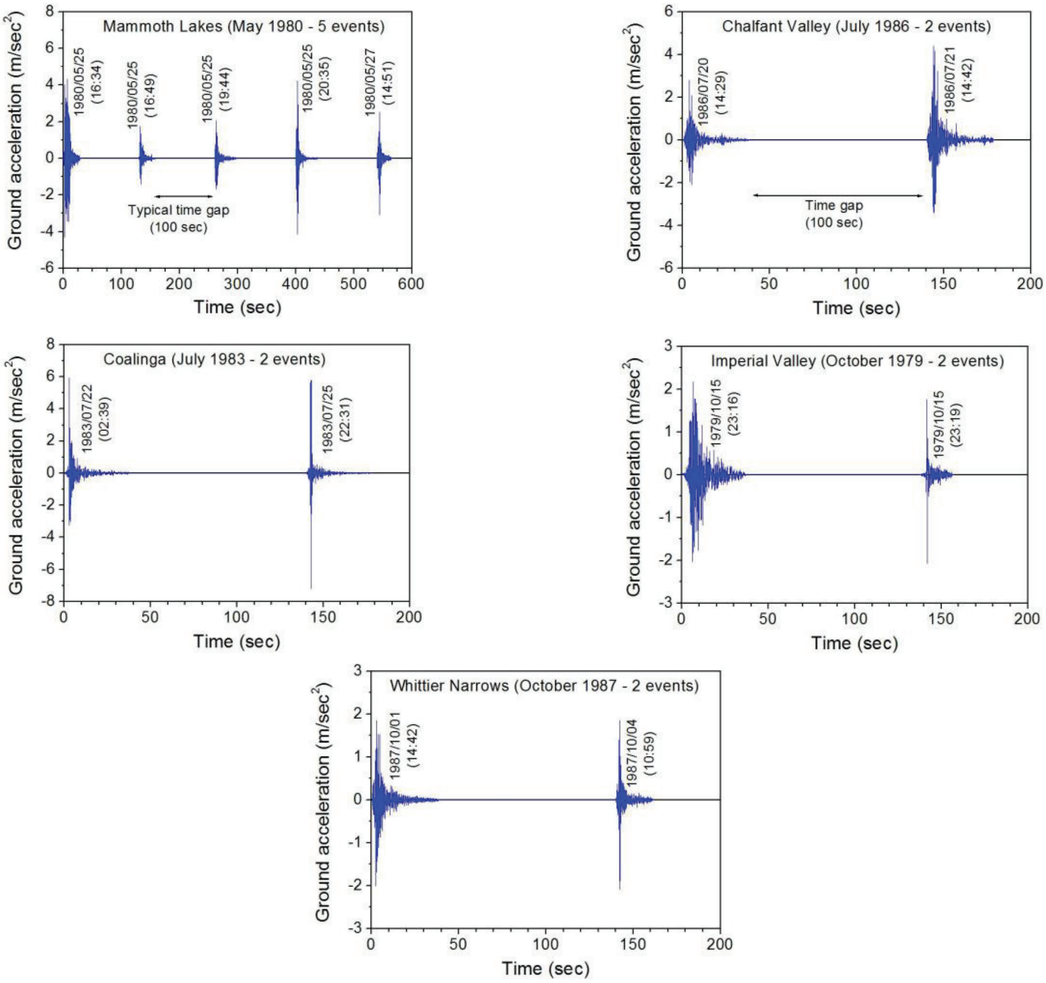

Figure 3. Ground acceleration records of the examined seismic sequences

4. SELECTED RESULTS

4.1. Single ground motions

This section provides with selected results examining the aforementioned nine pounding combinations under single earthquakes. The interstorey drift ratio (*IDR*) can be defined as the maximum relative displacement between two stories normalized to the storey height. This structural parameter is crucial both for assessment of structural members and non-structural displacement-sensitive components as infill walls. Figure 4 shows the averaged IDR values for the whole sample of pounding combinations. It is evident that in most of the cases, the collision of adjacent structures leads to mildly higher IDR values in comparison with the case of separated structures.

