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QUANTITATIVE EFFECTS OF SOFT-STORY IN LOW MASONRY BUILDINGS IN THE MEXICAN PACIFIC COASTS

Raul Gonzalez Herrera[1], Jorge Aguilar Carboney[2],
Carlos Narcia Lopez[3] and Alejandro Ruiz Sibaja[4]

ABSTRACT

The soft-story condition produces a lot damages in all kind of structures after appearing a moderate or intense earthquake. For this work, we developed analytical soft-story models for two and four stories buildings, typical of Chiapas, Mexico. The soft-story was located in the first level in some models and in the second level in another's ones. In the following stage of the study, soft story models considering L forms with projections since 10% until 100% in asymmetrical plants.

Introduction

Buildings may suffer damage when subjected to seismic excitations, however, for an identical configuration structural, region and earthquake; the damage is not homogeneous. This is determined by several factors, such as: The structural system, the earthquake characteristics, the quality of construction and maintenance (Gonzalez and Gomez, 2008). However, in accordance with experiences in recent earthquakes, the damage and its magnitude should be – mainly by- irregularities in both plant and in elevation; while that for structures casualties, the soft story represents a determining irregularity of its vulnerability and the possibility of severe damages, and even of collapse.

In Mexico the most used regulation for the design of these systems is the 2004 Mexico City Code (NTC-RCDF-2004), which is used as main reference for seismic design in the state of Chiapas. Nevertheless, this regulation refers to the soft story problem as a condition of irregularity and gives the same consideration as those of other structural characteristics that have less effect on the seismic behavior.

The Mexico City Code is limited for the application of increasing factors to design forces in all the structure. This approach, according with analysis of this work, show problems, due to it only amplifies the forces and does not take in account adequately the changes of structural stiffness,

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[1] Professor, Dept. of Engineering, UNICACH, Libramiento Norte Poniente, Ciudad Universitaria, Caleras Maciel, Tuxtla Gutierrez, Chiapas, México. Tel. y Fax: 52-961-125-1834; ingeraul@yahoo.com.
[2] Professor, Dept. of Civil Engineering, UNACH, Boulevard Belisario Dominguez Km # 1081, Tuxtla Gutierrez, Chiapas, México, jaguilar@unach.mx.
[3] Professor, Dept. of Engineering, UNICACH, narcia_lopez@yahoo.com.
[4] Professor, Dept. of Civil Engineering, UNACH, ruizsibaja@yahoo.es.

resistance and, mainly, the deformation capacity, that is the parameter analyzed in the present as which it determines the level of damages that the structure will suffer.

The proposal of the NTC-RCDF-2004 regarding of soft floor, either does not consider the superior levels of stress and demands of inelastic deformation in the structure, or the position of the soft story in height. This can lead to a dynamic instability, which is more significant as the structure is taller, even for low rise buildings. If the materials have very low resistance, as in the case of Chiapas, the masonry structures of more than three levels experience a concentration of stress in ground floor, which causes that the structure behaves like one with soft story.

In this work structure models were developed, using SAP2000 v10.0.1 Advanced, for buildings of two and four levels, considering the soft floor in the first and second level, respectively, and earthquakes with epicenter in the coasts of Chiapas occurred between 1995 and 2009. The building layout square, rectangular and in L shape, symmetrical as well as asymmetric.

The Soft Story, Codes and Earthquakes

The abrupt changes of stiffness generate additional stress, in the stories where the changes of rigidity or mass and in its connection with the lower or the upper story. These changes must be most gradual possible to avoid serious problems to the structure, nevertheless, that fact have not been considered by the architectonic designers, even more critical, it is not evaluated sufficiently in the Mexican Code.

Mass concentrations are more critical on higher stories, because increases acceleration in plants which have generally less rigidity, increasing the possibility of failure or overturning. In certain cases, the eccentricities of mass are most critical than stiffness. According to Tena and Lopez (2006), in several earthquakes as in Mexico City 1985, many of the buildings failures were induced due to the change of use of buildings, which were used as store area the upper floors or other modifications that concentrated the main weight.

