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VULNERABILITY OF BUILDINGS WITH IRREGULARITY DUE TO OUT-OF-PLANE OFFSETS IN MEXICO

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Abstract

In recent years, the structural system called "transfer-slabs" has been popularized; and it has been used in mid-rise buildings. We detected a significant increase in the construction of this type of structural system in Mexico. These structures are characterized by a floor system containing slabs with principal and secondary beams on the parking stories of the building, which supports a shear wall structure of four to six stories. Most of these shear walls are interrupted in the first level, and hence a discontinuity in elevation is observed, and therefore a significant Out-of-Plane Offsets irregularity is evident. This structural system requires a detailed seismic and structural research due to additional demands that may occur both in the transfer-floor, in the load-bearing walls, and in the connections between walls and slabs.

The final goal of this paper is to assign the vulnerability in buildings with out of plane offsets irregularity; and aims to define recommendations for buildings with transfer slab system. We have plans of some actual buildings constructed recently, these structures are located in “Colonia Roma”, one of the most affected areas during the 1985, Michoacán Earthquake. The buildings were reviewed to verify the requirements vertical and horizontal irregularity such as stiffness-soft story irregularity, Weak Story and Out-of-Plane Offsets, these last two were revised with new expressions proposed here. Nevertheless, in the case of the horizontal irregularity, out of plane offset, all buildings were classified with a high irregularity, because the total discontinuity in wall areas in each principal direction was ranging between 31% and 91%. This wall discontinuity generate that shear forces in bearing walls are increased considerately. Results in both directions of the buildings show that shear capacity is exceeded on a lot of discontinuous walls, and in many walls, shear force ratios are greater than 4.

Besides, in order to characterizing buildings structured with this systems, several models with irregularities are studied with ETBAS software. In this parametric study the variables are the discontinuous area, the wall shear force, the stiffness and resistance of the story over the floor transfer, the slab type (solid, waffle, plane), and wall position on the floor. The results showed that increasing the area of interrupted walls, the shear and axial forces in the walls are increased too, reaching to values that exceed the design resistance up to 3 times; a vulnerability index is then proposed. The most relevant results of this parametric analysis showed that increasing the discontinuity, i.e., as there are more walls that are interrupted and supported on the transfer floor system, the shear and axial forces in load-bearing walls are increased too, reaching values that exceed the nominal resistance and design up to more than 3 times.

In this research some of the recent findings obtained from analysis on irregular buildings are outlined. Both horizontal and vertical irregularities were considered. The studies involved developing simple equations that can be used by designers to estimate the likely increase in demand due to out of plane offsets irregularity. This study also provides a technical basis for revision of the Mexican Construction code.

Keywords: Irregularity in buildings; Horizontal irregularity; Transfer Floor Systems; Out of Plane Offsets.

1. Introduction

Architectural design which promotes open spaces on the first storey of buildings, as they were intended for housing or for office, became popular in the mid-20th century. According to regulations of building codes, these structural systems are categorized as vertical or horizontal irregularity, and depending on the degree of this irregularity will adopt the most appropriate seismic design criteria. The structural earthquake engineering attempts to identify some specific cases of structural system discontinuous, as the case of buildings identified with stiffness-soft story irregularity, where is evident a sharp decline of rigidity or the restriction of the movement of the ground story, respect to the rest of stories of the building. Another case occurs in building with weak story, where it is most evident change in lateral strength of the ground story.

Structures shall be defined as regular or irregular based upon the criteria stipulated in codes; which define an “irregular structure” as one that has a certain geometric shape or in which stiffness and/or mass discontinuities exist. While a “regular structure” is one in which there is a minimum coupling between the lateral displacements and the torsional rotations for the mode shapes associated with the lower frequencies of the system. Such classification shall be based on horizontal and vertical configurations defined in the codes.

Two common cases of vertical irregularities are, the *Stiffness-Soft Story Irregularity*, and the *Lateral Strength-Weak Story Irregularity* (Fig.1a). According to ASCE [1], *Stiffness-Soft Story Irregularity* is defined to exist where there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. Structures with *Stiffness-Extreme Soft Story Irregularity* shall not be permitted, this category is defined to exist where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above.

In the other hand, discontinuity in *Lateral Strength-Weak Story Irregularity* is defined to exist where the story lateral strength is less than 80% of that in the story above. (The story lateral strength, is the total lateral strength of all seismic-resisting elements sharing the story shear for the direction under consideration). When the story lateral strength is less than 65% of that in the story above, the building in classified whit discontinuity in *Lateral Strength-Extreme Weak Story Irregularity*.

Moreover, the Complementary Technical Standards for Seismic Design of the Mexican Code, NTCDS [2], include both extreme conditions simultaneously, i.e. the *Stiffness-Extreme Soft Story Irregularity* and the *Lateral Strength-Extreme Weak Story Irregularity*, through the condition of regularity number 10 in section 6 of the NTCDS, noting that "neither rigidity and strength to shear of any storey differ in more than 50 percent of the next lower storey." The last floor is excluded from this requirement, which means that the lower story floor should not be less than 67% of the rigidity of the story level above, nor be less than 67% of the strength.

Among the horizontal discontinuities in buildings, the *Out-of-Plane Offsets Irregularity* is defined to exist where there are discontinuities in a lateral force-resistance path, such as out-of-plane offsets of the vertical elements (Fig. 1b).

In buildings constructed recently in Mexico, each day is more frequent that floor systems are built to support load-bearing walls, whether confined masonry or reinforced concrete, which are discontinuous in elevation, and the *Out-of-Plane-Offset* irregularity is evident; reason why system formed by slabs and secondary beams must transfer the vertical and lateral loads to the bottom floor and to Foundation. In general, these walls are subject to shear forces greater than that would be if they were on rigid supports either if they were continuous until the Foundation. This situation can increase the vulnerability in buildings with discontinuity of height, and structured with transfer floor systems, especially when they have four or more stories, as shown in Fig.2.

