16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

SEISMIC BEHAVIOR OF ASYMMETRIC STRUCTURES WITH DIFFERENT DEGREE OF IRREGULARITY

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ABSTRACT

Irregularity in plan can significantly affect the desired ductile response of structures exposed to earthquake loading. Most of the seismic design codes contain provisions for control of structural irregularities. According to EN 1998-1, a building can be characterized as regular in plan, if six different conditions were satisfied, at all story levels. Some of these conditions are qualitative, but some of them that are based on the determination of eccentricity between the center of mass and the center of stiffness or torsional radius, are quantitative. In order to investigate the influence that the degree of irregularity in plan has on the behavior of the buildings on seismic loading, several mathematical models of five story RC frame structures are analyzed. The degree of irregularity is regulated with the length of the seismic wall placed at the external frame of the structure.

Nonlinear dynamic analysis is performed with purpose of numerical evaluation of the seismic behavior of the structures, whereupon input ground motions from three previous earthquakes are used, Imperial Valley – El Centro 1940, Victoria Mexico – Chihuahua 1980, Chi Chi Taiwan 06 – CHY028 1999. Input acceleration histories are scaled for three different levels of seismic hazard that correspond to PGA of 0.12g, 0.24g and 0.36g. In all analyses the seismic action was applied in one direction, perpendicular to the axis of irregularity.

From the obtained results it can be noticed that the maximal displacements and the interstory drifts of the structure always occur at the most distant frame from the center of stiffness. The rotations that occur at the top story of the structure are not varying significantly with respect to the degree of irregularity.

Keywords: EN 1998-1; Seismic behavior; Irregularity in plan; Nonlinear dynamic analysis;

1. INTRODUCTION

Irregularity in plan can significantly affect the desired ductile response of structures exposed to earthquake loading. Buildings with eccentricity between the center of the mass and center of stiffness or with lack of minimal torsional rigidity can undergo coupled lateral and torsional motions during earthquakes, which significantly can increase the seismic demand especially at perimeter frames. For these reasons most of the seismic design codes contain provisions for control of structural irregularities. If the prescript criteria for regularity are not satisfied, certain restrictions related to the selection of method or numerical model for seismic analysis have to be done. Moreover, due to

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potentially uncontrollable torsion oscillation and reduced ductile response, design seismic forces have to be obtained for a lower reduction factor.
High seismic vulnerability of plan irregular structures was a motivation for many researches in the past. An extensive review of different structural irregularities and systematization of conducted researches can be found in Rutenberg (2002), De Stefano and Pintucchi (2008), Varadharajan at al. (2013). Many of these researches, Cosenza at al. (2000), Humar, J. and Kumar, P. (2000), Zheng at al. (2004), Rasulo at al. (2004), Özhendekci and Polat (2008), are related to the analysis of codes provisions for plan irregularity.

2. CODES PROVISIONS FOR PLAN IRREGULARITY

According to EN 1998-1, a building can be characterized as regular in plan, if six different conditions are satisfied, at all story levels. Some of these conditions are qualitative, and can be checked in the preliminary design stage, but some of them that are based on the eccentricity between the center of mass and the center of stiffness or torsional radius, Equation 1 and 2, are quantities that have to be calculated additionally. In-depth discussion of the conditions for plan regularity according to EN1998-1, can be found in Penelis and Penelis (2014), Fardis at al. (2015).

$$e_x \leq 0.3 r_x ;\; e_y \leq 0.3 r_y \tag{1}$$

$$r_x \geq l_s ;\; r_y \geq l_s \tag{2}$$

For single story buildings these characteristics are uniquely defined and EN1998-1 allows to be calculated thru the moments of inertia of the cross section of vertical elements. In general, some additional parameters, like beams stiffness or shear deflections can affect the position of center of stiffness or torsional radius. In multi-story buildings, Eurocode 8 allows simplified definition for the classification of structural regularity in plan and for the approximate analysis of torsional effects only for buildings in which all lateral load resisting systems running from the foundation to the top and having similar deformation patterns under lateral loads. Moreover, Eurocode 8 accepts that in frames and in systems of slender walls with prevailing flexural deformations, the position of the centers of stiffness and the torsional radius of all stories may be calculated as those of the moments of inertia of the cross-section of the vertical elements.