Another conditions of irregularity included in the Mexican Code, indicates that must have rigid diaphragm between all levels and it must restrict all columns, or the restriction must be through beams. The weight of each level, including live load, according to the use, must not be greater than 110% of the immediate lower story, except at the last level, which may be less that 70% of such weight, but not more than 110%.

Additionally, other regulatory considerations indicate that no floor has an area bigger than 110% of the immediate lower story, or less that 70%, except at the last level, which can have an area smaller, but never greater than 110%. None story area exceeds by more than 50% than the all lower floors. Also, stiffness, nor any story shear resistance differ by more than 50% of the story immediately lower, being excluded the last story from this request.

In Table 1 are some examples of damage in structures during major earthquakes between 1985-2008, this information confirms that failures by irregularities are always show, emphasizing irregularities as soft story.

Table 1. Summary of the effect of recent earthquakes in buildings of concrete and masonry. Based on Solomon and Murat, 2008.

Name of the earthquake	**Date**	**M_w**	**Reference**	**Short column**	**Discontinuity of columns**	**Soft story**	**Torsion**	**Deficient structural design**	**Adjacent building**	**Regulations problems**	**Connections**	**Weak column and strong beam**	**Weak reinforcement**	**Liquation**	**Landslide**
Asnam, Algeria	10/10/80	7.3	EERI, 1983	●		●	●	●	●	●		●	●		
Viña del Mar, Chile	03/03/85	7.8	ICH, 1988		●		●	●		●		●	●	●	
Michoacán; Mexico	19/09/85	8.1	Popov, 1987 and Tena, 2004	●	●	●	●	●	●	●	●	●	●		
Loma Prieta, United States	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			●	●	●					●	●	
Aziris, 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	09/21/99	7.6	Tsai et al, 2000	●	●	●		●		●	●	●	●		
San Salvador, El Salvador	13/01/01	7.6	Alarcón, 2005			●	●	●	●	●		●	●		
Bhuj, India	01/26/01	7.7	Humar et al, 2001	●		●	●	●			●			●	
Tecomán, Mexico	01/21/03	7.8	Alcocer and Kligner, 2006			●	●	●		●			●		
Bingül, Turkey	01/05/03	6.4	Dogangün, 2004	●		●		●	●	●	●				●
Lefkade, Greece	14/08/03	6.2	Karakostas et al, 2005	●		●	●	●		●					
BAM, Iran	12/26/03	6.5	Tena, 2004			●	●	●		●			●		
Sumatra, Indonesia	12/26/04	9.3	CAEE, 2005	●		●		●		●	●	●	●		
Java, Indonesia	27/05/06	6.3	EERI, 2006		●	●	●	●		●		●		●	●
Pisco, Peru	08/15/07	8.0	Klinger, 2007, Elnashai, and others, 2008			●	●	●	●	●	●		●		
Wenchuan, China	12/05/08	8.3	Xiao, 2008	●		●	●	●	●	●		●	●		●

Table 1 refers to the study of Solomon and Murat (2008), while for our work - primarily - identified effects of irregularity and were analyzed other earthquakes with effects on structures with a typology similar to the study area.

As shown in this table, the damage data from 21 earthquakes has shown at least three irregularity parameters. It can say that any type of irregularity is one of the most common causes in the structural damage due to major earthquakes (see Figure 1).

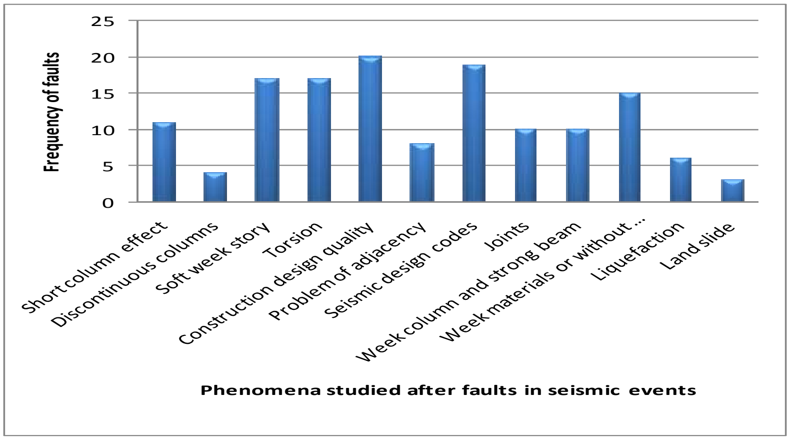

Figure 1. Frequency of seismic damage associated with different constructive, design or geotechnical problem.