The transfer floor system has been investigated using an experimental model [3], in order to analyze the interaction between the wall and the slab on which is supported. Besides, several slab-wall numerical models were also analyzed using ANSYS in order to characterize the behavior of a transfer slab system [4, 5]. In the experimental phase a full-scale slab-wall specimen was designed, built and tested by cyclic loads in the Laboratory of Structures at UAM-Azcapotzalco [6]. The prototype slab-wall was subjected to three load patterns: 1) gravitational load; 2) horizontal load only; and 3) a combination of gravitational and lateral loads.

We found some significant differences in behavior between these systems and the traditional ones that do not have discontinuities.

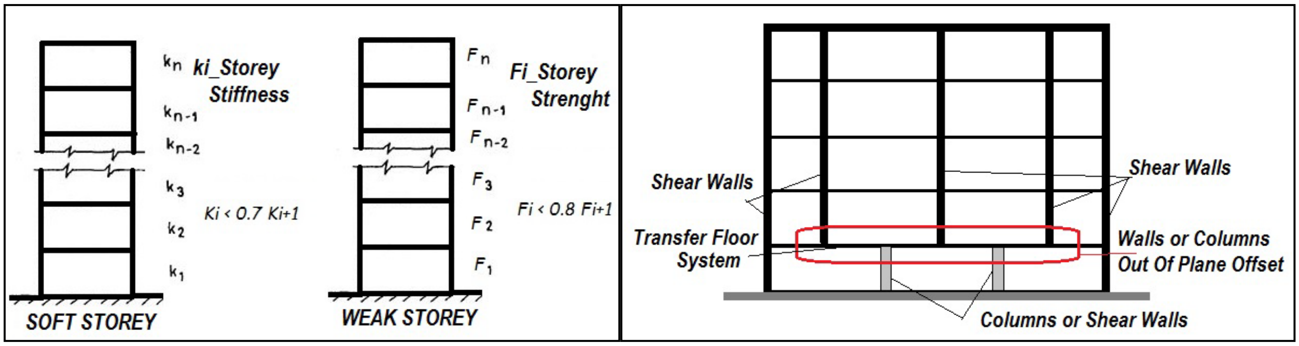

Fig. 1 – (a) Vertical Irregularities: Soft Storey and Weak Story. (b) Horizontal Irregularity: Out of Plane Offset

2. Buildings constructed with a transfer floor system

The construction of buildings structured with transfer floor systems has become a common practice in several cities in Mexico, some of which have a high seismic risk. This section summarizes some results of analysis of three buildings erected in Mexico City, which are part of the database of *Colonia Roma* buildings, and some results were presented by Gómez-Bernal et al [4].

The building A is for residential use, has six stories on the ground level and a basement walls as part of mat Foundation. The ground story (top of Fig. 2) is intended for parking, and their structure is of reinforced concrete frames; the five remaining stories are structured with load-bearing walls some of red brick masonry and others of reinforced concrete. Floor slabs are of various types, so the Mat foundation plate is reinforced concrete with concrete walls, the first floor level also are of reinforced concrete cast on site, but the remaining upper levels were constructed with prefabricated beam and block, lightened with polystyrene

Building B is also for residential use, has six levels on a waffle transfer slab, under which there are two basements for parking. The dimensions of plan type are 26 m x 14.5 m, with an area of 377 m^2. Has a basement walls as part of the mat foundation, with a thick slab of 30 cm. Both, the transfer slab and the upper floor of the basement, are waffle slabs lightened, with depth of 30 to 40 cm; While levels up are beam and block of a depth 0f 25 cm.

There are several cases of structural systems based on transfer floor systems. For example, the columns and walls of transfer floors can be supported on beams with different stiffness, which implies that these beams can be idealized as elastic springs, as it is the case of building A, whose plan is shown in Fig.3, the shaded area enclosed by the axes A-K and 8-12, is the part of the building which rests on the transfer floor system, which is formed by beams and a solid slab of 12 cm (most of the interior walls are interrupted at that level and do not rest on any beam). Another case of transfer floor systems is when transfer-slabs are built with waffle slabs without beams (Fig.4), showing the plans of building B (we can see that none of the walls of the axis of the short direction is aligned with the rigid frames of the floor immediately below).

Building C has two main bodies on a rectangular area of 26 m x 29.5 m, which share a central courtyard (Fig. 4). The ground story structure has reinforced concrete frames with 42 columns, on which there is a transfer slab of reinforced concrete with a thick of 15 cm. On this slab four upper stories were built with load bearing walls of masonry and reinforced concrete, in this stories the floor system consists of beam and block.