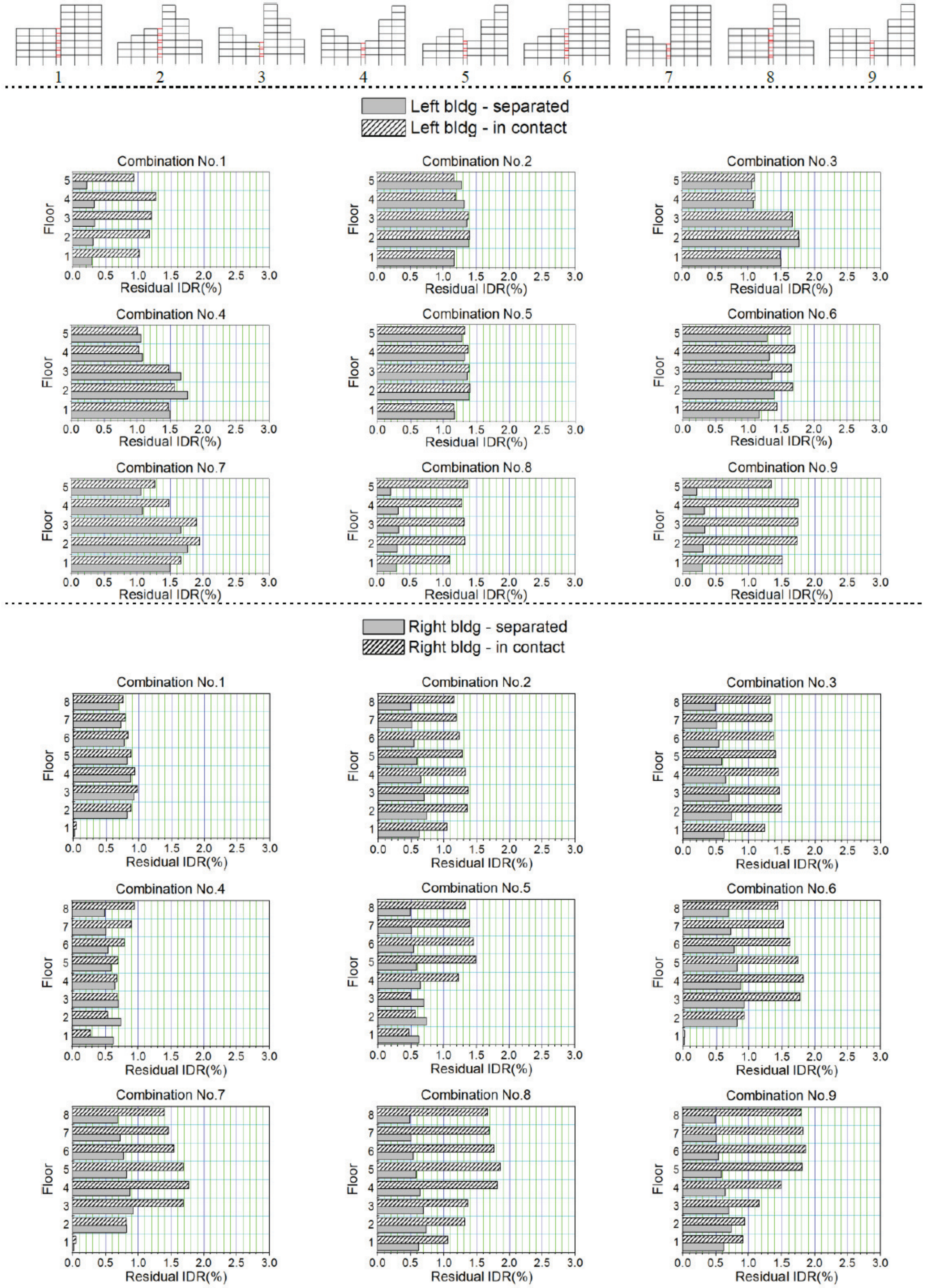

Figure 4. Averaged *IDR* values

Furthermore, Fig.5 depicts the maximum floor horizontal total accelerations both for separated structures and structures in contact. This figure comprises results from the whole sample of arrangements and examines averaged values for the whole sample of the examined strong ground motions. It is evident that structures subjected to pounding generally present higher floor total acceleration in comparison with separated structures. Therefore, it is obvious that the maximum floor horizontal accelerations of buildings are strongly affected by the seismic gap between the collided structures and their arrangement.

