The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

INFLUENCE OF PLAN IRREGULARITY OF BUILDINGS

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ABSTRACT:

This article shows an analytical description of the damages caused by different plan irregularities, during seismic events of different magnitudes. Although these effects of architectonic and/or structural configuration have been identified like not adapted in previous damages, have come maintaining their presence in constructions anywhere in the world. The effects of commented irregularities were studied with qualitative analyses of important and recent investigations, as much in Mexico as abroad. The work describes to the geometric forms that are repeated more in the urban areas in México (squared, rectangular, section U, section L and section T), as well as its variations from plants observed with extracted aerial photography of Google Earth. These architectonic plants were modeled in SAP2000 considering one, two and four levels to determine the effect of the geometric form in the seismic behavior of structures with elastic analyses. Also, effects of the extension in rectangular plants and the inclusion of projections in sections with architectonic plants U, L and T were studied. In all the studied systems, effects of different irregularities are analyzed based on the variation of displacements, with respect to regular systems.

KEYWORDS: Plan irregularity, earthquake damage, vulnerability, architectonic irregularity

1. INTRODUCTION

Constructions can suffer diverse damages when they are put under seismic excitations, although for a same structural configuration, region and earthquake, damages in the systems are neither equal nor homogenous. So, they are several factors for these like: structural system, earthquake characteristics, the quality of the construction, soil of location, and its maintenance that define the seismic behavior of the structure. However, in agreement with the experiences in past and recent earthquakes, most of the damages are related to architectonic and structural configuration in plant and elevation and site ground effects.

The effects that cause seismic action in irregular structures were observed in many recent earthquakes. Most of literature describes the effects only qualitative, and the codes used some percentages that limited the structural performance, but not necessary are obtained with large and deep investigation.

The literature since the past are continued show to technical community the negative effects of the irregularity of buildings, a good example is the textbook write by Arnold and Reitherman (1982). This book illustrated the building irregularity in configuration, in plant, and elevation, also some specific cases like torsion, mass irregularity, week story, discontinues elements, and so on.

Table 1.1. Summary of recent earthquakes and reported causes of structures failures.

Earthquake name	Date	M_w	Author	Short column effect	Discontinuous columns	Soft week story	Torsion	Construction design quality	Problem of adjacency	Seismic design codes	Joints	Week column and strong beam	Week materials or without reinforced	Liquefaction	Land slide
El Asnam, Algeria	10/10/80	7.3	EERI, 1983	•		•	•	•	•	•		•	•		
Viña del Mar, Chile	03/03/85	7.8	ICH, 1988		•		•	•		•		•	•	•	
Michoacán; México	19/09/85	8.1	Popov, 1987 y Tena, 2004	•	•	•	•	•	•	•	•	•	•		
L. Prieta, USA	17/10/89	6.9	EERI, 1989			•			•	•				•	
Spitak, Armenia	07/12/88	6.8	Tena, 2004				•	•		•	•		•		
Luzon, Philippines	16/07/90	7.8	Hopkins, 1993			•	•	•					•	•	
Erzincan, Turkey	13/03/92	6.7	Saatcioglu and Bruneu, 1993	•		•	•	•		•		•	•		
Northridge, United States	17/01/94	6.7	Tena, 2004	•			•	•		•	•				
Kobe, Japan	17/01/95	6.9	Tena, 2004				•	•	•	•	•		•	•	
Kocali, Turkey	17/08/99	7.4	Naeim et al, 2000	•		•	•	•		•	•	•	•		
Chi-Chi, Taiwan	21/09/99	7.6	Tsai et al, 2000	•	•	•		•		•	•	•	•		
San Salvador, El Salvador	13/01/01	7.6	Alarcón, 2005			•	•	•	•	•		•	•		
Bhuj, India	26/01/01	7.7	Humar et al, 2001	•		•	•	•			•			•	
Tecomán, México	21/01/03	7.8	Alcocer et al, 2006			•	•	•		•			•		
Bingül, Turkey	01/05/03	6.4	Dogangün, 2004	•		•		•	•	•	•				•
Lefkade, Greece	14/08/03	6.2	Karakostas et al, 2005	•		•	•	•		•					
Bam, Iran	26/12/03	6.5	Tena, 2004			•	•	•		•			•		
Sumatra, Indonesia	26/12/04	9.3	CAEE, 2005	•		•		•		•	•	•	•		
Java, Indonesia	27/05/06	6.3	EERI, 2006		•	•	•	•		•		•		•	•
Pisco, Peru	15/08/07	8.0	Klinger, 2007			•	•	•	•	•	•		•		
Wenchuan, China	12/05/08	8.3	Xiao, 2008	•		•	•	•	•	•		•	•		•

