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REVIEW OF RETROFIT AND STRENGTHENING STRATEGIES USED IN BUILDINGS IN MEXICO CITY AFTER STRONG EARTHQUAKES

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Abstract

Mexico City is often subjected to the action of strong earthquakes and then, thousands of severely damaged buildings in Mexico City have been repaired or retrofitted since the 1957 earthquake. Different integral techniques have been used, such as: a) column, beam and wall jacketing, b) addition of RC shear walls, c) addition of concentric steel bracing, d) post-tensioned exterior cable bracing, e) RC macro-frames, f) exterior exoskeletons, f) hysteretic energy dissipation devices and, g) reduction of stories (removal of top floors). These retrofitted and strengthened buildings techniques were again significantly tested during the M_w = 7.1 September 19, Puebla-Morelos continental normal faulting earthquake. In this paper, the observed seismic performance of the described strengthening and retrofit techniques of a representative inventory of buildings during the September 19, 2017 earthquake are reviewed. Both very good (most) and bad (fewer) performances are highlighted and discussed. It was observed and confirmed that, in general, most strengthened and retrofitted buildings performed well when the strengthening/retrofit strategy was integral, well executed, good maintained and the building was reasonably taken out of resonant responses or separated from their neighbors to reduce the potential of structural pounding. In addition, the dominant retrofit and strengthening techniques that are being used nowadays in Mexico City to rehabilitate buildings damaged as a consequence of the September 19, 2017 earthquake are also shown and discussed.

Keywords: Retrofit, strengthening, jacketing, steel bracing, exoskeletons.

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1 INTRODUCTION

In extended, old cities, such as Mexico City, significant damage is observed after the occurrence of major earthquakes because: a) there is a large inventory of old structures with no seismic design and improper seismic detailing and, b) most "modern" buildings were designed according to collapse-prevention seismic codes, so important, controlled structural damage is accepted for ground motions relatively close to those considered in the design earthquake scenarios.

Mexico City is frequently affected by the action of strong earthquakes from different seismic sources, primarily subduction earthquakes with epicenters along the Mexican Pacific Coast and intraplate normal faulting earthquakes. After the strong July 28, 1957 San Marcos earthquakes (M = 7.8), several hundred damaged buildings in Mexico City started to be locally repaired and strengthened. More damaged buildings during the March 14, 1979 Petatlán Earthquake (M = 7.4) required also to be strengthened or retrofitted (few dozens). Finally, after the September 19, 1985 Michoacán Earthquake (M_s = 8.1) several hundreds of damaged buildings required to be strengthened or retrofitted.

Depending on the extent and severity of the earthquake damage, replacement of damaged materials, local strengthening and other integral rehabilitation strategies were performed in several of these damaged buildings for strengthening and retrofit projects, in order to extend their useful life [1]. Local repairing techniques and replacement of materials and complete structural elements have been commonly used in Mexico City since the late 1950s, as described and documented in greater detail elsewhere [1-4]. However, in this paper the focus of attention is the observed performance of buildings which were retrofitted or strengthened since that time using different integral techniques, such as: a) column, beam and wall jacketing, b) addition of RC shear walls, c) addition of concentric steel bracing, d) post-tensioned exterior cable bracing, e) RC macro-frames, f) exterior exoskeletons, f) hysteretic energy dissipation devices, and, g) reduction of stories (removal of top floors). These previously retrofitted and strengthened buildings were again significantly tested during the M_w = 7.1 September 19, 2017 Puebla-Morelos continental normal faulting earthquake.

In following sections, some of the most important statistics taken an inventory of 112 previously rehabilitated buildings which experienced an extent of damage will be discussed, highlighting some of the few bad performances which were observed. Then, it will be briefly discussed and highlighted what it can be considered as good performances and relatively good performances observed in these techniques, showing pictures of the discussed techniques of the retrofitted buildings after the earthquake event. Finally, it will be briefly shown and discussed some of the dominant retrofit and strengthening techniques that are being used nowadays in Mexico City to rehabilitate newly damaged buildings during the September 19, 2017 earthquake.

2 DAMAGE STATISTICS OF RETROFITTED BUILDINGS DURING THE SEPTEMBER 19, 2017 EARTHQUAKE

In a previous work, the authors discussed in detail, from several angles [1], the observed performance of previously 110 retrofitted and strengthened building which experience from light damage to partial collapses during the Puebla-Morelos earthquake. In this section, a briefer discussion will be done of aspects that the authors consider very relevant in the seismic retrofit of buildings in region of high seismic risk.

The database of the authors is continuously enriched as reliable and relevant new information is obtained. Then, from an updated inventory of 1,842 buildings which experienced from light damage to collapse, 112 rehabilitated buildings were damaged (Fig. 1), but only 46 of them developed severe damage or have been already demolished. This is a small number, considering that in Mexico City there are more than 2,400 buildings retrofitted as a consequence of all previous strong earthquakes.

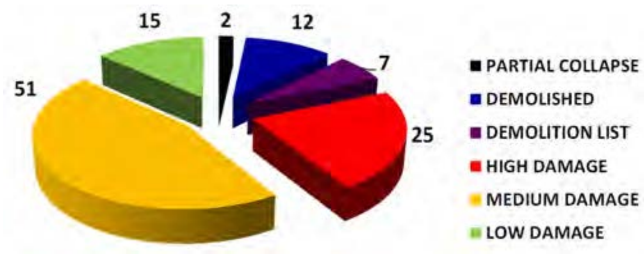


Figure 1: Damage inventory of retrofitted structures in Mexico City during the 2017 Puebla-Morelos earthquake

It is worth noting that the identified damage categories are the following [1]: a) partial collapse (building with a story collapse, black category), b) demolished buildings (blue category), c) demolition list (buildings where demolition was recommended but it has not been done yet, purple category), d) high damage (buildings with severe structural and nonstructural damage, foundation problems and/or very large tilting, red category), e) medium damage (buildings with either some structural damage and/or important nonstructural damage and/or important tilting, yellow category), f) light damage (buildings with some light nonstructural damage or incipient tilting, green category).

2.1 Main original structural system to carry lateral loads

Seriously damaged buildings during a strong earthquake event frequently have many weaknesses that sum altogether. Among the important weakness are the lateral-load resisting structural systems. It is frequent to have a structural system that it is competent to carry gravitational loads and sometimes strong winds. However, systems that have a reduced capacity to withstand significant lateral earthquake loads and/or have limited ductility capacity are often among the most affected ones, despite it has been retrofitted/strengthened to fix some of its original weaknesses. This can be confirmed in Fig. 2, where it is shown the relationships between the considered damage inventory of retrofitted buildings and the original main lateral-resisting structural system for each considered damage category. The description of each structural system is shown elsewhere [5]. It is not surprising at all that in the vast majority of retrofitted buildings which experienced significant damage again, the original structural system was composed of reinforced concrete flatslabs supported by columns only, either reinforced concrete columns (CC-FS system, 61 in total), or steel columns (SF-FS, 11 in total). In fact, reinforced concrete flatslabs over columns compose 64.3% of this 112 damaged building inventory. Why? Because many engineers do not understand the limitation of using flatslabs directly over columns to carry significant earthquake loads. Flatslabs cannot carry effectively the increasing story bending moments due to earthquake loading, particularly as buildings became taller. Flatslabs do not have enough ductility when using directly over columns. The resulting system is laterally flexible, heavy and with a limited lateral load capacity and reduced ductility. Then, as it has been witnessed in many earthquakes worldwide, including the 2017 Puebla-Morelos Earthquake in Mexico City [5], as well as very recently on the strong February 6, 2023 Turkish earthquakes, buildings just relying on flatslabs are prone to severe structural damage and spectacular collapses. In retrofitted flatslab buildings, unless an integral retrofit plan is seriously undertaken to correct most of its weaknesses (limited lateral strength capacity, significant lateral flexibility, limited ductility, potential diaphragm flexibility, etc.), the retrofit strategy would not be nearly as effective. This is observed in the statistics shown in Fig. 2, particularly if the original building is from an old code with the absence of ductile detailing requirements. Reinforced concrete moment frames with ribbed reinforced concrete slabs (RCF-RCS) also had a notable incidence (22). Most of them corresponded to old building codes with improper seismic detailing. The system identified as RC-MW-RCS, a first story reinforced concrete frame and masonry walls with reinforced concrete slabs in the remaining stories above (from 3 to 6, an old system for low-rise housing construction) had 6 buildings damaged again.

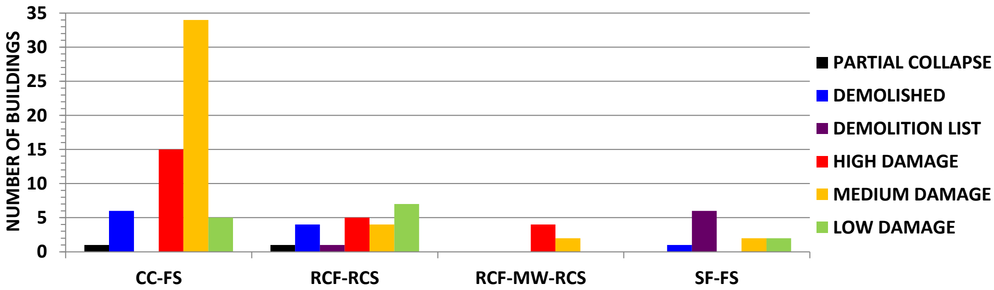
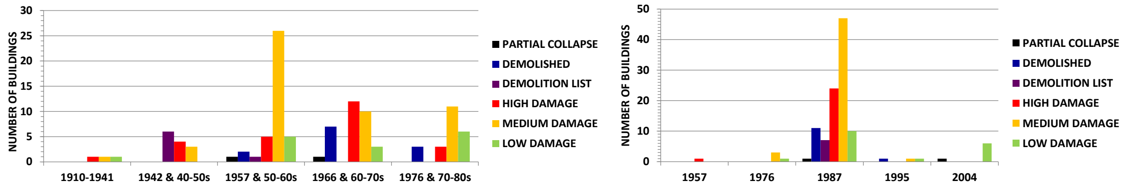


Figure 2: Damage inventory of retrofitted structures in Mexico City during the 2017 Puebla-Morelos earthquake

2.2 Decade of construction and building codes

Old, ancient cities have a large inventory of buildings from different decades. In fact, many of these buildings were constructed before there were a seismic building code. As the first seismic code for Mexico City is the 1942 building code, buildings erected before do not have a proper seismic design and detailing. The first seismic codes of Mexico (1942, 1957 and 1966) were working stress (WSD) design codes, with a very low design accelerations, as described in greater detail elsewhere [5]. The first collapse-prevention seismic code for Mexico City is the 1976 code. This code had some marginal seismic detailing for reinforced concrete structures. However, the proposed elastic design spectra had very low spectral accelerations compared to what it was learned after the 1985 earthquake. Given that large reductions were allowed to account for global ductility, the resulting reduced design spectra for ductile systems was very similar to the one established for the 1966 code, so the resulting design accelerations were small. After the strong September 19, 1985 earthquake, the elastic design spectra were considerably raised, and gradually, many improvements have been done to provide ductile detailing in the main structural systems used in Mexico. A greater description of the history of the seismic codes and their most relevant provisions is available elsewhere [5]. Considering what it has been briefly described above, it can be observed in Fig. 3a that most of the damaged retrofitted buildings were originally designed according to working stress design seismic codes: 1942 (13), 1957 (40) and 1966 (33), this is, 76.8% of this inventory. In these WSD codes, non-ductile detailing for reinforced concrete structures was the standard. For example, commonly, the stirrup spacing provided in beams and columns ranged from 20 to 30 cm. However, there were an important number of buildings (23 or 20.5%) originally designed according to the first collapse-prevention seismic code for Mexico City, the 1976 code. Besides the fact that design spectral acceleration reduced for ductility were small, the established stirrups spacing for RC beams and columns for the 1976 code were just marginally better with respect to the previous 1966 code. Then, spacing for stirrups was basically in the range from 15 cm to 25 cm for most RC structures in the 1976 code. For today´s standards, this stirrup spacing would not even classify as intermediate ductile detailing. This issue is important to highlight, as it is discussed in following sections, not all retrofit strategies were integral or generalized. Sometimes, many original structural elements were not improved locally to increase their strength and ductility. Then, these detailing deficiencies for today´s state of the knowledge on the seismic detailing of reinforced concrete structures (and steel structures as well) were present at the time the September 19, 2017 earthquake struck.



a) Code-decade of construction b) Ruling code for the retrofit project

Figure 3: Relationships between the original code or decades of construction and the ruling code for the last important retrofit with the number of damaged retrofitted buildings within Mexico City on September 19, 2017 according to their corresponding damage group

The relationships of the damage inventory of retrofitted buildings with respect to ruling code used for the last, integral retrofit strategy for each considered damage category is shown in Fig.3b. It has been common practice in Mexico City that in most professional retrofitting projects, the upgraded building has been raised to the standards of the ruling building code at the time. It can be clearly observed in Fig. 3b that although few buildings belonging to this inventory were retrofitted according to the 1957 and 1976 codes, most buildings were retrofitted after the September 19, 1985 earthquake and according to collapse-prevention codes. This is particularly the case for the 1987 code (100 buildings) and in lesser extent the 1995 code and the 2004 code, the ruling code at the time the 2017 earthquake struck. It is worth noting that the elastic design spectra for the 1987 code were considerably raised with respect to previous codes, it was basically endorsed in the 1995 code, and it was very similar with slightly higher spectral acceleration for the 2004 code [5].

2.3 Conditions of structural irregularity

The observed damage in a given building is not exclusively related to the intensity of the observed ground motions and its relationship with the design spectrum, the structural system and assumptions done in the global design process related to its global deformation capacity (“ductility). There are other sources which increase the vulnerability of buildings during earthquakes. One of them are those known as conditions are structural irregularity.

As most of the retrofitted buildings in this inventory were rehabilitated using the 1987 code as a reference (Fig. 3b), it is of interest to see how the observed damage correlate with the conditions of structural irregularity distinguished in the 1987 code. It is worth noting that most of the identified structural irregularities for the retrofitted buildings are related to the original designs. These designs were all done according to seismic codes that did not account for structural irregularities in the seismic design of buildings.

Horizontal irregularities such as large plan aspect ratios (L_1/L_2 >2.5), large floor openings (FLOOR-OP) and distinctive plan shapes such as L, I-H, etc. (identified as reentrant corners in seismic building codes) and other reentrant corners (OTHER RC) found in the damaged retrofitted buildings are shown in Fig. 4. It can be seen that most buildings had large plan aspect ratios (58 or 51.8%). It can be observed there that 42 of the damaged retrofit buildings (37.5%) had reentrant corners, 31 of them with distinctive plans. As expected, irregular geometries frequently used in corner buildings (L, C-U, polygonal and triangular) compose the greatest inventory of reentrant corners (19 buildings). Plans frequently used in apartment buildings in the middle of the street because of illumination and ventilation purposes (I-H plans) had also a high incidence (12 buildings). Although there were few Y, X and open-box plans, it is clear that their seismic response was very adverse, as the observed damage was high or above (demolition list).

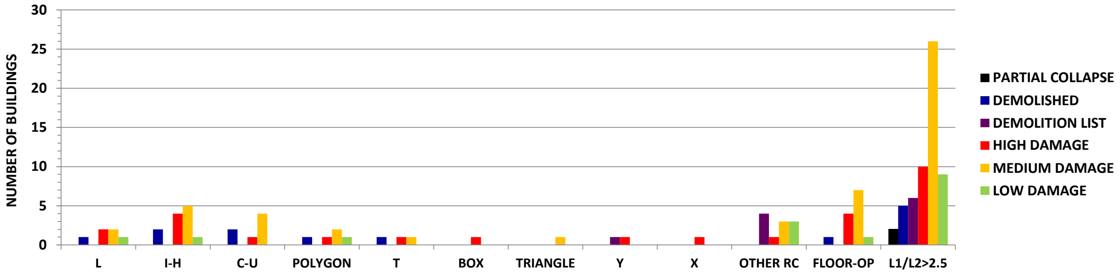


Figure 4: Relationships between horizontal irregularities and distinctive plans with the number of damaged retrofitted buildings within Mexico City on September 19, 2017 according to their corresponding damage

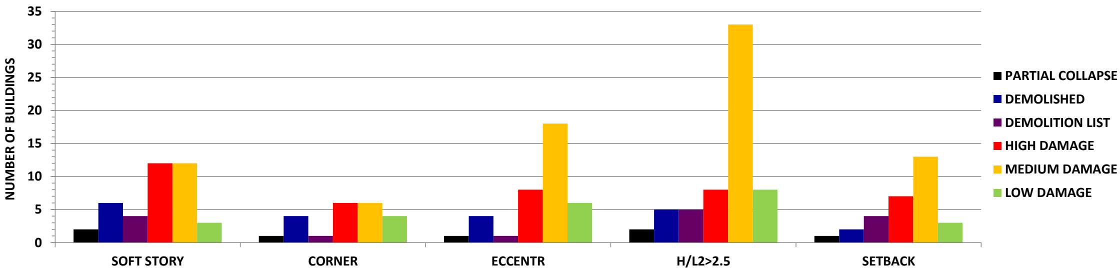


Figure 5: Relationships between vertical and strong irregularities with the number of damaged retrofitted buildings within Mexico City on September 19, 2017 according to their corresponding damage

The relation between the observed damage in retrofitted buildings with the vertical and strong irregularities as defined in the seismic codes of Mexico City from 1987 to 2004 are shown in Fig. 5. It can be observed that there was a high incidence of conditions which are currently classified in building codes as strong or extreme structural irregularities. Such extreme irregularities are soft and weak stories (39 in total), and those which favor strong torsional responses, like corner buildings (CORNER, 22), eccentric placements of shear and infill walls (ECCENTR, 38) and setbacks (30). Nevertheless, there were many retrofitted buildings (62) that were slender (H/L_2>2.5), a condition that many engineers do not consider as irregularity. However, as it can be observed, it had a strong correlation with observed earthquake damage.