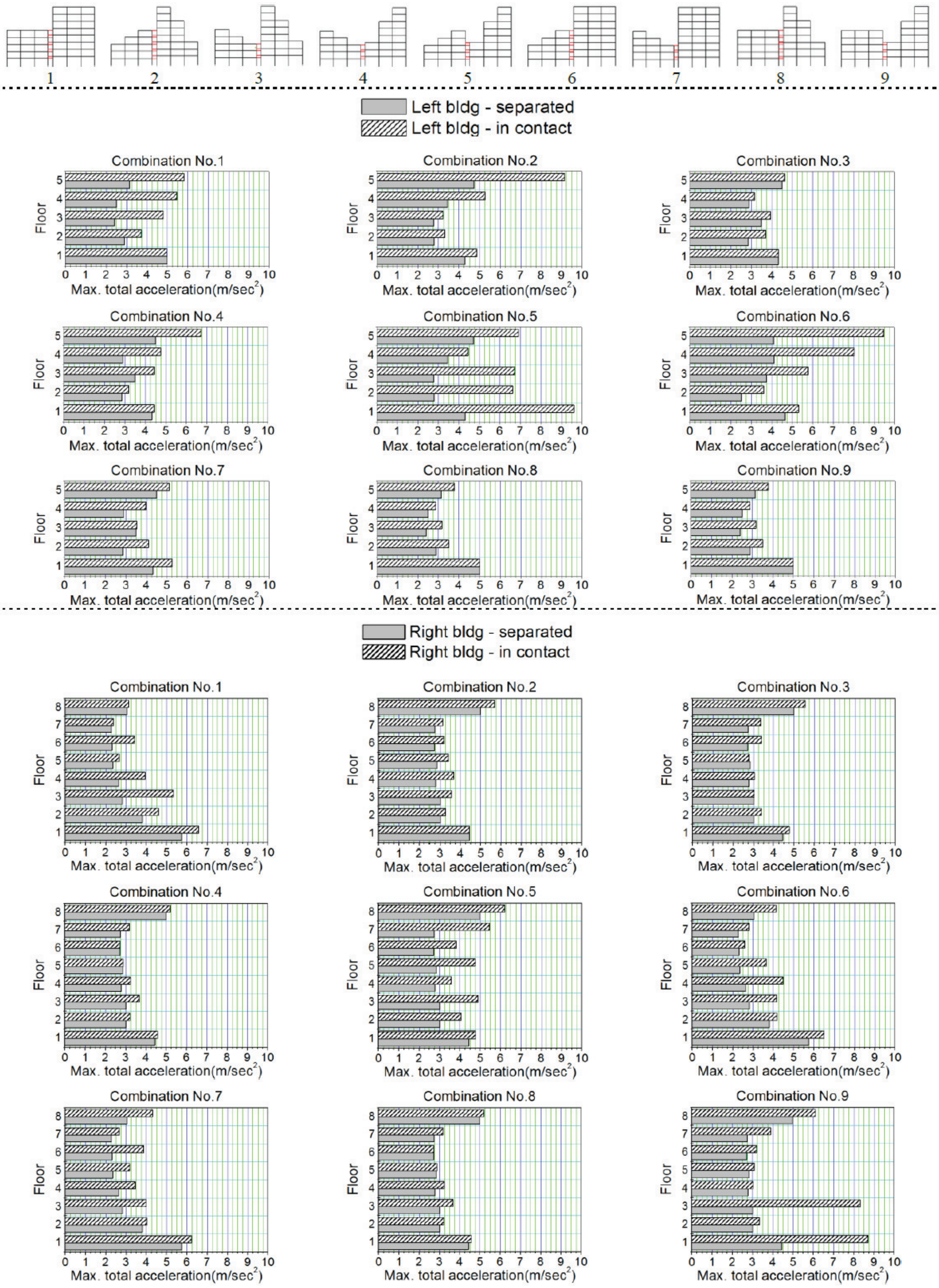

Figure 5. Averaged floor acceleration values

Another critical parameter is the residual *IDR*, which has to do with the permanent deformation of a structure that remains after a strong ground motion. Figure 6 shows the averaged residual *IDR* values for the whole sample of combinations. It is obvious that in most of the cases, the collision of adjacent structures leads to higher residual *IDR* values in comparison with the case of separated structures.