3. DEGREE OF IRREGULARITY

Determination of center of stiffness and torsional radius, as necessary parameters for categorization of regularity in plan according to EN 1998-1, depends on the selected methodology for analysis as well as the assumptions introduced in the mathematical model.
In order to investigate the influence that the degree of regularity in plan has on structures, six different multi-story models were created. All analyzed structures have five stories and are rectangular in plan and consists three frames in x, and five frames in the global y direction. The distance between the frames in both directions is 5 m, while the story height is 3 m. The columns are rectangular with a dimensions 50/50 cm at the first two stories and 45/45 cm on the upper 3 stories.
At the first model (M0), all columns have square cross section. At other five models (M1 to M5), the middle column in the one exterior frame in the global y direction, was replaced with the structural wall with a thickness of 40 cm and a length of 120, 160, 200, 400 and 700 cm, Figure 1.

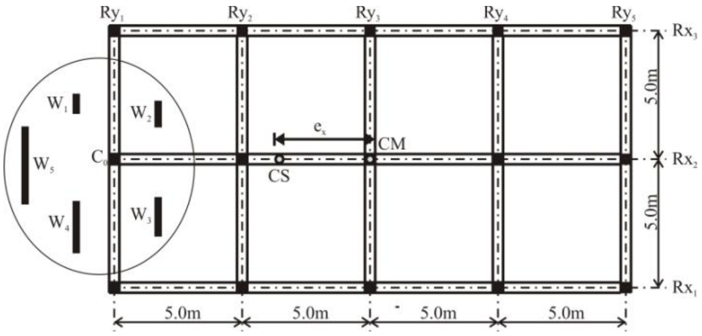


Figure 1. Plan view of analyzed structures

All beams are with rectangular cross section 40/45 cm. The mathematical model was modelled in SAP2000 and the interior beams are modelled as a T section with effective flange width of 180 cm, while exterior as Γ section with effective flange width of a 110 cm and thickness of 15 cm. The slabs were not modeled, but their weight was taken into account. In the nodes where columns and beams are joined, absolutely rigid zones are given with the length equal to half the side of the column in which the beam is embedded. Relative displacements between the nodes belonging to separate floors are prevented by a rigid diaphragm and the motion of the platforms is reduced to the movement of a rigid body into the plane.

For determination of the structural characteristics, as center of stiffness and torsional radius, the method proposed by Bisch et al (2012) was used.

From the obtained results, Figure 2, it can be noticed that all of the structures are categorized as irregular in plan, because all of the structures do not comply the provision that the distance between the center of stiffness and the center of mass should be lower than 30 % of the torsional radius, at every story level. It can be noticed that the provision that torsional radius should be larger than the radius of gyration of the floor masses is compiled for the structures M1, M2 and M3. It is noticeable that the degree of irregularity increases as the length of the wall increases, M1 has the lowest and M5 has the highest degree of irregularity in plan.

Criteria of regularity in plan								
	story	height	|e_ox,i|	<	0.3r_x,i	r_x,i	>	ls
M1	1	3	2,67	>	2,48	8,28	>	6,46
	2	6	1,98	<	2,50	8,34	>	6,46
	3	9	1,78	<	2,48	8,28	>	6,46
	4	12	1,61	<	2,48	8,28	>	6,46
	5	15	1,40	<	2,51	8,35	>	6,46
	story	height	|e_ox,i|	<	0.3r_x,i	r_x,i	>	ls
M2	1	3	4,26	>	2,38	7,92	>	6,46
	2	6	3,28	>	2,46	8,19	>	6,46
	3	9	2,83	>	2,52	8,41	>	6,46
	4	12	2,46	<	2,53	8,45	>	6,46
	5	15	2,04	<	2,50	8,32	>	6,46
	story	height	|e_ox,i|	<	0.3r_x,i	r_x,i	>	ls
M3	1	3	5,51	>	2,22	7,40	>	6,46
	2	6	4,49	>	2,36	7,85	>	6,46
	3	9	3,87	>	2,42	8,06	>	6,46
	4	12	3,33	>	2,49	8,30	>	6,46
	5	15	2,72	>	2,48	8,26	>	6,46
	story	height	|e_ox,i|	<	0.3r_x,i	r_x,i	>	ls
M4	1	3	8,27	>	1,53	5,08	<	6,46
	2	6	7,91	>	1,66	5,53	<	6,46
	3	9	7,42	>	1,82	6,05	<	6,46
	4	12	6,80	>	1,98	6,60	>	6,46
	5	15	6,10	>	2,09	6,96	>	6,46
	story	height	|e_ox,i|	<	0.3r_x,i	r_x,i	>	ls
M5	1	3	9,19	>	1,08	3,59	<	6,46
	2	6	9,23	>	1,05	3,51	<	6,46
	3	9	9,14	>	1,12	3,72	<	6,46
	4	12	8,96	>	1,23	4,09	<	6,46
	5	15	8,72	>	1,36	4,52	<	6,46