As it is very commonly observed, many of the retrofitted buildings simultaneously had more than one condition of structural irregularity. It was observed that most buildings had simultaneously two or more conditions of structural irregularity (95 or 84.8%) than just one condition of structural irregularity (16 or 14.3%). The weighted average for this inventory was 2.78 conditions of structural irregularity per damaged retrofitted building. According to the updated provisions of Mexican codes, strongly irregular buildings are those having a very strong torsional response or a well-defined soft and/or weak story. According to that classification, 65 damaged retrofitted buildings (58%) should be classified as strongly irregular. It is worth noting that 111 of the 112 detected damaged retrofitted buildings were classified as being irregular. Then, one can conclude that it should also be explicitly mandatory to review and consider structural irregularities in the design of retrofit projects for damaged buildings, not only in the design process of new buildings.

2.4 Other co-damageability conditions

Most of Mexico City is founded on the lakebeds of very large lakes which were intentionally and progressively surficially dried out during the last four centuries. In addition, as most of the water that it consumed within the city is extracted from wells of the deep lake deposits, a large differential subsidence occurs within the lake region [5]. Therefore, many buildings have additional issues during earthquakes as a consequence of being founded in very soft soils, with a high-water content, a water table close to the surface and differential soil settlements due both to consolidation and regional subsidence. As it can be observed in Fig. 6, soil differential settlements (SOIL-SET) and tilting were observed in 68 retrofitted buildings. In several cases, the settlements and tilting already existed, but they were amplified after the earthquake. Only in 7 buildings, soil tension cracks (SOIL-CRK) were observed, as most retrofitted buildings are within the most consolidated lakebed soils for the city.

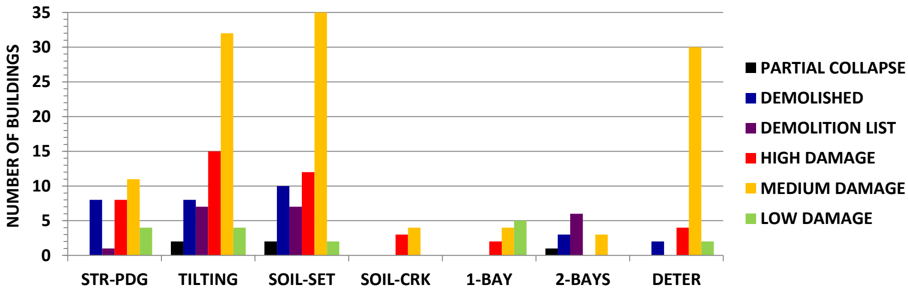


Figure 6: Relationships between other co-damageability conditions with the number of damaged retrofitted buildings within Mexico City on September 19, 2017 according to their corresponding damage

Structural pounding is prone in adjacent buildings when there are small building separations and out-of-sync structural dynamics between them. However, its potential is considerably increased in soft soils [6-8]. Then, 32 of the retrofitted buildings experienced structural pounding (STR-PDG, Fig. 6).

Lack of *ad-hoc* maintenance and previous deterioration (DETER) in buildings usually correlate well with damage. This was not the exception in many of the retrofitted buildings, as in 38 of them this condition was observed (Fig. 6). It is worth noting that in the cases of medium to low damage, it was a dominant condition for the reported damage, particularly for lack of maintenance in the foundation system. Significant water penetration in foundation cells due to nil maintenance was observed and, in many cases, it was responsible of previous building tilting before the earthquake struck. In the case of retrofitted foundations with control point-bearing piles, in some instances the penetration of water rotten the wood cubes of control piles, favoring the unsatisfactory performance of such foundation strengthening.

Low redundancy usually correlates well with the observed severity of the damage, particularly in the direction where a given structure is weakly redundant. It can be observed in Fig. 6 that 24 damaged retrofitted buildings (21.4%) were weakly redundant, at least in one of their main orthogonal resisting directions; 11 buildings had 1-bay frames and 13 buildings had 2-bay frames.

2.5 Main causes of the observed damage in retrofitted buildings

As it is discussed in detail elsewhere [1], the extent and severity of the observed damage in retrofitted building may not be directly attributed to the strengthening techniques and/or global retrofit strategy. Other factors could be even more relevant for the developed damage, such as conditions of structural irregularity (particularly strong irregularities and/or several simultaneous irregularities), the intensity of the ground motions, or the described conditions of co-damageability, for example. As 99% of the subject retrofitted buildings were found irregular, there is no need to remark here that structural irregularities were a major part of the developed and observed damage.

The total number of identified buildings where the strengthening/retrofitting technique was an important part of the observed extent of damage was 24, this is, 21.4% of the considered inventory. However, it is worth noting that if only seriously damaged retrofitted buildings are considered (high damage to above), in only 18 buildings (16.1%) the selected rehabilitation strategy was directly responsible of the observed damage. The cases where the strengthening/retrofitting technique was an important part of the observed extent of damage are identified in Fig. 7. It is worth noting that integral strategies usually have more than one solution, for example, element jacketing with floor reductions or lateral stiffening, adding beams and columns (added frames), etc. Then, the results shown in Fig. 7 counted them individually, but in a given building, one or more parts of the strengthening/retrofitting strategy may have responsible of the damage or experienced damage. Most of the cases are related to strengthening of existing elements such as latticed steel and reinforced concrete jackets (16) and masonry wall jackets (3), which do little to modify the dynamic characteristics of the repaired building when used alone or, even worse, locally. Adding columns (7) and beams (3) without an integral strategy to improve redundancy of the retrofitted building was proved no to be good enough. Integral strategies to improve lateral stiffness and strength do not work well when they introduce soft and weak stories or larger torsional effects, and that was the cases for steel bracing (4) and RC shear walls (2). Floor reductions (2) were not competent enough when the modified structural dynamics led the buildings to respond importantly in the nonlinear range, particularly if their lateral strength and ductility capacity were not improved. In most of these cases, the main reasons behind the bad performances were basically three: a) poor or insufficient conception for the selected retrofitting/strengthening strategy, b) poor execution and/or detailing of the selected strategy, particularly deficient connections between old and new elements, and c) inadequate maintenance.

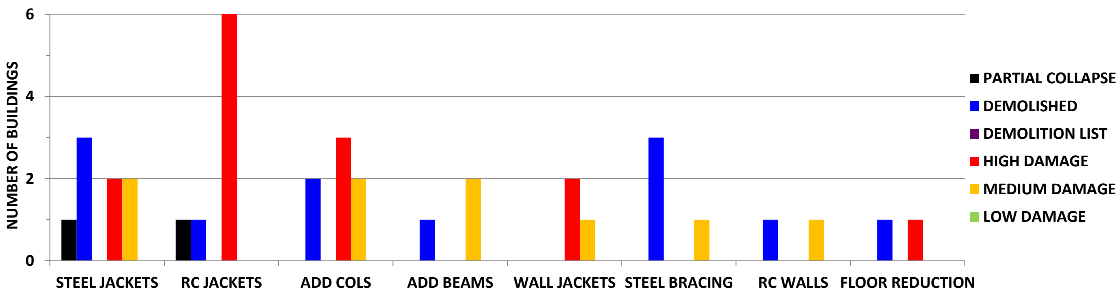


Figure 7: Number of damaged retrofitted buildings within Mexico City on September 19, 2017 for each corresponding damage group where the extent of damage was directly connected to the identified strengthening/retrofitting techniques used

In addition to structural irregularities, the co-damageability conditions which were directly connected to the observed extent of damage in retrofitted buildings are identified in Fig. 8. One can observe that tilting was by far the most important one (46) and in many instances directly connected to deterioration (35), mostly related to water penetration in foundation cells. The third more important co-damageability condition due to the severity of the observed damage was structural pounding (20).

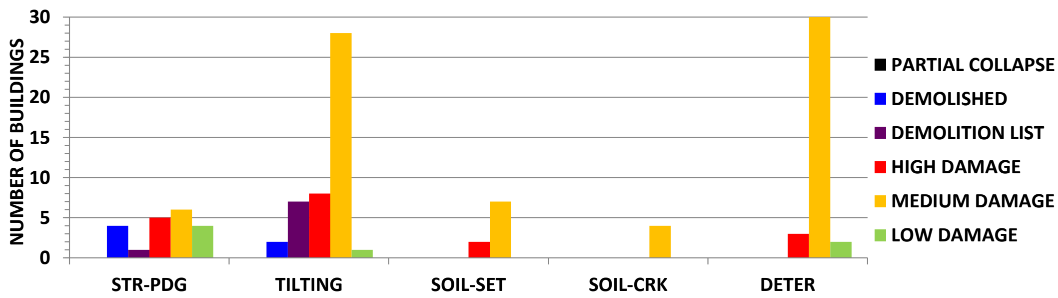


Figure 8: Number of damaged retrofitted buildings within Mexico City on September 19, 2017 for each corresponding damage group where the extent of damage was directly connected to the identified conditions of co-damageability (instead of the strengthening/retrofitting technique)

3 OBSERVED PERFORMANCES OF RETROFITTED BUILDINGS DURING THE SEPTEMBER 19, 2017 EARTHQUAKE

As previously mentioned, there are several hundreds of integrally retrofitted and strengthened buildings in Mexico City which were again significantly tested during the 2017 Puebla-Morelos earthquake. Then, as only 46 buildings were observed to experience moderate damage or above during the 2017 earthquake, it can be concluded that most retrofitted building had good seismic performances. Most strengthened and retrofitted buildings performed well, particularly when: a) the strengthening/retrofit strategy was integral, well executed, well detailed and good maintained, b) the building was reasonably taken out of resonant responses with the selected strategy and, c) care was taken to separate buildings from their neighbors to reduce the potential of structural pounding, which it is an important, historic co-damageability condition for buildings in the soft soils of Mexico City [5-8]. Then, very good performances which were observed for the integral techniques discussed in following sections are shown in following sections. It is worth noting that many of the buildings shown in following sections do not belong to the inventory outlined in Section 2. However, some of those included in the damage inventory will be also shown, to highlight the cases where: a) the damage classification was not connected to the retrofitting/strengthening strategy and, b) to show the few cases where the damage was caused by the retrofitting/strengthening strategy.

3.1 Column and beam jacketing

Element strengthening techniques such as RC jackets [1-4, 9-11] or latticed steel jackets [1-4, 12-20] have been used extensively in Mexico City to strengthen buildings since the late 1950s. They have been applied in RC beams and columns to: a) repair individual damaged members [1-4, 11], b) as an integral, strengthening strategy to increase both the global lateral strength and ductility of the subject structure [1-4, 9-10], and c) as a part of an integral retrofit strategy when modifying substantially the dynamic characteristics and balances of internal forces when used together with removal of top floors [13], additional RC shear walls [1-2, 4], additional steel braces [1-2, 4, 11-13, 14-17, 19-20] or hysteretic energy dissipation devices [18-19].

When integrally applied along the width and height of the building in the retrofitting/strengthening strategy, RC jackets and latticed steel jackets performed well during the 2017 earthquake. Perhaps one of the best illustrating examples is for one of the pioneering retrofitted buildings in Mexico City, the Uruguay 73-Bis building in downtown Mexico City (Fig. 9). This irregular 9-story building was constructed in the 1940s and has major setbacks and eccentric stairs-elevators core. The building has almost nil separations with all neighboring structures. The building experienced severe damage during the July 28, 1957 earthquake and was retrofitted at that time using latticed steel jackets in most columns, with the exception of few columns of the last stories at the setbacks (Fig. 9). As it can be observed in Fig. 9, despite being originally designed and retrofitted according to very old codes, the column jacketing has been effective to survive gracefully not only the 2017 earthquake, but previous strong earthquakes that have affected Mexico City (March 14, 1979 earthquake and September 19, 1985 earthquake). The building was included in the damage inventory because: a) there was interior non-structural damage due to structural pounding with both neighboring buildings and, b) important, progressive tilting have been developed through the times and increased after the earthquake event.

a) b)

Figure 9: Observed seismic performance of Uruguay 73-Bis building, retrofitted with latticed steel jacketing after the 1957 earthquake. Pictures were taken after the September 19, 2017 earthquake.

Other example of good behavior is the case of the corner building in the intersection of Puente de Alvarado and Guerrero avenues, in Buenavista District (downtown area). This building was severely damaged during the September 19, 1985 earthquake, including partial collapse of few boundary columns due to pounding. The building was rescued with a major strengthening intervention using RC jackets in both beams and columns, considerably increasing the original cross sections. As it can be observed in Fig. 10, the retrofit scheme was successful, as the building did not experience damage other than the spalling of the façade finishing in a column and beam. No evidence of structural pounding was found this time with its neighboring buildings.

Figure 10: Observed seismic performance of Puente de Alvarado and Guerrero building, retrofitted with RC jackets after the 1985 earthquake. Pictures were taken after the September 19, 2017 earthquake.

Nevertheless, as shown in Fig. 7, there were some bad performances, which were observed in old buildings with column jacketing only, where the original structural systems were primarily CC-FS. The bad performances are described and discussed in detail elsewhere [1].

From all the retrofitted buildings with jacketing which did not perform well, the one that caught more attention was the partial collapse of the San Antonio Abad 9-story office corner building (Fig. 11), at Tránsito District. This 1976 building was damaged during the 1985 earthquake (originally 17 stories) and was basically retrofitted after the 1985 earthquake by removing 8 floors and placing latticed steel jackets in some columns [1, 13]. As it is explained in much greater detail elsewhere [1], the reason behind the 5th story collapse was that only previously damaged perimeter and corner columns were jacketed, leaving other perimeter and corner columns unstrengthened (a partial jacketing). Then, it can be observed that the 5th story collapse was due to the completely crushed and collapsed corner column at the northeast corner of the building which was not jacketed, as well as the seriously damaged 6th story corner column above (Fig. 11b). Then, the collapse was more a consequence of an inadequately conceived partial retrofit plan rather than bad performance of the latticed steel jackets, as the collapse was precipitated by the unstrengthened original columns (Fig. 11b). The tough lesson to learn here is that in seriously damaged buildings, retrofit interventions should be integral and well planned. Then, cost savings are not a priority for the intervention. In the opinion of the authors, the final goal in seismic retrofit projects of seriously damaged buildings must be that the structural intervention should always be good, no cheap.

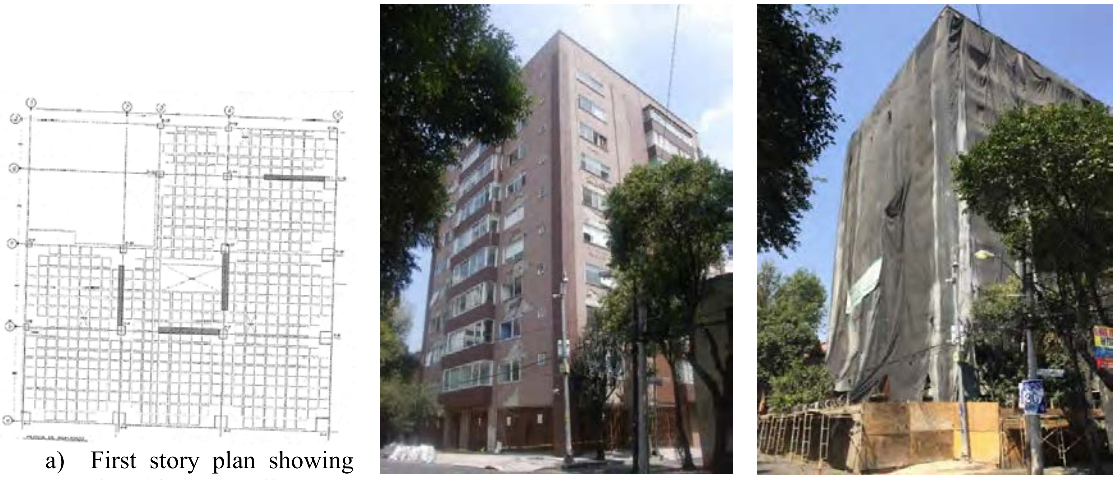
a) Rear view from Chavero street   b) Collapsed 5th story column

Figure 11: Rear views of the partial collapse of the 9-story San Antonio Abad corner office building during the September 19, 2017 earthquake.