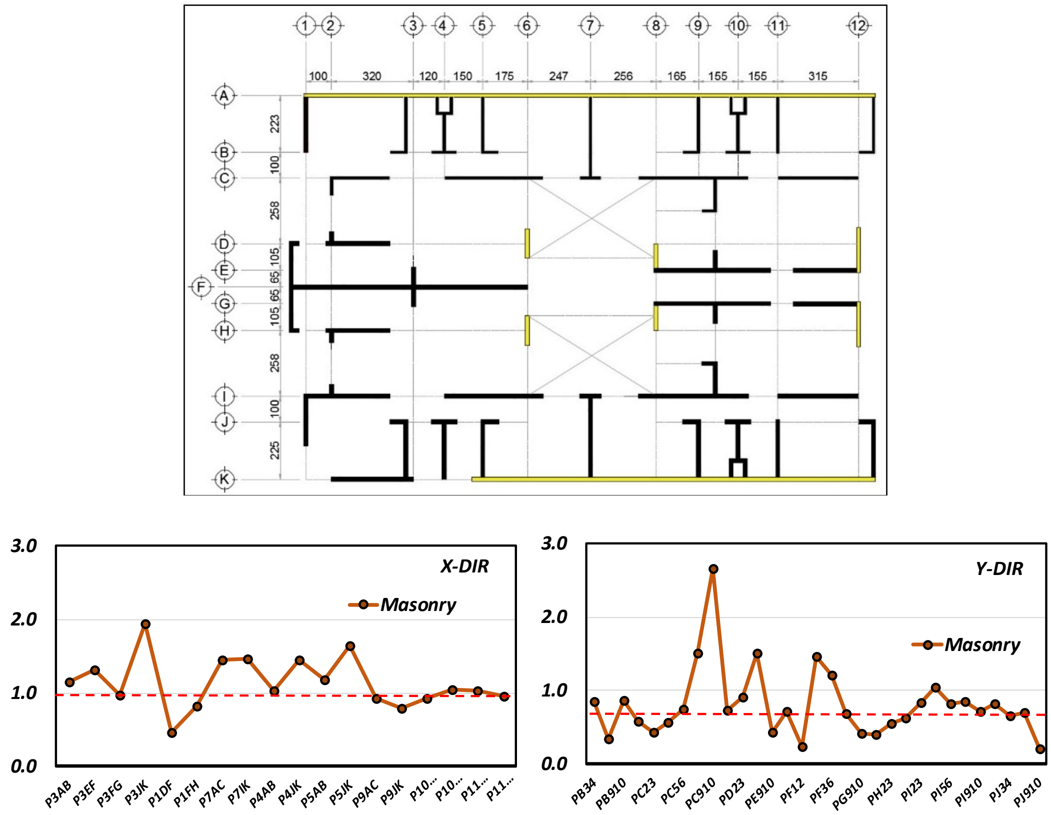

Fig. 2 – Transfer Floor Plan in Building A, and Shear Ratio in walls located on the Transfer Floor.

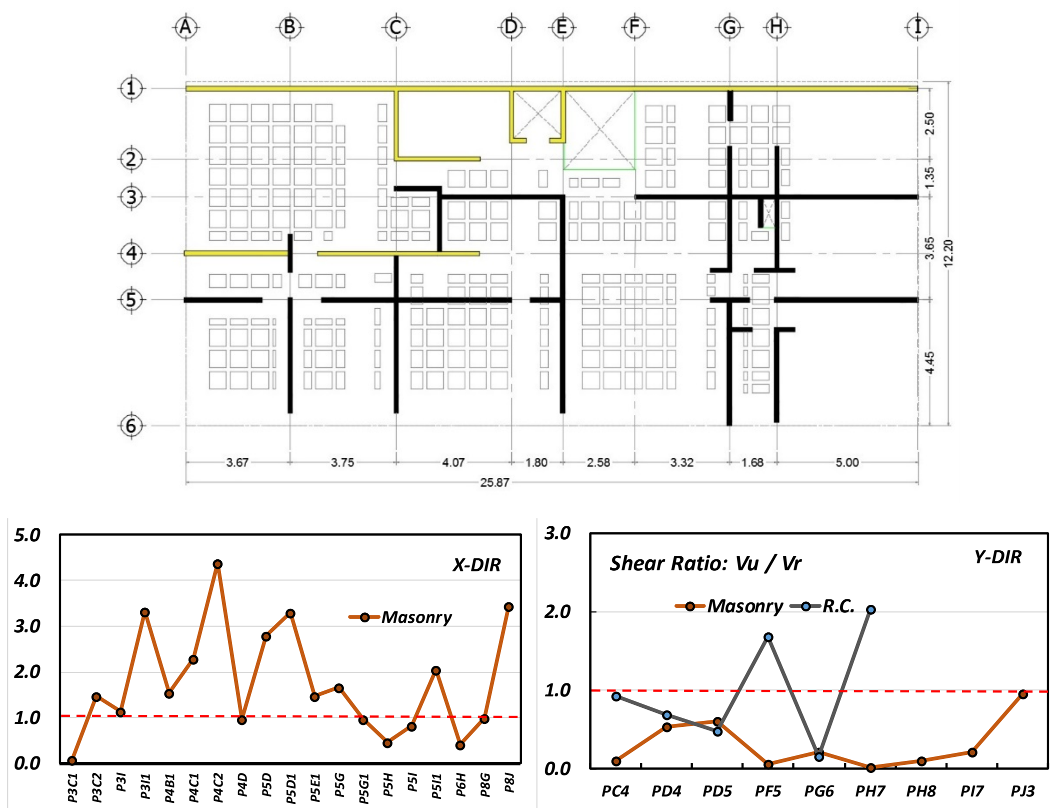

Fig. 3 – Transfer Floor Plan in Building B, and Shear Ratio in walls located on the Transfer Floor

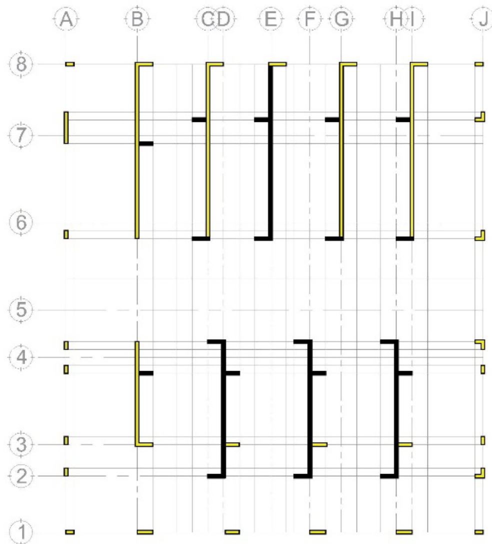

Fig. 4 – Transfer Floor Plan in Building C.

