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On the Seismic Response of Collided Structures

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***Abstract*—**This study examines the inelastic behavior of adjacent planar reinforced concrete (R.C.) frames subjected to strong ground motions. The investigation focuses on the effects of vertical ground motion on the seismic pounding. The examined structures are modeled and analyzed by RUAUMOKO dynamic nonlinear analysis program using reliable hysteretic models for both structural members and contact elements. It is found that the vertical ground motion mildly affects the seismic response of adjacent buildings subjected to structural pounding and, for this reason, it can be ignored from the displacement and interstorey drifts assessment. However, the structural damage is moderately affected by the vertical component of earthquakes.

***Keywords*—**Nonlinear seismic behavior, reinforced concrete structures, structural pounding, vertical ground motions.

I. INTRODUCTION

IN populous cities, due to insufficient separations between adjacent buildings, structural pounding can occur during strong earthquakes. In the pertinent literature, numerous incidents of damage due to this phenomenon have been referenced, e.g., the reader can consult [1], [2], amongst others. In many cases, collision can occur between buildings of different heights where local damage can be observed on columns as the floor of one building collides with columns of another. However, only few works examined the pounding phenomenon between buildings of different heights [3]-[5]. Furthermore, to the best of the authors' knowledge, the influence of vertical ground motion on the seismic response of collided structures has not yet examined.

Therefore, the necessity to investigate the influence of vertical ground motion on the pounding between adjacent planar reinforced concrete (RC) frames of different heights subjected to strong earthquakes is evident. This study examines this phenomenon investigating various couples of adjacent planar RC frames and useful conclusions from this investigation are provided.

II. STRUCTURAL DESIGN OF FRAMES

This investigation examines two RC frames (F1-F2) having 5 and 8 storeys. The geometry, sections and reinforcement of the frames are shown in Figs 1, 2. The total height of the 5-storey building is 15m and all their beams and columns are 30x50cm and 40x40cm, respectively. The 8-storey frame is 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.

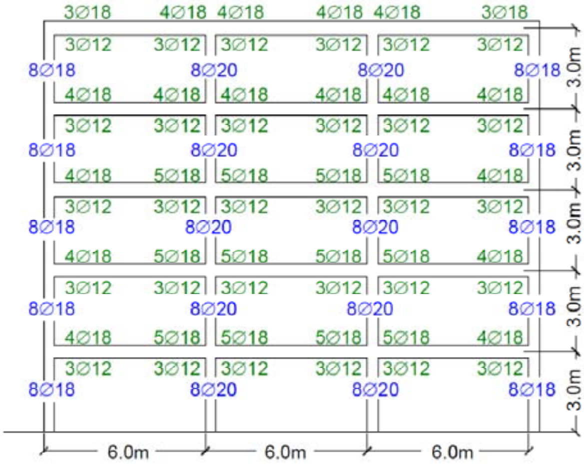

Fig. 1 Geometry of frame F1

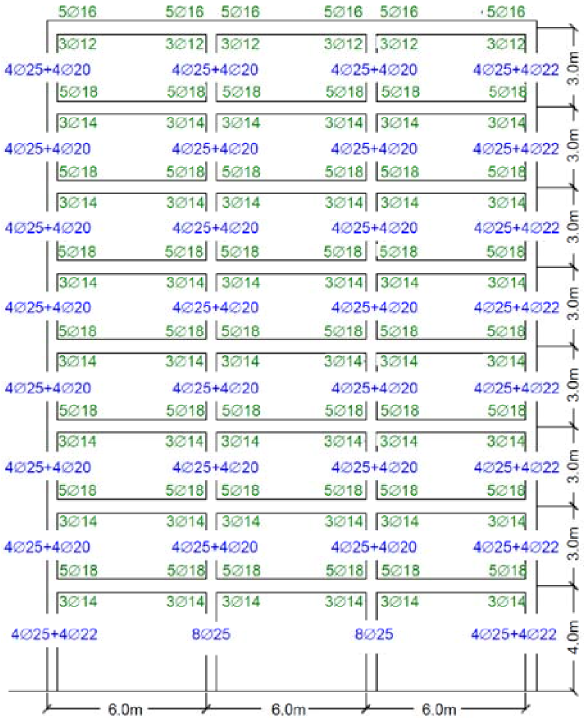

Fig. 2 Geometry of frame F2

Material properties are assumed to be 20 MPa for the concrete compressive strength (C20) and 500 MPa for the yield strength of both longitudinal and transverse

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reinforcements (S500s). These structures have been designed for earthquake loads with peak ground acceleration PGA=0.24g and soil class B according to EC8 [6], and dead and live loads *G*=20kN/m and *Q*=10kN/m, respectively, directly applied to beams. For more information about the geometry and the design of frames, the reader can consult [4]. Fig. 3 shows the examined pounding combination of the aforementioned single frames.

