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Floor-plan shape influence on the response to earthquakes

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ABSTRACT: Observations of earthquake-resistant design researchers, have shown that buildings with irregular floor plans are more vulnerable to torsional effects, than buildings with regular floor plans. Torsional effects might be generated by several design variables, but it has been observed that geometric irregularity in floor plans is one of the most significant factors. The results of applying a dynamic analysis to study torsional effects in buildings with H-shape and L-shape floor plans in order to corroborate this hypothesis, are presented. A computer program, SET (Structural Engineering Tool), has been used in order to evaluate the influence of variations on dimensions of reentrant areas in building performance.

1 INTRODUCTION

Observation of buildings that have been significantly damaged by earthquakes has shown that architectural decisions related to aesthetics, function, cost, circulation, spatial relationships and other concerns affect the shape, dimension, and location of structural and non-structural elements, determine the existence and/or location of appropriate force-resisting walls and cores, and establish other characteristics of a building that are significant in relation to its earthquake resistance.

Earthquake resistance is only one of many important issues that the architect must consider in the design of the total building, and this profesional has often relied on the structural engineer to satisfy the structural engineering requirements included in building codes, while dedicating more time to the development of functional and aesthetic aspects.

Buildings with irregular floor-plan shapes have been observed to be susceptible to significantly larger deformations and damage when subjected to earthquake motion than buildings with regular shapes. It is important to remember that the torsional effects produced on a building by an earthquake, will depend not only on floor-plan shape, but on the interaction between this factor and other important design aspects. One of these is the structural layout and type of structural system used, which is primarily concern of the structural engineer. Although building damage can not entirely be attributed to floor-plan irregularities, this aspect has been acknowledged as one of the main reasons for torsional effects on buildings. Irregular distribution of the lateral force resisting elements in a building produces an unbalanced condition in the building's mass and stiffness which in turn, produces torsional effects in the building when it is subjected to earthquake motions. When the center of mass in a story does not coincide with the center of rigidity of the vertical resisting components in the event of an earthquake, plan rotation, or torsion occurs. These torsional effects are difficult to assess properly and can be very destructive when overlooked.

In most of the worldwide official lateral force requirements, irregular floor plans have been considered as no recommendable, though, this type of floor plans are widely used, and will continue being used, for housing, schools and hospitals, since they provide a greater percentage of perimeter rooms with access to natural lighting and ventilation.

Accurate evaluation of the effects that irregularities in floor-plan configuration can produce in the overall response of a building to an earthquake is very important in the assessment of potential damage. This has to be considered by both, the architect and the structural engineer, in the early phases of the design process, when relevant decisions on floor-plan geometry are made. At present, prescriptive guidelines for architects, either on how to make this difficult assessment or how to incorporate the indexes given in building codes and other lateral force requirements into the floor-plan design, are not readily available.

This research is based on the work initiated by Guevara (1989) in her Ph.D. dissertation. Its purpose is to produce some guidelines for the architectural and structural designers on how to recognize and evaluate potential torsional effects when formulating the floor-plan shapes of medium-height housing in seismically active areas. This paper presents part of this research.

2 FLOOR-PLAN VARIABLES

This research is restricted to buildings with "irregular rectangulate" floor-plan shapes, in reinforced concrete frame structures. The process with some modifications will be similar for other building classes. The term "rectangulate", identifies shapes characterized by polygons with re-entrant corners whose sides meet orthogonally.

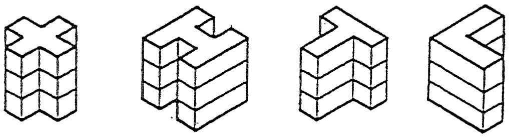


Fig. 1 Buildings with irregular rectangulate floor-plan.

The main variables that define the characteristics of floor plans are: "Symmetry," "Proportion," and "Reentrant Corners." However, even buildings when floor-plan shapes belong to the same family (for example, all those in the "H-shape" family), they do not possess the same degree of vulnerability to earthquakes. The vulnerability will depend on: (i) proportions of the rectangular components of the floor-plan shape, (ii) the location within the figure of reentrant corners, (iii) the number of axes of symmetry, and (iv) the displacement of the center of rigidity in relation to the center of mass (torsional eccentricity).