In table 1.1 a summary of recent earthquakes effects over constructions are presented. The construction types basically are masonry houses and concrete buildings. The structure of the table and some of the studied earthquakes are based at Solomon et al. (2008) investigation. In table 1.1, damages related to irregularities (column one to four) were listed first. As can be observed in these columns, 18 of the 21 earthquakes analyzed include at least two types of these irregularity pathologies. Being conscious with the summary, we can affirm that any type irregularity continues being one of the causes more frequent in earthquake damages in all type of constructions.

Literature review teaches us that an irregular structure needs a more careful structural analysis to reach a suitable earthquake system. For this reason, small mistakes, caused by incorrect analysis simplifications of these structures, could cause important damages during earthquakes and represent vulnerability conditions that are not quantified correctly in all occasions by some simplified methods.

1.1. Plan and elevation irregularity of buildings in Mexican Codes

The regularity or irregularity is determined by the architectonic composition as much in plant as in elevation and the configuration of the structure. The structural irregularity is defined by the location of the resistant elements: walls, columns, joints with nonstructural elements, floor systems, wall openings, masses, etc., and geometric arrangement.

The effect that produces the irregularities in plant summarizes in the NTCS (Earthquake Complementary Technical Norms), NTCC (Concrete Complementary Technical Norms), and NTCM (Masonry Complementary Technical Norms) of the RCDF (Federal District Building Code) of the years from 1977 to 1995, with a paragraph that was lent to interpretation errors. In this paragraph was indicated that the walls had both to be placed in plant "noticeably symmetrical" with respect to orthogonal axes. To the being this one a qualitative and subjective requirement, was in many of the constructions badly interpreted and contributed to the vulnerability of the constructions. With the actualization RCDF the confused paragraph was corrected with a limit of the ten percent of the static eccentricity of axe longitude, measured parallel to this eccentricity; this is one of the factors to consider a structure like regular (Tena et al., 2006).

In agreement with the RCDF-2004 code, we can make a structure classification like regular, moderately irregular and strongly irregular. This classification defines to the structural regularity when a structure fulfill the eleven points including in the NTCS, the moderately irregular ones stop fulfilling up to two of these eleven points and the strongly irregular ones are all the rest.

The plan irregularities in the RCDF-2004 code are:

- <u>Torsion irregularity</u> exists when the maximum relative displacement of the floor calculated including the accidental torsion, in the end of the structural cross-section to an axis is more than 1.10 times the average of the relative displacements of the floor of both extreme of the structure. The torsion also is induced with the positioning of rigid elements of asymmetric way, with the positioning of great masses or the combination of both.
- <u>Plan geometric irregularity</u>. A structural system is considered irregular, when the plants symmetrical axes are not noticeably regular and perpendicular to each other, when there are projections or entrants majors to 20%, when the vertical resistant elements to the lateral loads are not parallel, nor symmetrical with respect to main the orthogonal axes of the system that resists the lateral forces, when discontinuities in a trajectory of lateral force exist, like deviations outside the plane of the vertical elements.
- <u>Diaphragm discontinuity</u>. A plan system is considered irregular, when the diaphragms present discontinuities or variations of rigidity, including the caused ones by areas trimmed or with opens majors of 20% of the gross area locked up of the diaphragm or changes in the effective rigidity of the diaphragm of 50% of a following floor.

2. METHODOLOGY

The study of the irregularities reason for this paper was developed using a determinist methodology, with some probabilistic elements in its conception. In order to facilitate his study it was divided in three phases of analyses, but only the first one is developed in this paper. The objectives of the first stage are to determine the effect of the geometric form in plan eccentricity, as well as the phenomena of plan extension and projections. The second stage consider an elevation irregularity review, focus in weak story and irregularity masses. The final stage studies the wall position effect when an earthquake hit the structure.