2.1 Irregularity Analysis of Buildings

In basis on structural analysis from the three real buildings (A, B and C), shear force ratios in the masonry walls (ratio between ultimate shear and strength shear) are presented in Fig. 2, 3 and 4. Graphs in both directions of the building A show that resistance is exceeded on a lot of discontinuous walls, and in many walls, shear force ratios are greater than 2. However, in building B is more critical the situation, because in the X-dir, the shear force ratios in masonry discontinuous walls are exceeded by more than 4 times; While in the Y-dir, are exceeded by twice in two reinforced concrete walls.

Table 1 – Comparison of discontinuous parameters from the three studies buildings

	A-X	**A-Y**	**B-X**	**B-Y**	**C-X**	**C-Y**
Discontinuous Area in Reinf. Conc. Cols.	0.00	0.00	0.00	0.00	0.00	0.00
Discontinuous Area in Masonry Walls	6.12	9.91	5.22	3.57	0.00	4.01
Discontinuous Area in Reinf. Conc. Walls	1.64	0.54	1.71	1.61	2.16	3.15
Total Wall Discontinuity	**91%**	**69%**	**34%**	**61%**	**31%**	**47%**
Effective Wall Discontinuity	75%	44%	15%	46%	31%	79%
Story Strength Ratio (RGS/R1S)	1.18	1.30	0.75	1.54	1.11	0.63
Story Stiffness Ratio (K1S/K2G)	0.67	0.66	1.40	1.40	19.8	2.23

Table 1 compares areas of discontinuous walls of buildings (Fig. 2 to 4), i.e. the walls that are interrupted and do not reach the ground interstorey. As it can be seen in this table, total discontinuity of walls in every principal direction of the building is very high in all cases. Thus, in X-dir of building A is the highest value of wall discontinuity (91%).

In addition, Table 1 presents the ratios between the stiffness of the ground storey, and the stiffness of the first storey (KlS/K2G). Only in the building A, this stiffness ratio is less than 1 in both directions (0.67 and

0.66), so the building is classified as soft story irregularity. In the other hand, in terms of the strength ratio between the lower levels, which is used to identify weak story buildings, these values are calculated less than 1 in the BX and CY directions.

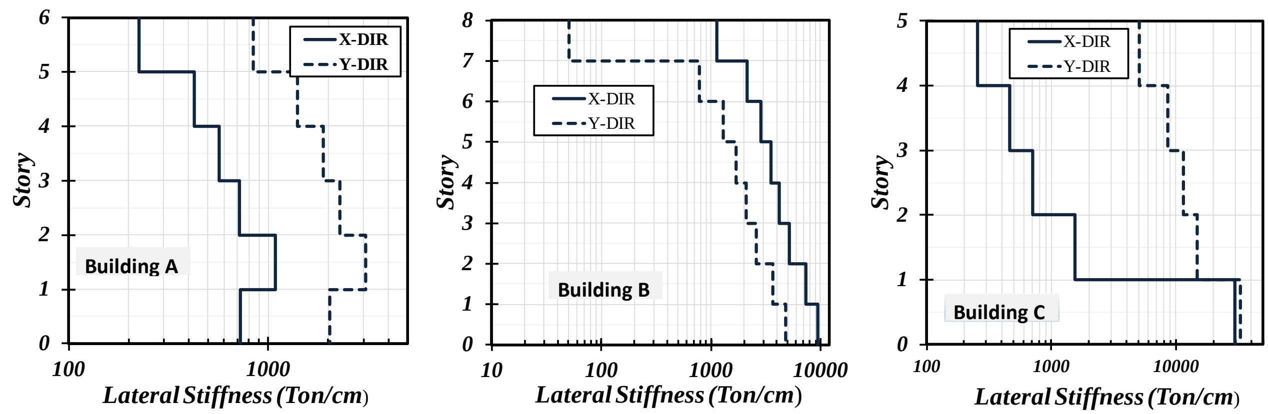

Fig. 5 – Lateral stiffness in the three studied Buildings

3. An expression to evaluate Buildings with *Out-of-Plane Offsets* Irregularity

According to the results presented in section 2, only the building A would be classified as *Stiffness-Soft Story Irregularity*, and directions B-X and C-Y with *Lateral Strength-Weak Story Irregularity*. They comply with some of the requirements set out in the code. However, these three buildings structured with transfer floors, can fall within the horizontal irregularity Out-of-Plane Offsets. This horizontal irregularity occurs when some structural systems (bearing walls and frames) of the story, are not aligned with the lower story, as Fig. 1 illustrates it.