Although there are other important factors that influence the response of buildings to earthquake forces, such as the mass of the building, the materials used, the structural system, and variations in the elevation geometry, the floor-plan shape affects the distribution of the torsional effects in a significant way.

3 ASSUMPTIONS

Hypothetical buildings with L-shape and H-shape floor-plans were studied, for the calculation of eccentricity, taking into account the relationship of the variables which determine the location of the center of mass of those building components that contribute to the reactive mass of the building, and the center of rigidity of the vertical lateral force-resisting elements.

The study of these models was undertaken by analyzing, for each floor-plan shape (H and L), first, a regular rectangular floor plan with determined proportions (initial models); and, second, the initial regular floor-plan shapes was transformed into irregular H- and L-shape floor plans, respectively, by taking chunks of different dimensions from the initial model.

The displacement stiffness method, which takes into account the rotation and horizontal displacements of floors and modal superposition technique using site dependent spectral shapes, was used to calibrate the assumptions of the simplified model.

3.1 Structural idealization

In this investigation, a procedure and a computer program were applied for the structural analysis of the selected models. The computer program applied, "Set-Building", is based on the analysis of frame and shear wall buildings subjected to both static and earthquake loadings. However, in this study shear walls are not included.

The building models are idealized by a system of independent frame elements interconnected by floor diaphragms which are rigid in their own plane. Within each column, bending, axial and shearing deformations are included. Beams and girders may be nonprismatic and bending and shearing deformations are included. Only rectangulate (rectangular, H-shape and L-shape floor plans) buildings with frames in the x and y directions on plane were considered (although the program can be run, as well for nonsymmetric, nonrectangular arbitrarily located frames and shear walls.)

The static loads were combined with a lateral earthquake input specified as an acceleration spectrum response for each building model, three dimensional mode shapes and frequencies were evaluated.

As widely accepted for the majority of buildings, the assumption that the floors are rigid in their own plane is a "realistic approximation" was incorporate in the idealization; bending deformations in the horizontal beam an floor slabs are included. It is important to mention, however, that for a limited number of buildings where the assumptions of rigid in their own plane diaphragms are not acceptable, a general program which includes flexible diaphragms should be the most appropriate type of program to use. An exact three-dimensional structural analysis is required for only a limited number of buildings.

The horizontal lateral loads are assumed to act at floor levels. Therefore, the lateral loads are transferred to the columns through these rigid floor diaphragms. These results in three displacement degrees of freedom at each floor level - translation in the x and y directions and a rotation about the vertical axis.

For the different analyzed models additional assumptions were made: the dimensions of the structural components are constant in all the floor levels and for all the analyzed models: rectangular girders, 30 cm x 60 cm, and columns ϕ = 75 cm; in all the cases, the story height in all the floors, is constant; the height of each of the analyzed models is 15 stories; mass is constant and uniformly distributed in the diaphragm, therefore, the following equation is used for the calculation of the diaphragm mass rotational inertia with respect to its center of mass (Inmicro, Inc., 1991):

$$Jcm = M * (IX'X' + IY'Y')/A$$

where Jcm is the mass rotational inertia; M the total mass referred to the diaphragm; IX'X', IY'Y', are the diaphragm inertia moments, around X' and Y' respectively and, in relation with the diaphragm center of mass; A is the diaphragm area.

3.2 Characteristics of ground response analyses

For engineering purposes it is often convenient to simplify the ground acceleration spectral shapes taking into account the influence of the local soil conditions. For any given soil the spectral shape representative of any group of earthquake ground motion is best characterized by first determining the normalized acceleration response spectrum for each motion in the group, and then a final normalized shape can be obtained, for example by averaging the resulting normalized shapes. The following figure describes the resulting normalized spectral acceleration recommended by Alonso (1992) for use in future building codes for deep cohesionless or stiff clay site deposits, similar to those commonly found in the Caracas Valley (average depth: 100 mts. depth)

In this study the mode superposition technique was used in conjunction with the normalized acceleration spectrum shown in Fig. 2.

