BEHAVIOR, DESIGN AND REPAIR OF TRANSFER SLABS EXPOSED TO SHEAR-WALL LOADS

E. Arellano-Méndez(1), A Gómez-Bernal(2), O. M. González-Cuevas(3), H. Juárez-García(4), G. Rangel-Torres(5).

(1) *Professor, Universidad Autónoma Metropolitana, eam@azc.uam.mx*
(2) *Professor, Universidad Autónoma Metropolitana, agb@azc.uam.mx*
(3) *Professor, Universidad Autónoma Metropolitana, omgc@azc.uam.mx*
(4) *Professor, Universidad Autónoma Metropolitana, hjg@azc.uam.mx*
(5) *Professor, Universidad Autónoma Metropolitana, grt@azc.uam.mx*

Abstract

With the purpose to study the behavior of a transfer slab system, two slab-wall full-scale specimens were designed, build and tested to cyclic loads in the Laboratory of Structures at UAM. The prototypes slab-wall were subjected to three load patterns: 1) gravitational load; 2) horizontal load only; and 3) a combination of gravitational and lateral loads. The first specimen consists of a masonry wall placed on top of a squared two-way slab of 4.25 m by side, thickness of 12 cm, on four reinforced concrete beams, while the second specimen was constructed with a reinforced concrete wall. The most important results presented herein are the change on lateral stiffness and resistance capacity of the load-bearing wall supported on a slab versus the wall supported on a fixed base, and the effects that these walls cause on the slabs. Analytical finite element slab-wall models were built using linear and non-linear models. During the experimental test process of horizontal loading, we detected that the stiffness of the slab-wall systems decreased by a third compared to the one on the fixed base wall; a result that supported by the numerical models.

Keywords: slab; repair; shear walls, transfer.

1. Introduction

In Mexican cities the construction of medium-rise buildings with a structural floor system called "transfer slabs" have been popularized over recent years. A recent survey [1] evaluated a set of new buildings constructed in a sector of Mexico City, which was severely damaged during the 1985 earthquake; in this evaluation was detected a high percentage of buildings that were designed with discontinuous walls, a structural configuration that induced soft story in some buildings. Furthermore, many of them are projected with transfer floor systems. This situation is worrying because it is known that buildings with discontinuity in elevation are vulnerable to seismic loads. This situation is critical when load-bearing walls, especially on the first floor, are not aligned with the vertical forces, therefore increasing seismic vulnerability.

These structures have a floor system (transfer slab or transfer floor) supported on one rigid level, which is used as a parking lot. On top of this transfer slab, a four-story shear wall super-structure is constructed. A large percentage of these walls are interrupted at the transfer floor level, and they are not continuous through the foundation. However, a few walls are continuous in height over the edges of the structure, but a significant percentage of walls in the upper stories are not aligned with the axes of the frames of the first floor. Numerical models have shown that this structural configuration causes a significant increase in the shear stress in these walls, as is observed and discussed in detail in the following references [2, 3]. This can be explained due to the excessive deflections that walls induce to the slab. The shear forces calculated are two to three times larger than those that these walls would have if they were continuous throughout all their height. In addition, the transfer slab is exposed to additional stresses and high deformations.

During the September 19, 2017 earthquake (M=7.1) an extensive damage was observed in Mexico City, some buildings structured with this system suffered important damage. For example, Figure 1a show the collapse of a building which had eight stories, only the first story. Other examples, Figure 1b shows two buildings structured with this system, when these structures were reviewed, minor diagonal cracks were detected at the ends of the beams of the floor transfer.

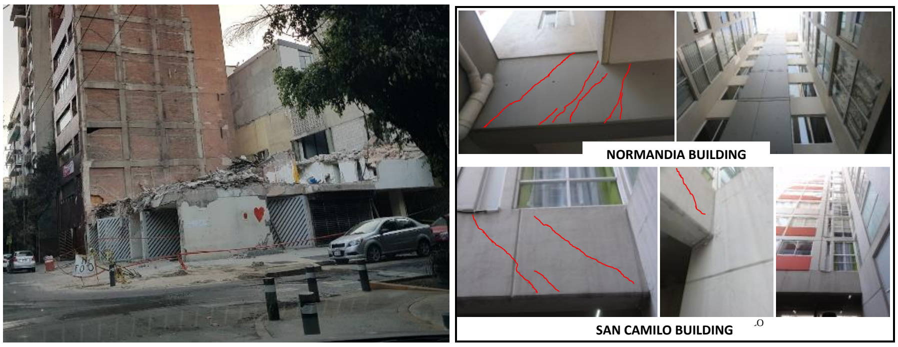


Fig 1 - (a) Collapse of a building with discontinuities; (b) Diagonal Cracks in the beams of the transfer floors in two buildings supporting six and seven levels respectively.