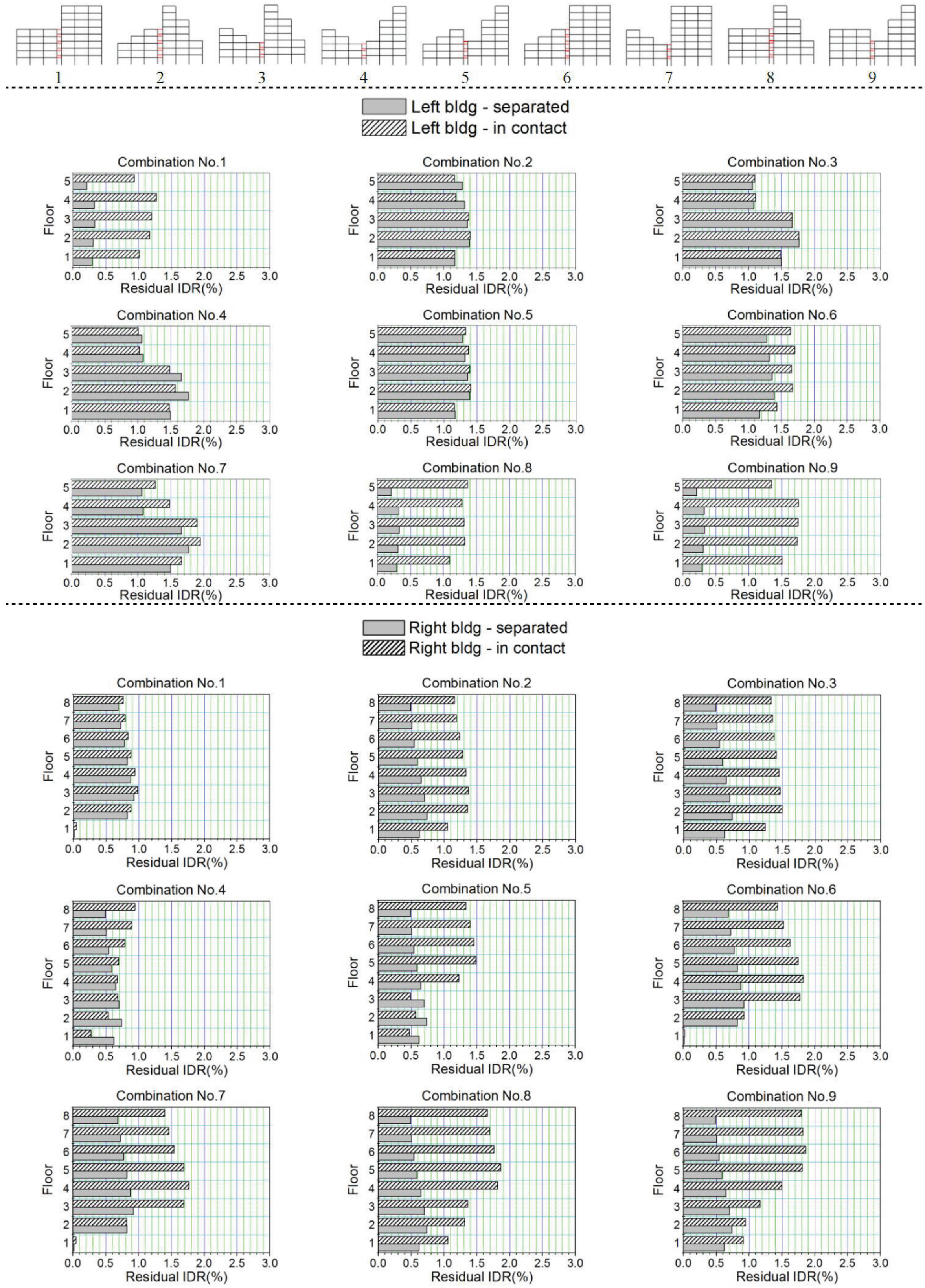

Figure 6. Averaged residual *IDR* values

4.2. Multiple ground motions

This section provides with selected results examining the aforementioned nine pounding combinations under multiple earthquakes. Thus, Fig.7 shows the maximum top horizontal displacements of the lower structure (Frame F2) for the pounding combinations No. 2 and No. 5, under Whittier Narrows (1987) seismic sequence.