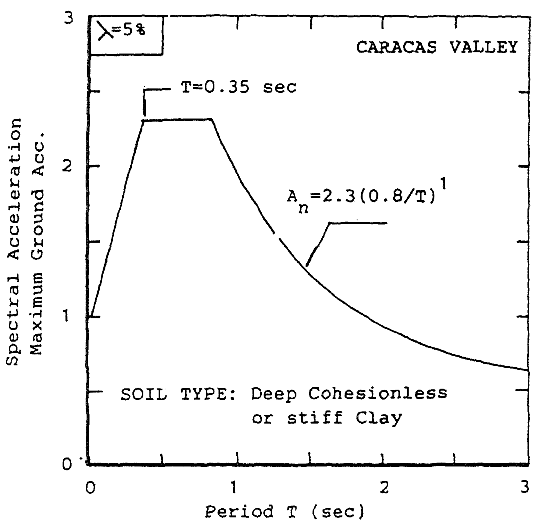


Fig. 2 Normalized Spectral Acceleration used in this Study (Alonso 1992).

3.3 Studied floor-plan models

The following figures illustrate the two case studies: (a) the initial model, a regular floor-plan shape (Fig. 3) , and variations in the dimensions of reentrant areas to obtain three different H-shape floor plans (H1, H2, H3); and (b) the initial model, a regular floor-plan shape, and a derived L-shape floor plan L1 (Fig. 4).

These models are composed of structural components which can be separated into a series of rectangular othogonal frames organized into an rectangulate irregular floor-plan shape. Isolated shear walls were not included. Each frame is treated as an independent substructure. The complete structure stiffness matrix is then formed under the assumption that all frames are connected at each floor level by a diaphragm which is rigid in its own plane.

Each joint has six degrees of freedom (displacement in, and rotation about each coordinate axis). The overall assumptions inherent in this approach can be found in different authors. For example Wilson E.L., J.R. Hollings J.P. & H.H. Dovey (1975)

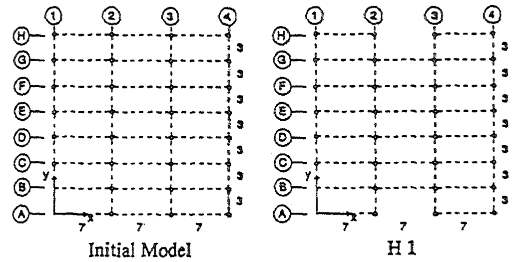


Fig. 3a H-shape models: Initial Model and H1

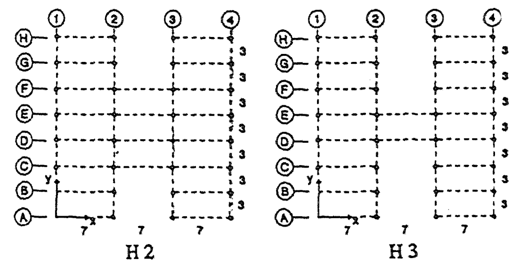


Fig. 3b H-shape models: H2 and H3

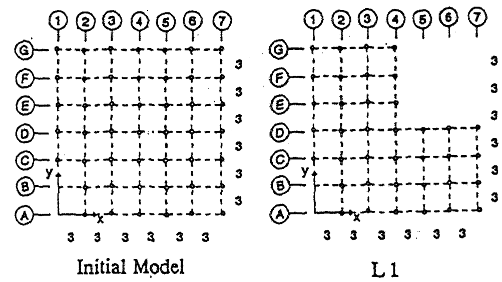


Fig. 4 Studied L-shape floor-plan models

3.4 Characteristics of the "Set-Building" program.

The Dynamic Spatial Analysis included in the "Set-Building" program developed by Inmicro, Inc. (1991) is based on the following assumptions: (a) for each building, the structure is constituted by horizontal diaphragms and vertical components; (b) diaphragms, are infinitely rigid in their own plane and transversely flexible; (c) a right cartesian coordinate system is used as a reference frame for the structure, where OX'Y' is a horizontal plane, and the vertical axis (OZ') positive orientation is upwards; (d) Each level's mass is associate to one or several rigid diaphragms and, as a consequence three degrees of freedom per diaphragm are considered, horizontal translation components in the direction of OX', OY' axes and, one rotation around vertical axis OZ' (Inmicro, Inc., 1991).