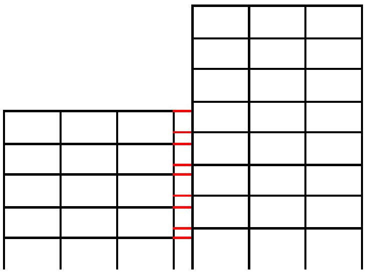

Fig. 3 Pounding combinations under consideration

III. DESCRIPTION OF EARTHQUAKES UNDER CONSIDERATION

The earthquakes that have been used here include five real couples of records and appear in Table I.

TABLE I
SEISMIC EVENTS UNDER CONSIDERATION

Seismic event	Station	Date	Comp.	Recorded PGA(g)	Normal. PGA(g)	Accel. ratio vert./hor.
Anza	Pinyon Flat	02/25/80	045 (hor.)	0.131	0.240	0.614
			Up (vert.)	0.081	0.148	
Chi-Chi Taiwan	CHY034	09/20/99	N (hor.)	0.310	0.240	0.294
			V (vert.)	0.091	0.071	
Coyote Lake	Dam-San Martin	08/06/79	250 (hor.)	0.279	0.240	0.434
			Up (vert.)	0.121	0.104	
Duzce Turkey	Duzce	11/12/99	270 (hor.)	0.535	0.240	0.667
			Up (vert.)	0.357	0.160	
Loma Prieta	Corralitos	10/18/89	090 (hor.)	0.479	0.240	0.950
			Up (vert.)	0.455	0.228	

These records were downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center (http://peer.berkeley.edu/nga), and have been used in many research studies in the past. In the following the aforementioned earthquakes are symbolized as ANZ, CHI, COY, DUZ and LOM.

It should be noted that the corresponding ratio of maximum vertical to the maximum horizontal ground acceleration varies from event to event, but it seems to be fairly broad in the adopted set of earthquakes (0.294~0.950). The records are normalized to have PGA=0.24g in order to be compatible with the design assumptions. The scale factors that have been used for this reason are compatible with the suggestions of Modern Engineering Seismology about the scaling of seismic records and they are ranged between 0.45 (Duzce earthquake) and 1.83 (Anza earthquake), avoiding this way extreme and unacceptable values.

The acceleration response spectra for the horizontal components of earthquakes under consideration are shown in Fig. 4.

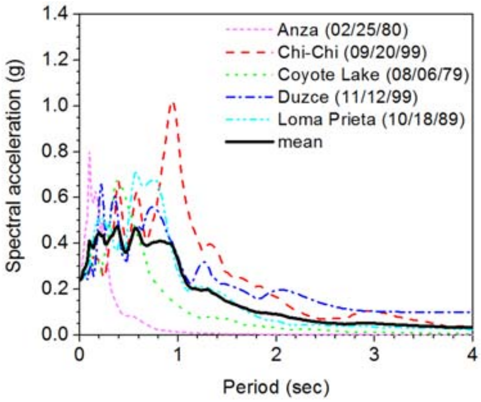

Fig. 4 Response spectra of examined earthquakes

Finally, the vertical spectral acceleration to horizontal spectral acceleration ratio for the earthquakes under consideration is shown in Fig. 5.

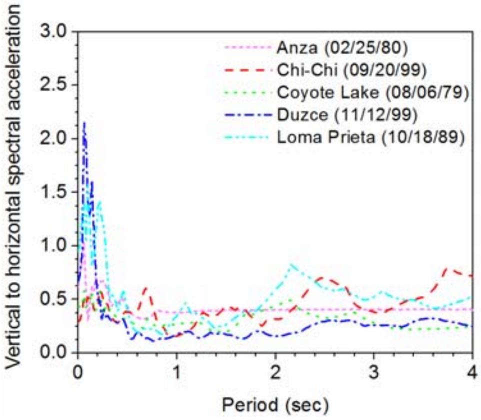

Fig. 5 Vertical to horizontal spectral acceleration

IV. SELECTED RESULTS

This section provides with selected results from dynamic nonlinear time history analyses and focuses on the examination of the influence of the vertical ground motions on the seismic response of collided structures.

