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INFLUENCE OF THE USE OF COUPLING BEAMS ON THE SEISMIC RESPONSE OF PLAN IRREGULAR RC FRAMED BUILDINGS

Juan Carlos VIELMA-PÉREZ[1], María Manuela MULDER MONTES DE OCA[2]

ABSTRACT

Irregular structures can lead to undesirable behavior under strong ground motions. For this reason, the seismic codes prescribe a series of recommendations that seek to limit the irregularity. For the specific case of plant irregularity, recommendations aim to limit the eccentricity, so limiting torsional moments, which have been identified as the origin of the catastrophic failure of structures in recent earthquakes. This work evaluates the seismic response of low-rise RC framed building, applying nonlinear dynamic analysis using records of destructive earthquakes. The buildings analyzed have different plan configurations, presenting irregularities produced by re-entrants. In order to mitigate the effect of torsion, coupling beams have been added in the areas of the re-entrants, achieving a reduction of both the torsional moments and the relative rotations of the plants, then becoming in a suitably solution in order to overcome associated problems with this type of irregularity.

Keywords: Plan irregular buildings; Torsional moments; Plan rotations; Flexible diaphragm; Non-linear analysis

1. INTRODUCTION

In the current process of seismic design of buildings, it is common to observe that the regulations discourage irregular structuring, in space for those buildings that are to be located in areas of high seismic hazard. In these cases, in which the architectural design requires to use an irregular structuring, the main seismic codes apply penalties in the design (American Society of Civil Engineers, 2016) (CEN, 2002). These penalties are produced by increasing the seismic design forces, by calculating the inelastic spectrum by a fraction of the response reduction factor corresponding to the structural typology.

In Latin American countries, in general, and in Venezuela, in particular, it is common to find buildings located in areas of high seismic hazard, which have been designed with irregular structural configurations. In the case of residential buildings, one of the most repeated configurations is that of buildings with plants with re-entrants. This has its origin in the architectonic distribution of the apartments, which is done considering common areas of circulation, which are the nuclei of stairs and elevators. In this way, buildings with plants with C, H, T or L shapes are generated, see Figure 1.

The dynamic response of these buildings is conditioned by several factors. The first, and perhaps the most important, is the eccentricity that is generated by the discordance between the center of stiffness with the center of mass of a plant, which leads to a dynamic response in which the effect of twisting is important and it affects unevenly the vertical supports of the structure. The second factor is associated to the magnitude of the area of the openings with respect to the total area of the plant, which can lead to the slab of the plant not reaching the stiffness necessary to guarantee a rigid diaphragm behavior.

In the case of the Venezuelan seismic code (Fondonorma, 2001), the first condition is included when requiring that the seismic analysis of the structure be carried out considering three degrees of freedom by level. The second condition is included, modeling the structure with the slabs acting as flexible diaphragms. Additionally, and as already mentioned, the seismic forces are determined with an inelastic design spectrum in which a fraction (75%) of the recommended value is used for the predominant

[1]Professor, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, juan.vielma@pucv.cl
[2]Professor, Universidad Centroccidental Lisandro Alvarado, Barquisimeto, Venezuela, mariamanuelamulder@gmail.com

structural typology, depending on the % of the relative area of the reentrant.
This paper presents a review of these normative procedures, with the objective of evaluating them based on the results of the torsional behavior obtained through non-linear analysis. To this end, a group of reinforced concrete buildings has been designed, with different plant configurations, to which has been applied conventional static non-linear analysis (Pushover Analysis), obtaining in each step of loading the set of values of the torsional moments and the evolution of the rotations of the center of mass.

Figure 1. Example of plan-irregular residential buildings (H-shape)

2. CODE PRESCRIPTIONS

The current version of the Venezuelan seismic code (Fondonorma, 2001) considers the following characteristics of irregularity in plan for the buildings (in parentheses there is the identification of the irregularity according to the code):

2.1 High eccentricity (b.1)

It happens when at some level the distance between the center of mass and the center of stiffness exceeds by 20% the radius of inertial rotation.

2.2 High torsional risk (b.2)

If at any level one of the following situations occurs:

- The torsional radius of gyration is less than 50% of the stiffness radius of gyration (b.2.i).
- The distance between the center of mass and the center of stiffness exceeds 30% of the torsional radius of gyration in any of the directions of analysis (b.2.ii).

2.3 Non-orthogonal structural system (b.3)

This situation occurs when the planes of the structural system are not parallel to the main axis in a specific direction.