4 RESULTS

The main reason for analyzing H-shape and L-shape

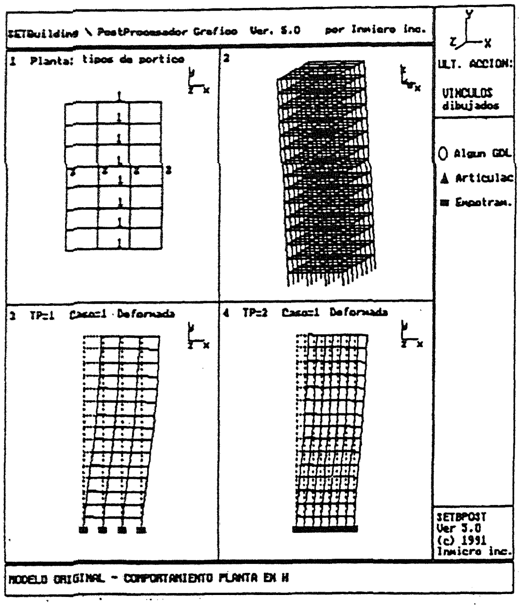


Fig.5 SETBuilding analysis of the H-shape floor-plan initial model

Table 1. Periods of vibration of the 10 first modes of vibration. Initial model of the H-shape floor plan.

Mode	Period	Gamma X	Gamma Y	Error
1	1.4118	0.89259	0.00000	0.167D-11
2	0.8826	0.00000	0.89309	0.102D-11
3	0.8462	0.00000	0.00000	0.820D-12
4	0.4559	-0.31497	0.00000	0.202D-12
5	0.2859	0.00000	-0.33739	0.117D-12
6	0.2738	0.00000	0.00000	0.185D-12
7	0.2571	0.19227	0.00000	0.748D-13
8	0.1716	0.14321	0.00000	0.111D-12
9	0.1610	0.00000	-0.18890	0.226D-12
10	0.1543	0.00000	0.00000	0.138D-12

floor plans was to corroborate through a dynamic analysis the hypothesis that buildings with these type of floor-plan shapes, behave inadequately under the action of seismic forces.

The following figures illustrate some of the obtained results from the dynamic analysis application to the H-shape model. Similar graphics were obtained for each of the analyzed models.

4.1 H-shape floor-plan model

The following tables 1 and 2, show only the results of the dynamic analysis applied to the initial model and the H3 model. The results of these two models were selected for this paper since, being the two extreme situations, they show the most significant data for comparison.

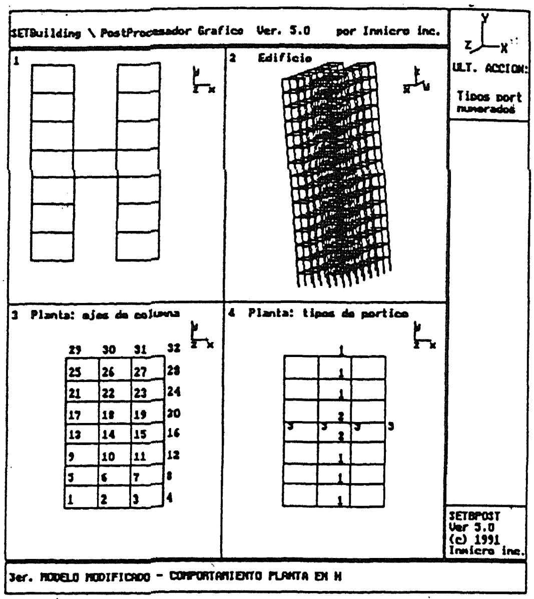


Fig. 6a SETBuilding analysis of the H-3 Model: Joints

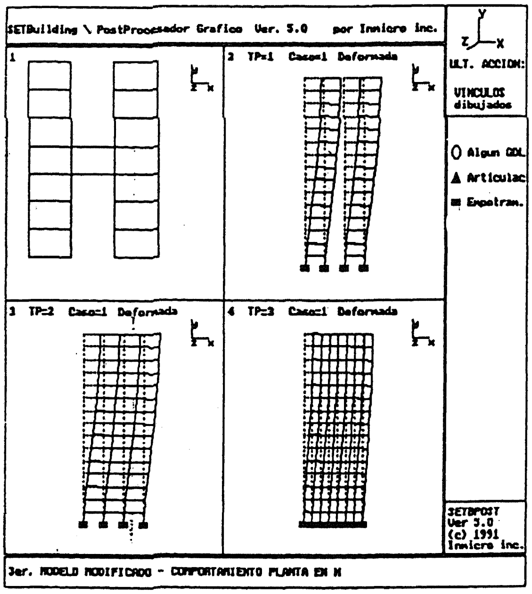
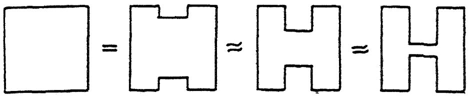


Fig. 6b SETBuilding analysis of the H-3 Model: numbered frames

From the comparison of these results, it is deduced that since it is assumed that diaphragms of the H3 model is rigid in its own plane, in the same way as they are in the initial model (regular floor-plan), the variations on the respective buildings periods, are neglectable. In all the case-studies, the location of the center of rigidity and the center of mass coincide. Therefore, no eccentricity is identified.