Characteristics of Studied Models

For this research were considered five regular plants, a 6 x 6 square and rectangular four with the relationships: 6 x 12, 6 x 15, 6 x 24 and 6 x 30, that means with relations short side to long side of 1:1, 1:2, 1:2.5, 1:4 and 1:5. The second and third of these relationships are which are handled as limits in the Mexican Code.

The effect of soft story was tested in regular structures with and without the effect of short to long side relationship, placing the soft story in both level one and level two, for four story models. Figure 2 shows some of the models studied in this work that were made using models from the study of the irregularities in plant by Gonzalez and Gomez (2008).

For structural modeling used the SAP2000 v10.0.1 advanced structural analysis program. Figure 2 shows the heights considered for models in three dimensions with FEM (Finite Element Method), for story heights of 2,600 mm, which are the usual in the city of study; made structural models of one, two and four levels.

The phenomenon of change of stiffness with height, even in two story buildings, such as in the case of residential low-rise buildings that have been modified for commercial use on ground floor, or those whose architectural projects encourage common areas on first floor with sparsely walls (room, dining room, kitchen, among others) and bedroom areas on top floor with high wall density, with a abrupt change of vertical stiffness (Figure 3).

Left picture of Figure 2 corresponds to a two story house building with soft floor and horizontal and vertical irregular layout. Due to its characteristics shows that it comes from a self-build process. Picture at center corresponds to a four level building that will be used as offices. The structure in construction relies on a rigid floor of masonry and the upper stories intended to work as a system of frameworks, with 250 x 200 mm columns, spans of about 400 mm, and 200 x 300mm beams. Also it is a self-build construction, and presents important conceptual errors, as the possibility of generating a soft floor in the second level.

Figure 2. Examples of structures with soft floor and problems of abrupt change stiffness and mass in the city of Tuxtla Gutierrez, Chiapas.

Finally, right picture shows a more vulnerable construction. The structure is a three story building which will have a commercial use with a first floor with rigid masonry, which was weakened to fit a commercial use, and the two upper levels intended to work as frameworks system with 300 mm x 200 mm columns, spans of 500mm, and 300 x 200mm beams. There are slender columns and with evident structural problems. The three buildings are located at downtown of the city Tuxtla Gutierrez, Chiapas.

Analysis of soft story effect

For the study were developed 480 structural model with three story heights (2,700 mm, 5,400 mm and 10,800 mm,), eight plants (one square, three rectangular three and four L shape), ten earthquakes and two floor options with soft story at first and second level. As reference, it was considered a building with a 1:1 to compare results with different aspect ratio with the other models. Figure 3 presents the shear and flexion stress in models from one and up to four levels, respectively.

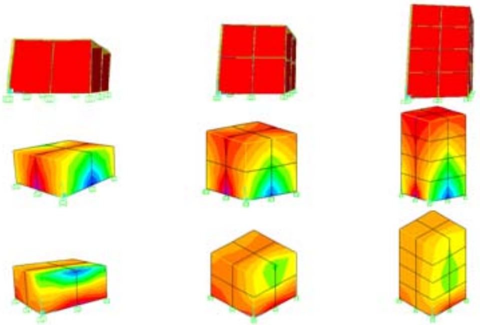

Figure 3. Shear and flexion stress in models from one and up to four levels.

Figure 4 shows buildings that walls of the façade were remove, then the back walls and finally the lateral walls removed, simulating a construction practice in which the ground floor is used as commercial area or parking and the upper levels as residential use, Office, etc. The shear and flexion stress distribution are shown.