Figure 2. Criteria verification of plan irregularity

4. NONLINEAR DYNAMIC ANALYSIS

4.1 Description of the Analyzed Structures

In order to compare the seismic response of multi-story structures with different degree of irregularity in plan, detailed nonlinear time history analyses for three different input acceleration histories (Imperial Valley 1940, Victoria Mexico – Chihuahua 1980, Chi Chi Taiwan 06 – 1999) applied in direction perpendicular to the axes of irregularity, scaled to three different levels of seismic hazard (PGA 0,12g, 0,24g and 0,36g), were performed.

The structures were modelled in SeismoStruct 2016 and the geometric characteristics of the structural elements are same as described above.

On Figure 3 are presented the mechanical characteristics of the used materials. For the concrete model, nonlinear model proposed by Mander et al. was used, where the mean compressive and tensile strength is 25/2.5 MPa, the modulus of elasticity is 25000 MPa and the strain at peak stress is 0.002. The material model for the rebar, proposed by Menegotto and Pinto, was used. Whereas the modulus of elasticity is 200000 MPa and the yield strength is 500 MPa.

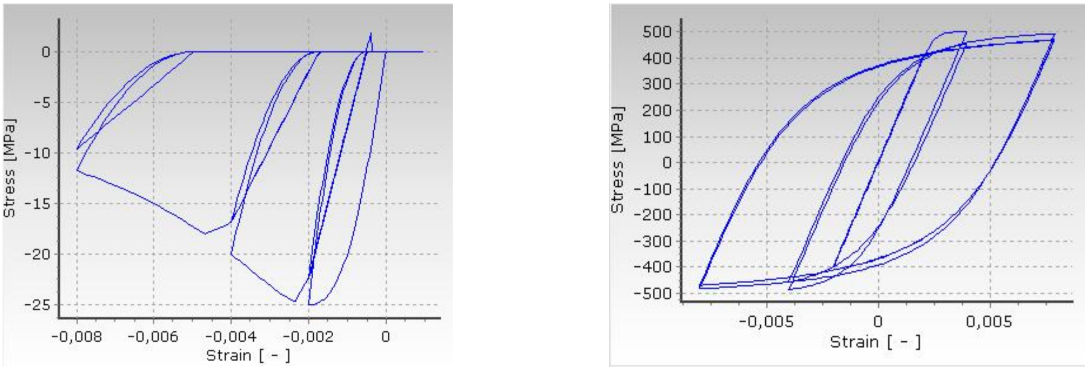


Figure 3. Mechanical characteristics for concrete and rebar

The columns and beams are dimensioned according to the recommendations of EN 1992 and EN 1998, and have the same reinforcement for all of the analyzed models. The only difference in the reinforcement is at RC walls which are reinforced with minimal ratio of reinforcement Figure 4. The slab was not modelled but according to EN 1992 the collaboration between the slab and the beams was taken into account. Relative displacements between the nodes belonging to separate floors are prevented by a rigid diaphragm and the motion of the platforms is reduced to the movement of a rigid body into the plane. The structural elements were modeled as inelastic force-based plastic hinge frame element.

The characteristics of the plastic hinges were determined thought discretization of the cross sections with fibers, whereupon the columns are discretized on 100 elements and the beams on 150. The length of the plastic hinges is 16,67% of the length of the element.