The transfer floor system requires further investigation, and in this work the fundamental objective is to analyze, using an experimental model, the interaction between the wall and the slab on which is supported. There are significant differences in behavior between these systems and the traditional ones that do not have discontinuities. Several slab-wall numerical models were also analyzed using numerical models (Finite element) in order to characterize the behavior of a transfer slab system. In the experimental phase two full-scale slab-wall specimens were designed, built and tested by cyclic loads in the Laboratory of Structures at UAM-Azcapotzalco. The prototypes slab-wall were subjected to three load patterns: 1) gravitational load; 2) horizontal load only; and 3) a combination of gravitational and lateral loads.

Mexico and other countries have conducted experimental research on the behavior of load-bearing walls subjected to lateral forces in order to characterize the seismic effects. Walls that have different characteristics, in terms of materials, reinforcement, load conditions and other properties have been tested [4-

7], and some of the most notable results were documented [8]. Moreover, in terms of the experimental behavior of concrete slabs, there is less information due to the limited number of tests performed. In the limited research the slabs were subjected to distributed or concentrated loads; however, there was no specific linear loads information directly applied on the slabs (walls supported on the slabs).

2. Experimental Models

The experimental test included three load protocols: (1) gravitational loads with less than 8 Tons, which is the vertical loading observed in buildings that have the stated floor system, (2) horizontal cyclic loads with a relatively low value that are used in order to study the linear response, and (3) gravitational constant loads with less than 8 Tons that are combined with horizontal increased loading cycles until the failure of the system is reached.

2.1 Geometry and reinforcement

The first specimen, SP1 (Figure 2), consists of a masonry wall placed on top of a squared two-way slab of 4.25 m in width, and 12 cm thick, with four reinforced concrete beams (25 x 77) cm along the perimeter. The slab and beams were monolithically casted. The concrete strength was f'c=250 kg/cm². The details and steel reinforcement in the slab were designed using conventional procedures, such as the ones used in real buildings in Mexico City. On the outer strips, the spacing of the bottom re-bars was set to 40 cm. On the central strip, the spacing was set to 20 cm in both directions. In the top of the slab, the reinforcement spacing was also set to 20 cm. Figure 3 shows details of the reinforcement used in the slab specimens.

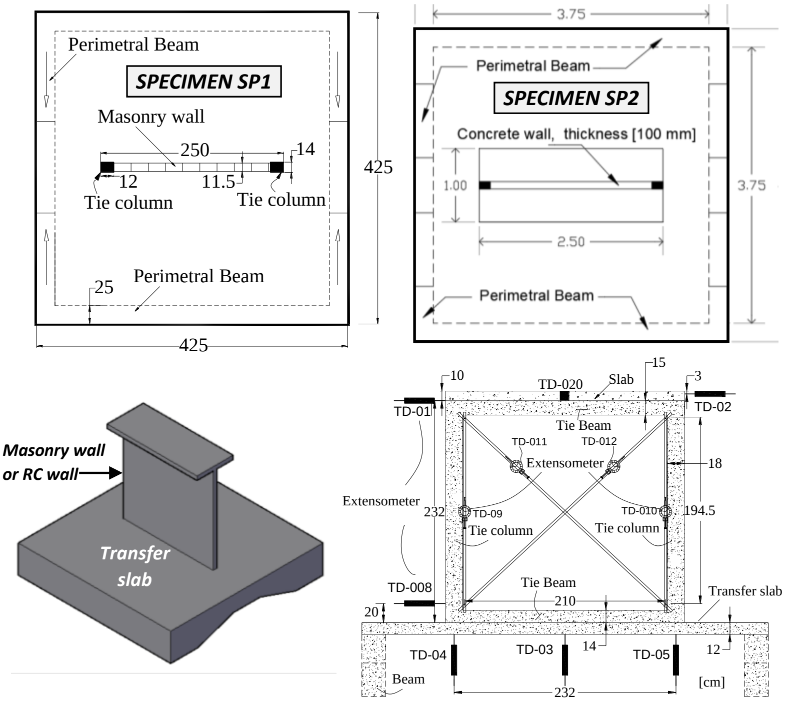
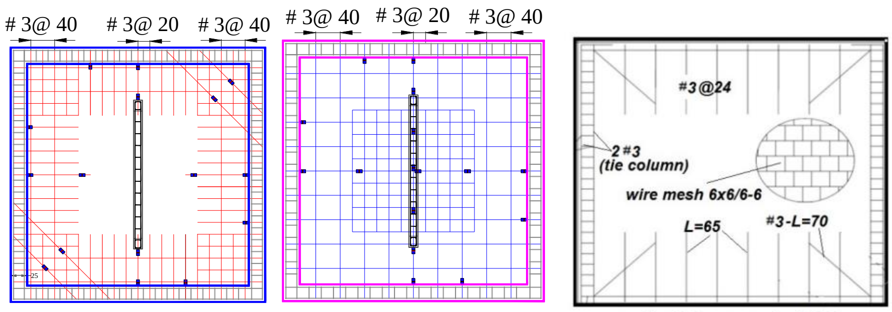


Fig. 2 - Geometry and details of Slab-Wall specimens.