3.2 Addition of few structural elements in first soft stories

In order to try to solve locally (and cheaply) a first soft and weak story problem, the addition of new, punctual structural elements [3-4] has been used in Mexico City. Usually, RC columns, RC walls and diagonal steel braces have been used. Additional beams (only) were mainly used to strengthen and stiffen damaged floor systems. As it is discussed in greater detail elsewhere [1], adding columns as “non-invasive” local-retrofit strategy to try to mend a soft-story problem was proved to be unsuccessful.

In fact, the addition of structural shear walls and steel braces cannot be enough either, particularly when trying to solve a soft-story problem in a corner building, and care is not taken to reduce potential torsional responses. That was the case of Cozumel 52 building, a CC-FS 10-story building constructed in 1974 in Roma Norte District and which experience severe damage during the 1985 earthquake. The L-shaped plan building was retrofitted by adding four RC shear walls at the first level only (Fig. 12a) and the RC jacketing of some damaged columns [21]. Although the soft first story potential was reduced, the potential torsional response was not, as the placement of the walls increases the torsional flexibility of the building at the first story (Fig. 12a). As a consequence, during the September 19, 2017 earthquake, the building was severely damaged due to torsional effects from the first to the 6th story at [21]: a) the façades (Fig. 12b), b) some columns (fissures), c) coupling beams, d) some joists of the waffle flatslabs and, e) infill and partition masonry walls. Some tilting was also measured. For these reasons, it was classified in the high damage category. This building is currently under a new retrofit intervention, which details are still unknown (Fig. 12c).



a) First story plan showing the added RC walls [19] b) September 25, 2017 c) Ongoing retrofit works

Figure 12: Observed seismic performance of Cozumel 52 corner building, retrofitted with RC shear walls at the first story only after the 1985 earthquake. Pictures were taken after the September 19, 2017 earthquake.

3.3 Addition of shear walls

RC shear walls have been used in Mexico City to both increase the lateral stiffness and strength of the original structure [1-4, 10-12, 14-16]. Depending on the effective added mass over effective added lateral stiffness ratio for a given structure, the fundamental period of the retrofitted structure may be or may not be drastically changed, particularly when considering soil-structure interaction effects in soft soils. In general, it can be concluded that retrofits adding RC shear walls were effective and performed well during the September 19, 2017 earthquake when retrofit strategies were integral.

One good example is the retrofit of the 22-story towers part of the Nonoalco-Tlatelolco housing complex (Fig. 13). These seven buildings were original built in the early 1960s, and the main structural system was CC-FS with some deep spandrel RC beams at the façades. These buildings experienced significant damage during the September 19, 1985 earthquake. As a part of a comprehensive retrofit plan for the whole housing complex, the towers were integrally retrofitted adding C-shaped RC shear walls at the four corners (Fig. 13), as well as T-shaped RC shear walls at the perimeter-interior. The foundation box was augmented and additional piles were inserted. As noted, the performance of the retrofitted buildings was excellent. Only one tower, the Veracruz tower, was classified in the medium damage category. The reason was that because of the lack of maintenance of the box foundation, significant water penetration occurred through the time, and important progressive tilting has been measured through the years. The tilting increased during the 2017 earthquake. Only minor shear cracks were observed in few masonry partition walls.

Figure 13: Observed seismic performance of Nonoalco-Tlateloco Towers, retrofitted with RC shear walls. Pictures were taken after the September 19, 2017 earthquake.

Another good example is the seismic retrofit (preventive) of the "B" building at our University Campus at Azcapotzalco. The original CC-FS building was erected in the late 1970s and it has a very long plan aspect ratio, low redundancy and plenty of masonry infill walls, used to separate classrooms. Although the building did not experience significant damage during the 1985 earthquake, it had to be strengthened to satisfy code standards (1995 code) for school use. Then, the preventive retrofit project started in the late 1990s, and consisted of adding hollow-box-shaped RC walls at both building ends (like a buttress or exoskeletons, Figs. 14a and 14b), and conventional rectangular shear walls next to the stairs (Fig. 14c). Then, the retrofit was planned to stiffen and strengthen considerably the building in its weakly redundant direction. The retrofitted building performed extremely well during the September 19, 2017 earthquake. It is worth noting that 4-story RC buildings were among those most severely affected [5].

a) b) c)

Figure 14: Observed seismic performance of classroom Building B of Universidad Autónoma Metropolitana, Azcapotzalco Campus, retrofitted with RC shear walls, ending ones as buttresses or exoskeletons. Pictures were taken after the September 19, 2017 earthquake.

There were also few bad performances, as reported in Fig. 7. These exceptions occurred when bad-planned retrofit strategies were implemented, as commented in detail elsewhere [1]. One of such bad performances was for the 10-story Glorieta de Etiopía corner office building, which was constructed in the late 1950s. This original CC-FS building experienced important damage during the 1985 earthquake. The building was retrofitted with narrow shear walls in the perimeter and in the interior after the 1985 earthquake. The building possesses very important irregularities, such as a V-shaped plan and eccentric placement of resisting shear walls. As a consequence, the building experienced a strong torsional response, which was observed through the videos taken by people and uploaded at the times in internet, where the false front façade was seen to fall (Fig. 15a). The building also experienced structural pounding with the neighboring 4-story building along "Diagonal de San Antonio" Avenue (Figs. 15b and 15c), which caused severe damage in most neighboring exterior RC walls and within the interior. Differential settlements and tilting (Figs. 15b and 15c) were also observed. After considering its demolition, the building is on hold, deciding whether or not it should be retrofitted.

a) b) c)

Figure 15: Observed seismic performance of Glorieta de Etiopía office building, retrofitted with RC shear walls. Pictures were taken after the September 19, 2017 earthquake.

3.4 Addition of concentric steel bracing

Concentric steel bracing of original framed-structures has been extensively used in Mexico City, particularly after the March 14, 1979 earthquake [4, 11-12, 14-17, 19-20]. As a part of this integral technique, column and beam jackets are used, predominantly, latticed steel jackets, as well as local strengthening of the beam-column-slab joint connections [4, 11-12, 14-17, 19-20]. When this retrofitting technique is integrally conceived, structural engineers are considering to increase significantly both the lateral stiffness and strength of the retrofitted structure to take it out of resonant responses. This is very important in the soft soils of Mexico City, with site periods (T_s) within the range 1.0s ≤ T_s ≤ 3.5s [5]. It should be accounted that local and global ductility is reduced with this technique, so important nonlinear responses should be avoided in the retrofit strategy. In most practical, successful retrofit cases, it has been common that structural engineers designed the added bracing to carry by itself 80% to 100% the lateral loads related to the design spectra of the ruling seismic code at the time that the retrofit project was planned [12, 14-17]. As the ratio of the effective added mass to the mass of the original structure is small related to the increased lateral stiffness, in this technique the fundamental period of the retrofitted structure may be drastically reduced, but soil-structure interaction effects in soft soils may reduce its effectiveness [14-16].

Many buildings have been successfully retrofitted using this technique when taking the building out of resonant responses, as they did not experience any structural damage (resilient, immediate occupancy performance), as shown in Figs. 16 to 20 and Figs 22 to 25. The performance of integral, retrofit strategies in low-rise buildings was superb. For example, the Dinamarca and Marsella 5-story apartment corner building, originally a CC-FS building. This building was integrally retrofitted in the late 1990s using concentric chevron braces and latticed jackets in the columns (Fig. 16a). The observed seismic performance was outstanding, no damage at all. The Dr. Andrade corner public 4-story building was originally a CC-FS building built in the early 1980s. The building was retrofitted in 2011 using concentric X-bracing and latticed jackets in the columns (Fig. 16b). The performance of this building during the earthquake was excellent, as no damage was observed, despite the fact that the building has some important structural irregularities due to architectural requirements, such as a large opening closed by a truss system nearby an auditorium zone (Fig. 16b). The 5-story San Cosme Subway Station office building originally was a CC-FS system. This building was retrofitted after the 1985 earthquake with concentric steel braces at the exterior bays (Fig. 17). The building performed very well, having an immediate occupancy status. It is worth noting that low-rise RC buildings (4 to 6 stories) were among the most severely affected during the 2017 earthquake [5].

a) Dinamarca and Marsella building b) Dr. Andrade building

Figure 16: Observed seismic performance of low-rise buildings, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b)

Figure 17: Observed seismic performance of San Cosme Subway Station low-rise office building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

Many public schools in Mexico City were damaged during the September 19, 1985 earthquake. Different strengthening/retrofitting strategies were used. Among those that performed extremely well during the September 19, 2017 earthquake was the lateral stiffening using concentric steel X-bracing (Figs. 18 to 20). Usually, braces were surrounded by additional steel columns and beams and then uniformly connected them to the existing RC columns and beams, as perhaps more clearly observed in Fig. 20. The observed performance in most retrofitted schools with this system was excellent, as observed in Figs. 18 to 20. This includes the additional stiffening of Legaria Secondary School (Fig. 20), the first base-isolated building in the firm soils of Mexico City (1974) with a sliding system proposed by González-Flores, as documented elsewhere [22]. This building survived gracefully the 1985 earthquake (no damage), but somehow school public authorities decided to place the steel bracing anyways, perhaps attending social pressures from the concerned parents, as most public schools were being retrofitted at the times.

a) b)

Figure 18: Observed seismic performance of Public Primary School Pedro Ascencio (San Simón Ticumac), retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b)

Figure 19: Observed seismic performance of Public Secondary School 187 (Tránsito District), retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

However, it is worth noting that there was one public school retrofitted with this type of bracing and that experienced structural damage (Fig. 21a), and it was decided to be demolished (Fig. 21b). This school is located in the virgin soft soils of Iztapalapa District and experienced shear damage in un-strengthened beams and columns due to abrupt soil settlements, tilting and tensile cracks that occurred in the soils as a consequence of the earthquake. It can be observed that the damage was not caused by the concentric steel bracing, as the surrounding elements were in good shape after the earthquake (Fig. 21a) and during the demolition process (Fig. 21b).

a) b)

Figure 20: Observed seismic performance of base-isolated Public Secondary School 168 (Legaria), strengthened with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b)

Figure 21: Observed seismic performance of Public Secondary School 249 in Iztapalapa District, retrofitted with concentric steel bracing. Pictures taken from internet

During the 2017 earthquake, midrise RC buildings from 7 to 11 were also severely affected [5]. Then, it is worth noting that midrise buildings retrofitted with concentric steel braces performed well in general. Among the ample number of examples are the following. The 8-story Av. Juárez office building (Fig. 22a), originally a CC-FS building. The 13-story Lafragua and De la República office corner building (Fig. 22b), originally structured with steel columns and RC flatslabs (SC-FS). However, the most interesting cases study to show and briefly discuss are some of the iconic retrofits of midrise buildings with concentric steel braces in the Mexican structural engineering community.

One of such retrofits is the Plaza Villa de Madrid office building (Fig. 23). This 12-story, corner and highly irregular building with setbacks originally was a CC-FS building built in the 1950s. The building experienced severe non-structural damage during the September 19, 1985 earthquake. The original structure had many structural deficiencies, such abrupt changes of column sections along the height, non-ductile detailing, etc. The building had a seriously cracked column-slab connection at the 7-story, some cracks in the waffle flat slab at the third story, and massive cracking of interior partition walls, boundary infill walls, stairs walls and glasses in most stories, plus a foundation emersion (the first author did a detailed damage reconnaissance survey of this building at the times). The original owner decided to sell the building for the price of the land, as he could not afford to retrofit the building or its demolition costs. Then, a well-respected structural design firm in Mexico City, famous for the design of steel buildings, decided that it was a good investment to buy this building. Then, they designed an integral retrofit project using steel braces and jacketing the original columns, plus strengthened the damaged slabs. As it can be observed in Fig. 23, the building survived gracefully the September 19, 2017 earthquake, presenting only minor spalling of the cover at the base corner column nearby the plate connections of the braces (Fig. 23b).

a) Av. Juárez building b) Lafragua and De la República building

Figure 22: Observed seismic performance of midrise buildings, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b) c)

Figure 23: Observed seismic performance of Plaza Villa de Madrid midrise office building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

Another iconic retrofit is for the Jalapa office building (Fig. 24), a 14-story CC-FS office building originally built in 1981. Due to the damage experienced during the September 19, 1985 earthquake, the building was first strengthened in 1986 by jacketing some columns and adding some perimeter RC shear walls [11]. As this strengthening was not good enough as the building experienced additional non-structural damage after a moderate earthquake that struck Mexico City in December 1994 [11], the building was finally integrally retrofitted using chevron concentric braces (Fig. 24). This building, known in the literature as the JAL building [11], is iconic because a detailed health-monitoring program for the response of the retrofit has been conducted, which more interesting results are reported elsewhere [11]. As it can be observed in Fig. 24, the global performance of the retrofitted building during the September 19, 2017 earthquake was good, with some minor spalling of the outside finishing of perimeter walls (Figs. 24b and 24c), but the building operated regularly after the earthquake (immediate occupancy status).

a) b) c)

Figure 24: Observed seismic performance of Jalapa (JAL) midrise office building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b) c)

Figure 25: Observed seismic performance of Park España midrise apartment building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

It is worth noting that structural pounding still is an important hazard when using steel braces despite the lateral stiffening intended to reduce lateral displacements. This is because seismic pounding also depends on how out-of-sync is the resulting structural dynamics of the retrofitted building with respect to neighboring structures, particularly in soft soils and if the gaps (separations) are small [8]. This has been the perennial shortcoming of a well-designed retrofitted building with steel braces, Park España building [12, 14-16, 19]. During the September 19, 1985 earthquake, the observed mild damage was due to structural pounding with two neighboring structures (3 and 4 stories) one of them separated 7 cm from this building [14-16, 19]. During the September 19, 2017 earthquake, the observed interior non-structural damage was related to the observed structural pounding (light) with both low-rise neighboring structures (Figs. 25a and 25b). For such cases, local repairing techniques to minimize pounding effects should also be considered to complement a successful retrofit strategy.

An interesting retrofit case study was also witnessed for the 7-story, Fray Servando and 5 de Febrero corner office building (Fig. 26). As it can be observed in Google Maps (street views), this old RC moment frame building was still a moment frame building up to March 2016. The building started to be retrofitted at the end of 2016 with chevron steel braces connected to the original beams with an additional steel beam and using a RC jacketing for the columns (Fig. 26b). The September 19, 2017 earthquake caught this building with all the braces and jackets already finished, but without the interior and façade finishing, as shown in Fig. 26. Then, it was clearly observed that the constructed retrofit performed well, as no damage was observed in the braces, jackets, connections and even the original secondary floor beams (Fig. 26b).

a) b)

Figure 26: Observed seismic performance of Fray Servando and 5 de Febrero midrise office building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

There were other case studies that the ending story of the retrofit project was not as successful as planned. These cases were for corner buildings with additional structural irregularities, and that had an important damage record in past earthquakes. For example, the 7-story Amsterdam and Teotihuacán CC-FS apartment building was seriously damaged during the September 19, 1985 earthquake. The building was retrofitted adding concentric X-braces in the perimeter and using latticed steel jackets in the columns (Fig. 27). As the building is slender and the irregular last-story setback for the penthouse owner remained, the building experienced important nonstructural damage in the interior due to torsion. As the building had a restaurant for lease, and there was no damage there, the apartments were abandoned first (Figs. 27a and 27b) and then, all finishing have been taken out (Fig. 27c) to check the health of the waffle floor system and the connections, in order to evaluate if a complementary retrofit should be done, or other decision might be wiser.

a) b) c)

Figure 27: Observed seismic performance of Amsterdam and Teotihuacán midrise apartment building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b) c)

Figure 28: Observed seismic performance of Amsterdam and Sonora midrise apartment building, retrofitted with concentric steel bracing. Pictures were taken after the September 19, 2017 earthquake.

Other interesting case study was for the Amsterdam and Sonora 13-story corner, slender, reentrant corners and setback apartment building. The original structural system built in 1977 was a CC-FS system. The building experienced non-structural damage in a moderate earthquake in 1982, and then an integral retrofit scheme was planned with braced frames in one direction and added RC walls in the other orthogonal direction. The retrofitted building survived the September 19, 1985 earthquake with only small non-structural damage in the partition walls of the staircases, plus some broken glasses, and evidence of the lateral flexibility because the waffle flat slab movement was marked and caused some spalling in the exterior façade finishing. During the September 19, 2017 earthquake (Fig. 28), moderate structural damage and nonstructural damage (medium damage category) was observed in the interior due to torsional effects, where steel braces were intact (Fig. 28c) and there was no evidence of losing connections. Exterior damage was similar to the one observed in 1985: façade spalling (Fig. 28b). However, in 2020 it was decided to demolish this building instead of upgrading the retrofit, because of the observed foundation emersion of point-bearing piles and all the described irregularities, plus the need to modify its fundamental period, given the site stiffening due to subsidence.

3.5 Addition of steel exoskeletons

The use of what nowadays is distinguished in structural engineering as exoskeletons has been used in Mexico City for the seismic retrofit of structures since 1979. It was one of the innovative solutions at the times to retrofit damaged buildings during the March 14, 1979 Petatlán earthquake [12]. Mexican structural engineers know them since then as "additional exterior steel-braced frames", which are attached to the original structure within the perimeter. They have been used as an integral retrofitting strategy to increase lateral stiffness and strength, as well as detuning buildings from potential resonant responses with the site by modifying substantially their fundamental periods [4, 12, 14-17, 23].