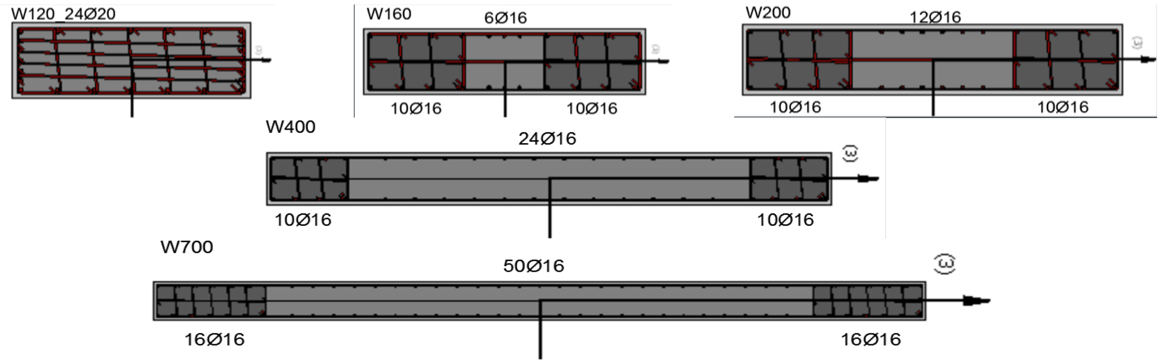
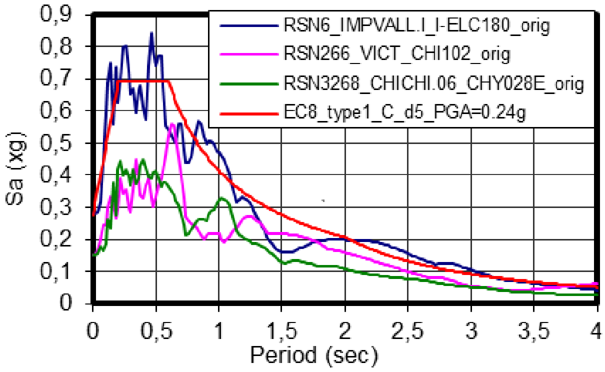


Figure 4. Reinforcement pattern in walls

4.2 Seismic Excitation

In accordance with the recommendations given by EN 1998-1 for conducting nonlinear (time history) dynamic analysis, as the most sophisticated tool for determination of the dynamic response of the structures, minimum three input motions of previously occurred or synthetically generated earthquakes have to be used. While choosing the input motions for the analysis, the compatibility of the elastic spectra with the site location should be taken into account. For the use of the analysis three input motions were used (Imperial Valley – El Centro 1940, Victoria Mexico – Chihuahua 1980 and Chi Chi Taiwan 06 – CHY028 1999) and they were scaled by amplitudes and frequencies. Target spectral ordinates were determined for spectrum Type 1, soil type C and peak ground acceleration of 0,24g. The original acceleration spectra and spectra obtained from scaled input motion, as well as the average spectra of the scaled input motions are presented at Figure 5 and 6. Three levels of seismic hazard were used in performing the analysis that corresponds to PGA of 0.12g, 0.24g and 0.36g, whereof analyzed structures were exposed to seismic action only in direction Y.