The first step of the process is the selection of basic geometric figures and some of its variations from the plants observed with aerial photography extracted of the Google Earth. We determined with the pictures to the plan extension and projections.

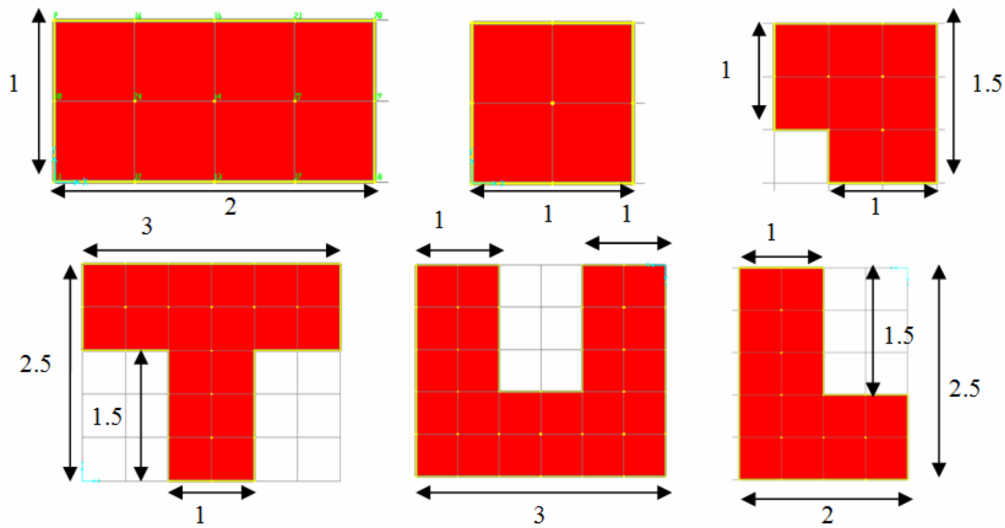

Figure 2.1. Relation of geometric forms selected in first stage and its general dimensions standardizing in reference to the square plant. The forms were selected from the aerial photography. We continued in the paper call the forms like: rectangular, square, L-1, T, U and L-2.

Shown irregular plants in figure 2.1, present rectangular, square, and sections L-1, T, U and L-2, whose dimensions are standardized with respect to the side of the square section whose length assigned a value of one. The elastic models were made in program SAP2000 v10.0.1 Advanced and with ten accelerograms signal registered in the Mexican Pacific Coast.

The ten accelerograms signal used for the structural analysis was select from Mexican Catalog of Strong Motion Earthquakes. The registered period was 1994 to 2000. The three direction of the each signal was considered in the analysis.

The wide long relation 1:1 determines the squared section considers regular, which is used of reference in the comparison of displacements by plan irregularity, through

$$Dif\,(\%) = \frac{R_R - R_{IR}}{R_R} \qquad (2.1)$$

where RR is the maximum response of regular structure and RIR is the maximum response of the irregular one.

Irregular plants with extensions have relations 1:1, 1:2, 1:2.5, 1:4 and 1:5. T sections were used with salient relations of 10, 20, 50, 100 and 150%, as well as an asymmetric section T with the same relations of projections. It was handling in similar way to sections in U and L forms, symmetrical as much asymmetric.

3. PRELIMINARY RESULTS

The plan variation and the effect of this in the vulnerability was studied because literature has shown the disadvantages of using it qualitatively, but it is important to study in which percentage influences the structure performance quantitatively.

The statistics of the obtained results of parameter of equation 2.1 are show in table 3.1, where the maximum responses of elastic models are observed considering the ten selected earthquakes, and the six plants to study the geometric performance shown in figure 2.1.

Table 3.1. Statistics of the differences percentage between the regular model (square) and the irregular models.