3.1 Total discontinuity ratio at floor transfer level, in a principal direction of a building

With the aim of characterizing buildings with the horizontal discontinuities, Out-of-Plane Offsets Irregularity, due to the structure with transfer floors, we propose the following parameters of discontinuity. Total discontinuity of a building can be estimated when areas of the resistant vertical elements are compared, such as load-bearing walls and columns, in each principal building direction, as:

$$\text{DiscTot}\,(\%) = [\textstyle\sum(\text{Adis\_plane\_i}\ \ i=1,2,3\ldots n] \,/\, [\text{Atm}_{1s} + \text{Atc}_{1s} + \text{Atcc}_{1s}] \tag{1a}$$

where:

$$\text{Adis\_plane\_i} = (\text{Am}_{1s} + \text{Ac}_{1s} + \text{Acc}_{1s} - \text{Am}_{gs} - \text{Ac}_{gs} - \text{Acc}_{gs}) \geq 0 \tag{1b}$$

In these expressions:

DiscTot_ total discontinuity ratio, in a principal building direction at floor transfer level.
Adis_plane_i- discontinuity area in the plane i (or axis i)
Am_{1s} – masonry wall area in the first storey (1s) of plane i
Ac_{1s}- reinforced concrete wall area in the first storey (1s) of plane i
Acc_{1s}- reinforced concrete column area in the first storey (1s) of plane i
Am_{gs}- masonry wall area in the ground storey (gs) of plane i
Ac_{gs}- reinforced concrete wall area in the ground storey (gs) of plane i
Acc_{gs}- reinforced concrete column area in the ground storey (gs) of plane i
Atm_{1s} - masonry wall area in the first storey (1s) of principal building direction
Atc_{1s}- reinforced concrete wall area in the first storey (1s) of principal building direction
$Atcc_{1s}$ – reinforced concrete column area in the first storey (1s) of the principal building direction

In order to take in to account the resistance of each material (masonry or reinforced concrete wall), the above expression can be modified as:

$$\text{DiscEffect (\%)} = [\textstyle\sum(\text{Adis\_plane\_effi})] / [Atm_{1n} + 8*Atc_{1n} + 4*Atcc_{1n}] \quad (2a)$$

where:

$$\text{Adis\_plane\_eff\_i} = (Am_{1n} + 8*Ac_{1n} + 4*Acc_{1n} - Am_{pb} - 8*Ac_{pb} - 4*Acc_{pb}) \geq 0 \quad (2b)$$

and:

DiscEffect_ effective discontinuity ratio, in a principal building direction at floor transfer level

3.2 Lateral Strength Ratio in a Building Story

Besides, in order to estimate the strength ratio between the ground story, which supports the transfer floor, and the next story up (first story), and with the intention to detect if the building have a weak story, we propose the following simplified expression for the lateral strength story, LatSS, as:

$$\text{LatSS} = [Am_{1n} + 8*Ac_{1n} + 4*Acc_{1n}] / [Am_{pb} + 8*Ac_{pb} + 4*Acc_{pb}] \quad (3)$$

4. Parametric analysis of buildings with Out of Plane Offsets Irregularity

This section presents results of a parametric analysis of building models, the aim is to study the effect that has the interruption of the walls on the first floor of the buildings or transfer floor, i.e. the impact on the wall discontinuity in elevation; besides, the effect of rigidity variation between two consecutive stories. Emphasis is made on the variation of shear forces and axial forces in load-bearing walls, where many of which rest directly on the transfer slab.

The analyzed models include a basic five-story building, or Basic Continuous Masonry Model (BCMM), with the plan distribution shown in Fig. 6; This basic model has no discontinuity of any load-bearing wall, i.e., the ground interstory is the same as the rest of the stories. In addition, other six different models were studied, in which the same structural configuration of the upper stories remained as the basic model BCMM, and only the ground inter story was modified (Fig. 7). Each building has a rectangular plan of 15 m x 9 m, a height of 3.0 m for the ground interstory and 2.5 m for the remaining stories.

The seven models were structured with masonry walls, in the first model (BCMM) all walls are continuous, i.e. it has no out of plane offset irregularities; besides, were also analyzed other six different Discontinuous Masonry Models: DMM1, DMM2, DMM3, DMM4, DMM5 and DMM6, the values of discontinuous wall areas for each case are shown in Table 2, also are shown the ratio values between the ground storey stiffness (Kb), and the first story stiffness (K1).

The masonry walls have a thickness of 12 cm and are confined by tie-columns of cross section of 15 x 15 cm, which are separated according with regulations of the Mexican Construction Code NTCEM [7]. Transfer slab girders and secondary beams have a cross section of 30 x 60 cm, and 25 x 55 cm respectively, while the columns have a cross-section of 60 x 60 cm. The thickness of transfer slab is 12 cm.

The material properties of the structural elements used are as follows: Reinforced concrete has a volumetric weight is 2400 kgf/m³ and a compressive strength, f 'c, of 250 kg/cm², except in the tie-columns where a value f'c of 200 kg/cm² was used. In masonry walls, a compressive strength of 50 kg/cm2 and a modulus of elasticity of 15,000 kg/cm² were used The yield strength, Fy, of steel reinforcing bars was defined equal to 4200 kg/cm².

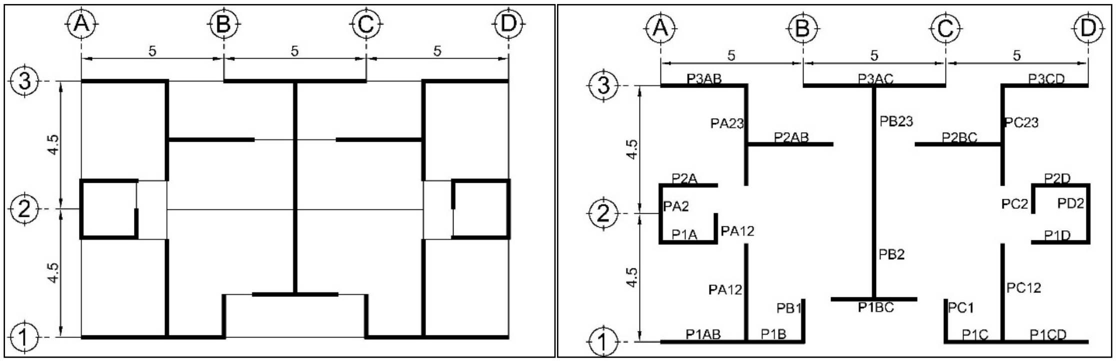

Fig. 6 – Ground Story Plan, GS (left). First Story Plan, S1, in Basic model, BCMM, and in all models (right).