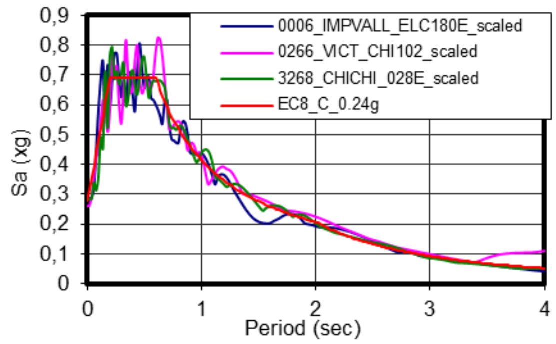


Figure 5. Elastic spectra for original and scaled input motions

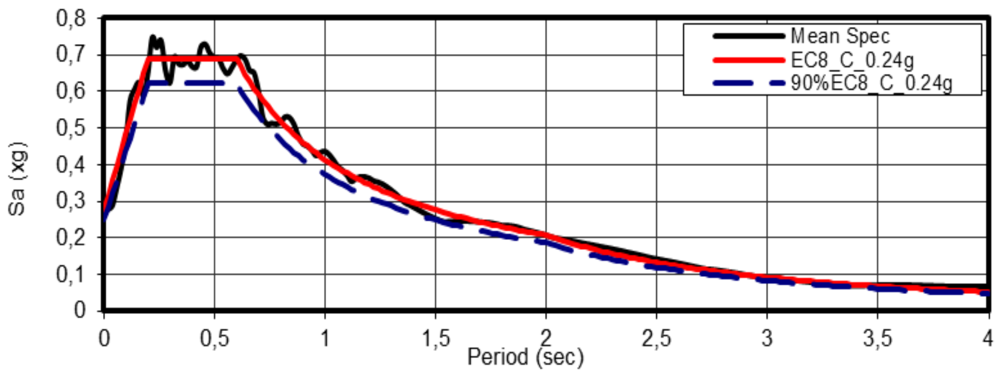


Figure 6. Average elastic spectra of scaled input motions

4.3 Comparison of results

Systematic elaboration and comparison of the results from the obtained analysis was made. Maximal achieved displacements occur at the most flexible frame (R_{y5}) of the structures i.e. the frame (R_{y5}) that is the most distant from the center of stiffness. The maximal displacements at the structure M0 are same for all frames, because the center of stiffness overlap the center of mass.

The dependence of the achieved maximum displacement, in both directions, in function of the hazard level is displayed on Figure 7. From the graphs it can be noted that the relation of the maximal displacements of the structures, depending on the level of hazard, is not linear. The difference that occurs in the values of the displacements between 0.12g and 0.24g and between 0.24g and 0.36g, in the direction where the absolute maximum displacements are reached, is more often greater in displacements for the higher levels of the excitement. Also it can be noticed that at the most of the analyses the maximal displacement does not occur for the structure with the highest degree of irregularity. This is due to the fact that the structure has entered into a nonlinear range, and thus the plastificatiton of the structural elements has occurred through pattern which cannot allow development of larger displacements from the reached, as well as the increased lateral stiffness and load capacity of the structure due to the presence of the RC wall at frame R_{y1}, which at structure M5 is 7 m. In case where the increment of the displacements in the region of 0.24g and 0.36g is smaller than the increment of the displacements of 0.12g and 0.24g, the structures are likely to have come out of the dominant frequency range of the observed input motions after the occurrence of nonlinearity in the structural elements. The maximal reached displacements for PGA 0,36g is in range of 22,81 - 27,03 cm, for PGA 0,24g is 15,89 – 17,30 cm and for PGA 0,12g is 6,86 – 9,27 cm. In relation to the maximal displacement of the regular structure M0, the absolute maximal displacements are 23,1 – 37,5 % larger for PGA 0,36g, for PGA 0,24g and 0,12g are 20,6 – 20,9 % and 24,8 – 37,7 % larger. Although in some of the analyses the maximal displacements are reached in structures with lower degree of irregularity in plan, this does not imply that the response of the structure with the highest degree of irregularity in plan (M5), is more favorable.