When exoskeletons are designed and constructed to protect the structure uniformly along the height of the structure, its seismic performance has been outstanding. This was observed during the September 19, 1985 earthquake with one of the pioneering applications, the 12-story, RC moment frame (haunched beams) Durango medical building. The original retrofit plan [12] and related post-earthquake experimental and analytical research studies for Durango building [14-16] have been extensively documented. Again, the seismic performance of the 12-story Durango medical building during the September 19, 2017 earthquake was outstanding, no damage at all, immediate occupancy status (Fig. 29a). Another of the integral, pioneering exoskeleton retrofit applications is the 19-story, Reforma and Río Marne office building, which also performed well during the 1985 and 2017 (Fig. 29b) earthquakes. Unfortunately, the original retrofit plan has not been publicly documented.

a) Durango building

b) Reforma and Río Marne building

Figure 29: Observed seismic performance of midrise buildings, retrofitted with exoskeletons (additional exterior steel-braced frames). Pictures were taken after the September 19, 2017 earthquake.

Given the excellent performance observed during the September 19, 1985 earthquake for the Durango and Río Marne buildings, the addition of exterior steel exoskeletons gained a great recognition in the Mexican structural community. Then, they were extensively used for the retrofit of buildings of different characteristics, as shown in Figs. 30 to 34. Exoskeletons were used to retrofit low-rise buildings, such as the French Institute for Latin-America (IFAL) 4-story building (Fig. 30a), and the 6-story Sagar parking building (Fig. 30b). These types of exoskeletons are also known in Mexico as "exterior macro-braced steel frames". Both buildings survived the September 19, 2017 earthquake with no damage.

a) IFAL building　　b) Sagar parking building

Figure 30: Observed seismic performance of low-rise buildings retrofitted with steel exoskeletons. Pictures were taken after the September 19, 2017 earthquake.

a) SSP building　　b) Av. Juárez building

Figure 31: Observed seismic performance of midrise buildings retrofitted with steel exoskeletons. Pictures were taken after the September 19, 2017 earthquake.

Macro-braced steel frames or exoskeletons were also successfully implemented in midrise buildings. One of the iconic applications for the Mexican structural engineering community is the retrofit of the 17-story SSP office building, originally a CC-FS building, which experience no damage after the earthquake (Fig. 31a). Unfortunately, its retrofit plan was not publicly documented. Another of the iconic applications is the 10-story Av. Juárez office building, originally a 10-story steel moment frame building built in the 1950s, which retrofit with exoskeletons after the 1985 earthquake was documented [23]. The building was already abandoned at the time the September 19, 2017 earthquake struck, but its seismic performance was excellent (Fig. 31b), just showing a little distress in the sidewalk nearby one of the connections. The building was recently demolished, attending to other reasons: its life cycle was over, and it was located in a high-priced land nearby Alameda Park in Mexico City.

Another interesting application of exoskeletons using macro-braced steel frames in midrise buildings which it is documented is the one for the 11-story, Londres and Berlin corner apartment building (Fig. 32). The building was erected in the late 1960s and its original structural system was composed of CC-FS on a foundation box over friction piles [4]. During the 1985 earthquake, the building experienced extensive non-structural damage due to its lateral flexibility. That it is why a stiffening and strengthening with exoskeleton was carefully planned, as described in detail elsewhere [4]. Of course, additional piles were added to take the loads of the exoskeletons [4]. The retrofit works started in the mid-1990s, but for some unknown reasons, it was left unfinished for years (all bracing and additional piles finished), until 2006, when it was retaken (Fig. 32a) and finished somewhat later. The observed seismic performance during the September 19, 2017 earthquake was excellent, achieving an immediate occupancy status (Fig. 32b), with only a small detail of pounding-related nonstructural damage with the flexible frame of the entrance door of the neighboring structure (Fig. 31c).


a) November 16, 2006


b) October 17, 2017


c) October 17, 2017

Figure 32: Observed seismic performance of Londres and Berlin apartment building retrofitted with steel exoskeletons.

A successful retrofit story with exterior macro-braced steel frame exoskeletons is the one for the buildings of the phone company (Fig. 33). At the times of the September 19, 1985 earthquake, all these buildings (around 25-30) were used across Mexico City to host very heavy telephone switching equipment at the upper stories. Most of them were significantly damaged. One of these buildings which damage was well documented is the one located at the corner of Puebla and Monterrey streets, in Roma District. The original building was an 8-story RC moment frame built in the late 1960s, which experienced cracking at the beam-column joints due to torsional effects in the first 4 stories during the 1979 earthquake, as well as cracking in partition and boundary masonry walls [24]. The retrofit consisted in strengthening the affected beam columns joints with cube jackets, as well as replacing the damaged walls [24]. During the 1985 earthquake, and as observed by the first author in a reconnaissance survey study, the damage due to torsional effects was extensive in beams and columns in the strengthened 4-stories, and substantially worse in stories 5 to 8, where the joints were not strengthened and developed torsional and diagonal tension cracks. The damage in partition and infill masonry walls was also extensive. Structural pounding with the 2-story adjacent building (same complex) was observed. In most control pile caps, the threaded anchor bolts of the control device buckled [4]. The strengthening technique used after the 1985 earthquake was integral, by using RC jackets for the damaged columns and beams, placing new C-shaped RC shear walls in the interior, adding exterior steel macro-braced frames (exoskeletons) in the exterior, replacing damage control piles and adding 70 new control piles [4]. The observed seismic performance of the retrofitted Puebla and Monterrey telephone building during the 2017 earthquake was excellent, with no damage this time and immediate occupancy status (Figs. 33a and 33b). As most telephone buildings were retrofitted using a similar strategy [17], as the one described above, their observed seismic performance was also excellent, as illustrated for the Ejército Nacional building (Fig. 33c).

a) Puebla and Monterrey b) Puebla and Monterrey c) Ejército Nacional

Figure 33: Observed seismic performance of Telephone Company buildings retrofitted with steel exoskeletons. Pictures were taken after the September 19, 2017 earthquake.

It was observed that some steel exoskeleton applications did not perform well enough during the September 19, 2017 earthquake. One that was reasonable, but not excellent, was the one observed for the 9-story, Colima and Córdoba corner apartment building, originally a CC-FS building. The building was retrofitted after the September 19, 1985 earthquake adding as exoskeletons the exterior, very slender steel bracing shown in Fig. 34a. This building experienced moderate non-structural damage in the interior, basically in non-structural walls, walls in the staircases and infill boundary walls. This damage was also related to the structural pounding observed with its neighboring 2-story house along Córdoba street (Fig. 34b), given the small gap between them. The observed seismic performance of the 8-story Odesa apartment building during the September 19, 2017 earthquake was so bad (Fig. 34c), that the building was finally demolished. The analysis of the reasons why this partial exoskeleton retrofit (only stories 2 to 5 were retrofitted, Fig. 34c) are explained in detailed elsewhere [1]. The case of the Amsterdam apartment building, which was so heavily damage that it has been already demolished, will be described and analyzed in detail in following sections.

a) Colima and Córdoba b) Colima and Córdoba c) Odesa

Figure 34: Observed seismic performance of midrise buildings retrofitted with steel exoskeletons. Pictures were taken after the September 19, 2017 earthquake.

3.6 Addition of exterior post-tensioned cable bracing systems

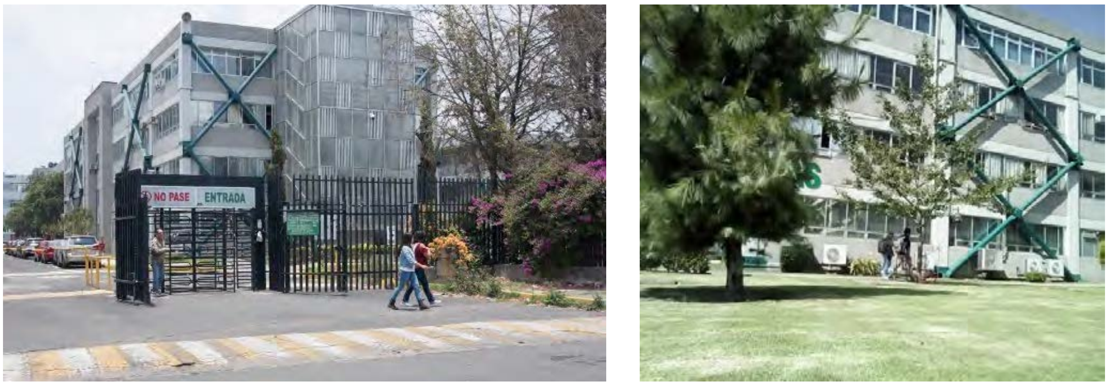
Exterior post-tensioned cable bracing systems were extensively used in Mexico for the retrofit of low-rise school buildings after the September 19, 1985 earthquake [4, 25-29]. It has been found that this technique is very effective in increasing substantially the lateral stiffness and strength of the retrofitted structure, and very effective to reduce fundamental periods of vibration, leading to elastic responses in both soft soils of Mexico City [25-28] and firm soils [28] for strong ground motions recorded during the M_s = 8.1 September 19, 1985 Michoacán earthquake and the M_w = 8.0 October 9, 1995 Manzanillo earthquake. This technique was also used later to retrofit a 13-story office building in soft soils of Mexico City [1, 29]. As expected, the seismic performance of school buildings retrofitted with post-tensioned cable bracing system was excellent during the September 19, 2017 earthquake in Mexico City, as shown in Figs. 35 to 37. These includes school buildings which retrofit has been extensively documented and studied [27-28], like the 4-story Secondary School No. 4 (Fig. 36), or it has been well documented [4], like the 4-story building AS of Universidad Autónoma Metropolitana at Iztapalapa Campus (Fig. 37).

a) Special Education School Vallejo b) Primary School Víctor María Flores

Figure 35: Observed seismic performance of public-school buildings retrofitted with post-tensioned steel bracing. Pictures were taken after the September 19, 2017 earthquake.

a) b)

Figure 36: Observed seismic performance of public Secondary School No. 4 Moisés Sanz at Santa María La Ribera District retrofitted with post-tensioned steel bracing. Pictures were taken after the September 19, 2017 earthquake.



a) b)

Figure 37: Observed seismic performance of classroom and lab Building AS of Universidad Autónoma Metropolitana, Iztapalapa Campus, retrofitted with post-tensioned steel bracing. All pictures were taken from internet after the September 19, 2017 earthquake.

3.7 Reinforced concrete macro-frames

Reinforced concrete macro-frames were proposed for the retrofit of 27, 14-story RC buildings at Nonoalco-Tlatelolco housing complex in Mexico City after the 1985 earthquake [1]. It consisted basically in forming equivalent two-story (first story) and three-story (remaining stories) moment frames by considerably enlarging the original RC columns sections to thick RC wall sections and increasing the depth and reinforcement of RC spandrel beams (Fig. 38a). The lateral stiffness, strength and ductility was improved with this solution. However, as the mass was considerably increased, the effective impact on reducing the fundamental period of the retrofitted structure was smaller than for other solutions. During the September 19, 2017 earthquake, the observed performance of all retrofitted macro-frame buildings (9 complexes, 27 buildings) was good, as they remained practically undamaged (Fig. 38b), as described and discussed in detail elsewhere [1].

a) Construction detail

b) ISSSTE 11 housing complex 9/26/2017

Figure 38: Observed seismic performance of ISSSTE 11 buildings of Nonoalco-Tlateloco housing complex during the September 19, 2017 earthquake retrofitted with reinforced concrete macro-frames

3.8 Retrofits using hysteretic energy dissipation devices

Hysteretic energy dissipation devices (HEDD) have been also used for the seismic retrofit of buildings in Mexico City [18, 22, 30-32]. HEEDs are attractive in retrofit projects because they are designed as structural seismic fuses. Then, the potential nonlinear response is concentrated mostly in the HEDDs, leading beams, columns, braces and other supporting elements to respond mostly elastically, allowing to achieve a true resilient seismic retrofit [18, 22-23, 30].

The first three retrofitted buildings in Mexico City with HEDDs used ADAS devices [18, 22]. The first retrofitted building with ADAS devices in Mexico and the entire world was the 15-story Izazaga commercial building in 1989-1990, which retrofit plan and related studies are reported in detail elsewhere [18]. The original structure was built in the late 1970s and consisted of CC-FS system with RC shear walls in some axis in both directions [18]. The building experienced moderate structural damage during the September 19, 1985 earthquake due to its lateral flexibility and torsional coupling, as it has an irregular T plan [18]. After a partial strengthening conducted basically in the damaged walls and columns using jackets which was proved not to be effective in two moderate earthquakes which affected Mexico City in 1986 (M = 7.0) and early 1989 (M = 6.9), a major retrofit using ADAS devices mounted on chevron braces was executed [18]. Since then, the building has survived gracefully all moderate earthquakes felt in Mexico City with no damage. It is worth noting that, previous to the September 19, 2017 earthquake, the building was under a major façade renovation and conditioning, as it had a new owner. According to Google Maps (street view), these renovation works started between December 2016 and April 2017, where one can see the works in the first three stories. At the time of the September 19, 2017 earthquake, the building was caught with no glasses and in painting conditioning. Then, it was possible to see that the structural system responded very well, with no damage at all, as depicted in Figs. 39a and 39b. The building was operating regularly after the façade renovation was finished, as depicted in Fig. 39c.

The second retrofit with ADAS devices in Mexico City was the 5-story former Cardiology Hospital at IMSS Medical Center Complex [1, 18, 22]. ADAS devices were placed between the original building and exterior steel buttresses (Fig. 40). The details of the retrofit plan and numerical analyses that validate them are reported elsewhere [18]. During the September 19, 2017 earthquake, a resilient, immediate-occupancy performance was reported by IMSS authorities. Unfortunately, the authors do not have their own pictures taken after the earthquake to share. However, using Google maps, one can see that the Hospital looks about the same after the earthquake occurred (Fig. 40b) compared with its status previous the earthquake (Fig. 40a).

a) October 2017 b) October 2017 c) February 2020

Figure 39: Observed seismic performance of Izazaga commercial building retrofitted with ADAS devices during the September 19, 2017 earthquake

a) January 2017 b) August 2019

Figure 40: Observed seismic performance of the Cardiology hospital building retrofitted with ADAS devices mounted on exterior buttresses. All pictures taken from Google Maps.

The third retrofit application with ADAS devices in Mexico City was for IMSS headquarter building complex, originally composed by three 12-story large RC moment frame buildings built in the late 1940s [18, 30]. These buildings experienced moderate structural and nonstructural damage during the 1957 earthquake [18], and a local strengthening of the damaged elements was done. During the September 19, 1985 earthquake, these buildings experienced a smaller damage [18], but being an important building, it was required to be retrofitted to satisfy the requirements of the 1987 building code. The retrofit plan included adding ADAS devices mounted in chevron braces in many interior frames, as described in the detailed studies reported elsewhere [18, 30] and shown in other works [1, 22]. Retrofit works started in 1992 and were finished in 1998. During the September 19, 2017 earthquake, their seismic behavior was outstanding, having an immediate occupancy category (Fig. 41).

The fourth building retrofitted with ADAS devices was the 13-story Torre Monterrey office building [22, 31], owned by the government of Mexico. This office building was originally a RC moment frame built in 1976. This building experienced light structural damage (cracks in some beams) and in walls in the neighborhood due to structural pounding during the March 14, 1979 earthquake [24]. After local repairments of the cracked beams, as the neighboring structure was demolished and a larger separation was placed with the new neighboring building, the building experienced moderate structural damage due to diagonal tension in beams and extensive damage in nonstructural masonry walls (the first author participated in a damage survey reconnaissance of this building). The building was again locally strengthened in the damaged beams and replaced the damage walls. However, because the building had perennial problems in the masonry walls in moderate earthquakes due to its lateral flexibility, in 2002 it was integrally retrofitted using ADAS devices mounted in chevron braces, as described elsewhere [31]. In the opinion of the authors, the seismic performance of Torre Monterrey during the September 19, 2017 earthquake was very good, as noted in all the pictures taken externally just after the earthquake, when it was part of Cofepris government agency (Fig. 42a). However, as another government agency took control of this building in the meantime, it was rather surprising to the authors to see later that the building was closed and taken out the façades, even today (Fig. 42b), ignoring if there was a significant interior damage. The authors requested the new government tenant to allow a technical visit, but they did not receive an answer. Finally, the second author was able to get inside the building in May 2022 with a local permission from the in-site security personnel. Then, he was able to check that the ADAS devices, columns, beams, floor systems and the connections were all in good shape (Fig. 42c). All the building had was accumulated dust, as even partition walls in the interior were in good shape. Then, the problem with this building has been that the new administration wanted a renovation of spaces and façades, and since it is a public building, perhaps there was not a budget to spend for it!

a) East building b) West building

Figure 41: Observed seismic performance of IMSS Headquarters 3-building complex, retrofitted with ADAS devices. Pictures taken on September 25, 2017

a) September 25, 2017 b) November 25, 2022 c) May 24, 2022

Figure 42: Observed seismic performance of Torre Monterrey office building, retrofitted with ADAS devices.