In order to quantify the effect of vertical ground motions on the seismic response of structures, the relative difference, *R.D.*, between the cases of considering (*C*) and ignoring (*I*) the vertical ground motions on various parameters is examined. This ratio can be defined for each structural parameter, *P*, as:

$$R.D. = 100\% \left|\frac{P_C - P_I}{P_C}\right| \quad (1)$$

Thus, without loss of generality, Fig. 6 presents the relative difference for the maximum horizontal displacement of the top of the 5-storey building (bldg on the left in Fig. 3). For comparison reasons both the cases of separated, independent buildings and collided buildings are examined. It is obvious that, in any case of ground motion under consideration, the relative difference for the maximum horizontal displacement is higher for collided structures than the case of separated structures. However, these values are rather small (<5%), for both the cases considering and ignoring the vertical component of earthquakes.

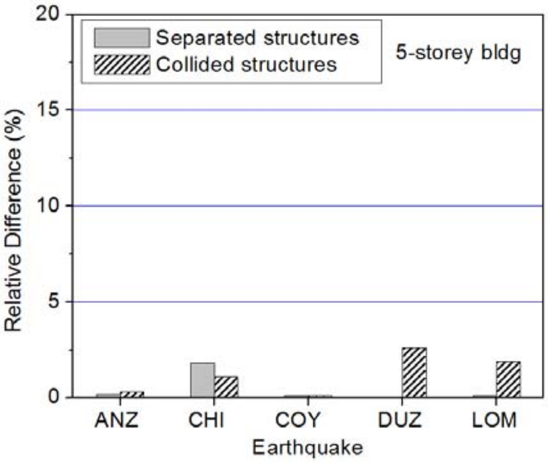

Fig. 6 Relative difference for top displacements of 5-storey bldg

Additionally, Fig. 7 depicts the relative difference for the maximum horizontal displacement of the top of the 8-storey building on the right. For comparison reasons both the cases of separated, independent buildings and collided buildings are examined. It is obvious that, in any case of ground motion under consideration, the relative difference for the maximum horizontal displacement is higher for collided structures than the case of separated structures but, in any case, these values are very small (<5%). Therefore, according to the assessment of displacements, the vertical component of earthquakes can be ignored.

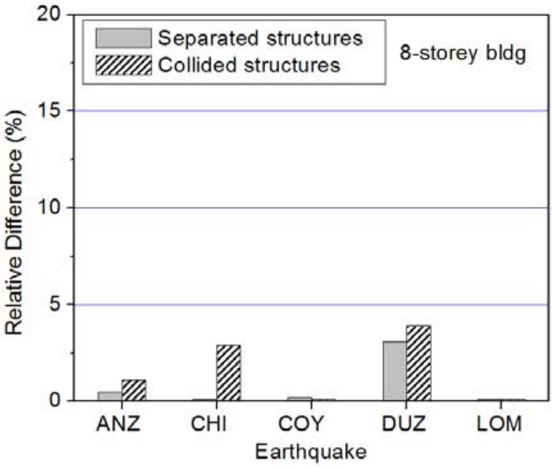

Fig. 7 Relative difference for top displacements of 8-storey bldg

Another critical structural parameter that is examined herein is the interstorey drift ratio, IDR. This parameter can be defined as can be defined as the maximum relative displacement between two successive stories normalized to the storey height. This is crucial both for assessment of structural members and for non-structural components as infill walls. Fig. 8 shows the IDR values for the cases under consideration.

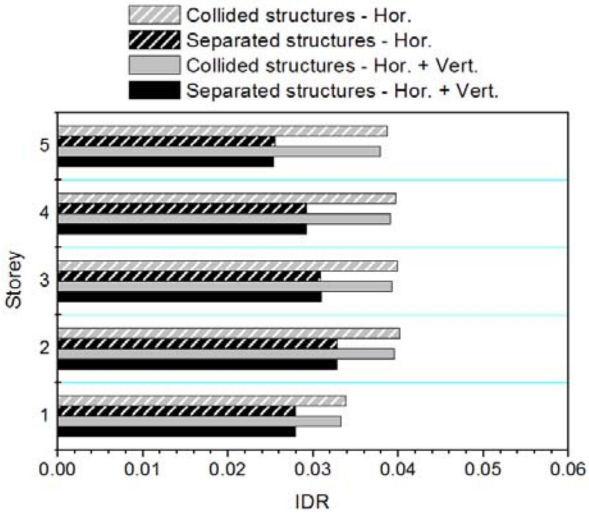

Fig. 8 Inter-storey drifts for the 5-storey bldg

It is evident that the influence of vertical components of earthquakes on the response of collided (and separated) buildings is insignificant.