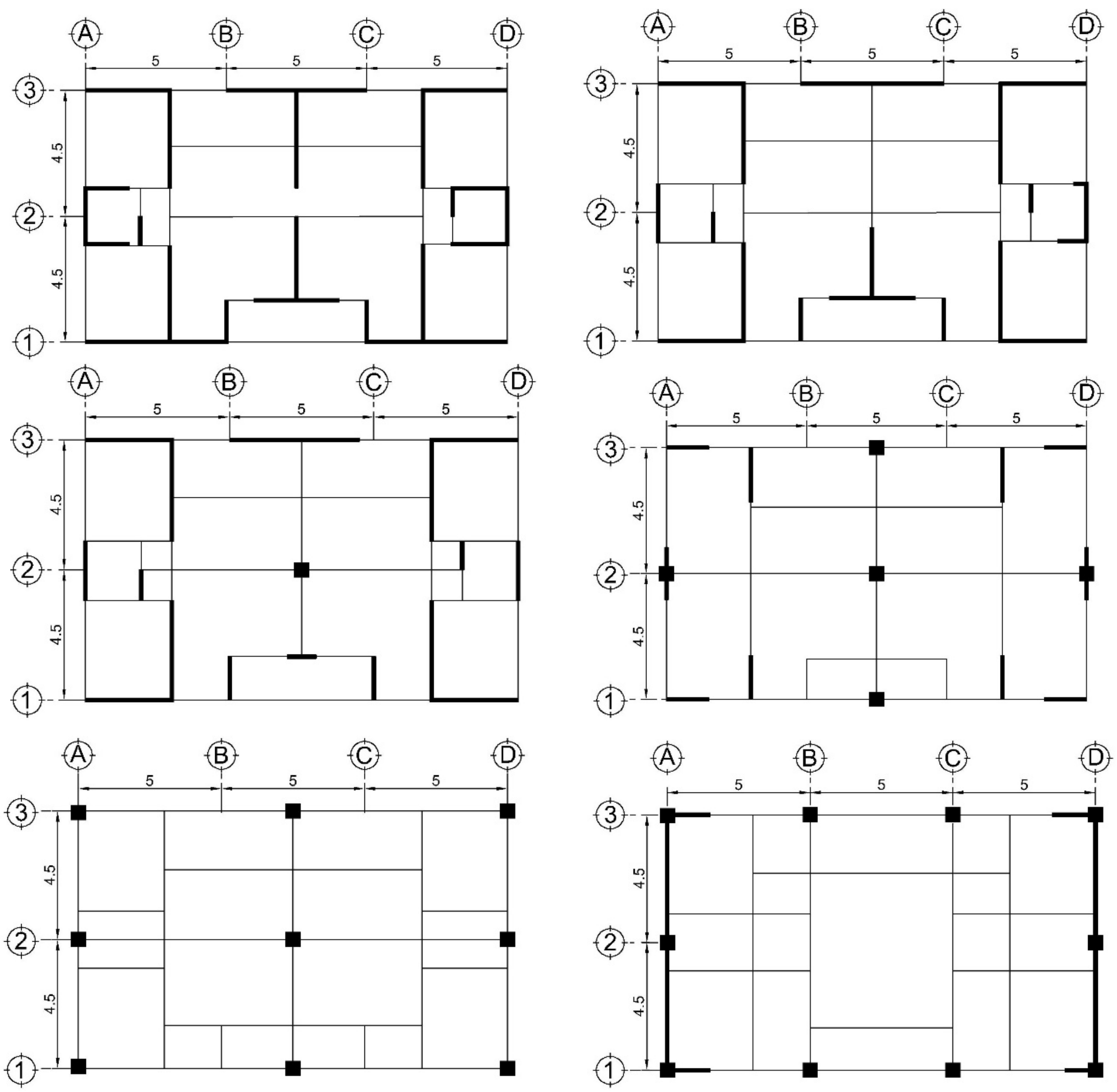

Fig. 7 – Ground Story Plan of six models with wall discontinuities: DMM1, DMM2, DMM3, DMM4, DMM5 and DMM6, respectively.

In this research the building prototypes were designed with forces calculated from reduced spectra with seismic behavior factors Q=2 (Ordinary design), according to Mexican Construction Code [8]. In total, 7 different buildings were designed, all of them were subjected to both static and dynamic analysis.

In order to estimate the impact of the vertical discontinuity on the load-bearing walls in the first and second stories, the shear forces from the walls of the ground story and the first story of the models, were used as parameters of evaluation. The walls are identified as listed in Fig. 5, and determines the shear and axial forces generated at the base of the walls, due to gravitational loading and to the seismic loading

Table 2 – Discontinues wall areas ratios and stiffness in the studied models

Model Id	CMMB	DMM1	DMM2	DMM3	DMM4	DMM5	DMM6
Ground Story, GS, stiffness (Ki/Kb)	100%	80%	60%	50%	40%	20%	67%
Wall discontinuity Ratio, X-DIR	0%	20%	43%	53%	74%	68%	58%
Wall discontinuity Ratio, Y-DIR	0%	3%	16%	18%	44%	67%	77%
Effective discontinuity Ratio, X-DIR	0%	20%	33%	42%	45%	45%	45%
Effective discontinuity Ratio, Y-DIR	0%	3%	16%	0%	39%	62%	77%

Fig. 8 shows the ratios between the shear forces of the first story walls of each discontinuous model, and the shear forces of the first story walls of the basic continuous model (BCMM); the graphs are presented for each of the two main directions (X and Y); in the figure, the horizontal axis shows the ratio of discontinuous walls, and in parentheses, are indicated the relationship between the first story stiffness in each discontinuous model and their corresponding of the basic continuous model. It can see, from this figure, that the shear wall ratios increase as it increases the discontinuity of walls, these become greater than six times in the X-direction, and up to 9 times in the Y-direction, in the more critical cases. In Fig. 9, the results for the second story are shown, in this case also there are high wall ratios, reaching up to 8 times in X-direction.