The masonry wall that is 2.50 m wide by 2.41m high, was placed on the slab's central strip. The wall is confined with two tie-columns, 14 cm x 18 cm, and with a tie-beam, 14 cm x 14 cm. The bottom tie-beam was integrated with the slab. The concrete resistance of the tie-columns was f'c=150 kg/cm2, with four re-bars in the corners. The re-bars complied with the minimum steel requirements of the Mexico City code for masonry structures [9].

The second specimen [10], SP2 (Figure 2), consists of a Reinforced Concrete (RC) wall placed on top of a squared two-way slab, with the same characteristics of the SP1 specimen. The RC wall is 2.50m wide by 2.40 m high, and with a thickness of 10 cm.



Top reinforcement Layout Bottom reinforcement Layout **wall reinforcement of SP2**

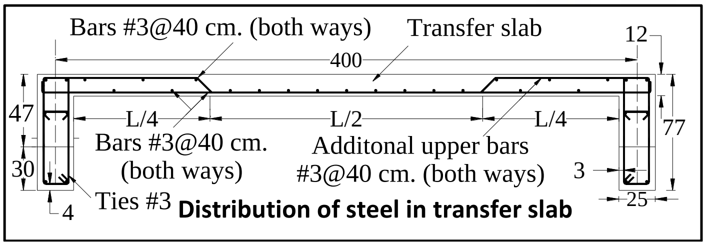


Fig. 3 - Reinforcement details in transfer slab and wall SP2; assembly of strain-gages in bars are included.

2.2 Setup, devices, and instrumentation

We designed and built three mechanical steel devices that helped with the experimental protocol of the specimen: one for attachment purposes, the second one for using in vertical loading, and the third one for horizontal loading. The attachment device prevented the slab-wall specimen from moving in a horizontal or vertical way during the test whenever the loads were applied to the wall. This anchor system consists of a set of steel girders that are fixed in the Laboratory's reaction slab. The gravitational load device was constituted by a system of steel beams, eight tensors and their anchorages (see Figure 2). The main girders have a box section that is made out of two I section welded together by its flanges, and reinforced with stiffeners. At the top of the girders there are four vertical actuators (each with a 25 Ton capacity), supported on a base plate, which keeps them in an upright position and prevents them from slippage. At the ends, there are re-bars that connect down to the perimeter reinforced concrete beams. The third device was designed for the incremental cyclic horizontal loading. We used a double-action hydraulic actuator with a 30 ton push capacity, and a 21 ton pull capacity. We estimated that the lateral capacity of the wall would reach 12 tons. The corresponding LVDT's were attached to each actuator (four verticals and one horizontal).

The measurement of the strains in the specimens was possible due to a set of strain gages (SGs) that were installed in the reinforcement of the concrete elements. The slabs had 16 SGs in the bottom and 16 SGs in the top of the slab. The tie-columns of the masonry wall had 20 SGs in the longitudinal re-bars. And finally, there were 10 SGs in the concrete slab and the tie-columns. In order to record the displacements of the slab and the wall, twenty extensometers (TD) were also installed at strategic points, Figures 1 and 3.

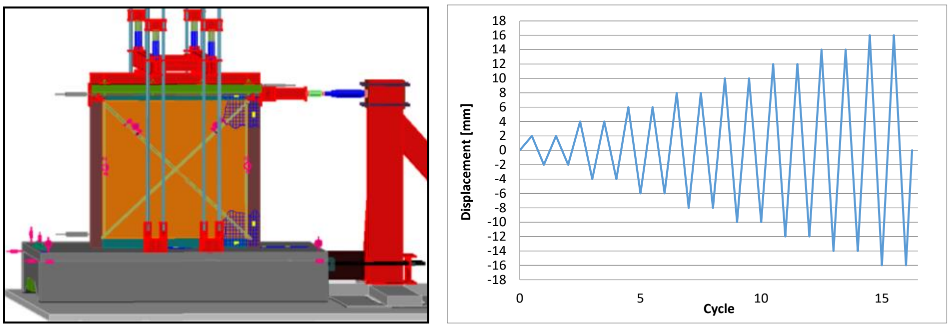


Fig. 4 - Test set up and typical displacement time history.