As it has been already shown, most retrofit applications in Mexico City before the September 19, 2017 earthquake have been employing the ADAS devices. Nevertheless, other HEDDs have been used. For example, the 22-story SAGAR building, originally a CC-FS with boundary RC shear wall system, was retrofitted in 1999 with a flexural beam-type device [22, 32], known in Mexico as the DV device, which was significantly tested before using in the retrofit [32-33]. The retrofit scheme consisted on placing these DV devices receiving the reactions of V steel braces (Fig. 43). The observed seismic performance of the retrofitted SAGAR building during the September 19, 2017 earthquake was excellent, immediate occupancy category (Fig. 43).

a) b)

Figure 43: Observed seismic performance of SAGAR office building, retrofitted with DV devices. Pictures were taken after the September 19, 2017 earthquake.

An interesting application which the first author found by chance in the mid 2000s is the retrofit for a 5-story, health center for elderly people using an I-section, low-yield steel as shear panel mounted on chevron braces (Fig. 44b), which unfortunately it is not documented. The retrofitted building originally was a CC-FS system apparently built in the 1960s. As it can be observed in Fig. 44, the seismic performance of this building after the September 19, 2017 earthquake was excellent, having an immediate occupancy status.

A more recent retrofit application using HEDDs is the seismic retrofit (preventive) of the "G" building at our University Campus at Azcapotzalco. The original 4-story CC-FS building was erected in the late 1970s with a very long plan aspect ratio, low redundancy and plenty of masonry infill walls, to separate classrooms and labs. This building also had to be strengthened to satisfy code standards for school use. Then, the preventive retrofit project started in 2011 and consisted of adding buckling restrained braces (BRBs) and jacketing the columns, plus strengthening the existing waffle-slab at the connections with BRBs, using plates. The retrofit was designed using performance-based analysis and design [34]. Retrofit works started in 2015 (Fig. 45a) and were finished in early 2017 (Fig. 45b). The observed seismic performance during the September 19, 2017 earthquake was excellent (as all our Campus, fortunately), having an immediate occupancy status (Figs. 45c and 45d).

Slotted bolted connections (SBC) were used to retrofit, in the early 1990s, the five main buildings of Hospital 20 de Noviembre [1, 22, 35], one of the most important hospitals of ISSSTE security system for government workers. These hospital buildings were originally constructed in 1961 as RC moment frame building, and it had to be strengthened to satisfy the ruling code for a hospital use [35].

a) b)

Figure 44: Observed seismic performance of Dr. Gómez Santos Health Center Building for elderly people, retrofitted with low-yield steel shear panels. Pictures were taken after the September 19, 2017 earthquake.

a) February 2016 b) February 2017

c) September 2017 d) September 2017

Figure 45: Observed seismic performance of Building G of Universidad Autónoma Metropolitana, Azcapotzalco Campus, retrofitted with BRBs.

Then, four of the 6-story buildings were retrofitted using exterior steel truss buttresses with SBC, in order to be able to use these facilities whereas the retrofit project was under way (Fig. 46). As it can be observed, the overall seismic performance of the executed retrofits was very good, as the buttresses performed well (Fig. 46a) and the SBC performed good as well (Fig. 46b). However, some localized deterioration was observed in the painting of some tubes composing the buttresses, as well as some localized damage in non-structural masonry walls in the external consulting area at the first floor. The exterior 10-story annex building of the complex used exterior concentric X braces (exoskeletons) with SBC (Fig. 47). The performance of this building was excellent, no damage at all and the connections were just on excellent shape (Fig. 47c).

a) b)

Figure 46: Retrofit of 20 de Noviembre hospital buildings in Mexico City using exterior steel buttress with SBC. All pictures taken after the September 19, 2017 earthquake

a) b) c)

Figure 47: Retrofit of the Annex building of 20 de Noviembre hospital in Mexico City using exterior concentric steel braces (exoskeletons) with SBC. All pictures taken after the September 19, 2017 earthquake

3.9 Retrofits using viscous dampers

Viscous dampers have also been used to retrofit buildings in Mexico City before the September 19, 2017 earthquake [18, 22], another strategy to try to achieve resilient seismic retrofit projects. In retrofit projects in Mexico City, basically viscous dampers have been done to increase damping considerably and mounted on concentric steel braces, having a rigid connection between the beam-column-slab joint and the brace where the damper is being supported. Then, in this retrofit scheme, local strengthening of reacting joints is important. The retrofit then involves a moderate lateral stiffening, local strengthening and substantial increment of viscous damping. To the authors´ knowledge, the first building retrofitted with viscous dampers is the 10-story Revillagigedo parking building in downtown Mexico City, originally a RC moment frame building built in the 1960s, and which was retrofitted with Taylor devices between 2002 and 2004 [36]. As it can be observed in Fig. 48, its seismic performance during the September 19, 2017 earthquake allowed an immediate occupancy status.

a) b) c)

Figure 48: Retrofit of Revillagigedo parking building in Mexico City using Taylor viscous dampers. All pictures taken after the September 19, 2017 earthquake

Another successful retrofit with viscous dampers is for the 16-story, Río Lerma office building. This building was originally a 1983 RC moment frame with brick infill walls in the perimeter, and with an important setback from the 4th to the 16th stories [37]. The building experienced a small emersion and very reduced measured tilting and, as a consequence, some fissures were observed in few beams [37]. After studying different options, the best retrofit solution included the epoxy injection of the fissures, separate the masonry infill walls from the frames to reduce torsional coupling, and add 76 Mageba nonlinear viscous dampers mounted on concentric steel braces [38]. The planned retrofit allowed to increase significantly the damping, reduce and control lateral drifts and reduce the fundamental period from 2.17 s to 2.03 s in the most flexible direction [37-38]. As it can be observed in Fig. 49, the seismic performance of Río Lerma office building during the September 19, 2017 earthquake was excellent.

Finally, it is worth noting the retrofit of an iconic former 27-story, 105 m tall public office building in Mexico City. This building was inaugurated in 1975 as the Exterior Commerce Ministry offices. The building was found to have a significant tilting of 30 cm in 2015, so a straightening and retrofit was necessary. The building, now known as the Executive Tower for the Ministry of Economy of Mexico, was in an advanced construction of its retrofit project using Mageba nonlinear viscous dampers, exactly at the time the September 19, 2017 earthquake struck (Fig. 50). The building under retrofit performed well during the earthquake. The retrofitted building was put in use in 2018. The finished project now has 29 stories and 108.5 m in height, as a former architectural detail at the top, with only glasses which covered two stories, was remodeled to gain two-story spaces during the retrofit process.

a) Side view b) Front view c) Rear view

Figure 49: Retrofit of Río Lerma office building in Mexico City using Mageba viscous dampers. All pictures taken after the September 19, 2017 earthquake

a) June 2017 b) February 2019 c) November 2021

Figure 50: Retrofit of the Executive Tower of the Ministry of Economy of Mexico in Mexico City using Mageba viscous dampers. All pictures were taken from Google Maps

4 OBSERVED UNSATISFACTORY PERFORMANCES OF TWO BUILDINGS

As already shown within the paper, the seismic performance of most retrofitted buildings was satisfactory during the September 19, 2017 earthquake, particularly when the retrofit plan was integral and well executed. However, it is also worth noting those performances which were not good enough. In a previous work [1] three cases were discussed in detail. In this paper, the authors discuss other two cases, as they are important for the lessons we have to learn also from unsatisfactory performances.

4.1 Amsterdam building

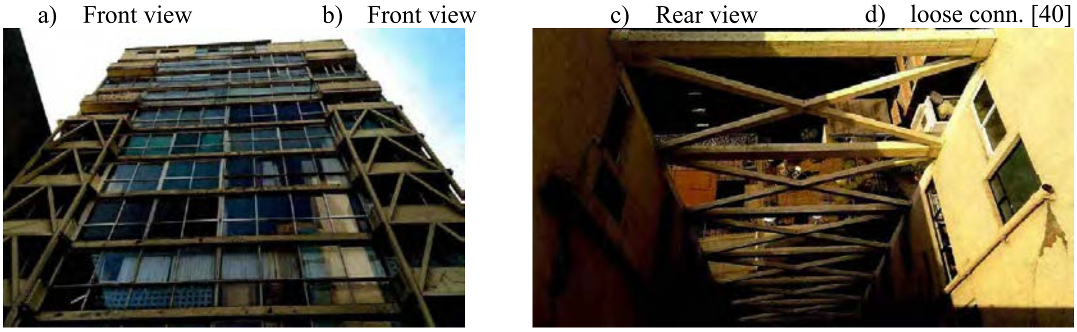
The 12-story Amsterdam apartment building was originally erected in 1967 according to the 1966 code. It was composed of reinforced concrete columns, a 30 cm thick waffle flatslab floor system and reinforced concrete shear walls 15 cm thick in elevators, stairs central core and in the boundaries (extreme of the flanges of an I-shaped plan). The original foundation consisted of a mat, box foundation over friction piles 27 m in depth [39-40]. It had the following structural irregularities: I-shaped plan, global slenderness and the 12-story setback at the front (Fig. 51a). The original structure was weakly-redundant in the transverse direction (normal to the street, Fig. 51a), as the flanges of the I section had only two columns per flange (one equivalent frame) in that resisting direction. The building was severely damaged during the September 19, 1985 earthquake. Then, it was retrofitted by adding exterior steel braced frames from stories 1 to 6 in the longitudinal direction (Figs. 51c and 51d). In addition, concrete braces were placed in the perimeter to connect the flanges of the I-shaped plan from stories 1 to 5 [40] and then switched to added steel braced frames placed between stories 6 to 10 (Figs. 51b and 51f).

The retrofitted building was severely punished during the September 19, 2017 earthquake, as it can only be seen with detail in the interior (the exterior was somewhat deceiving, Figs. 51a-c). An impressive emersion of 70 cm was observed (Fig. 51i), denoting that the original friction piles worked as point-bearing piles. Tilting was somewhat evident (Fig. 51c). Evidence of structural pounding with the neighboring 6-story building to its right was observed (Fig. 51a). The connections between the added steel braced frames to the original slab-column joints got loose after the earthquake (Figs. 51d and 51g), and significant local damage was observed there. RC columns experienced severe shear cracks (Fig. 51h) and spalling for the concrete with exposure of the longitudinal steel reinforcement at the lower levels. Shear walls experienced diagonal tension shear cracks of more than 3 mm in thickness and spalling in the first two stories.

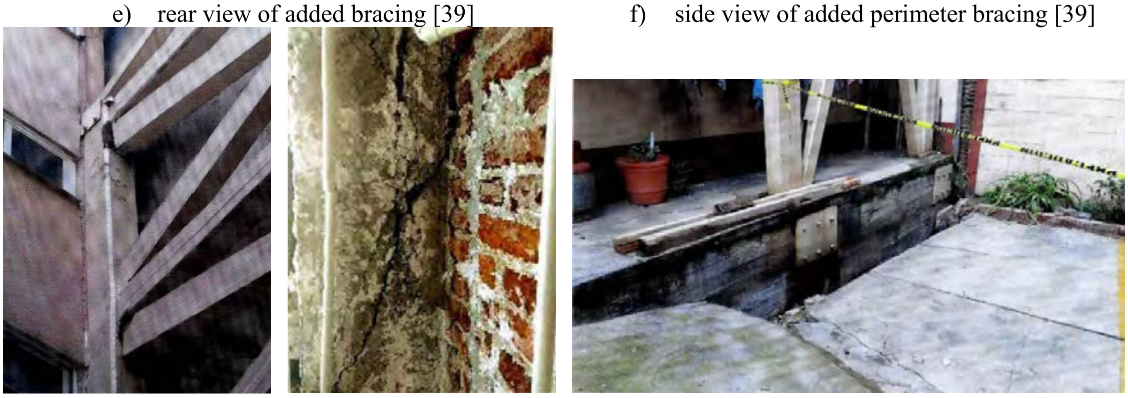
Despite of the severity of the observed damage, the owners of the building requested a detailed structural safety review. This review included the collected field-reconnaissance information, original blueprints for the buildings, topographic verticality measurements, free ambient vibration tests, and calibrated 3D ETABS models to meet the structural safety standards for the new 2017 code [39]. The measured tilting was 17 cm at the top story, which considerably exceeded the allowable drift by the code. From ambient vibration tests, the measured fundamental periods were T_x = 1.37s in the direction perpendicular to the street (e.g., Fig. 51f) and T_y = 1.06s in the direction parallel to the street (e.g., Fig. 51e). Then, an equivalent-elastic 3D ETABS model of the existing structure was calibrated and the building reviewed according to the 2017 code. As expected, the equivalent nonlinear drifts obtained from equivalent-elastic analyses according to a traditional force-oriented, collapse-prevention seismic code methodology considerably surpassed the allowable drift limits in both orthogonal directions, but particularly in the perpendicular direction, where it was close to 3.5% [39]. Then, it was recommended and confirmed that the building should be demolished, as it finally was done.

As station CI05 is very close to the subject building (about 5 blocks walking distance towards its south and west) an educated guess of the impact of the recorded ground motions was done using displacement ductility demand spectra [41] for the identified critical transverse direction and the CI05 N90W record (Fig. 51j). From the measured periods from ambient vibration tests of the already damaged structure, T_d = 1.37s was measured. Then, the initial elastic period, considering the observed damage, and that a global developed ductility of two might be related to an effective reduction of period close to $\sqrt{2}$, then the likely initial elastic period before the earthquake struck was estimated as T_e = 0.97s.

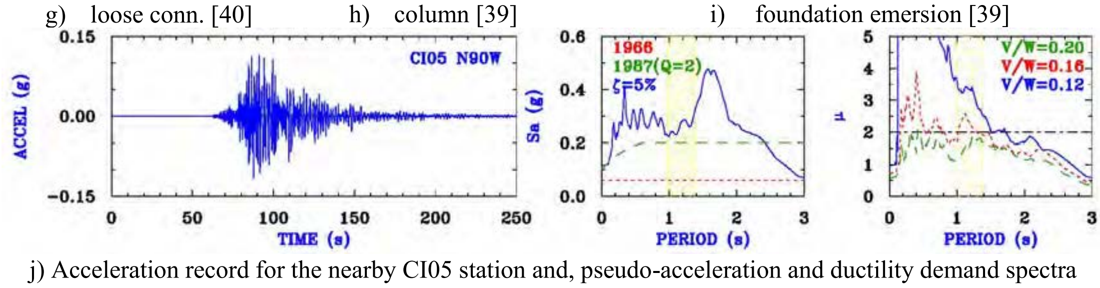
a) Front view b) Front view c) Rear view d) loose conn. [40]



e) rear view of added bracing [39] f) side view of added perimeter bracing [39]



g) loose conn. [40] h) column [39] i) foundation emersion [39]



j) Acceleration record for the nearby CI05 station and, pseudo-acceleration and ductility demand spectra

Figure 51: Observed damage for the 12-story Amsterdam apartment building during the September 19, 2017 earthquake