2.4 Flexible diaphragm (b.4)

the existence of a flexible diaphragm should be considered when one of the following situations occurs:

- When the stiffness in the plane of the slab is less than the equivalent stiffness of a slab 4 cm thick (b.4.i).
- When a significant number of levels of the building have reentrant, whose smaller dimension is greater than or equal to 40% of the smallest dimension of the rectangle that inscribes the projection of the floor of the building, or when the area of the reentrant is greater than or equal to the 30% of the total area of the rectangle that inscribes the building floor (b.4.ii).
- When the sum of the areas of the reentrants exceeds 20% of the sum of the net areas of the plants (b.4.iii).
- When there are prominent openings to the earthquake resistant planes of the structure, or when there is no connection between them (b.4.iv).
- When in some plant the relation between length / width of the rectangle that inscribes the plant is greater than 5 (b.4.v).

3. ASSESSMENT MTETHODOLOGY

The assessment methodology consists into study a set of buildings designed according the current version of the seismic Venezuelan Code. This set must reflect the predominant irregular typology of the structures built in Venezuela, with special emphasis on the presence of reentrants. The set of designed cases is then modelled and analyzed in order to determine the effect of the different irregular conditions to the non-linear response. Finally, results obtained for each case are compared in order to estimate the variation of two parameters: the ratio of torsional moments, and the values of the rotations of the mass centers.

3.1 Cases studied

The set of cases studied consist in seven low-rise reinforced concrete buildings, designed for high seismic hazard zone (design acceleration of 0,3g) and located in a very stiff soil (soil type S2), with a response reduction factor R=6, see the elastic and inelastic design spectra in Figure 2.

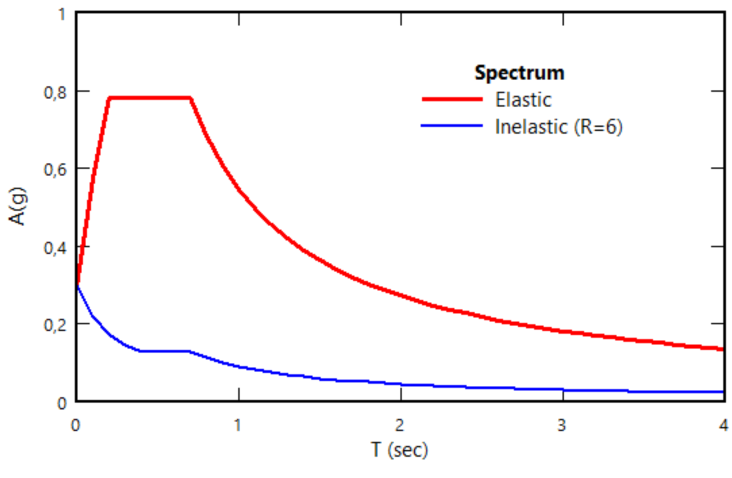

Figure 2. Elastic and inelastic design spectra

Buildings have different plan configurations with three 3,00m high stories. The structures of the buildings consist in special moment-resisting frames, with three 6,00m length spans in each direction. Buildings are endowed with 25cm width RC solid slabs. Figure 3 summarizes the plan configurations of the seven cases considered herein (Vielma & Mulder, 2017) and (Vielma & Mulder, 2017). Note that cases 2 to 7 are plan irregular because the presence re-entrants in the slabs, but cases 2, 4 and 6 are provided with continuous beams in the open side, coupling the frames and avoiding the loss of stiffness in such frames, also avoiding the stress concentration in frames and adjacent zones which can occur during the application of lateral loads, see Figure 3. The specifications set for the materials are: concrete $f_c' = 25MPa$ and steel reinforcement $F_y = 420MPa$.