IM H1 H2 H3

These results do not correspond with the actual behavior observed on H2 and H3-type buildings severely damaged in recent worldwide earthquakes.

Table 2. Periods of vibration of the 10 first modes of vibration. H3 model of the H-shape floor plan.

Mode	Period	Gamma X	Gamma Y	Error
1	1.3859	0.88550	0.00000	0.116D-10
2	0.7967	0.00000	0.00000	0.107D-11
3	0.7459	0.00000	0.89309	0.191D-11
4	0.4406	-0.32683	0.00000	0.190D-11
5	0.2567	0.00000	0.00000	0.257D-12
6	0.2421	0.19590	0.00000	0.215D-12
7	0.2416	0.00000	-0.33739	0.849D-13
8	0.1590	0.14682	0.00000	0.710D-13
9	0.1436	0.00000	0.00000	0.457D-13
10	0.1360	0.00000	-0.18890	0.226D-12

Table 3. Periods of vibration of the 10 first modes of vibration. Initial model of the L-shape floor plan.

Mode	Period	Gamma X	Gamma Y	Error
1	0.6269	0.00000	0.89024	0.107D-11
2	0.6269	0.89024	0.00000	0.107D-11
3	0.5198	0.00000	0.00000	0.327D-11
4	0.2019	0.00000	-0.34369	0.188D-12
5	0.2019	-0.34369	0.00000	0.188D-12
6	0.1674	0.00000	0.00000	0.173D-12
7	0.1127	0.00000	-0.18985	0.662D-13
8	0.1127	-0.18985	0.00000	0.662D-13
9	0.0934	0.00000	0.00000	0.104D-12
10	0.0779	0.00000	-0.13572	0.100D-12

Table 4. Periods of vibration of the 10 first modes of vibration. L1 model of the L-shape floor plan.

Mode	Period	Gamma X	Gamma Y	Error
1	0.6442	-0.57348	0.57348	0.544D-11
2	0.6276	0.62623	0.62623	0.465D-11
3	0.5600	0.25074	-0.25074	0.383D-11
4	0.2020	-0.24391	0.24391	0.117D-11
5	0.2000	-0.24988	-0.24988	0.118D-11
6	0.1779	-0.05800	0.05800	0.143D-11
7	0.1103	-0.13485	0.13485	0.571D-11
8	0.1102	-0.13548	-0.13548	0.115D-12
9	0.0973	0.01331	-0.01331	0.745D-12
10	0.0759	-0.09648	0.09648	0.787D-12

Table 5. Probable maximum values of the L-shape floor-plan initial model.

Probable Maximum Values.

Level	Diaph	Shearing force VX	Shearing force VY	Torsional moment T
15	15	105.153	0.000	0.000
14	14	206.676	0.000	0.000
13	13	303.616	0.000	0.000
12	12	395.150	0.000	0.000
11	11	480.648	0.000	0.000
10	10	559.628	0.000	0.000
9	9	631.688	0.000	0.000
8	8	696.474	0.000	0.000
7	7	753.662	0.000	0.000
6	6	802.949	0.000	0.000
5	5	844.052	0.000	0.000
4	4	876.696	0.000	0.000
3	3	900.631	0.000	0.000
2	2	915.714	0.000	0.000
1	1	922.161	0.000	0.000

4.2 L-shape floor-plan model

From the comparison of the results obtained from the L-shape model analysis, shown in the following tables, in table 3 the results of the initial model (regular floor plan), it is observed that there is an alternation in the periods of vibration in directions x and y (see factors Gamma X and Gamma Y).
In the results of the derived L-shape floor-plan model (L1), however, the double symmetry is the cause of the obtained results (table 4), which show that in this case the periods of vibration in directions x and y, are the same, at the same period of time.
From the comparison of the results obtained in tables 5 and 6, probable maximum values, it is observed in the results of the initial model, shown in table 5, that shearing forces appear in one direction only (shearing forces VX) and no torsional moments are identified.
In table 6, however, shearing forces appear in both directions, x and y, which are very different to each other on each level, and significant torsional moments are identified.