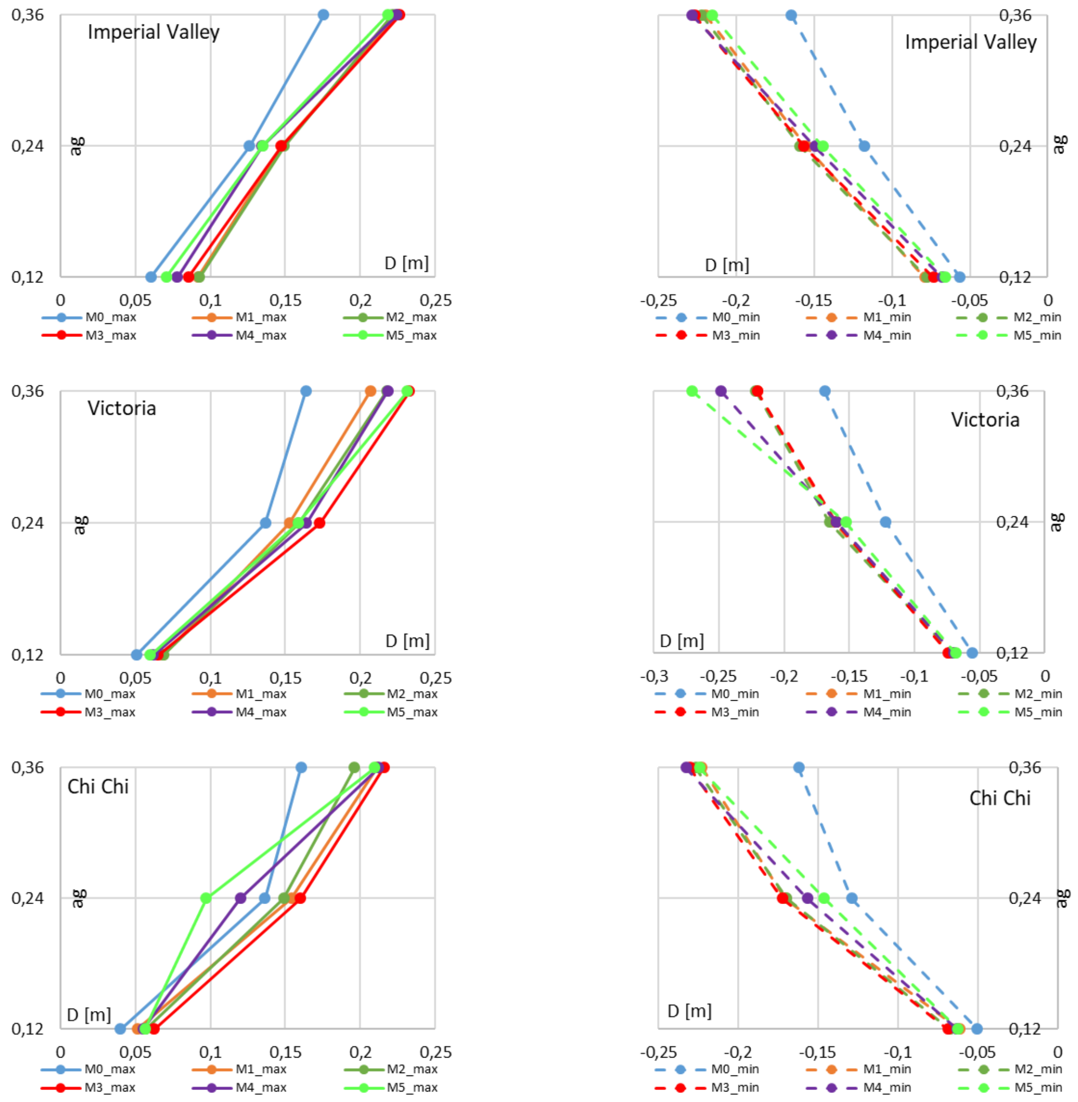


Figure 7. Total displacements

On the graphs in Figure 8 it is presented how the value of the maximum relative story drifts, from the analysed structures, is changing within the frames R_{y1} and R_{y5}, for given excitation. It can be noticed that at the frame $R_{y1,}$ where the RC wall is placed, the relative story drifts are decreasing as the degree of irregularity in plan for the structures increases. The lines of the graphs intersect for frame R_{y5}, this indicates that there is no certain pattern of increasing of the relative story drifts, as the irregularity increases. This is showing the unpredictable response of the structures after entering the nonlinear range. It is noticeable that only for the input motion Imperial Valley the largest relative story drifts occurs at structure M5. The maximal reached relative story drifts for PGA 0,36g are in range of 5,12 – 8,50 cm, for PGA 0,24g are 3,68 – 5,18 cm and for PGA 0,12g are 1,49 – 2,61 cm. The maximal reached relative story drifts are in range of 0,5 to 3 % of the story height, at all of the analyzed structures.