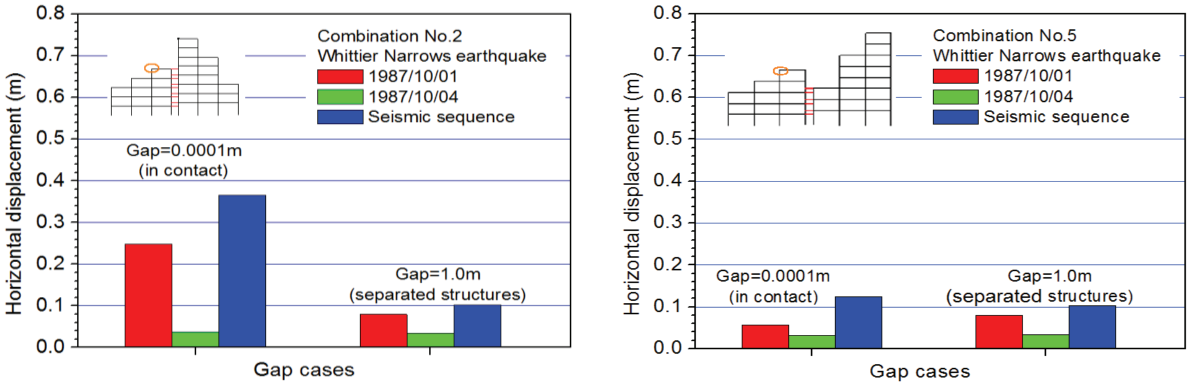

Figure 7. Max. horizontal top displacement of Frame F2 for pounding combinations No. 2 and 5.

It is evident that the seismic sequence causes greater horizontal top displacement in comparison with the corresponding values of single seismic events. Furthermore, as it is expected, pounding combinations No. 2 and 5 lead to identical maximum displacements for the cases of separated structures. On the other hand, the different arrangement of the same structures in contact leads to quite different maximum horizontal top displacements.

Figure 8 show the *IDR* of the 8-storey frame for the pounding combinations No. 3 and 8, respectively, and for the cases of structures in contact. The examined cases have to do with the Mammoth Lakes seismic events, which are investigated both independently and as a seismic sequence. It is evident that seismic sequences lead to larger *IDR* in comparison with the corresponding single events.

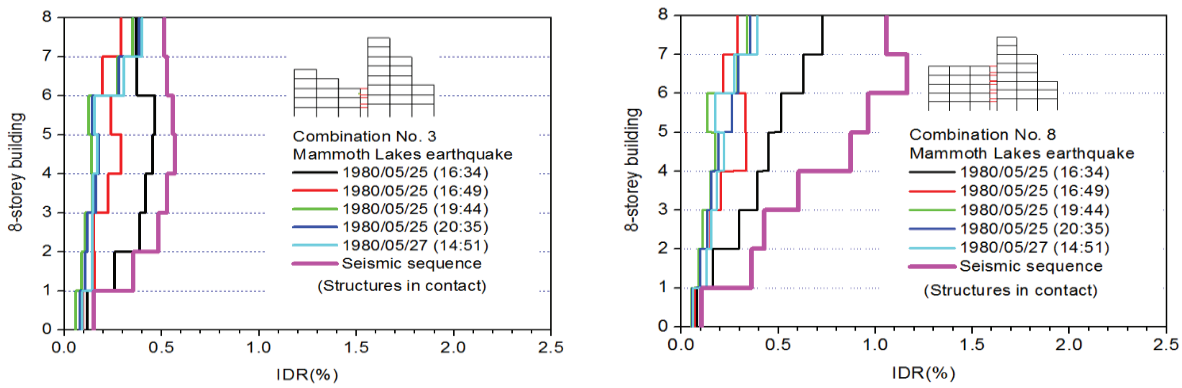

Figure 8. *IDR* diagram of pounding combination No. 3 and 8 – Structures in contact

It is obvious that, although the same 8-storey building is on the right of these two pounding combinations, the use of different adjacent structures on the left leads to quite different IDR values for the 8-storey buildings.