Section	Mean (%)			Standard deviation (%)		
	x	Y	z	x	y	z
Rectangular	15.7	24.6	58.2	0.0024	0.0051	0.0216
L-1	23.4	29.9	61.2	0.0026	0.0059	0.0225
L-2	35.8	37.0	66.7	0.0051	0.0074	0.0271
T	54.9	68.5	80.1	0.0075	0.0090	0.0218
U	43.6	59.7	77.5	0.0067	0.0045	0.0224

Results of table 3.1 show that the rectangular plan is the one that presents minor irregularity effect, but the plants of figures T and U, already show important demands respect to a regular figure from 50 to 80%, also with important dispersion. The irregular figures detonate an unstable behavior under seismic demands, since the demands are increased considerably. These results can be observed in figure 3.1, where the first graph is a related comparison cradle in points x, y and, z, whereas in the second the tendency of the geometric form is presented.

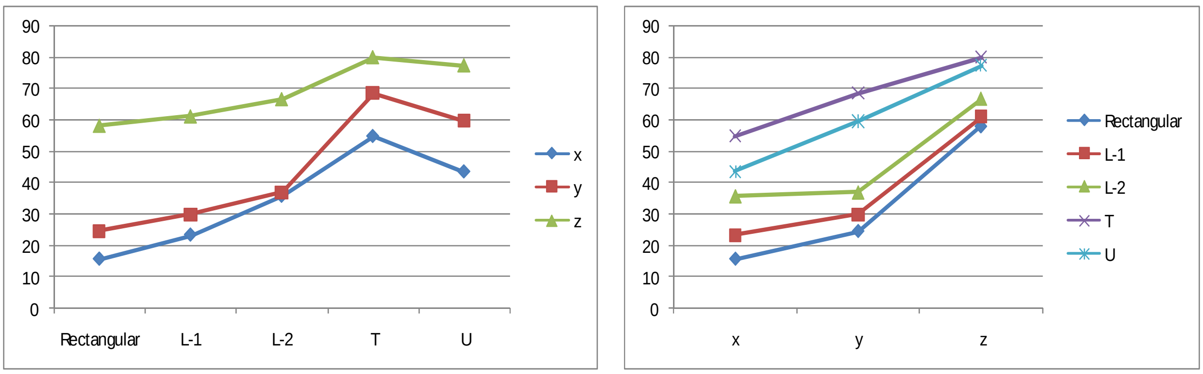

Figure 3.1. Percentage differences between the regular model (square) and the irregular five models (Rectangular, L-1, L-2, U and T)

Due to the importance of exemplifying the studied phenomena, a field work was realized in Tuxtla Gutiérrez city, in the south of the country. In the images corresponding to figure 3.2 we observed that the phenomenon of extended plants is common in the city of study, and its effect increase the vulnerability of the systems.

Figure 3.2. Examples of plans extensions in México.

The behavior and deformation of the extended plant were similar to the flexural beam this effect worsens when vertical slenderness is had (more than two levels), as it is observed in deformed of the models of one, two and four levels for the aspect ratios of 1:4 and 1:5.

Another important effect in the extended plants consists of the flexibility that appears in the diaphragm, limiting its functions. The effect of the diaphragm is extremely important in the performance of the structural system and increases or diminishes the system fragility.

In graphs of figure 3.3 are the results of the analysis of extended plants, where it is appraised how it is reduced to the capacity of displacement and rotation in extended plants of masonry structures (although it is reduced for all type of structural systems, but not in the same proportion). The results of the graphs for the different relations are standardized with respect to square architectonic plants with wide long relation 1:1. The displacement capacity is reduced until a 50% and the one of rotation until an 80%.