3. Definition of specimen response

Different configurations, or deformation modes, of the slab-wall model in each of the three loading protocols (vertical, horizontal, and combined), define the structural behavior and the failure of the system (Figure 4). Thus, the failure in the tested walls will depend on the bending (ΔF) and shear (ΔC) deformations induced by lateral loading. However, in this case, since each wall is supported by a slab, the lateral displacement due to the wall rotation (ΔL), induced by the slab deformation, must be considered. Total displacement at the top of the wall ΔT is then induced and presented in Figure 5.

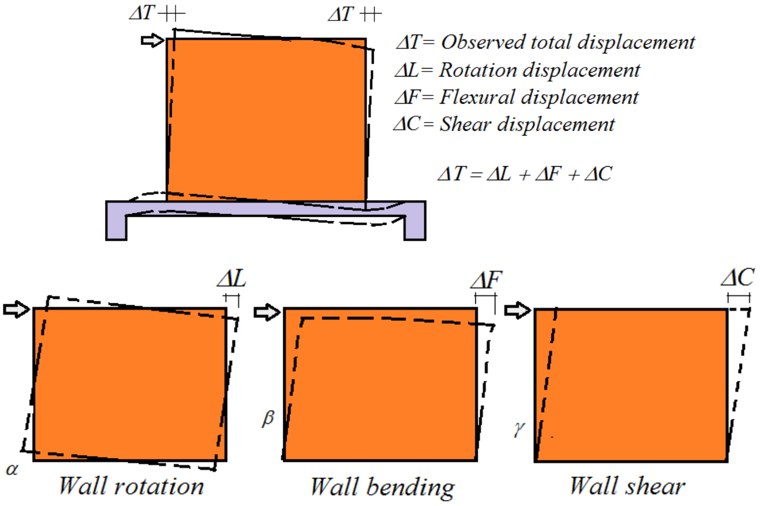


Fig. 5 - Total deformation (above), and principal deformations modes.

Shear deformations in the wall can be obtained from the records of displacement transducers that are installed in diagonal directions. Based on the strength of materials theory, the unitary angular deformation, γ is due to the shear stress acting on the wall element [4]. In general, the reversible cyclic load is defined by the following expression:

$$\gamma = \frac{\delta_2 L_2 - \delta_1 L_1}{2 l_m h_m} \tag{1}$$

where:
γ = angular deformation of wall,
δ_1, δ_2 = shortening or elongation measured on the diagonals,
L_1, L_2= initial length of diagonals
l_m, h_m = are the width and height of the wall respectively.

And the total distortion (R_{tot}) or effective distortion (R_{Eff}) is calculated as:

$$R = \Delta E / H \tag{2}$$
$$\Delta E = \Delta F + \Delta C - \Delta L \tag{3}$$
$$\Delta L = (\Delta I - \Delta D) * H / L \tag{4}$$

where:
R= effective drift of the wall.
ΔE= effective lateral displacement at top of the wall,
ΔL, ΔF, and ΔC _are defined in Figure 5
ΔI, ΔD _ are vertical displacements at ends in wall-slab joint,
H= distance between TD-01 y TD-08 (Figure 2)
L= distance between TD-04 y TD-05 (Figure 2)

4. Experimental results

For the first specimen, rotation, γ, of the wall due to shear deformation is calculated according to the strength of materials theory. Micrometers on wall diagonals did not record any deformation during the first six loading cycles; therefore, it can be concluded that the wall did not have any shear deformations in the first part of the loading process. It only suffered bending and rotation at the base due to slab rotation. However, during the seventh cycle, the diagonal micrometers (TD011 and TD012) began recording shear strains. Until the tenth cycle, the masonry wall exhibited linear behavior, after which the wall experienced non-linear deformations. Figure 8 shows the hysteresis cycles of shear deformations on the wall.

For the second specimen, it can be observed that the slab rotation is practically equal to the wall bending (Figure 9). It can be concluded that the wall did not have any shear deformations (Figure 9).

In Figure 9, four limits are proposed to define the behavior of the specimen [11]. A behavior without damage (green color), a behavior with moderate damage (yellow color), a behavior with serious damage that can be repaired (orange color) and a behavior with serious damage that cannot be repaired (red color).