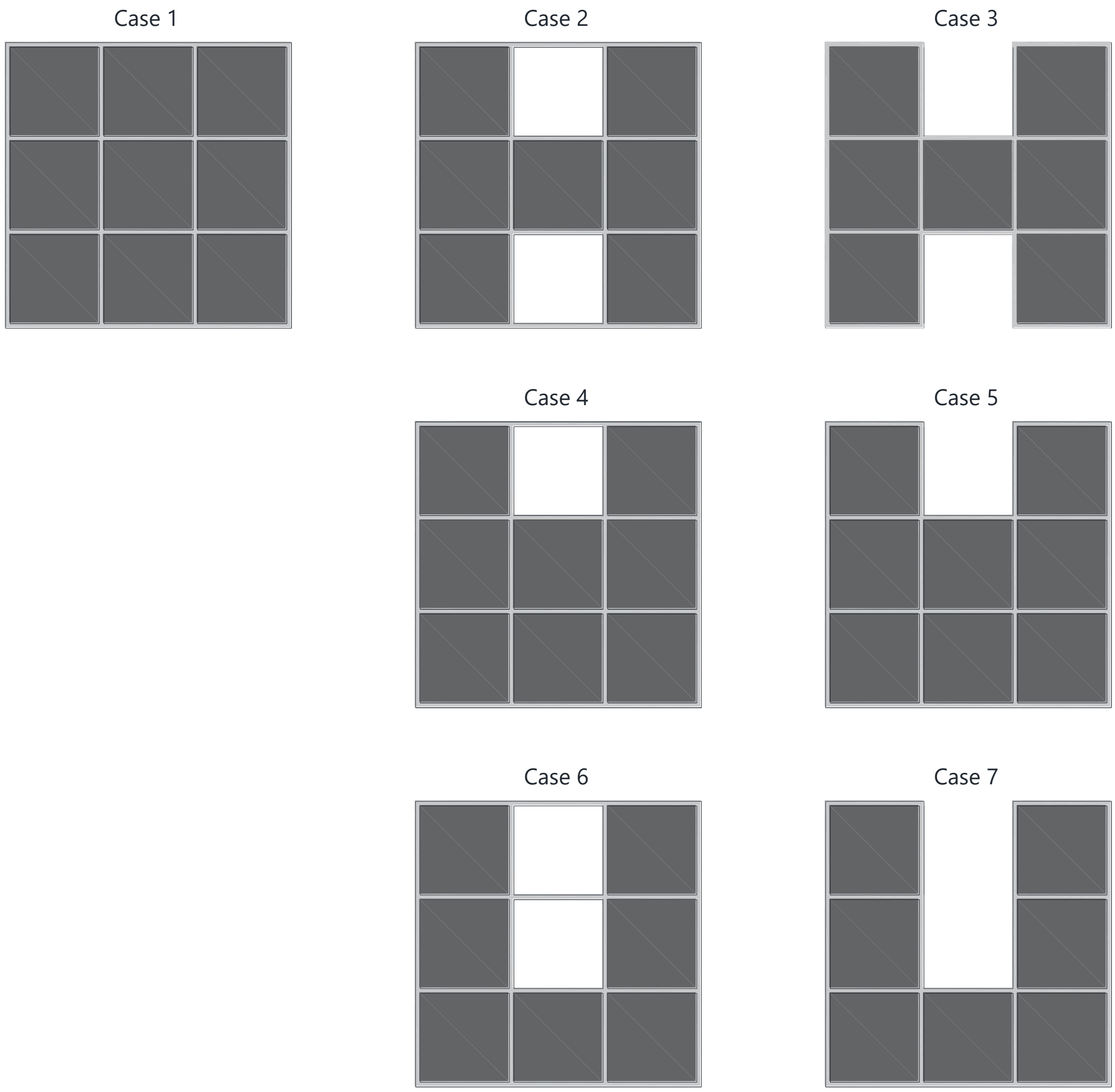

Figure 3. Plan configurations of cases studied

3.2 Plan irregularity verifications

In the next following sub-sections the results of the verification of the code-prescribed in-plan irregularity are shown.

3.2.1 High eccentricity (b.1)

High eccentricity must be checked comparing the value of the eccentricity obtained for both directions of the structure versus the radius of gyration in these directions. Results are summarized in Table 1.

Table 1. Comparison of eccentricities versus radius of gyration

Case	ex/rx(%)	ey/ry(%)	Verification
1	0,00	0,00	✓
2	0,00	0,00	✓
3	3,66	0,00	✓
4	0,00	0,00	✓
5	16,26	0,00	✓
6	16,15	0,00	✓
7	3,59	0,00	✓

3.2.2 High torsional risk (b.2)

Results of the analysis of the high torsional risk verification are shown in Tables 2 and 3. There is a high torsional risk if any of the following conditions is achieved:

- The torsional radius of gyration is less than 50% of the stiffness radius of gyration (b.2.i).

Table 2. Torsional radius of gyration comparison in both directions

Case	rtx/rx (%)	rty/ry(%)	Verification
1	182,57	182,57	✓
2	195,40	163,04	✓
3	204,30	173,21	✓
4	195,40	163,04	✓
5	179,75	163,04	✓
6	204,30	173,21	✓
7	179,35	163,04	✓

- The distance between the center of mass and the center of stiffness exceeds 30% of the torsional radius of gyration in any of the directions of analysis (b.2.ii).