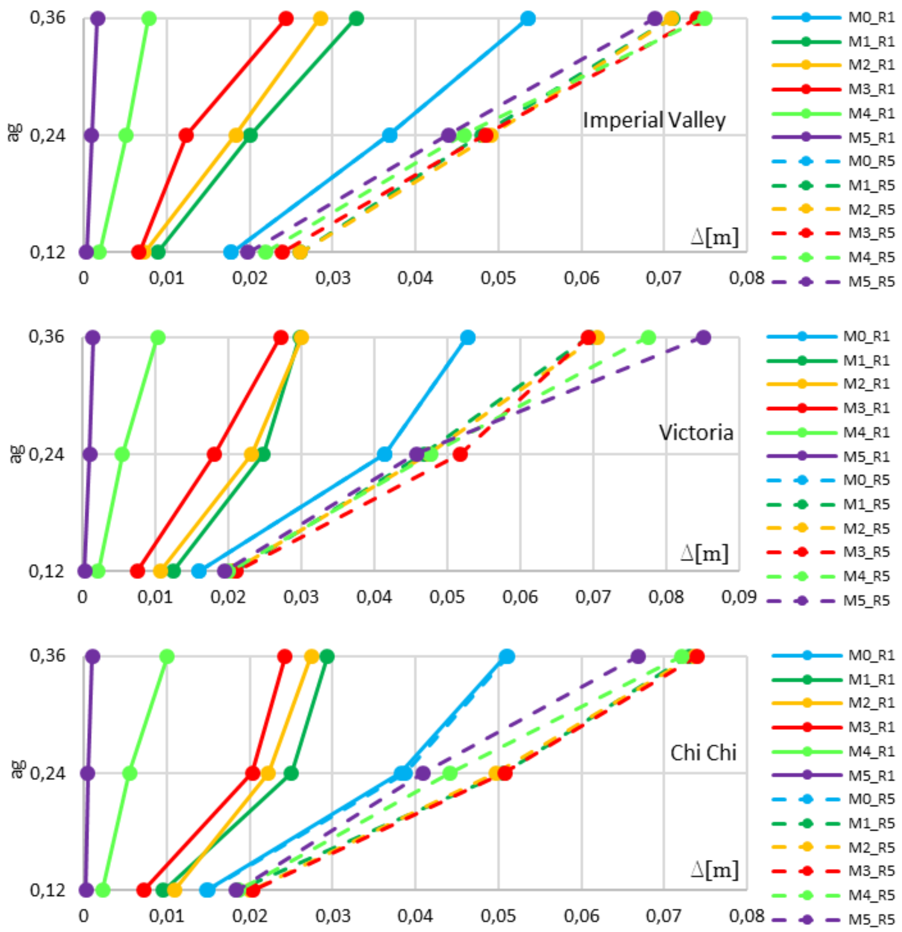


Figure 8. Maximal relative story drifts for frames R1 and R5 of the analyzed structures

Figure 9 is presenting the maximal rotation in both directions (+/-), which occur at the fifth story of the analyzed structures, in relation to the degree of irregularity in plan and the degree of hazard. Generally observing, as the level of excitation increases, the maximal rotations increases also, and in most cases the increase is almost linear, but in some of the analyses, it is noted that there is a progressive growth or fall in the value of the maximum rotations. In regular structures, the rotations are equal to zero, because these structures have only translational motion as they have no eccentricity between the center of stiffness and the center of mass.

The largest absolute maximal rotations occur in structures analyzed for the input motion of the Victoria Mexico earthquake and they range from 0,53˚ for structure M1 to 0,77˚ for M5, for PGA 0,36g. For the other two motions these rotations range from 0,51˚ to 0,73˚.

From the presented results, it can be noted that the maximal value of the maximal rotations in the structure with the highest degree of irregularity in plan occurs only in one of the analyzes that are carried out. Generally, it can be said that the values of the maximal rotation do not differ significantly and the range of the maximal values of the structures vary unpredictable around the average value of the maximal rotation.