5 CONCLUSIONS

Next paragraphs describe the conclusions based on the results of the comparison between regular and derived H- and L-shape floor plans by considering variations in the dimensions of the reentrant area.

5.1 H-shape floor-plan model

The structural response analysis used in this study which considers the already described assumptions, might lead to inaccurate results. The results obtained from the structural response analysis do not reflect the expected behavior of the H-shape models, which was anticipated based on empirical research placed upon observation of significantly damaged buildings in recent worldwide earthquakes: H-shape floor plans induce torsions in buildings subject to ground motions.

It is important to mention, though, that the

Table 6. Probable maximum values of the L-shape floor-plan initial model.

Probable Maximum Values.

Level	Diaph	Shearing force VX	Shearing force VY	Torsional moment T
15	15	75.368	12.999	181.707
14	14	147.678	25.520	353.007
13	13	216.301	37.476	513.464
12	12	280.713	48.804	661.998
11	11	340.538	59.424	797.850
10	10	395.501	69.240	920.469
9	9	445.392	78.165	1029.468
8	8	490.034	86.145	1124.598
7	7	529.267	93.146	1205.729
6	6	562.940	99.130	1272.835
5	5	590.908	104.057	1326.003
4	4	613.029	107.905	1365.447
3	3	629.172	110.682	1391.526
2	2	639.282	112.412	1404.484
1	1	643.559	113.143	1389.351

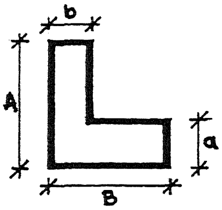


Fig. 7 Relative dimensions of the different sides of the L-shape Floor-plan.

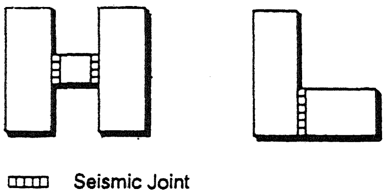


Fig. 8 H-shape and L-shape floor plan separated in rectangular blocks

analysis method, as well as the assumptions used in this study, are worldwide used by 90% of the available dynamic analysis programs, such as ETAB and STADD.

As a consequence, we conclude that the assumption of infinitely rigid in their plane diaphragms, does not reveal what occurs in actual cases.

In the H-shape model it is evident that due to the symmetrical distribution of the lateral-force-resisting elements, there is no eccentricity. It is recommended to analyze the H-shape models with a structural response analysis which includes the flexible diaphragm assumption.

5.2 L-shape floor-plan model

According the comparison of the results obtained from the analysis of the L-shape floor-plan models, it is concluded that, although the assumption of the rigid diaphragm in the analysis of the two selected models permits to identify a displacement on the location of the center of rigidity in the L1 model, and to recognize that there is a different behavior between the initial model (regular floor-plan) and the derived L-shape model (L1) where significant torsional moments are generated, this assumption would not be accurate when the relative dimensions between the different sides of the L are very different.

If the model presents the following characteristics, A >> a and/or B >>b, then, it is considered indispensable to use an analysis method that includes flexible diaphragms in its assumptions.

5.3 General conclusions

It is recommended for future studies and evaluation of H-shape and L-shape floor plans, to consider:

1. the application of structural response which include the following assumptions: (a) flexible diaphragms in their own plane; and, (b) variations on the resisting characteristics of some of the structural components, anticipating accidental unbalanced mass distribution or construction deficiencies which could lead to asymmetrical resistance distribution.
2. the analysis of H-shape and L-shape floor plans by dividing each of them in regular rectangulate blocks (rectangles) separated by seismic joints. Each regular rectangulate block should be analyzed individually, and then their modes of vibration compared in order to establish how would each of them move when they next to each other and how each of them could affect the adjacent one. These results could allow to design adequate seismic joints, or just to decide modify the characteristics of the floor plan.

These considerations might permit to obtain more realistic models to analyze the influence of variations on the dimensions of reentrant areas in H-shape floor plans.

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