Table 3. Comparison of eccentricities versus torsional radius of gyration

Case	ex/rtx(%)	ey/rty(%)	Verification
1	0,00	0,00	✓
2	0,00	0,00	✓
3	1,79	0,00	✓
4	0,00	0,00	✓
5	9,07	0,00	✓
6	7,91	0,00	✓
7	2,00	0,00	✓

3.2.3 Non-orthogonal structural system (b.3)

This situation occurs when the planes of the resistant system are not parallel to the main axis in any specific direction.

Table 4. Condition of orthogonal resistant lines

Case	Verification
1	✓
2	✓
3	✓
4	✓
5	✓
6	✓
7	✓

3.2.4 Flexible diaphragm (b.4)

Results of verifications are summarized in Table 5.

Table 5. Verification of conditions to use rigid diaphragm

Case	b.4.i	b.4.ii	b.4.iii	b.4.iv	b.4.v
1	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓
4	✓	✓	✓	✓	✓
5	✓	✓	✓	✓	✓
6	✓	×	✓	✓	✓
7	✓	×	✓	✓	✓

Finally, Table 6 summarized the actions required by code in order to perform the modelling and analysis of the cases studied, according to the results of the verifications showed in previous sub-sections. Note that only two actions are included according the analysis of the seismic code: penalty to the response reduction factor (R) for the structures which do not meet the criteria of the of points b.1 and b.2 of the code, and modelling the structures with flexible diaphragm, for those structures that do not comply with any of the normative provisions of point b.3.

The analysis, design and detailing of the buildings was performed according to the current Venezuelan seismic code for residential use only. However, interstory drift check was performed using an alternative energy-based procedure (Vielma, Barbat and Oller, 2010) and (Vielma, Barbat and Oller, 2010), thereby producing stiffer structures than the obtained according to the standard code procedure. The structures were analyzed using SeismoStruct software (Seismosoft , 2016). Each structural member was split into four elements, in order to capture the chord rotations in the special zones in which the concentration of the seismic damage is expected. Cross-sections obtained from the design process, were modeled using fibre elements, with the accurate location of every reinforcing bar, and taking into account the effect on the enhancement of the concrete confinement, provided by transversal and longitudinal reinforcement bars.

Table 6. Captions of tables; first letter capitalized, period at end, and centrally aligned.

Case	R	Model
1	6,00	Rigid diaphragm
2	6,00	Rigid diaphragm
3	6,00	Rigid diaphragm
4	6,00	Rigid diaphragm
5	6,00	Rigid diaphragm
6	6,00	Flexible diaphragm
7	6,00	Flexible diaphragm

Once the structures were modeled, standard pseudo-static non-linear analysis (Pushover Analysis) was performed for each case, using a linear distribution shape for lateral forces, with a target roof displacement estimated as 4% of the total building height. The analysis was performed for both directions of the buildings, in order to account the influence of the plan irregularity in the capacity curve determination and in the damage distribution for each structural member. According to the criterion expressed in (Priestley, Calvi and Kowalski, 2007) no relocation of center of mass produced by accidental eccentricity was performed.

4. RESULTS AND DISCUSSION

In this section, the results of the analyses are presented. Two are the main characteristics of the response picked in order to assess the quality of the torsional behavior of the cases studied. The first one is the ratio of torsional moments, defined as the coefficient resulting from dividing the torsional moment reached in the support of the column at the position ij of the $k-th$ case in the $l-th$ direction, by the torsional moment reached in the support of the column in position ij of case 1, in the $l-th$ direction. These torsional moments are extracted from the non-linear analysis (Pushover Analysis) for a displacement at roof level determined for each case according to the procedure N2 (Fajfar and Gašperšič, 1996) and (Magliulo, Maddaloni and Cosenza, 2012). In the following equation the ratio of torsional moments is shown:

$$r_{klij} = \frac{tm_{klij}}{tm_{1lij}} \qquad \text{with} \qquad \begin{array}{c} k = 2\ to\ 7 \\ l = 1,2 \\ i = 1\ to\ 4 \\ j = 1\ to\ 4 \end{array} \tag{1}$$

The results obtained are shown in Figures 4 and 5, which group the ratios according to the directions of analysis. The results in the x direction (irregular) show that the torques are amplified moderately in the supports of the columns of cases 2, 4 and 6 (cases with coupling beams), while they are significantly amplified in cases 3, 5 and 7 (without coupling beams), In addition, it can be noted that the greatest amplifications occur in cases 5 and 7 in which irregular geometry of the plants is added to the irregularity in the distribution of stiffness, which increases the eccentricity. This results are consistent with the obtained in the study of the response of RC buildings with other type of plan-irregularities (Herrera et al., 2013).