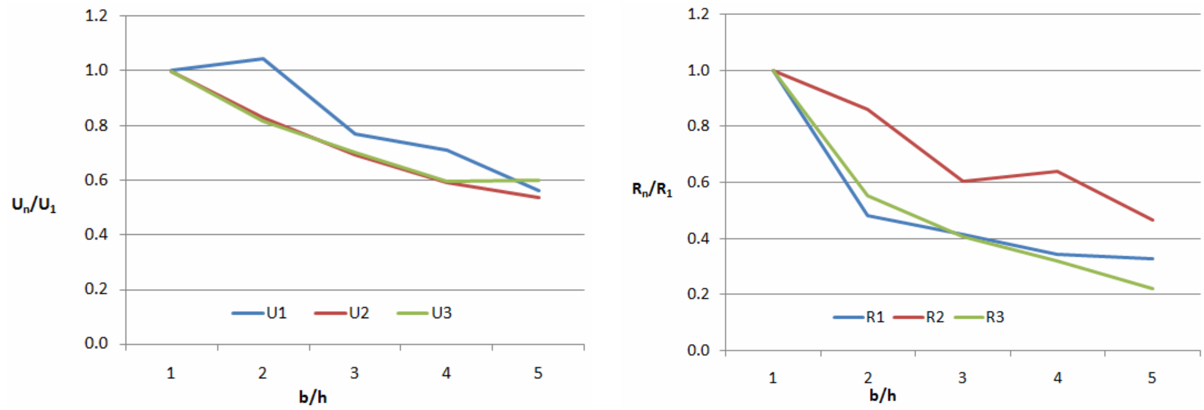

Figure 3.3. Displacement and rotation capacity for week structures with large to base relationship from 1:1 (left) and to 1:5 (right).

Considering asymmetric section T, U and L in both axes, we can analyze that the demand is smaller in all the length of the longest arm with respect to the demand in the projection of the short side. In the connection of the main body with the projection of smaller dimension, a concentration is observed of high stress level, although in the majority of the cases the inertial mass of the projection of the short side is minor who stops the connection of the long side.

The models in figure 3.4 present projections of 150, 100, 50, 20 and 0%. As it is also observed in symmetrical sections T, U and L, between minor length it is the projection, is bigger the collaboration of his body in the process of resistance of all the architectonic plant.

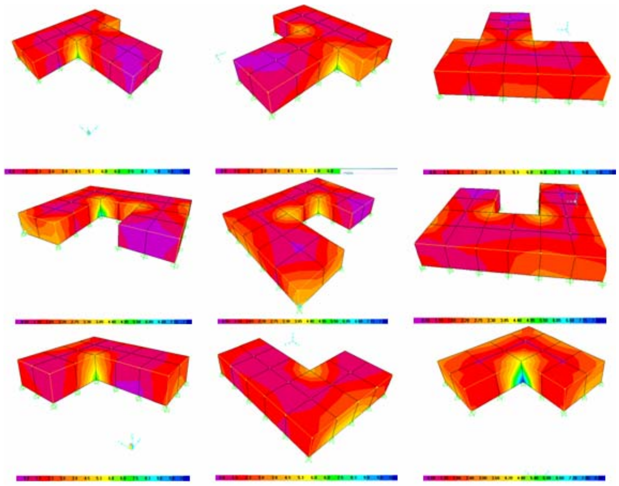

Figure 3.4. Shear stresses effect in asymmetric sections T, U and L for different percentage from projection, from 20 and to 150%.

CONCLUSIONS

A parametric studied of the influence of different plan irregular systems in the elastic displacements responses are presented in this paper. To do that elastic models or regular systems (square plant) and irregular models of rectangular, T L and U plants were subjected a ten characteristics accelerograms. The realized parametric studies allow us to identify the most important conditions of vulnerability in a qualitative and quantitative way. Within the most important results to date we can indicate the following:

- A summary of important seismic events from 1980 to 2008, where it is observed building damaged due to different irregularities causes. We conclude that constructions are more vulnerable when more irregular are.
- The demands distribution of acceleration in constructions with plan or/and elevation irregularity problems in many occasions surpasses to the lineaments established in the Federal District Codes. This reflection forces us to continue investigating in the matter to place more restrictive limits or to solicit for stricter analyses.
- The linear analyses provide important information for torsion behavior of weak structures like the studied. Despite we understand that elastic analysis underestimates the interstory drifts when the superstructure enters in nonlinear performance, and the behavior is adopted torsion mode.

ACKNOWLEDGES

The authors are thankful to UAM (Metropolitan Autonomous University, Azcapotzalco unit), UNICACH (University of Sciences and Arts of Chiapas), Federal District Government and CONACyT (National Advice of Science and Technology) by its support to develop the present investigation.

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