In order to confirm the slight or the considerable effect of vertical ground motion on the response of collided structure, the structural damage is also investigated. The best-recognized damage index (DI) is the Park-Ang one [7]. This is defined as a combination of maximum deformation and hysteretic energy in the form

$$D_{Park-Ang} = \frac{\delta_\mu}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h \qquad (2)$$

where δ_μ and δ_u are the maximum and the ultimate deformation of the element, respectively, β is a hysteretic model constant parameter (usually, β=0.05~0.20) to control strength deterioration, dE_h is the hysteretic energy absorbed by the element during the earthquake, and P_y is the yield strength of the element. In this work, parameter β is set equal to 0.20 [4]. This damage model can also be extended to the storey and overall scales by summation of damage indices using appropriate multiplication weights. Various scales have been proposed to connect the damage indices with the physical appearance in structures. For example, Table II, which has been adopted from [8], shows five characteristic degrees of damage, i.e., from slight damage to collapse and the corresponding cases of physical appearance, damage index and state of building.

Fig. 9 depicts the relative difference for the structural damage of the upper right column of the 5-storey building, which suffers to damage due to pounding taking into account its configuration. For comparison reasons both the cases of separated, independent buildings and collided buildings are examined.

TABLE II
THE RELATION BETWEEN DAMAGE INDEX AND DAMAGE STATE [8]

Degree of Damage	Physical Appearance	Damage Index	State of Building
Slight	Sporadic occurrence of cracking	< 0.10	No Damage
Minor	Minor cracks; partial crushing of concrete in columns	0.10-0.25	Minor Damage
Moderate	Extensive large cracks; spalling of concrete in weaker elements	0.25-0.40	Repairable
Severe	Extensive crashing of concrete; disclosure of buckled reinforcement	0.40-1.00	Beyond Repair
Collapse	Partial or total collapse of building	>1.00	Loss of Building

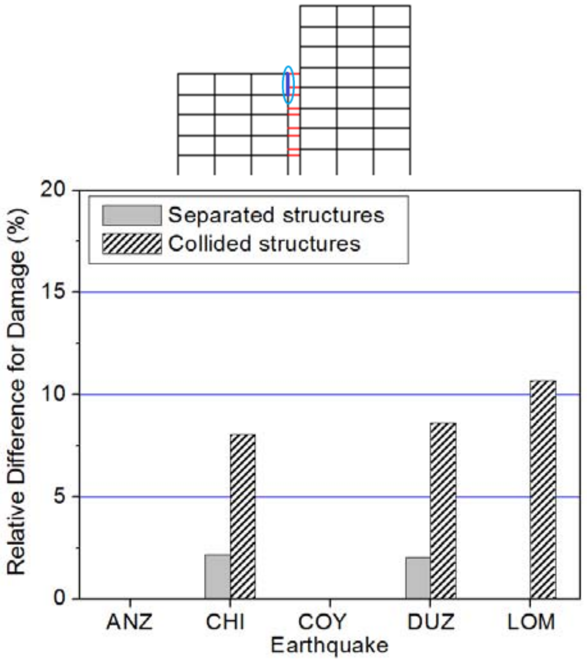

Fig. 9 R.D. for damage of upper-left column of 5-storey bldg

It is obvious that, in any case of ground motion under consideration, the relative difference for the structural damage is higher for collided structures than the case of separated structures. From this investigation, it is obvious that the vertical ground motions can affect the damage levels of some structural members. For example, the damage index for the abovementioned member of the 5-storey building (see Fig. 7) is equal to 38% ignoring the vertical component of Duzce (1999) earthquake and 42% considering this component. Therefore, it is evident that, according to Table II, ignoring the vertical component of Duzce (1999) earthquake, the damage can be characterized as “moderate” or “repairable” while considering the vertical ground motion, the damage is characterized as “severe”.

V. CONCLUSION

In the proposed research, the effect of vertical ground motion on the seismic pounding of adjacent planar reinforced concrete (R.C.) frames subjected to strong ground motions is investigated.

It is found that the vertical ground motion mildly affects the seismic response of adjacent buildings subjected to structural pounding and, for this reason, it can be ignored from the maximum displacement and peak inter-storey drifts assessment.

The structural damage is moderately affected by the vertical component of earthquakes and for this reason its consideration in the inelastic time-history analysis seems to be unavoidable. At this point, it should be mentioned that nonlinear static procedures, such as pushover analysis, ignore completely the vertical component of earthquakes. Therefore the evaluation of structural damage using nonlinear static procedures seems to be problematic. Finally, according to the authors' opinion, the more intense effect of vertical components of earthquakes on the structural damage has mainly to do with the increment of bending moments for beams and the variation of axial forces for columns, which react on the alteration of maximum damage values through the bending moment – axial force bounding curves (for 2-D elements) or bounding surfaces (for 3-D elements).

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