It is very important to investigate permanent displacements under repeated seismic events due to the fact that the examined type of deformation is directly related to the proper seismic joint (gap) between structures. Thus, the time-history of the top horizontal displacement of the 5-storey frame (pounding combination No. 1 – separated structures, gap=1.0m) is given in Fig. 9 for the case of the Imperial

Valley earthquake. It is obvious that the seismic sequence leads to cumulative permanent deformation. Similar results are obtained by examining the same building, pounding combination and earthquake but for a separation gap =0.0001m, i.e., for structures in contact, where the time history of the top displacement is also shown in Fig. 9. Moreover, it is found that structures in contact appear to have larger values of maximum and permanent displacements, in comparison with the case of separated structures.

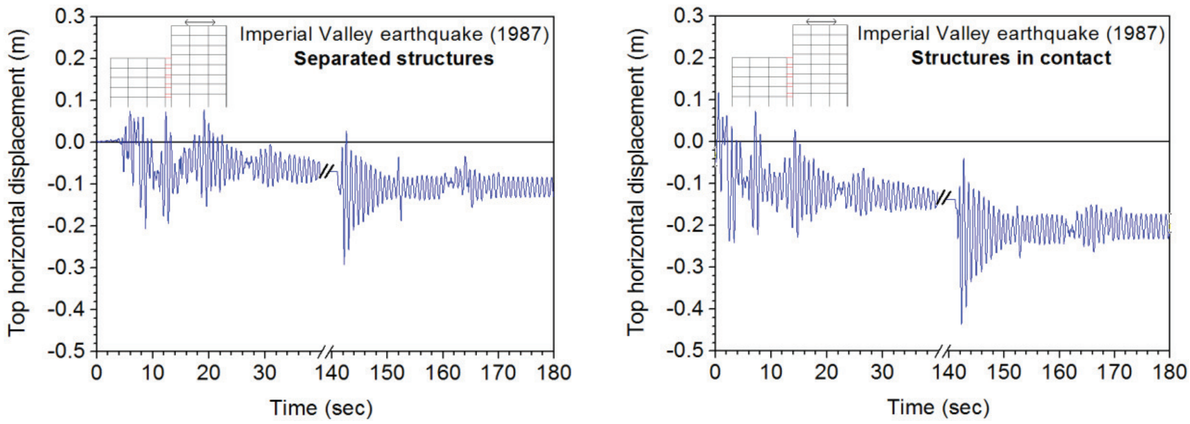

Figure 9. Top displacement time-history of the 8-storey frame (Comb. No. 1)

5. CONCLUSIONS

This study has examined the effect of different configurations on the seismic behaviour of adjacent RC buildings. Four planar frames have been examined, which have been combined together to produce 9 different pairs of adjacent RC structures, which can be either separated or in contact. All these structural cases have been subjected to 6 artificial earthquakes which are compatible with the seismic design spectrum. Selected characteristic and total results have been provided in Section 4. It is found that for all the examined cases, the pounding phenomenon appears to be detrimental than beneficial and this is more intense for the tallest buildings. The examined RC planar frames have also been examined under seismic sequences. It is found that sequences of earthquakes increase the damage at structural members (local damage) and at the whole structure (global damage) more than individual seismic events. Ductility demands are significantly increased when the frames are subjected to seismic sequences in comparison with the case of single seismic events. Permanent deformation of structures seems to be a factor of special importance since the earthquake may lead the structure to behave plastically and may result in a decrement of seismic joint between the frames. In many cases, even when structures are separated by proper seismic joint according to international rules and codes, after an intense earthquake, the new seismic joint may not agree any more with these regulations. This property appears to be problematic for any oncoming intense ground motion.

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