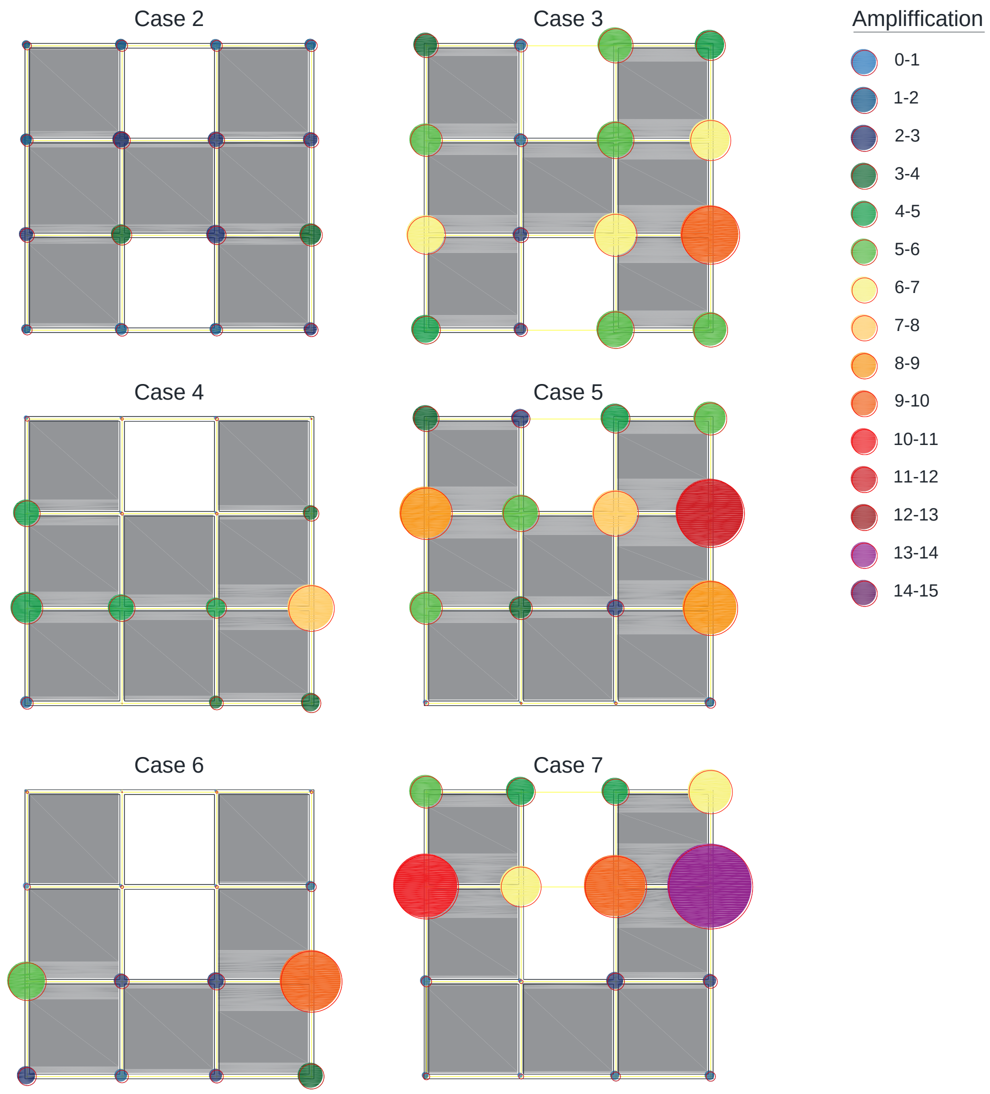

Figure 4. Ratios of torsional moments of cases studied analyzed in *x* (irregular) direction

Results of the ratio of torsional moments obtained from the analysis in y direction (regular) show a truly uniform response in each case, regardless of the presence of coupling beams. Large magnifications of torsional moments are not appreciated, so it can be concluded that the coupling beams in the regular direction of the building do not provide improvements to the response of this type of buildings with reentrants.