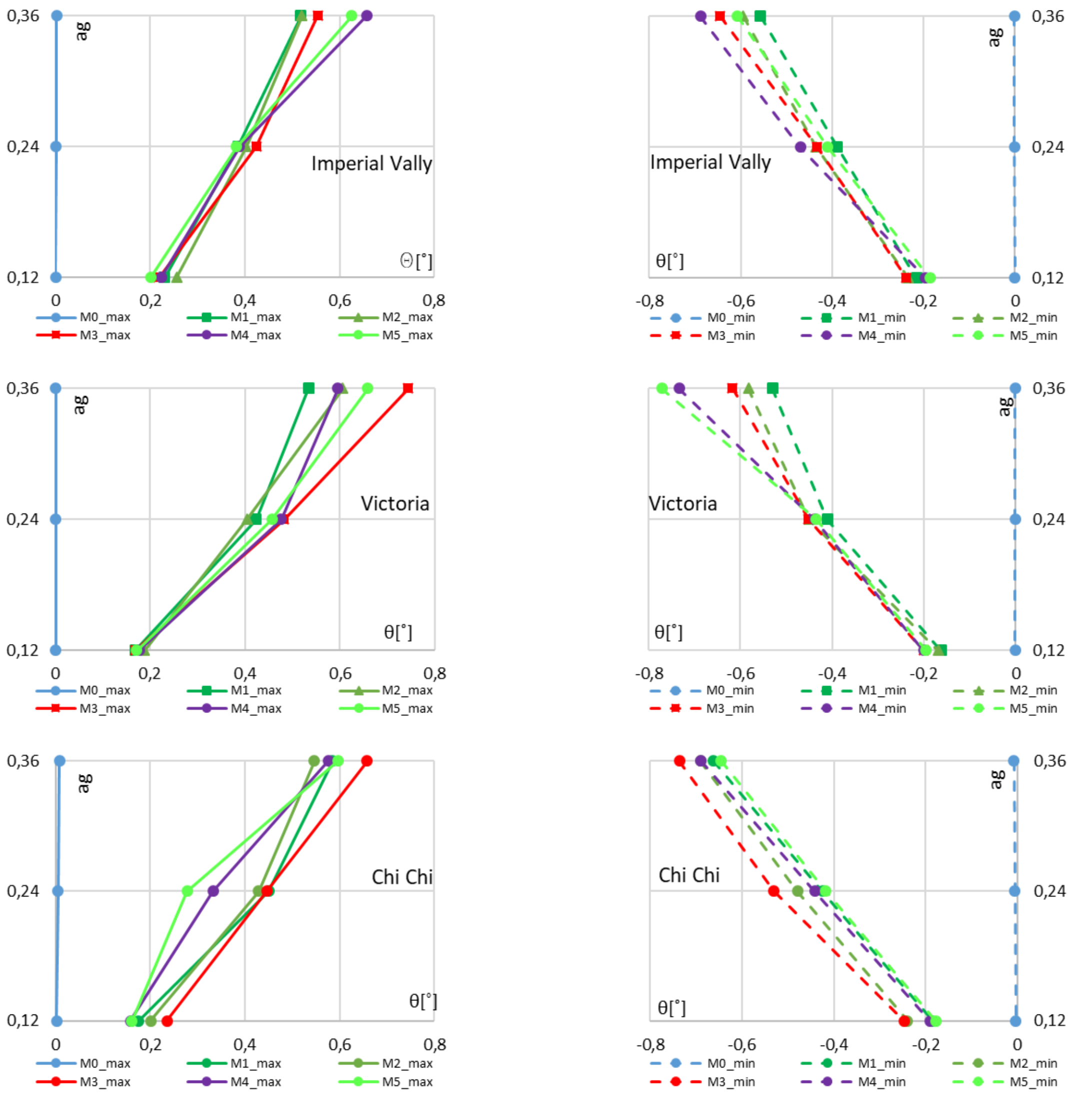


Figure 9. Maximal rotation of the Vth story

5. CONCLUSIONS

In the sequel are given some final remarks drawn from the conducted analyses and the elaboration of the results.

The response of the structural systems largely depends on the layout of the structural elements in plan, their symmetry, the distribution of the mass and the regularity in plan.

The criteria of regularity in plan of the structure has significant role in the design of the seismic resistant structures, by showing us whether the structure has the potential to enter in torsional forms of oscillations, which can be dangerous in relation to the desired response of the considered structure.

From the results of the nonlinear (time history) analysis it can be concluded that the maximal displacements always occur at the most distant frame (R_{y5}) from the center of stiffness. The increase of the maximal achieved displacements of the structure does not always follow the increase in the degree of irregularity in plan. On the other hand, it was noted that the increment in the maximal achieved displacements of the frame (R_{y1}) where the RC wall is placed, frame with concentrated stiffness, is inversely proportional to the degree of irregularity in plan.

The increment of maximum displacements depending on the level of excitation is not linear. In structures with a higher degree of irregularity, the difference in the increment of the displacements is increasing between the higher levels of excitation, which is probably due to the degradation of the

structural elements, and thus to the reduction of the global rigidity of the structure. The greater increment in displacements, at lower levels of excitation, for certain structures, is due to the degradation of the stiffness and the abandonment of the dominant frequency domain of the observed input motions after the emergence of nonlinearity in the structural elements.
The maximum relative story drifts for all structures are obtained on the third floor of the farthest frame from the center of stiffness. In the frame where the RC wall is laid, as with the maximal displacements, the relative story drifts are decreasing by increasing the degree of irregularity in plan.
There are no major differences in the values for the maximum rotations occurring on the fifth floor of structures for the structures with large differences in the degree of regularity in the plan.

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