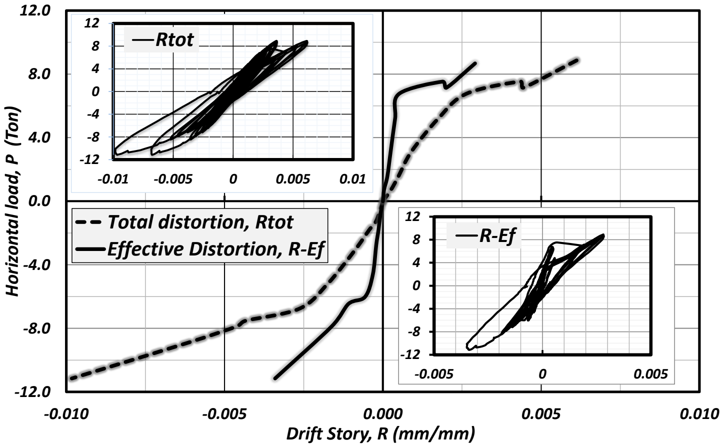
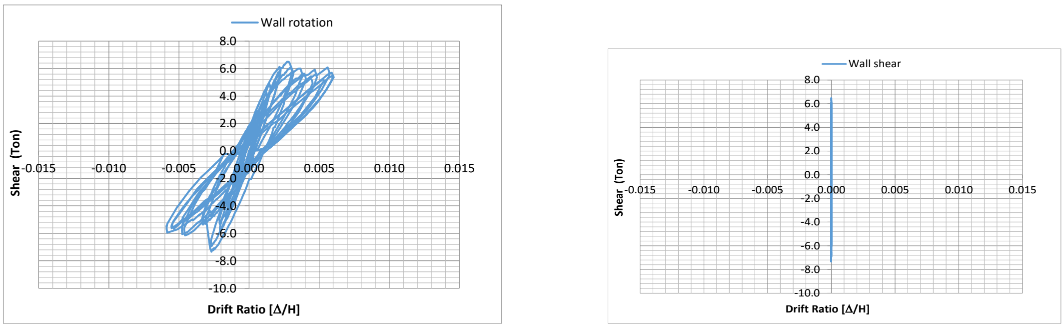
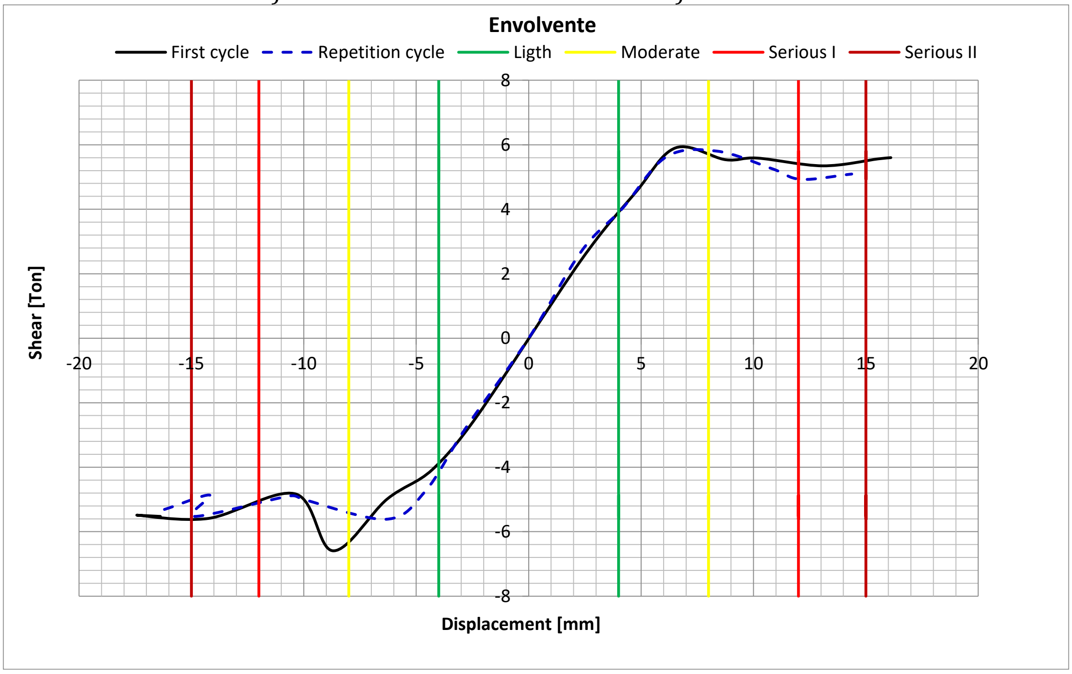