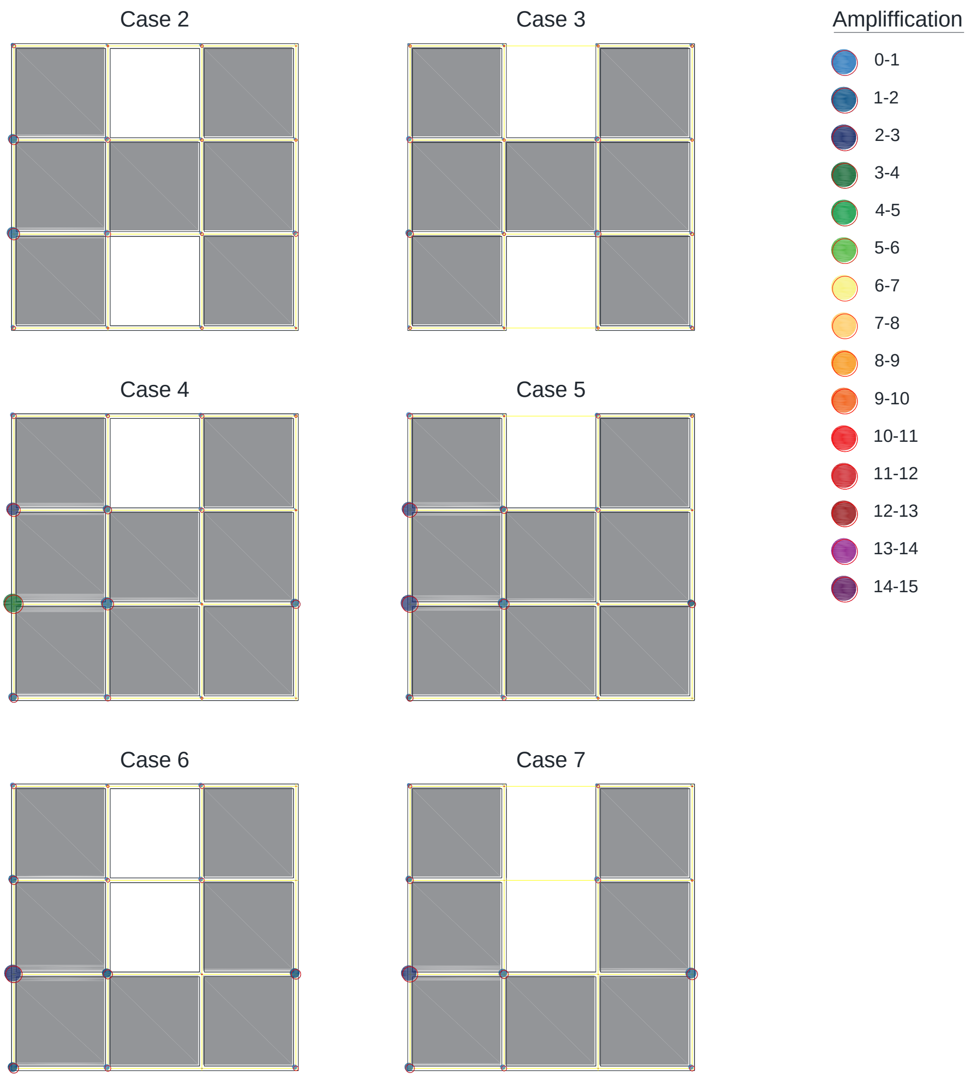

Figure 5. Ratios of torsional moments of cases studied analyzed in *y* (regular) direction

The second interesting characteristic is the rotation angle reached at the center of mass of the different cases studied. These rotations could be computed for every center of mass in each load step, according to the standard Pushover Analysis procedure, then leading to plot these values vs the roof level displacement.