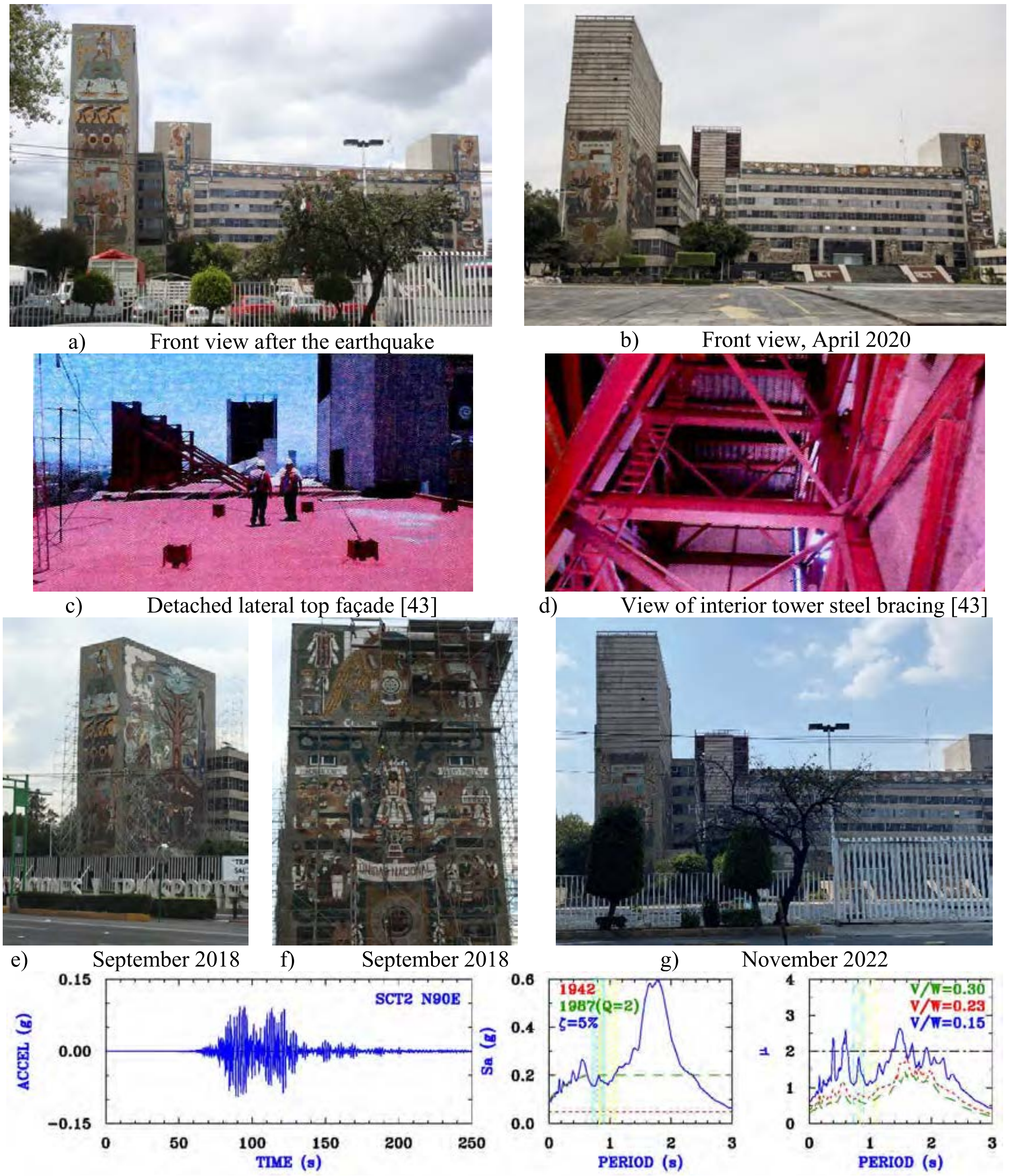
Therefore, in the spectral plots of Fig. 51j, the period range 0.97s ≤ T ≤1.37s where this structure was expected to respond during the event is shaded in yellow. According to the 1966 code, the building was a Type B, Class 1 structure in soft soils, then the constant design acceleration was a=0.06g. According to the 1987 code, the retrofitting of this building should be designed at least for Group B-2. Assuming a global deformation capacity or "ductility" Q = 2, then, the design acceleration for the plateau is $c/Q' = c/Q$ = 0.20g (Fig. 51j). It is observed in Fig. 51j (central plot) that in the period range of interest, the design spectra for the 1987 assuming a global ductility factor Q = 2 is below the observed spectral accelerations for CI05 N90W. In addition, the period range of interest is near the ascending branch towards resonant responses, so important damage should be expected. Therefore, just attending to this reasoning, damage close to the collapse prevention was likely, as it was observed. For the ductility demand spectra, three lateral strengths were crudely assessed: a) V/W = 0.20, as it is the requested estimate to comply with the 1987 code, b) a minimum strength related to the 1966 code V/W = 0.12 considering a global overstrength Ω = 2 and, c) an intermediate capacity between the two just assumed, V/W = 0.16. The Takeda hysteretic model [42] with parameters β_0=0.1 and β_1=0.9 was used. It can be observed from the ductility demand spectra in Fig. 51j (right plot), that in the period range of interest (0.97s $\leq T \leq$ 1.37s), the building most likely responded in nonlinear resonance, as unidirectional peak ductility demands were close to $Q = \mu$ = 2 even when V/W = 0.20, and if the lateral strength effectively developed during the earthquake was smaller than that (e.g., V/W = 0.16), then, the observed damage should be considerably higher.

It can be concluded that although the observed extent of damage in Amsterdam building was due to likely resonant responses in the nonlinear range, several structural weaknesses worsen the response. Among them are the identified conditions of structural irregularity, the reported large emersion (Fig. 51i), the measured tilting and the weakness of un-strengthened original columns with a weak shear detailing (Fig. 51h). Also, the selected retrofit strategy was not integral, as not all stories were stiffened and strengthened by the added steel frames, as described above. Then, it was observed again that partial retrofits along the height of a previous seriously damaged building do not necessarily respond well after a strong earthquake.

4.2 Iconic SCT buildings

Iconic SCT office buildings were originally planned to be hospital buildings for the IMSS medical center which construction started in 1954 (designed according to the 1942 code). However, these facilities were later assigned to be the headquarters of the Federal Ministry of Communications and Transportations of Mexico, and were inaugurated in 1957. The main front building complexes (A and B) originally had 11 stories. Building complexes, A and B are in fact composed of three independent buildings, as there are two end-buildings (A1 and A2, B1 and B2) separated from the central buildings (A and B) by expansion joints. The structural system for A1, A2, B1 and B2 buildings was composed of steel I columns and I beams with solid RC flatslabs. In main central buildings A and B, the central I columns were filled with an exterior square lightly reinforced concrete section; this is, among pioneering composite SRC columns worldwide [43]. The foundation was composed of 1-story (about 4 meters in depth) independent box foundations (used as basement for offices and labs) over point-bearing piles [44]. The original buildings had the following structural irregularities: a) global slenderness, b) soft story potential because abrupt changes of cross I-sections of beams and columns in a given story and, c) in the case of buildings A and B, long rectangular plans. Besides, all buildings were weakly redundant in the transverse direction (2-bay frames).

As a consequence of the partial top three-stories which collapsed in buildings A and B during the September 19, 1985 earthquake [1], and because of both their importance and the artistic value of the murals of their façades (painted by famous Mexican muralists), these buildings were rescued using a complex retrofit project (Fig. 52).



a) Front view after the earthquake
b) Front view, April 2020
c) Detached lateral top façade [43]
d) View of interior tower steel bracing [43]
e) September 2018
f) September 2018
g) November 2022
h) Acceleration record for the SCT2 station and, pseudo-acceleration and ductility demand spectra

Figure 52: Observed damage for the SCT buildings (A, A1, A2, B, B1 and B2) during the September 19, 2017 earthquake.

As a part of this integral retrofit, all original buildings had a floor reduction to six stories. In order to preserve most of the original murals, end-buildings A1, A2, B1 and B2 had new additional stories, composed of braced steel frames with I sections for columns, beams and braces (Figs. 52b, 52d and 52g), leaving apparently setback buildings (Fig. 52a). To rescue the original murals of the seven story of A building, steel buttresses were built at the six-story roof [43] to hold this part of the murals (Fig. 52c). The foundations of A1, A2, B1 and B2 buildings were intervened with additional point-bearing piles [44]. Expansion joints between buildings were protected with neoprene gaskets. Original murals were first carefully retired by experts, and then mounted on metal racks which were attached to the retrofit buildings [44].

During the September 19, 2017 earthquake, interior damage was reported on nonstructural elements, plafonds, partition walls in staircases, etc. [43-44]. However, the added structural elements, including braced elements remained undamaged (e.g., Figs. 52b-d, 52g). There were evident problems in some metal racks which clearly detached from the structure in buildings B1, B2 and A2 (Fig. 52a) or fell down (Fig. 52c). Neoprene gaskets and expansion joints were severely damaged [43-44], particularly those connecting building A2 with building B. More importantly, however, excessive tilting was observed in all referred building (noticeable without using instruments). The measured tilting in building A1 towards the southeast was 36 cm, equivalent to 1.8%, which it is higher than the maximum 1.5% tilting allowed by the code [43]. Besides, evidence of incipient failure of the box foundations was observed in their transverse direction. Soil lateral displacements within the perimeter and soil detachment from box foundations were found, jeopardizing the global stability of the buildings in future strong earthquakes [44]. Then, it was recommended to demolish these buildings, because of the dangerous foundation potential failure and the already out-of-code tilting. It is worth noting that in a previous private study conducted by the same firm [44], it was found that all buildings would not comply for the design subduction earthquake scenario covered by the design spectra of the ruling code NTCS-04 [45]. Because of the artistic relevance of the murals, works started slowly to detach carefully the murals and metal racks (Figs. 52b, 52e-g) before starting formal demolitions.

To gain some insight on the severity of the ground shaking and the observed response for the retrofitted structures during this earthquake, the in-site SCT2 N90E record was used (Fig. 52h). There is no public information for the natural periods of the retrofitted structures, either experimentally measured or analytically estimated. Then, it was roughly considered that for the braced 11-story steel buildings (A1, A2, B1 and B2), fundamental periods may oscillate between $0.075N$ to $0.10N$, depending on the effectiveness of the strengthening and soil-structure interaction (SSI) effects. Then, a period range $0.875\text{s} \leq T \leq 1.10\text{s}$ was considered for these buildings and are marked in yellow shading in Fig. 52h. For the 6-story buildings A and B, it was considered that mostly, the retrofit in that section was the reduction of stories and fewer added braces (not shown). Then, a variation between $0.12N$ and $0.15N$ was roughly considered for the natural periods of these buildings including SSI. Then, a period range $0.72\text{s} \leq T \leq 0.90\text{s}$ was considered for these buildings, and are marked in cyan shading in Fig. 52h. According to the 1942 code, these buildings were Type II, so a constant acceleration $a = 0.05$g should have been used for their design. According to the 1987 code, the retrofitted buildings should be designed for Group A (importance factor I=1.5), and assuming a global deformation capacity or "ductility" $Q = 2$, then, the design acceleration for the plateau is $c/Q' = c/Q = 0.30$g (Fig. 52h). It can be observed that in the period range of interest, the design spectrum for the 1987 assuming a global ductility factor $Q = 2$ covers tightly the spectral accelerations for SCT2 N90E, so some damage should occur, as it was observed. For the ductility demand spectra, three lateral strengths were crudely assessed: a) $V/W = 0.30$ to comply with the 1987 code, b) a minimum "real" strength related to the 1942 code $V/W = 0.15$, considering that overstrength in steel structures are much higher than in RC structures [46] because of the use of a more limited universe of steel I sections, so $\Omega = 3$ was used and, c) an intermediate capacity between the two already described, $V/W = 0.23$. An elastic-perfectly plastic hysteretic model was used to represent the global response of the steel structures.

It can be observed from the ductility demand spectra in Fig. 52h (right plot), that in the period ranges of interest, both the 11-story buildings and the 6-story buildings most likely would have responded within the elastic range if the yield strength associated to a retrofit according to the

1987 (V/W = 0.30) or somewhat smaller than that (V/W = 0.23) should have been developed. These results correlate well with what it was reported with main structural elements. If the strength of these buildings would have been closer to an unretrofitted condition (V/W = 0.15), some damage could have been developed, especially for the 6-story buildings (cyan shaded region). Granted the gross estimates using educated guesses to assess plausible ranges of fundamental periods and global lateral strengths, it can be concluded that the erected retrofit project was well planned from structural dynamics viewpoint, to take the retrofitted buildings away of potential resonant responses. The observed elastic response of main structural elements was due to this strategy. Unfortunately, the foundation intervention was not enough to restrain the measured tilting, the soil distress and detachment from box foundations.

Additional tests were conducted (vibration tests, soil tests, etc.) to judge if these SCT buildings could be rescued. In the authors´ opinion, this should not be a wise decision, not because these buildings were not well retrofitted above the foundation, but because: a) these buildings have had chronicle soil-foundation problems, such as notorious differential soil settlements along buildings A and B, b) the observed tilting and foundation distresses during the September 19, 1985 and 2017 earthquakes and, c) a detailed evaluation conducted previously by a design firm concluded that the buildings would not warranty a satisfactory performance for the subduction earthquake scenario according to NTCS-04 and their useful life is over [44]. It should be better, safer, faster and cheaper to demolish these buildings and erect new, modern facilities, after retiring completely the valuable murals (Figs. 52b, 52e-g), which can always be placed back or used in other public facility. Finally, after more than 5 years, it seems that they concluded that these buildings should be demolished, as the government recently announced that a politician (an engineer) would be in charge of the "new project" for the SCT complex.

5 ON-GOING SEISMIC REHABILITATION PROJECTS OF SOME DAMAGED BUILDINGS DURING THE 2017 EARTHQUAKE

As consequence of the September 19, 2017 earthquake, and taking aside collapsed and demolished buildings, around 1,405 buildings of all uses experienced moderate damage or severe damage [5, 47], so they have to be strengthened or retrofitted. The most severely damaged sector was apartments buildings for housing, where around 1,000 buildings were on those medium and high damage categories and have to be retrofitted [5, 47]. According to the data reported in the web site Reconstrucción CDMX by city authorities [48], up to March 16, 2021, 324 apartment buildings are being rehabilitated using public funds and the donations from the people and Mexican charitable associations [47-48]. Then, around 32.4% of these damaged apartment buildings are being strengthened and retrofitted with public funds, whereas in the remaining inventory, the damage is being repaired by particulars (or no action is being taken at all). Therefore, there are many different strategies that have been used and are being used in Mexico City to rehabilitate this damage inventory, from integral retrofit plans, to replacement of materials only, or no-action (damaged, abandoned buildings). In following sections, the authors briefly present some of the strategies that are being taken, many of them already conceptually explained in previous sections.

5.1 Column jacketing only

The jacketing of columns and beams has a big reputation in Mexican practice, as their perceived performance has been good, specially when all columns are jacketed, this is, an integral, global strengthening strategy has been used. For these reasons, many damaged buildings during the 2017 earthquake are being reinforced with column jacketing. As an example, there is the Atlixco and Michoacán 8-story corner building, an original CC-FS building from the late 1960s.

This building experienced cracking damage in many masonry infill walls due to its lateral flexibility and torsional response, and was catalogued in the medium damage category. The building was retrofitted using RC jackets which increased considerably their original cross sections (Fig. 53), increasing both lateral stiffness and lateral strength.

a) September 2018 b) September 2018 c) September 2018

Figure 53: Retrofit of the Atlixco and Michoacán corner apartment building in Mexico City using RC column jacketing.

A similar strategy was followed for the 19-story Insurgentes Sur and Monterrey office building, a CC-FS structure built in the 1970s. This building was classified in the medium damage category by the city (no details), something that was not evident from the exterior shortly after the earthquake struck (Fig. 54a). The building was operating normally, but in 2021-2022, an integral retrofit-strengthening plan was executed using latticed steel jackets in the columns (Fig. 54b). The rehabilitated building went to normal operation at the end of 2022 (Fig. 54c).

a) September 2017 b) May 2022 c) November 2022

Figure 54: Retrofit of the Insurgentes Sur and Monterrey corner office building in Mexico City using latticed steel column jacketing.

After a major earthquake, there are always retrofit stories like the following one. The 8-story Colima apartment building was apparently undamaged from the exterior when the September 19, 2017 earthquake struck. That it is why it was not detected by the authors (who walked around there), and it was not included in the database of city authorities. However, there should have some extent of unknown interior damage which perhaps was augmented during one or both of the moderate earthquakes that struck Mexico City in June 2020 and September 2021. Then, that it is why this damaged building "went out of the closet", and in March 2022, it was observed that an integral strengthening using latticed steel jackets was under way (Fig. 55)

a) March 2022　b) March 2022　c) March 2022

Figure 55: Retrofit of Colima apartment building in Mexico City using latticed steel column jacketing. Pictures courtesy of Omar Villegas-Jiménez

5.2 Wall jacketing only

The jacketing of masonry infill walls with a welded-wire mesh is also a strengthening technique that has a good reputation in Mexico to rehabilitate low to medium rise buildings, where the main structural system is composed by masonry shear walls. Then, there are some old apartments buildings that are being rehabilitated using this technique using public funds. The 8-story, Ferrol and Escocia apartment building was originally a building with a first story with columns and flatslabs and with flatslabs over masonry structural walls in the stories above. The building was erected in 1980. Its twin building, the Edinburgo and Escocia building, collapsed during the 2017 earthquake. The Ferrol and Escocia building experienced severe damage in many walls due to structural pounding. This building was strengthened by only jacketing the walls with welded-wire mesh and mortar (Fig. 56), a technique where both the strength and the local ductility of the walls is improved, as observed in lab tests [49-50]. However, given that the twin structure had a complete, spectacular collapse, the authors are not sure if this was the best decision for this particular building. A similar strengthening was done for the 5-story Romero de Terreros apartment building (Fig. 57), built in 1965 with a similar system: moment frame in the first story, RC slabs over masonry shear walls above. This building was severely damaged in September 2017 (high damage category). It experienced generalized shear damage in the masonry walls and some beams and columns in the first story. This building was strengthened by using RC jackets in columns and beams in the first story, and jacketing the masonry walls with welded wire mesh and mortar (Fig. 57).

a) May 2019 b) May 2019 c) October 2020

Figure 56: Retrofit of the Escocia and Ferrol corner apartment building in Mexico City using wall jacketing with welded wire mesh and mortar.

a) March 2021 b) March 2021 c) November 2021

Figure 56: Retrofit of Romero de Terreros apartment building in Mexico City using wall jacketing with welded wire mesh and mortar.