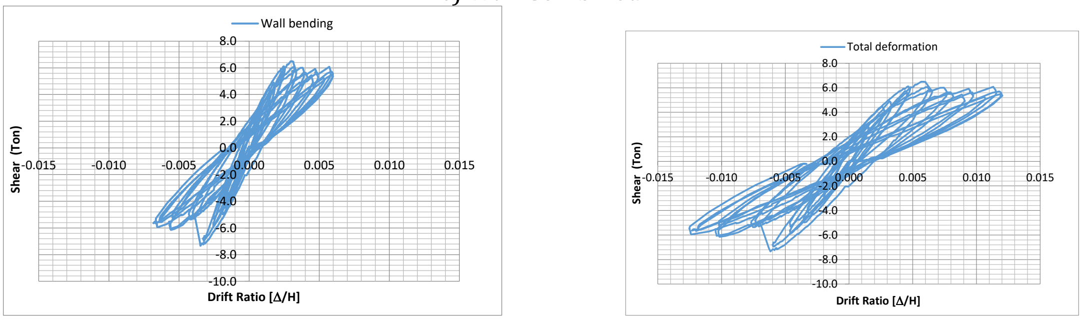
Fig. 8 - Global (Rtot) and effective (Reff) distortions of specimen 1 (with masonry wall) during the combined load, as well as their respective envelopes.



a) Wall rotation b) Wall Shear



c) Wall Combined



d) Wall Bending e) Total deformation

Fig. 9 - Distortions of specimen 2 (with RC wall) during the combined load, as well as their respective envelopes.

The cracking of the fist specimen occurs in bout wall and slab (figures 10 and 11), but in the second specimen was concentrated in the slab (figure 11), the concrete wall was practically without cracks (figure 10), and because the seismic force is transmitted as a shear in the most resistant direction of the wall and in the slab is passed as a bending with respect to the axis of least inertia.

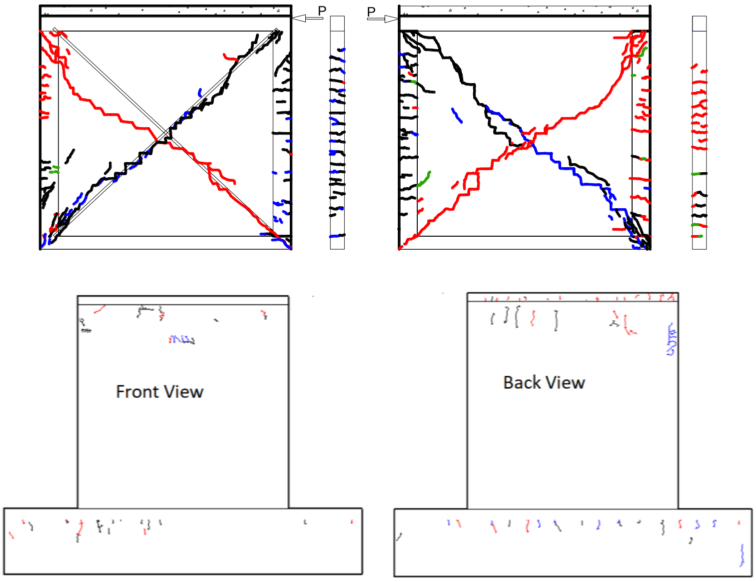


Fig. 10 - Cracking on the masonry wall (top) and on RC wall (bottom), after applying the complete load cycles. Cracking on the front side and back side of the wall are illustrated.

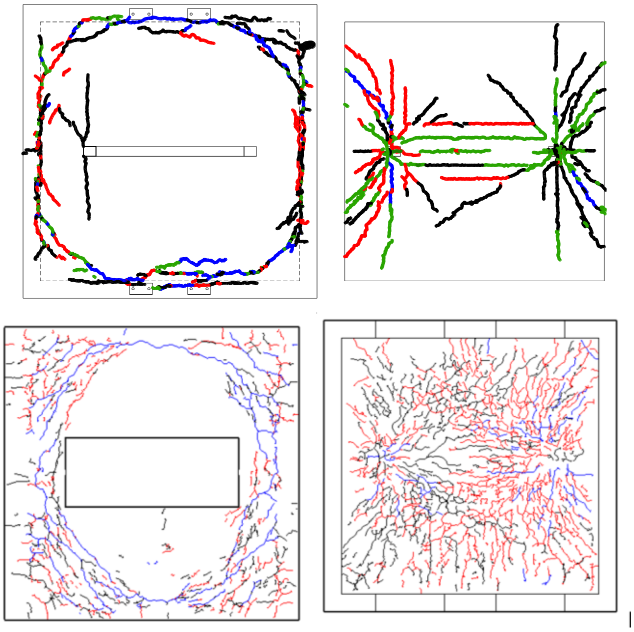


Fig 11 - Cracking in the RC slab after applying the complete load cycles in the RC wall-slab prototype.

4.1 Cracking in the slab

When a vertical load was applied to the specimen, the first cracks were observed at the edges of the slab, near the adjacent beams, and normal to the wall. However, at the end of the test, crack patterns at both sides of the slab was observed (Figure 11). Cracks in the up side of the slabs were concentrated on the perimeter edges, and some cracks were observed at the edges of the walls (Figure 11 Top-left and Bottom-left). However, in the down side of the slabs, concentrated cracks were observed along the line of the walls in horizontal and radial position. Most the cracks had a common origin, which were the unions in the end of the walls and the slabs.