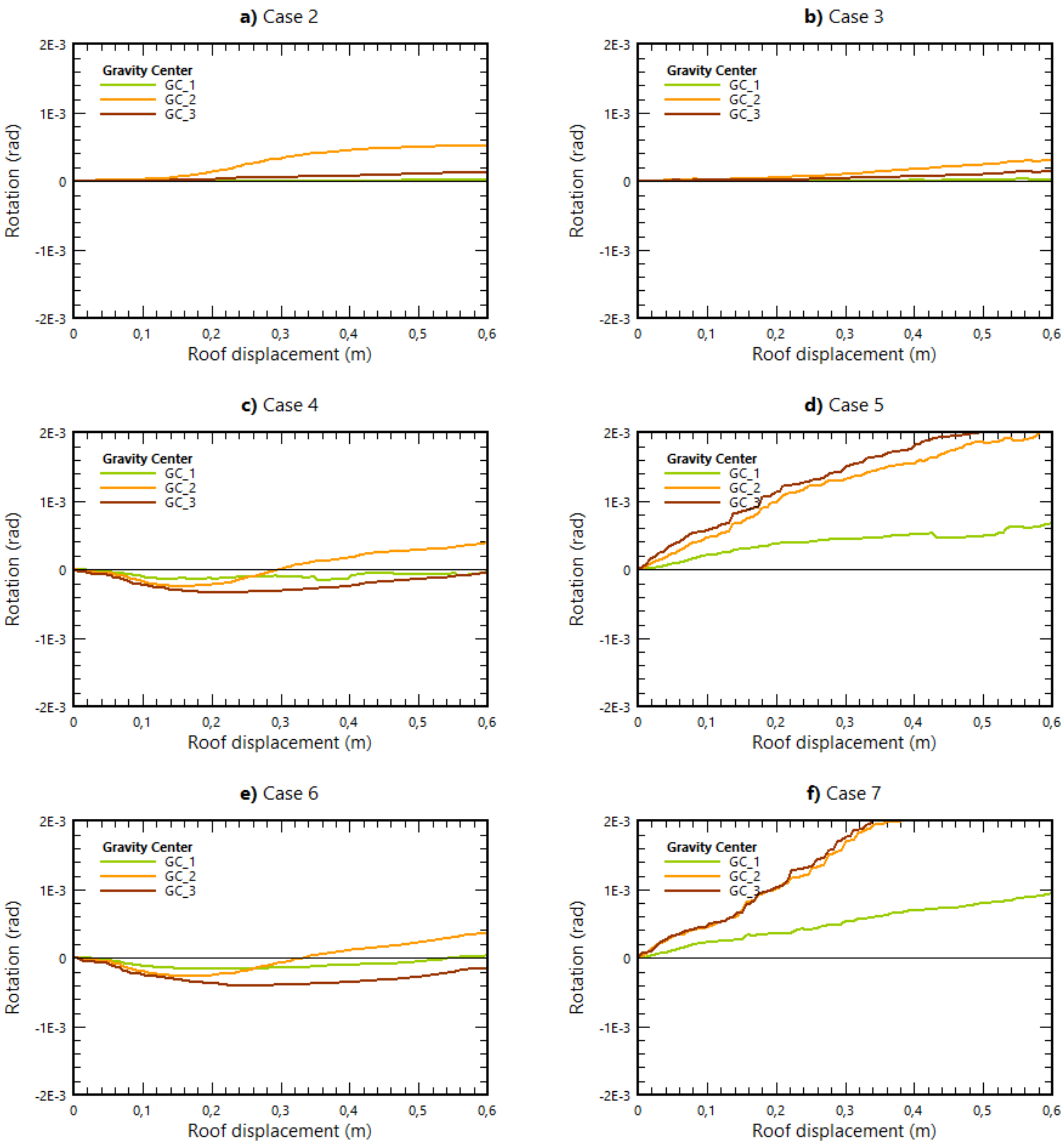

Figure 6. Rotations at the center of mass of cases analyzed in x direction

The results of the analysis in the *x* direction (irregular direction) show that the rotations of the centers of gravity of the cases with coupling beams (cases 2, 4 and 6), remain fairly uniform and do not exceed the value of 5E-4 rad. On the contrary, the cases that do not have coupling beams (cases 3, 5 and 7) reach rotations in the upper levels that approach the value of 5E-3 rad (10 times greater than the rotations of the cases with coupling beams), see Figure 6.