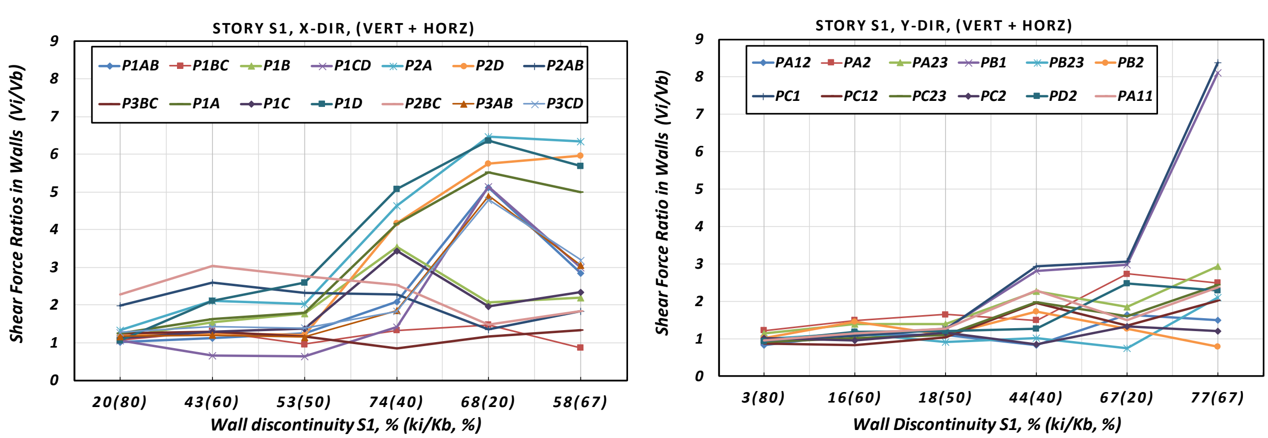

Fig. 8 – Ratios between the shear force in S1 story walls of each discontinuous model, and the shear force of S1 story walls of the corresponding of the basic continuous model (BCMM).

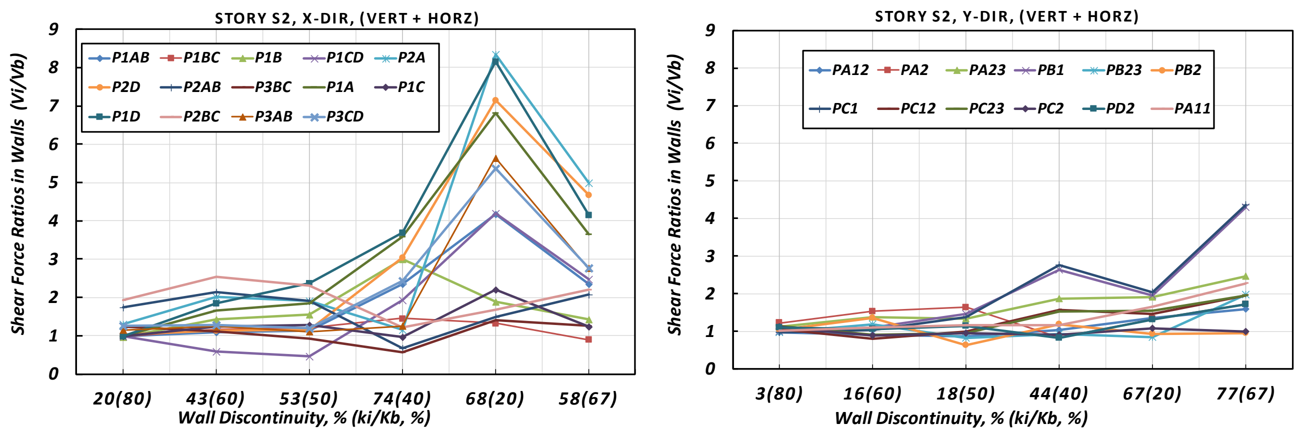

Fig. 9 – Ratios between the shear force in S2 story walls of each discontinuous model, and the shear force of S2 story walls of the corresponding of the basic continuous model (BCMM).