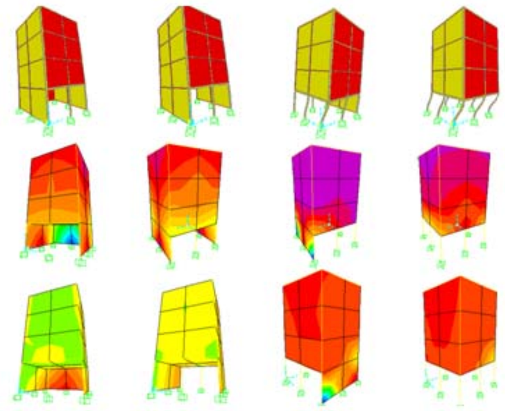

Figure 4. Shear and flexion stress in models from one and up to four levels, in the walls of the building with the ratio 1:1, buildings of 4 levels with soft story.

The deformed Figure 4 presents a fragile behavior on your floor, which operates almost as fuse, since to gradually reduce the walls begins a distribution concentrated efforts on a smaller number of items, which involves a very significant increase in demands. Rigidity changes are so abrupt ending structure collapsing (by the level of effort and) (achieved deformation) to withdraw all the walls of the ground floor in buildings of four levels.

A similar process with two story buildings displays the same fragile behavior of four story models. However, because the mass is on the over the soft story, the increase in stress is less important. Even so, the vulnerability is high and there is an important torsion effect, as the shear and flexion stress distribution are shown in Figure 5.

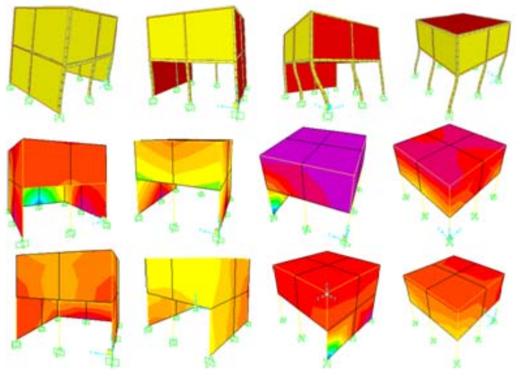

Figure 5. Stress distribution in two story buildings with soft story, with the ratio 1: 1.

After the analysis of square plant, with 1:1 ratio, we made models with two heights (5,400 mm and 10,800 mm) and for different long to short side ratios, taking the same criteria to removing walls. Figure 6 presents the deformed shape as well as shear and flexion stress of those buildings.

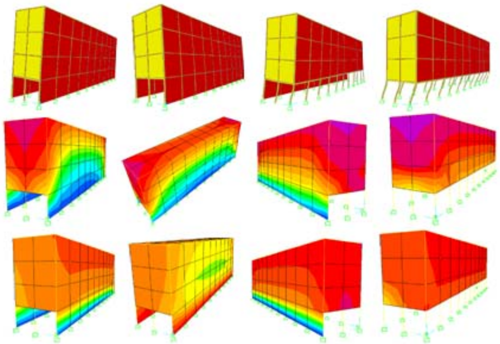

Figure 6. Stress distribution in four story buildings, with the ratio 1: 5.

The structures shown in Figure 6 have a fragile behavior in ground floor (same pattern than the previous ones), which is equivalent a structural fuse. Unlike the models analyzed before, removing walls in the short direction do not affect the structural behavior as much in those models without a log side.

When the walls in long direction are removed the collapse is almost immediate. The stress distribution shows concentrations only in the first two stories, with insignificant participation of the upper levels.

In the next stage of the study were analyzed asymmetric models with L shape and two to four stories. These models were compared with symmetric L plant, with the same considerations to remove walls. In Figure 7 shows the deformed structure and stress distribution.

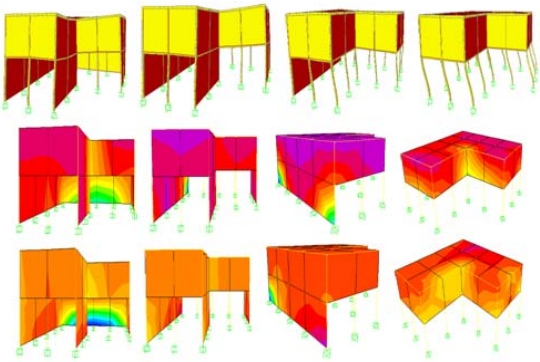

Figure 7. Stress distribution of L shape plant two story buildings.