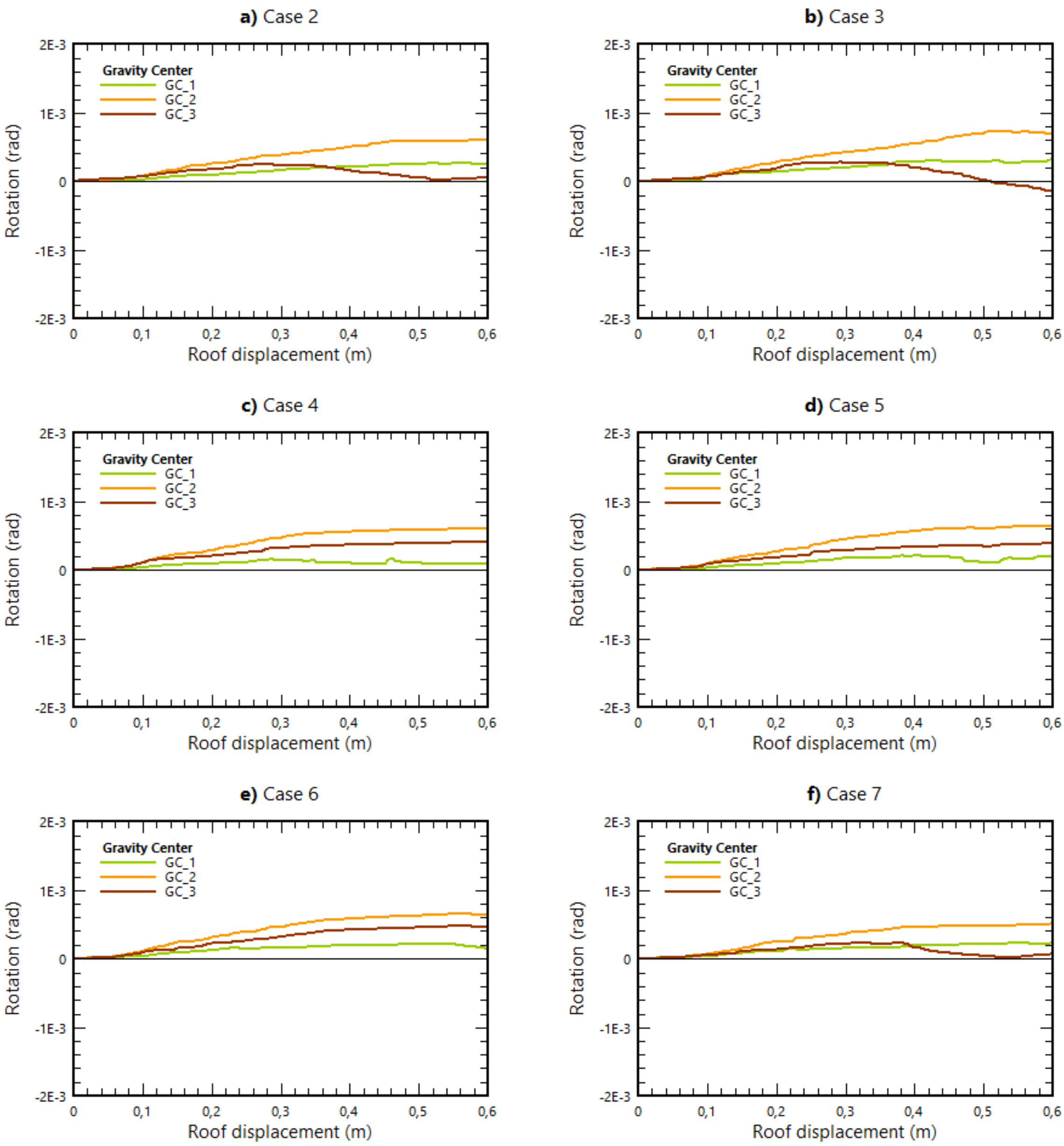

Figure 7. Rotations at the center of mass of cases analyzed in y direction

As for the results obtained in the direction and (regular) rotations of the centers of mass of all cases are fairly uniform, confirming the low influence of the coupling beams on the response in the regular direction. Logically, this result must be carefully interpreted, since it is expected that the seismic action affects the structure in a skewed manner with respect to the resistant planes, see Figure 7.

5. CONCLUSIONS

In this work we have reviewed the particularities of the current version of the Venezuelan seismic standard regarding the analysis of buildings made of reinforced concrete with irregular plants.
The results obtained from the non-linear analysis of the set of cases, in which efforts have been made to mitigate the effect of the irregularity produced by the reentrants by using coupling beams of the gantries, show that the irregularity generates an appreciable increase in demand of torsional moments in the supports. The increase in the values of the rotations of the centers of gravity of the floors is also verified. It has been found that the addition of the coupling beams of the frames significantly improves the

response with respect to the mentioned parameters.
For all the above, and despite having complied with all the normative provisions applicable to the case studies, it can be clearly noted that these are insufficient to guarantee an adequate behavior in the face of seismic actions. It would be advisable to consider more stringent measures in terms of the grade of the irregularity in plant, combined with a greater penalty in the phase of seismic analysis of those that exist in the current version of the standard.
It is recommended to continue studying the effect of these coupling beams in tall buildings, incorporating directionality and performing non-linear time history analysis.

6. ACKNOWLEDGMENTS

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