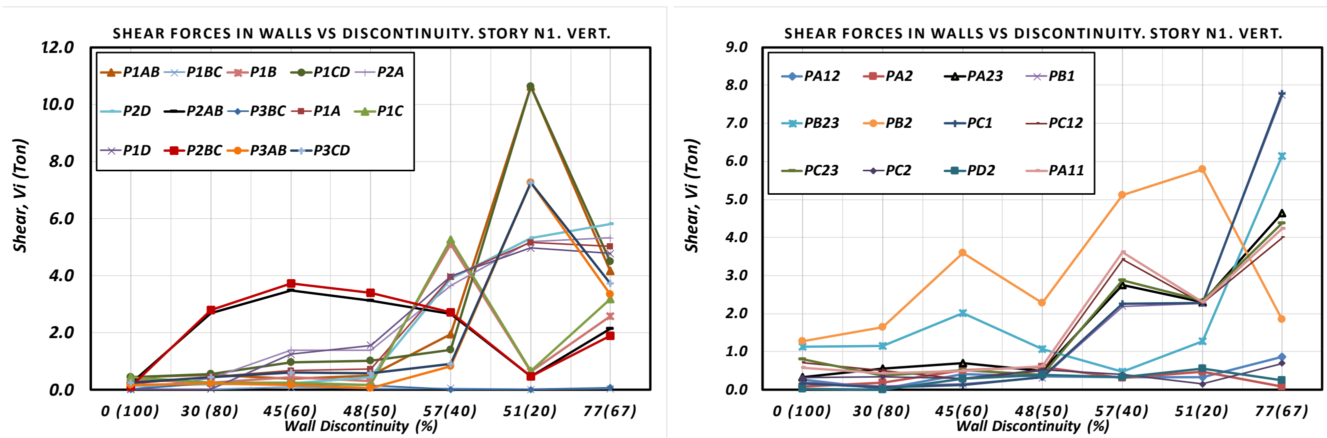

Fig. 20 – Shear force in walls of S1 story of each model.

On the other hand, in Figure 10 values of the shear forces are presented in each of the walls of the first story corresponding to the vertical load condition for all models studied. In this figure, it can see the same trend shown in previous figures, i.e., that the ratios of the sharp increase as it increases the discontinuity of walls.

Finally, Figure 11 shows the ratio of ultimate shear forces, Vu, from combined condition (vertical load plus horizontal loading), between their respective shear resistances, Vres; It is detected in this figure, a lot of walls to exceed its resistant capacity in all cases of discontinuity, and for the model with 67% of rigidity exceeds the value of 2. The shear resistant walls were estimated according to the NTCEM [7], which proposed that the shear force resistant design of confined masonry walls is given as:

$$V_{mR} = F_R\,(0.5 v_m^* A_T + 0.3P) \leq 1.5\, F_R\, v_m^* A_T \tag{1}$$

where:

V_m^* = diagonal compressive strength of masonry
A_T = cross section area of the wall including tie-columns
P = vertical load on the wall, positive in compression
F_R = shear strength reduction factor, equal to 0.75.

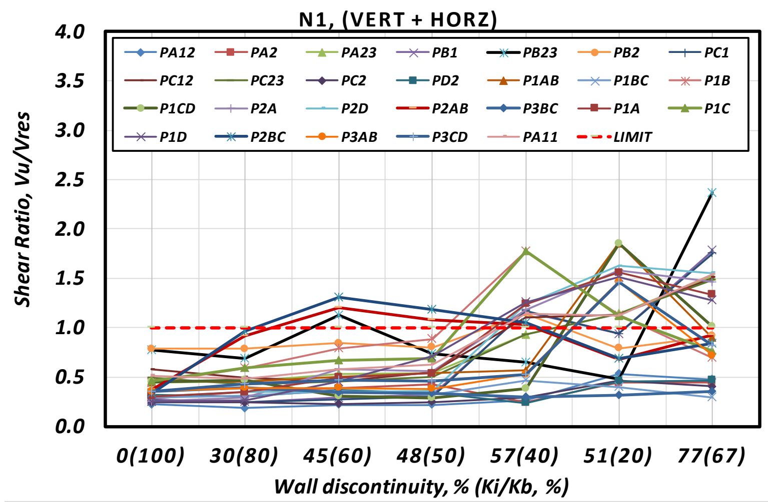

Fig. 31 – Shear force Ratios (Ultimate, Vu / Strength, Vres) in walls of S1 story of each model.

5. Summary and Conclusions

We reviewed three buildings recently constructed in Mexico City in order to verify the next vertical and horizontal irregularities conditions: (1) soft storey, (2) weak storey, and (3) out of plane offsets. With respect to the review as a weak floor, a simplified expression was proposed and used in this research, which estimates roughly the strength relationship between two consecutive stories. When the simplified expression proposed here was used, it was found that only C building, has a value in the limit, in one of their direction according to the Mexican code.

Besides, with the purpose of characterizing the buildings structured with transfer floor systems, also known as systems with irregularities out of plane offset, a parametric study of models of buildings with discontinuities in height it was performed. Several models are defined as buildings of five stories, a basic ground story model, which was modified with the idea of going by varying the rigidity of this ground inter-story on a model basis, where there is no discontinuity. The rest of the stories were structured with masonry load-bearing walls, and these were kept unchanged for all models.

We conclude that the horizontal irregularity out of plane offset can increase in a significant way the building vulnerability, and is independent of the other two irregularities. Because, only a building was detected with a soft story, and other is considered as building with weak floor. Nevertheless, in the case of the horizontal irregularity, out of plane offset, all buildings were classified with a high irregularity, because the total discontinuity in wall areas in each principal direction was ranging between 31% and 91%. This wall discontinuity generated that shear forces in bearing walls are increased considerately. Results in both directions of the buildings show that shear capacity is exceeded on a lot of discontinuous walls, and in many walls, shear force ratios are greater than 4.

The most relevant conclusions from the parametric analysis is that increasing the discontinuity, i.e., as there are more walls that are interrupted and supported on the transfer floor system, the shear and axial forces in load-bearing walls are increased too, reaching values that exceed the nominal resistance and design up to more than 3 times. Then it is recommended in the conceptual design of the buildings, that the total area of discontinuous walls never can exceed 40% in a main direction; neither more than 30 % in the two directions simultaneously. In addition, the collector elements and connections that transfer lateral loads must be designed increasing their design strength by 25%.

In this research some of the recent findings obtained from analysis on irregular buildings are outlined. Both horizontal and vertical irregularities were considered. The studies involved developing simple equations that can be used by designers to estimate the likely increase in demand due to out of plane offsets irregularity. This study also provides a technical basis for revision of the Mexican Construction code.

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