5.3 RC shear walls

RC shear walls are being used in integral strategies where substantial lateral stiffening and strengthening is required, and when torsional response should also be controlled. Then, it is being applied in building severely damaged (high damage category) during the September 19, 2017 earthquake. The retrofit of nine apartment buildings from Multifamiliares Conjunto Urbano Tlalpan housing complex adding L shear walls has already been described in detail elsewhere [47]. Another of the applications is the retrofit of the 9-story, Xochicalco and Obrero Mundial corner building (Fig. 57a), built in 1970 with a CC-FS structural system. This building experienced shear cracks in columns from stories 1 to 5 due to torsion, as well as severe cracking of masonry infills, due to the torsional response. The executed retrofit included the addition of RC shear walls in the perimeter to reduce torsional responses (Fig. 57b) as well as RC jackets for all columns (Fig. 57b). The 8-story, República de Perú office building, built in the late 1960s with a CC-FS system, experienced severe damage due its lateral flexibility and structural pounding with its neighboring building to its left (Figs. 58a and 58b). As consequence, interior and border columns and infill masonry walls were affected, particularly in the 4th story (pounding contact), where the flatslab was also damaged. The building was retrofitted by using RC jackets and adding new RC shear walls at the perimeter to reduce its lateral flexibility and add lateral strength (Fig. 58c).

a) February 2020 b) February 2020

Figure 57: Retrofit of Xochicalco and Obrero Mundial apartment building in Mexico City using RC column jacketing and adding RC shear walls.

a) October 2017 b) October 2017 c) February 2019

Figure 58: Retrofit of República de Perú office building in downtown Mexico City using RC column jacketing and adding RC shear walls.

The case study of the 9-story Romero de Terreros and Patricio Sanz corner apartment building (Fig. 59) is particularly interesting. One can illustrate with this case study the extended practice worldwide in civil engineering, to give priority to initial costs rather than a sound structural safety plan in the long-term. In the opinion of the authors, this a wrongdoing: structural safety is always first. The building was initially constructed in 1980 with a CC-FS system and brick infills within the perimeter. During the September 19, 2017 earthquake, the building experienced severe and extended damage in the brick infills (interiors and exteriors, Fig, 59b) due to its lateral flexibility and torsional responses, so it was classified in the high damage category. For this reason, it was rather surprising for the first author to witness, in May 2019, that the building was in full operation by just replacing damaged materials and a good paint (compare Fig. 59c with Fig. 59a), when the building experienced significant damage (Fig. 59b). This wrong practice of just replacing materials in badly damaged buildings is known in Mexico as: "anti-seismic painting". That name is used to highlight that with this practice, the vulnerability of the building is not reduced at all to future moderate and strong earthquakes, although it certainly has a therapeutic action for most users. As it can be observed, when using anti-seismic painting, an important action is to change the original color, so people will not relate mentally the color with the previous damage. On June 23, 2020, a M = 7.4 subduction earthquake with epicenter in Oaxaca was felt moderately in Mexico City, causing damage to the anti-seismic painting solution. Then, as it was observed in October 2020, a more serious retrofit solution was under way for this building (Fig. 59d), which included to build RC shear walls at the front (Figs. 59e and Fig. 59f) and within the interior to reduce lateral flexibility and torsional coupling. By comparing the final solution (Fig. 59f) with the original damaged building (Fig. 59a), one still wonders if the added front RC wall will be good enough to reduce torsional responses and lateral flexibility in a future strong earthquake. However, it certainly is much better than the anti-seismic painting solution (Fig. 59c).

a) December 2017 b) December 2017 c) May 2019

d) October 2020 e) March 2021 f) March 2022

Figure 59: Retrofit of the Romero de Terreros and Patricio Sanz apartment building in Mexico City adding RC shear walls and replacing brick masonry infills

The next two case studies are related to apartment buildings which were built according to the 2004 building code. According to the intensity of the ground motions in the sites of interest, these buildings should not have developed such a large extent of damage, as shown and discussed elsewhere [51].

The 7-story Tepic and Amealco corner apartment building was built in 2008 using the new version of a CC-FS system with masonry infill walls. The flatslabs were made very with large styrofoam block, which do not compose rigid diaphragms (in fact, semi-flexible diaphragms). The building was badly damaged during the September 19, 2017 earthquake, particularly the brick infills (Fig. 60a), so it was classified in the high damage category. After a large time of being abandoned, retrofit works started in March 2021. As it can be observed, an integral retrofit is being executed, where RC shear walls are being added at the perimeter, plus RC beams and RC columns (Figs. 60b and 60c). This is being done in order to reduce the previous lateral flexibility, torsional responses and increase lateral strength.

a) December 2017 b) November 2022 c) November 2022

Figure 60: Retrofit of the Tepic and Amealco apartment building in Mexico City adding RC shear walls and perimeter RC beams and columns

The two, 17-story apartment buildings: Tlalpan and Antonio Maura, with a CC-FS with masonry infills structural system were built between 2007 and 2011. These buildings have an I plan shape with an addition web, and their flanges and webs are very slender. Then, during the 2017 earthquake, these buildings experienced severe damage in most interior walls and stairs, due to its lateral and torsional flexibility, which was visibly marked at the exterior infill walls (Fig. 61a), so they were classified in the high damage category. As 390 families were affected, the retrofit plan of these buildings with public funds has been careful, but somewhat sloppy and tortuous. The original retrofit solution included RC shear walls at the flanges of the I section tied together with steel braces (Figs. 61b and 61c). However, this solution was stopped for more than a year, because the owners of the buildings protested about the firm who was in charge of the retrofit plan. Then, after changing design firms, it seems that in the final retrofit, the RC shear walls remain (Fig. 61d), but original RC columns are being jacketed, and new perimeter beams are constructed at the perimeter of flatslabs (Figs. 61e and 61f).

5.4 Conventional addition of concentric steel braces

As previously discussed, the seismic retrofit using steel braces for seriously damaged buildings due to their lateral flexibility, weak strength and potential resonant responses, has a big reputation in the Mexican structural design community. Then, it is not surprising that it is being used extensively to retrofit a large inventory of the damaged buildings during the September 19, 2017 earthquake. Most of the retrofitted buildings with braces were classified in the medium and high damage categories, but it is even being used in apparently undamaged buildings.

a) March 2018 b) November 2019 c) March 2020

d) November 2022 e) November 2022 f) November 2022

Figure 61: Retrofit of the Tlalpan and Antonio Maura apartment building complex in Mexico City adding RC shear walls, jacketing RC columns and adding perimeter RC beams

Starting with the more traditional solutions, where steel braces are added to connect directly with the existing columns (and beams), is the retrofit of 8-story Universidad and Eugenia apartment building, which was built in the late 1960s with a CC-FS system. This building was just renovated (only finishes) in the 1990s. The building was red targeted in September 2017 because experienced severe damage in interior masonry walls and staircases, for its lateral flexibility and torsional response. Besides, it was evident that the building had a significant tilt (Fig. 62a). The retrofit consisted in adding tubular concentric braces which were directly connected to original columns using a local steel sleeve segment (Fig. 62b). The first author does not think this connection was the right one to use. The original RC columns should have largely spaced stirrups, as that was the practice from the building code it was originally designed. Then, a complete jacketing of the original columns should have been done. Besides, the eccentric K bracing connected at the middle of the first story column seems extremely dangerous, for the same reason (see close to the left corner of the building in Fig. 62b).

a) September 2017 b) May 2021

Figure 62: Retrofit of Universidad and Eugenia corner apartment building in Mexico City adding steel bracing.

Another retrofit using steel braces that the first author thinks it has a dangerous detail is the one for the 12-story Bruselas office building, another CC-FS with masonry infill walls structural system. This building had medium damage during the 2017 earthquake for its lateral flexibility, as masonry infill walls were damaged at the interior and exterior (Fig. 63a). The building was quickly retrofitted using very slender steel braces at the rear façade (Fig. 63b) and at the front façade (Fig. 63c). The added braces should be effective to reduce the lateral flexibility. However, the discontinuity of the braces at the front façade at the first story due the parking entrance (Fig. 63c) may cause a problem during a strong earthquake if the perimeter walls are not strong enough, and if a soft and weak first story in the frontal frame is triggered.

a) February 2018 b) April 2019 c) April 2019

Figure 63: Retrofit of Bruselas office building in Mexico City adding steel bracing.

The 7-story, Anaxágoras apartment building was built in 1976 using a CC-FS with brick infills structural system, and it was severely damaged (red category) during the September 19, 2017 earthquake (Fig. 64a). After a long time of being abandoned, the building was finally integrally retrofit using concentric steel braces, jacketing the original RC columns with latticed steel jackets and adding a new column axis with steel box sections to complete the frame where the braces are connected (Figs. 64b and 64c). Although the added braces seem somewhat robust for a building of this size (Fig. 64c), the solution seems adequate to solve the former earthquake-resistant deficiencies of the building.

a) September 2017 b) March 2021 c) March 2021

Figure 64: Retrofit of Anaxágoras apartment building in Mexico City adding steel bracing and RC jackets

Perhaps one of the cleanest and well-executed retrofits using concentric steel braces are the one conducted for the 10-story Dinamarca and Liverpool corner building, built in the late 1970s with a CC-FS system and masonry infills. The building was red targeted, as it experienced substantial damage in most masonry infills (Fig. 65a), plus a column shear failure (buckled bars) at the first story, due to both torsional responses and soft story potential. A major retrofit plan was conducted adding chevron braces at both street facades and jacketing all columns next to the braces (Figs. 65b and 65c), reducing both the lateral flexibility, the soft story and the torsional response.

a) October 2017 b) March 2021 c) March 2022

Figure 65: Retrofit of Dinamarca and Liverpool corner apartment building in Mexico City adding steel bracing and RC jackets

The retrofit of the corner apartment building at Villalongín, Río Grijalva and Río Tigris is worth noting. This 8-story, steel moment frame building was built in 2006 according to the 2004 code. This building should not have experienced significant damage, as the response spectrum of the recorded ground motions nearby were less than half of those of the elastic design spectrum used for its design [51]. However, the building was red targeted because the very irregular polygonal plan, its lateral flexibility and its soft story potential caused extensive damage in the concrete block masonry infills (Fig. 66a). The retrofit plan consisted in introducing concentric tubular steel braces to reduce the lateral and torsional flexibility in all directions (Fig. 66b and 66c). The retrofit was finished in September 2019, and the owners decided to leave mostly the original looking for the façades. The only visible exterior sign of the retrofit are the chevron braces at the first story, which are somewhat hidden with the more elegant granite façade finishing that it was placed (Fig. 66d).

a) September 2017

b) March 2019

c) March 2019

d) September 2019 (Google Maps)

Figure 66: Retrofit of Villalongín, Río Grijalva and Río Tigris corner apartment building in Mexico City adding steel bracing

The ongoing retrofit for the 7-story Oaxaca apartment building is one which the authors are paying particular attention, due to the severity of the damage experienced by the building during the September 19, 2017 earthquake. This building originally was a CC-FS built in 1980, which experienced moderate damage during the September 19, 1985 earthquake, in masonry infill walls and damaged walls were just locally reinforced with a thin wire mesh [52]. During the 2017 earthquake, the building was red targeted, as it experienced substantial damage. Besides the tilting and structural pounding observed, there was extensive diagonal tension shear cracks in masonry brick infills and partition walls at all stories (Fig. 67a, 67c and 67d), plus severe shear cracks in some columns (Figs. 67c and 67d). One column was so damaged (Figs. 67c and 67d) that it was necessary to locally repair it while a final decision was made for the building (Fig. 67e). Recently, an integral seismic retrofit was started using eccentric tubular V braces, with a shear link, and jacketing the surrounding columns with latticed steel jackets (Fig. 67b). The authors have the reasonable doubt if the existing and visibly deteriorated flatslab (Fig. 67b) would be able to support the reactions of the eccentric V braces and the connection, despite the fact local steel plates are being placed at the top and bottom of that region to connect them (Fig. 67b).

a) September 2017 b) November 2022

c) September 2017 [52] d) November 17 [52] e) December 2017 [52]

Figure 67: Retrofit of Oaxaca apartment building in Mexico City adding eccentric steel V bracing and latticed steel jackets

The 6-story, Sor Juana office building, original an CC-FS system built in the 1970s, experienced moderate damage during the 2017 earthquake, primarily extensive damage in masonry façade infill walls (Fig. 68) and within the interior. This building was retrofitted by demolishing the two top stories (Fig. 68b), and then placing concentric steel X-bracing within the perimeter (Figs. 68b and 68c) and tying the flanges of the I-shaped plan with steel beams (W sections, Fig. 68b).

a) March 2018 b) September 2021 c) September 2021

Figure 68: Retrofit of Sor Juana Inés de la Cruz office building in Mexico City with a 2-story floor reduction and adding concentric steel X bracing and additional W beams.

5.5 Addition of steel braces to retrofit buildings with I-H and C-U plan configurations

As described and reported in detail elsewhere [5, 52], there were many buildings which were severely damaged during the September 19, 2017 earthquake and which had typical I-H or C-U plans. These plan layouts are extensively used in Mexico City to solve natural illumination and ventilation for the buildings. These plan layouts are highly vulnerable to earthquakes, particularly if one adds that, in apartment buildings, there are soft first-stories, as this story is usually destined to parking. In C-U shaped plans, torsional responses are also frequent. Many of these damaged buildings have been retrofitted by using concentric steel braced frames to tie the flanges of the I-H or C-U plan layouts at all stories (Figs. 69 to 75).

a) 2016 (Google Maps) b) February 2018 c) February 2018

Figure 69: Retrofit of Tlacotalpan apartment building in Mexico City using concentric steel braces to tie the flanges of an I-shaped plan layout. This building was finally demolished in 2021 (no shown).

One interesting case study is the one for the 9-story, Tlacotalpan apartment building (Fig. 69), and I-shaped plan building with CC-FS system which was red targeted because it experienced severe damage in masonry infills and some columns in the first story. The building was being retrofitted in early 2018 by tying the flanges of the I-shaped plan with concentric chevron steel braces (Figs. 69b and 69c), and preparing the jacketing of existing RC columns. Nevertheless, this retrofit did not advance much, as in April 2019 was about the same, according to Google Maps. In fact, in Google Maps one can see that the building was demolished in March 2021, perhaps attending to additional severe damage during the June 2020 Oaxaca earthquake.

The 9-story Monterrey apartment building (Fig. 70), originally was a CC-FS system built in the 1960s. This building was classified as medium damage during the September 19, 2017 earthquake, because the structural pounding with the 5-story building to its left that caused extensive damage in masonry infills in the first six stories. It is worth noting that a column at the first story was locally repaired with latticed steel jacketing after the 1985 earthquake. The building was retrofitted by tying together the flanges of the I-shaped plan with concentric steel X-braces (Figs. 70b and 70c).

a) January 2018 c) April 2019 d) February 2020

Figure 70: Retrofit of Monterrey apartment building in Mexico City using concentric steel braces to tie the flanges of an I-shaped plan layout.

The 8-story Av. Coyoacán apartment buildings (Fig. 71) were originally RC moment frame buildings erected in 1987. These buildings were classified as high damage during the September 19, 2017 earthquake, because they had generalized vertical cracks in the first story columns and needed to be propped up (Fig. 71b), besides having generalized cracking in masonry infills. The two buildings have back to back C-shaped plans, so they look from an aerial view as an I-shaped plan. An integral retrofit plan was started in 2019, where columns were jacketed using thin RC jackets (Figs. 71c and 71d). Exterior jacketed columns were prepared so bolts were preinstalled (Fig. 71d). This was done to facilitate the installation of connection plates and the concentric X- bracing which will tie the flanges of the C-shaped plan (Fig. 71e). Additional tying I-beams were also used at some stories (Fig. 71e). The retrofitted building was ready in early 2022.

The 12-story Uxmal apartment building (Fig. 71) was built in 1968 with a CC-FS structural system. The building was red targeted during the September 19, 2017 earthquake, as it developed generalized shear damage in infill masonry walls. As it can be observed, the flanges of the C-plan were already tied by steel beams in 2017 (Fig. 71a), which probably was a previous retrofit after the 1985 earthquake. The building was strengthened by replacing damaged walls, and stiffening the pre-existing frame that tied the flanges of the C plan by adding additional steel columns and concentric steel braces (Figs. 71b and 71c). The retrofitted building was ready and in full service since August 2019.

a) January 2018 b) January 2018 c) March 2019

d) April 2019 e) March 2021 f) March 2022

Figure 70: Retrofit of Av. Coyoacán apartment buildings in Mexico City using concentric steel braces to tie the flanges of two C-shaped plan layouts.

a) September 2017 b) March 2019 c) May 2021

Figure 71: Retrofit of Uxmal apartment building in Mexico City using concentric steel braces to tie the flanges of its C-shaped plan layout.

The 10-story San Francisco apartment building was originally a CC-FS structural system with brick infills built in 1957. This building experienced generalized damage in the masonry infill and façade walls during the 2017 earthquake (Figs. 72a and 72b) and it was red targeted. A reasonably retrofit started in 2019, where the damaged walls were renovated (Fig. 72c), columns as the soft first story were jacketed using latticed steel jackets (Figs. 72e and 72f), and the flanges of the C-shaped plan layout were tied attaching a new steel braced frame (Fig. 72d).

a) January 2018 b) January 2018 c) May 2019

d) October 2020 e) October 2020 f) October 2020

Figure 72: Retrofit of San Francisco apartment building in Mexico City using concentric steel braces to tie the flanges of its C-shaped plan layout.