The deformed structure in Figure 8 presented a fragile behavior on ground floor, which operates almost as fuse. When gradually remove the walls the concentration of stress is presented on a smaller number of structural elements, which implies a significant increase in structural demands. Stiffness changes are not so abrupt as in other cases, because there are parallel walls in both directions, although the irregularity in plant becomes more critical to the possibility of collapse than the soft story.

Mexican Code (NTC-RCDF-2004) often refers to the soft story problem as a condition of irregularity and is grouped with other conditions less important in the seismic behavior. To solve this problem, the NTC-DS-RCDF-2004 (Seismic design) just applies incremental factors to the forces for design over all the structure. This approach, according to this work, underestimates the effects of soft stories because only amplifies the forces and not properly consider the changes in stiffness, resistance, and specially, the deformation capacity. Also are not considered high level of stress and inelastic deformation demands in the structure as well as the vertical position of the soft story, which may lead to a dynamic instability.

The problem of soft story is more critical because the practice structural engineers have not enough knowledge of the phenomenon, but know the problem only in a qualitative way, this problem do not permit that practice engineers propose appropriate solutions. Miranda (2005) found the following consequences as this issue is handled by misinterpretation and/or deficiencies of the regulation in this area:

a) Global deformation demand increases from two to five times. In the study of Miranda (2005) is proposes the following equation (see Figure 8):

$$\frac{T_{1eb}}{T_{1r}} = \frac{1}{-13.62 + 14.6\left(\frac{K_{1eb}}{K_{1r}}\right)^{0.015}} \tag{1}$$

Where: T_{1be} is the period of the structure with soft story,
T_{1r} is the period of the regular structure,
K_{1be} is the rigidity of the structure with soft story and,
K_{1r} is the stiffness of the regular structure.

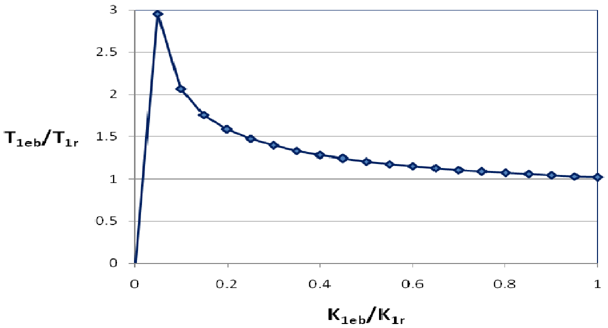

Figure 8. The main period variation with the decrease the stiffness from Miranda (2005) equation.

According to Figure 8 ace a soft story weakened the structure, so it has a longer period, which is correspond a less seismic response. This fact is perhaps one of the main reasons because these structures have survived mayor earthquakes. This phenomenon which may seem similar to the seismic isolation, it is more important in the areas with greatest spectra.

b) Lateral deformation demand is concentrated in the soft story, having the greatest inelastic drift. Elastic analyses underestimate the lateral deformation demand, as shown in Figure 9, where compared with the Miranda model and a similar elastic model developed in this work. Figure 10 shows the effects of the irregularity combined with the soft story, where the effects are amplified in more than 2.5 times.

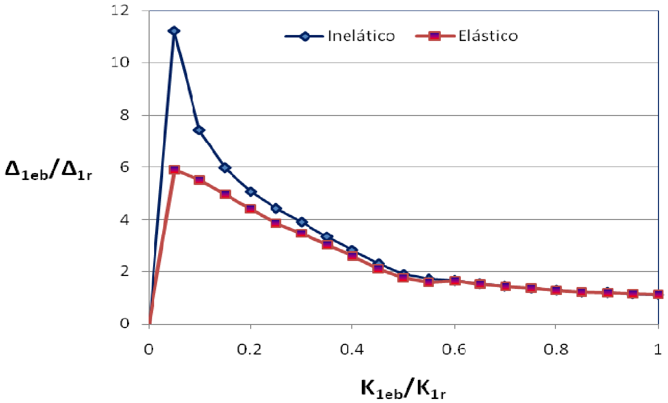

Figure 9. Variation of maximum displacement with a reduction in the stiffness with Miranda (2005) methodology for one rectangular structure of four levels without soft story.