4.2 Repaired specimen

Due to the concrete wall was not damaged, the decision was made to repair it. The repair consisted in the incorporation of two C shaped steel channel (figure 12).

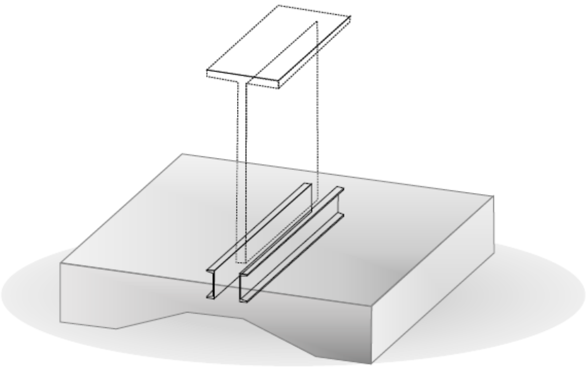


Fig. 12 - Reinforcement system with two C shaped steel channel.

The reinforcement system was designed neglecting the load capacity of the slab. Considering a vertical load of 8 tons applied to the wall and a lateral load applied to the upper end of the wall of 6.5 tons. The beams were considered fixed at their ends. For bending design the steel beams it was considered that they worked in a simple section.

Stud shear connectors were placed in the steel profiles to achieve a composite section (figure 13). The steel profiles were fixed to the perimeter beams by steel plates that were fixed by fasteners. A space of 1 cm was left between the concrete slab and the steel profile to fill it with grout, thereby ensuring that the concrete slab is in contact with the profile along its entire length. The concrete slab was drilled so that the stud shear connectors could be placed (figure, 13), finally the grout was placed.

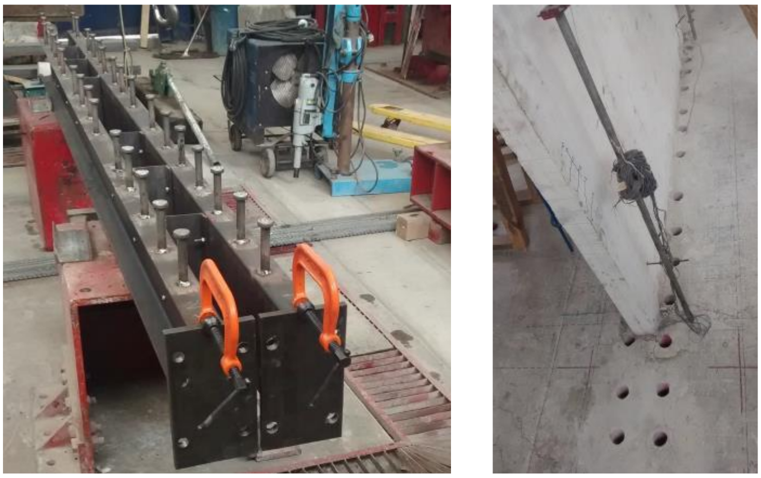


Fig. 13 - C shaped steel channel with stud shear connectors (left), drills in the concrete slab

When the second specimen was repaired, it is possible to increase some of the most important mechanical properties, such as strength, rigidity and deformability (figure 14). The resistance of the original specimen is 6.59 tons while the resistance of the repaired specimen is 15.4 tons, that is, it increased 2.34 times. The initial rigidity of the original specimen is 2.64 ton/m, while the initial rigidity of the repaired specimen is 4.32 ton/m, that is, an increase of 64% was achieved. The maximum displacement in the first specimen was 16.1 mm, which corresponds to a 0.6% drift ratio, the maximum drift ratio in the repaired specimen was 45.15 mm, which corresponds to a drift of 1.8%, that is, the capacity of displacement was tripled.

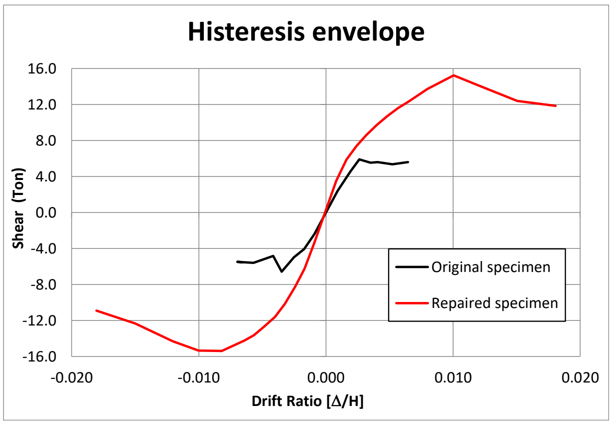


Fig. 14 - Comparison of hysteresis envelopes of the original and repaired specimen.