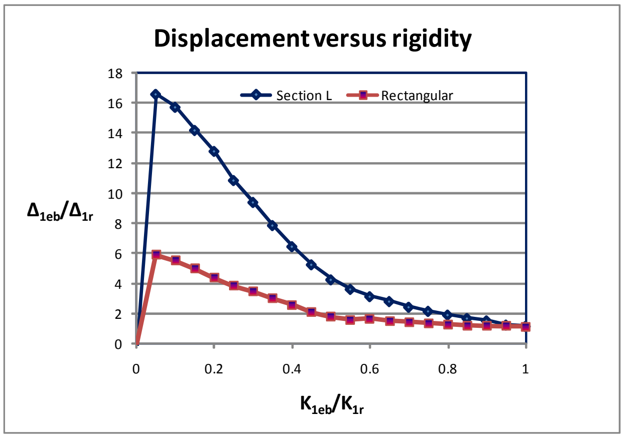

Figure 10. Variation of maximum displacement with a reduction in the stiffness for a rectangular structure of four stories without and with soft story, and an irregular L shape plant.

c) Large lateral deformations combined with axial load can cause geometrical irregularities, besides the nonlinear behavior of the materials (P-Δ effect and p-δ). This combination causes structural dynamic instability.

Other studies recommends for the appropriate analysis of this phenomenon: use different ductility factors in soft story with regard to the rest of the structure, adequately consider the overstrength and over stiffness that bring the structural and non-structural elements to the system as well as properly estimate displacements. These measures are closer to determine the real seismic behavior, but not enough if the stiffness abruptly changes is more than 40%.

Table 2 shows the factors of Q´ based on the irregularity of the structure, NTC-DS-RCDF-2004 allow stiffness changes up to 50%. These increase the stiffness of the whole structure, thus not take in account the problem. The regulation not makes specific reference to the location of the soft story, or the number of stories of the structure.

Table 2. Increasing factors for seismic forces because of the effect of the irregularity in the

NTCS-RCDF-2004.

Condition	Q´	Equation
Regular	1.00	1. 00C /Q´ s
Slightly irregular	0.90	1. 10 C s/Q´
Irregular	0.80	1. 25 C s/Q´
Strongly irregular	0.70	1. 42C /Q´ s

Where: C is the seismic coefficient and Q´ is the factor of seismic behavior.

The effect of soft story are common in structures without significant changes in the vertical distribution of stiffness, but that have weak masonry walls that have not capacity for support the concentration of inelastic demand mainly in lower stories.

The effect of the soft story goes in opposite direction of a desirable seismic design for masonry buildings, is disable a stable behavior with gradual degradation, but a soft floor there may produce a abrupt deterioration of resistance and capacity.

Conclusions

Parametric studies allow us identify the most important conditions of vulnerability due to irregularity produced by soft stories in qualitative and quantitative way. From results obtained, we can say:

- This work shows that the seismic analysis of buildings with different irregular configurations make constructs more vulnerable regardless of the structural system or the materials used. This conclusion is supported with analytical studies done in Mexico and abroad.

- Elastic analyses were performed with a small base of earthquakes registered in the area of interest. It is needed more analysis to confirm the trend of the results obtained. Due to the lack of actual records in the zone, is necessary to simulate earthquakes for these analyses.

- The distribution of the acceleration demands in structures with irregularities problems in plant and elevation exceeds often to the Mexico City Code.

- An irregular structure request of more careful analysis to achieve a proper earthquake resistant system. That is why, some a design assumptions in by simplified methods may result in significant damage during earthquakes and represent conditions of vulnerability not quantified correctly.

- Linear analyses provide important information of the torsion behavior of weak structures as that were studied. However we understand that this type of analysis underestimates story deformations when the superstructure enters the non-linear range and main modes are coupled with the torsion modes.

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