It is concluded that the repair with steel profiles placed under the slab, is effective in improving the mechanical characteristics of rigidity, strength and displacement capacity. This type of reinforcement can be used on transfer slabs that do not have sufficient capacity for the demands to which they can submit and prevent the damage.

5. Conclusions

In the first stage the specimen was subjected to a process of semi-cycles of increased vertical loading. We observed the first cracking of the concrete slab when the vertical load reached 5.8 Tons. The recorded deflection was 0.5 mm at the centerline of the slab; the load was very close to the design load. After the first stage, the specimen regained its elastic behavior.

Whenever a low horizontal load was applied, we observed that the stiffness of the slab-wall system was a third of the one observed for a wall on a fixed base. The wall had horizontal displacement mainly because of the slab bending (66%) and the wall bending (33%). The shear deformations were not measured.

During the combined loads process, we observed that the slab sustained deformation in such a way that, after each cycle, a residual deformation in the center line of the slab was growing bigger. The rate was 0.5 mm per cycle without returning to its initial position, due to the intensity of the constant vertical load and the increasing horizontal load.

In the combined loads process, the wall did not suffer shear strains during the first six loading cycles, and was only deformed by bending and rotation of the base, due to the bending of the slab. However, from the seventh cycle, the shear deformation started. Up to the tenth load cycle the behavior was elastic, and after that cycle we consider that the behavior was non-linear.

It is concluded that the repair with steel profiles placed under the slab, is effective in improving the mechanical characteristics of rigidity, strength and displacement capacity. This type of reinforcement can be used on transfer slabs that do not have sufficient capacity for the demands to which they can submit and prevent the damage.

The use of steel profiles as a reinforcing system allowed to increase the strength more than 2 times and the displacement capacity 3 times. This increase on the strength and the displacement capacity have an impact in to the dissipated energy capacity, in the effective stiffness and in the viscous equivalent damping.

6. References

[1] Gomez-Bernal A., Manzanares D.A., Juarez-Garcia H., (2013) Interaction between shear walls and transfer-slabs, subjected to lateral and vertical loading. *Proc. Vienna Congress on Recent Advances in Earthquake Engineering and Struc. Dynamics*. Pap 447, 28-30. Viena, Aut.

[2] Gómez-Bernal A, Manzanares-Ponce D, Vargas-Arguello O., Arellano-Méndez E, Juárez-García H, González-Cuevas O (2015): Experimental behavior of a masonry wall supported on a RC two way slab. *J. DYNA, 82, 194. DOI: http//dx.doi.org/10.15446/dyna.v82n194.46333.*

[3] Carrillo J, Alcocer S, González G (2012): Deformation analysis of concrete walls under shaking table excitations. Revista *DYNA, año 79, No. 174, pp. 145-155. ISSN 0012-7353.*

[4] Gouveia J.P., Lourenço, PB (2007): Masonry shear walls subjected to cyclic loading: influence of confinement and horizontal reinforcement. *Proc. Tenth North American Masonry Conference*, St. Louis M. USA.

[5] Preti, M., Migliorati, L., Giuriani, E (2015): Experimental testing of engineered masonry infill walls for post-earthquake structural damage control, *Bulletin of Earthquake Engineering, Vol 13, Issue 7, pp 2029-2049, 2015. DOI 10.1007/s10518-014-9701-2.*

[6] Meli, R. (1994): Mampostería estructural, la práctica, la investigación y el comportamiento sísmico observado en México. *CENAPRED reporte Seguridad sísmica de la vivienda económica, n17 julio*, México.

[7] Park, R., Gamble, W.L. (2000): *Reinforced Concrete Slabs*, Wiley & Sons, 2nd edition.

[8] Vecchio, F, Tang, K (1990) Membrane action in reinforced concrete slab. *Can. J. Civ. Eng. 17, 686-697*

[9] Reglamento de Construcciones del Distrito Federal. (2004) NTC de Mampostería. *Gaceta Oficial del Gobierno del D. F. México*.

[10] Arellano-Méndez E, Quiroz Guzmán LA, Gómez-Bernal A, González-Cuevas OM, Rangel-Torres G, Juárez-García H (2016): Estudio experimental de pisos de transferencia, *XX Congreso Nacional e ingeniería Estructural, SMIE*, Mérida, Yucatán.

[11] Báez-Hernández E (2018) Proyecto de instrumentación para losas de transferencia, *Tesis para obtener el grado de maestría, Posgrado en ingeniería Estructural, Ciencias Básicas e Ingeniería, Universidad Autónoma Metropolitana.*