The 11-story Prolongación de Uxmal apartment building (Fig. 73) was originally a CC-FS structural system with brick infills built in 1978. This building experienced generalized damage in the masonry infill and façade walls during the 2017 earthquake, and was red targeted. This slender building has an I-shaped plan layout with a very eccentric web, so it is almost C-shaped. Apparently, the steel I-beams tying the flanges of the larger reentrant corner (Fig. 73a) were placed after the 1985 earthquake. As it can be observed in Figs. 73b and 73c, the built retrofit, besides renovating the damaged masonry infills, consisted in adding inclined exoskeleton braces and tying the flanges together, using a concentric steel braced frames in both reentrant corner sides.

a) September 2017 b) May 2021 c) May 2021

Figure 73: Retrofit of Prolongación de Uxmal apartment building in Mexico City using concentric steel braces to tie the flanges of a very eccentric I-shaped (almost C-shaped) plan layout.

The 11-story Calzada de Tlalpan apartment building (Fig. 74) was built in 1978 using a CC-FS system with masonry block infills. The building was moderately damaged during the 2017 earthquake due to its lateral flexibility, primarily in masonry infills (Fig. 74a). An integral retrofit plan started in January 2019, which included the replacement of block infills, the steel latticed jacketing of columns (Fig. 74c), the lateral stiffening in the slender direction using concentric steel bracing (Figs. 74b and 74c), and tying the flanges of the I-shaped plan together with additional steel frames (Figs. 74b and 74c). Although the retrofit project was not still finished at the end of 2022, it seems likely that only additional exterior steel frames were used to tie the flanges. Hopefully, the additional lateral stiffening and strengthening of the building would help this solution to be successful in future strong earthquake. It is worth noting that the performance of that tying solution was not as good as expected in other buildings in the September 2017 earthquake, as shown before (Figs. 70a, 71a and 73a).

a) October 2017 b) November 2022 c) November 2022

Figure 74: Retrofit of Calzada de Tlalpan apartment building in Mexico City using concentric steel braces, latticed steel jackets and steel frames to tie the flanges of its I-shaped plan layout.

The 8-story Zapata apartment buildings (Fig. 75) were built in 1982 with a CC-FS system with masonry brick infills, having RC Saint Andreas crosses in perimeter walls (Fig. 75a). The three buildings were severely damaged during the 2017 earthquake; 80% of the brick masonry walls were damaged and some columns of the first story. These buildings were retrofitted by tying the web flanges of buildings B and C together, adding concentric steel X-shaped frames (Fig. 75b), by using latticed steel jackets in all first story columns (Fig. 75c), and attaching braced steel exoskeletons at the opposite side of the buildings (Fig. 75d).

a) September 2017 b) August 2019

c) August 2019 d) August 2019

Figure 75: Retrofit of Zapata apartment buildings in Mexico City using exoskeleton steel braces, latticed steel jackets and concentric braced steel frames to tie the flanges of the eccentric I-shaped plan layout.

5.6 Addition of exoskeletons (exterior steel braces)

Given the big reputation that in Mexico City have previous seismic retrofits using exterior steel braces as exoskeletons, many buildings are being retrofitted with this type of exoskeleton. The authors have already shown some mixed strategies to retrofit I-H and C-U plans with exo-skeletons (Figs. 73 and 75). In this section, the authors show three buildings where exoskeletons are the main solution. In the following section, it is shown one solution where exoskeletons are combined with HEDDs (Fig. 81). The first example is the red-targeted 6-story Miguel Laurent apartment building (Fig. 76), built in 1982 with a CC-FS system and brick infills. This building experienced severe damage due to pounding (Figs. 76a and 76b). Not only brick infills were severely damaged, but six first story columns were also damaged. Besides the jacketing of in-terior fist columns and the renovation of the damaged walls, the building was stiffened and strengthened by adding exterior steel braced frame exoskeletons (Fig. 76c), hoping to prevent severe pounding, despite the existing gap between adjacent buildings is almost null (Fig. 76b).

a) September 2017 b) September 2017 c) October 2020

Figure 76: Retrofit of Miguel Laurent apartment building in Mexico City using exoskeleton steel braced frames.

The 4-story and 8-story Márquez Stearling apartment buildings were built in 2010 according to the 2004 code with a CC-FS system and brick infills. These buildings were catalogued in the medium damage status, because there were some tensional fissures in columns and in masonry infills due to its lateral flexibility. These buildings are currently being retrofitted with exterior braced exoskeletons (Fig. 77). However, it is still unclear if the atypical barbed connections between the braces at the rear façade are intended to dissipate energy (Figs. 77b and 77c).

a) b) c)

Figure 77: Retrofit of Márquez Stearling apartment buildings in Mexico City using steel braces as exoskeletons.

The 13-story Londres apartment building, with a plus (+) plan layout, was originally a CC-FS system with brick infills erected in the 1970s. The building was catalogued as medium-damaged building after the September 19, 2017 earthquake, given the extent of damage of brick infills due to its lateral torsional flexibility, and some pounding contacts with its neighboring building (Figs. 78a to 78c). Retrofit works started in 2021 by attaching braced steel frames as exoskeletons in most flanges of the plus-shaped plan section (Figs. 78d to 78f), and the retrofit work was finished in 2022 (Figs. 78f to 78h).


a) October 2017


b) October 2017


c) October 2017


d) July 2021


e) July 2021


f) February 2022


a) March 2022 (Google Maps)

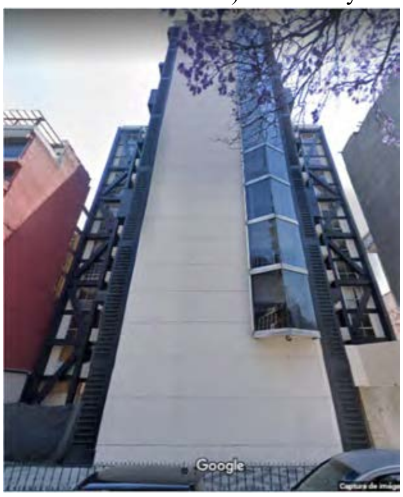

b) March 2022 (Google Maps)

Figure 78: Retrofit of Londres apartment building in Mexico City using exoskeleton steel braced frames.

5.7 Hysteretic energy dissipation devices and viscous dampers

HEDDs are also being used for the seismic retrofit of some buildings damaged during the September 19, 2017 earthquake, given the excellent performance observed in the 2017 earthquake in buildings previously retrofitted with HEDDs. In addition, initial costs are lowering down, because applications in new buildings have been raised in recent years, worldwide and in Mexico. One of such applications is the retrofit of the 10-story, Félix Cuevas corner office building using column jacketing and BRBs (Fig. 79). This highly-irregular building was originally erected as a CC-FS system in the early 1980s. In September 2017, this building was classified as medium damage, due to developed tilting and pounding evidence, plus their lateral flexibility, soft story potential and some interior damage. This building was retrofitted using BRBs and latticed steel jacketing in the columns next to the new BRBs (Fig. 79b).

a) September 2017 b) March 2020 c) July 2022

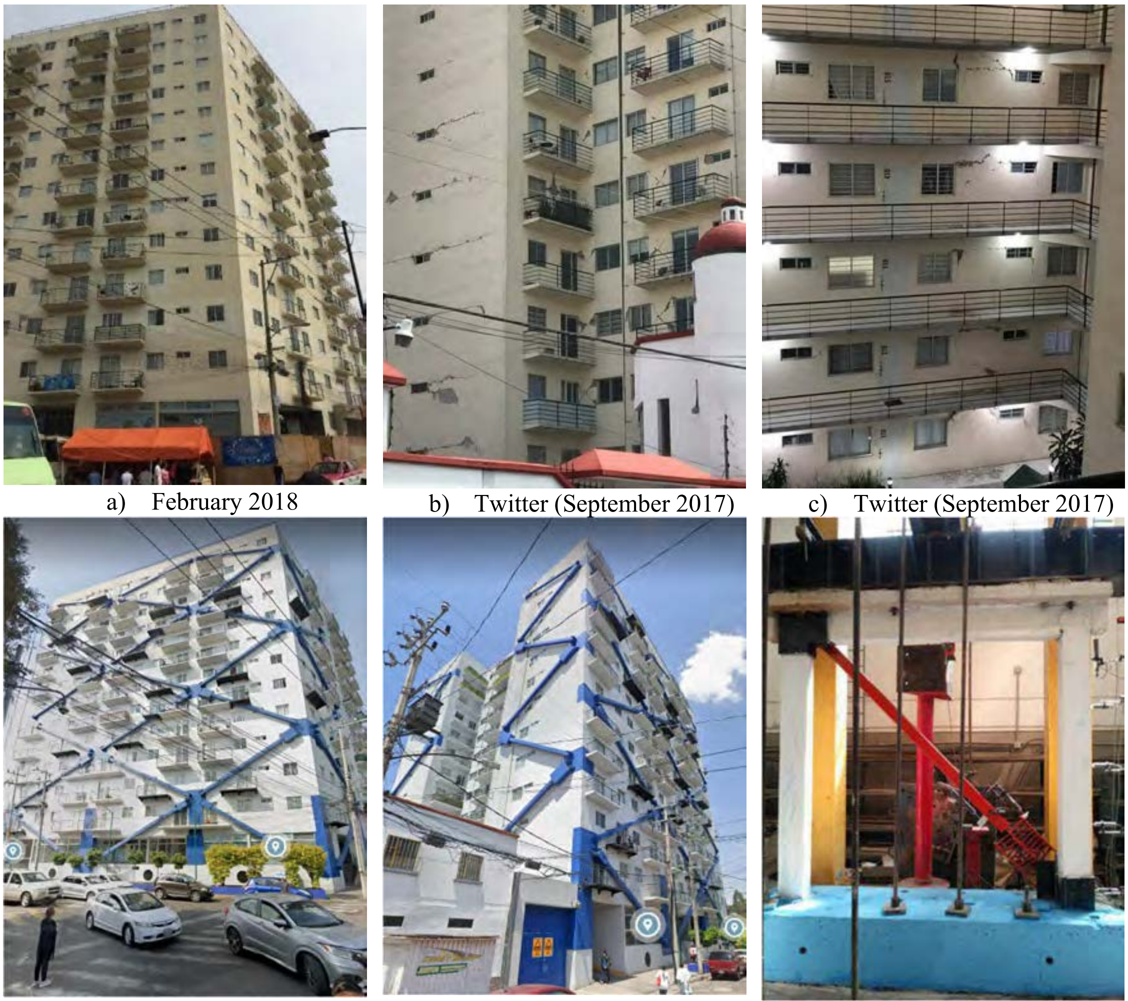
Figure 79: Retrofit of Félix Cuevas office building in Mexico City using BRBs and latticed steel jackets.

Another retrofit with BRBs which is still and process (somewhat slow) is the one for Av. Mexico and Citlaltépetl corner building, a 7-story building originally a CC-FS system erected in the 1970s. The building has a segment of a ring plan layout and experienced structural pounding with its neighboring building at Citlaltépetl. Retrofit works started since early 2019, and they have not been finished yet. From what it has been observed so far, the retrofit project involves RC column jacketing at the curve façades (Figs. 80a and 80b), BRBs at the rear façade (Fig. 80c), and perhaps the demolition or remodeling of the last story (Fig. 80a).

Two apartment buildings which were designed according to the most modern 2004 code and which experienced important damage, and they should not, given the measured intensities of the ground motions recorded nearby, were retrofitted with passive energy dissipation devices. The 13-stories Insurgentes Norte apartment building was constructed in 2012. The building has a very irregular pentagonal plan layout, with a large reentrant corner at the back, and a large interior diaphragm opening in L. The building was constructed with a very flexible floor system: the new flatslab system composed of some ribs and very large and wide Styrofoam blocks, a floor system which lateral flexibility has been already reported [54]. The vertical resisting elements were RC columns and masonry infill walls. During the September 19, 2017 earthquake, this building experienced important damage in most masonry infills, due to its lateral flexibility and torsional response (Figs. 81a to 81c). Some wallets between windows failed as short columns (Fig. 81b). Some interior columns experienced fissures.

a) Façade intervention b) Column jacketing c) BRBs at rear façade

Figure 80: Retrofit of Av. México and Citlaltépetl corner building in Mexico City using RC jacketing and BRBs.



a) February 2018 b) Twitter (September 2017) c) Twitter (September 2017)

d) Google Maps (Oct 2022) e) Google Maps (Oct 2022) f) Implemented HEDD [55]

Figure 81: Retrofit of Insurgentes Norte corner apartment building in Mexico City using HEDDs in exoskeletons.

Given the described damage, it was obvious that this building required a major retrofit. Then, an exterior braced steel exoskeleton was designed [55] and implemented (Figs. 81d and 81e). It is worth noting that in the interior of the box-plates, there are a new HEDDs recently tested at UNAM (Fig. 81f), as reported elsewhere [55].

Finally, the 9-story Cuauhtémoc apartment building, erected in 2006, experienced severe damage [56] during the 2017 earthquake (Figs. 82a and 83b). The building has a rectangular-shaped plan layout, with two large openings (an 8-shape). The building originally has a precast structure: precast columns and double-T beams as floor system, and a great number of masonry infill walls. This building was primarily repaired replacing damaged material and adding fluid viscous dampers from Mageba, and locally strengthening the connection between the old structure and the braces where the viscous dampers are mounted (Figs. 82c and 82d).

a) December 2017

b) September 2017 [56]

c) March 2019

d) March 2019

Figure 82: Retrofit of Cuauhtémoc apartment building in Mexico City using fluid viscous dampers.

5.8 Retrofit of soft first story buildings

Soft and weak first story buildings are usually among the most severely affected during strong earthquakes, as it was confirmed during the September 19, 2017 earthquake [53]. When there are additional weaknesses (torsional response, lateral flexibility, etc.) integral strategies are used, as those already described in previous sections. However, some retrofit solutions that have been implemented in the past, like adding shear walls or steel braces at the soft first story only, are being used again. Some of them have shown some improvements, like integrally jacketing resisting elements above the first story.

For example, the 11-story Nicolás San Juan and San Borja corner apartment building (Fig. 83) was originally a CC-FS structure built in 1972 with non-ductile shear detailing for columns. The building exhibited tilting after the earthquake, plus some fissures in columns at the first story and some stories above. Besides, there was evidence of pounding with its neighboring building along San Borja street and then, the building was red targeted. Nevertheless, the retrofit of this building only included the repairment of damaged materials (Fig. 83b), jacketing of damaged columns and the addition of shear walls in both directions at the first story only (Fig. 83c), to reduce the soft and weak story potential, and the torsional response. The authors are of the opinion that a major intervention was needed instead. Hopefully, it will work better than the one already observed for the Cozumel building, which had a similar retrofit back in 1985 (Fig. 12).

a) March 2018 b) October 2020 c) October 2020

Figure 83: Retrofit of Nicolás San Juan and San Borja corner apartment building in Mexico City adding RC shear walls at the first story only.

A similar solution was conducted for the 11-story Heriberto Frías and Concepción Beístegui corner apartment building (Fig. 84), a CC-FS structure built in 1980. The building exhibited extensive shear damage in masonry infill walls inside and at the façades (Fig. 84a). The retrofit of this building included the repairment of damaged materials (Fig. 84b), and the addition of concentric chevron braces, additional steel beams and the latticed jacketing of existing columns at the first story only (Fig. 84c) to reduce the soft and weak story potential and torsional responses there.

Other building which was recently repaired using concentric steel chevron braces at the first story and latticed steel jackets at the columns is the Monterrey and Durango corner, 4-story commercial building (Fig. 85). This building experienced structural pounding damage with its neighboring building along Durango street during the 2017 earthquake. The original structure is a CC-FS system built in the 1970s.

An integral retrofit that the authors want to highlight is the one which was planned and executed for Los Girasoles III housing complex, which includes 30 identical buildings. The 5-story, I-shaped plan layout buildings with a clear soft and weak first story were built in the early 1970s. The structural system used was a RC moment frame with deep beams at the first story with a ribbed RC slab, whereas in the stories above the structural system was composed of confined masonry walls made with extruded clay bricks and a beam and block floor system (Fig. 86). A mat foundation 3m in depth was used. These buildings are located in the south-center-eastern region of Mexico City, in Lake Xochimilco, where the recorded ground motions exceeded considerably the design spectra for the 1987 to 2004 seismic codes [5, 47]. Then, for buildings designed according to lower standards, it was expected that severe structural damage may occurred. In fact, only three buildings experienced severe damage, basically shear fissures in beams and columns at the first soft story, as well as severe diagonal tension damage in the walls above [57]. Other six buildings were classified as medium damage. Detailed reports are available for the damage observed in each building, as the one shown for one of the most severely damaged building [57].

a) September 2017 b) October 2020 c) October 2020

Figure 84: Retrofit of Heriberto Frías and Concepción Beístegui corner apartment building in Mexico City adding chevron braces, steel I beams and latticed steel jackets at the first story only.

a) May 2019 b) May 2019

Figure 85: Retrofit of Monterrey and Durango corner commercial building in Mexico City adding chevron braces and latticed steel jackets at the first story only.

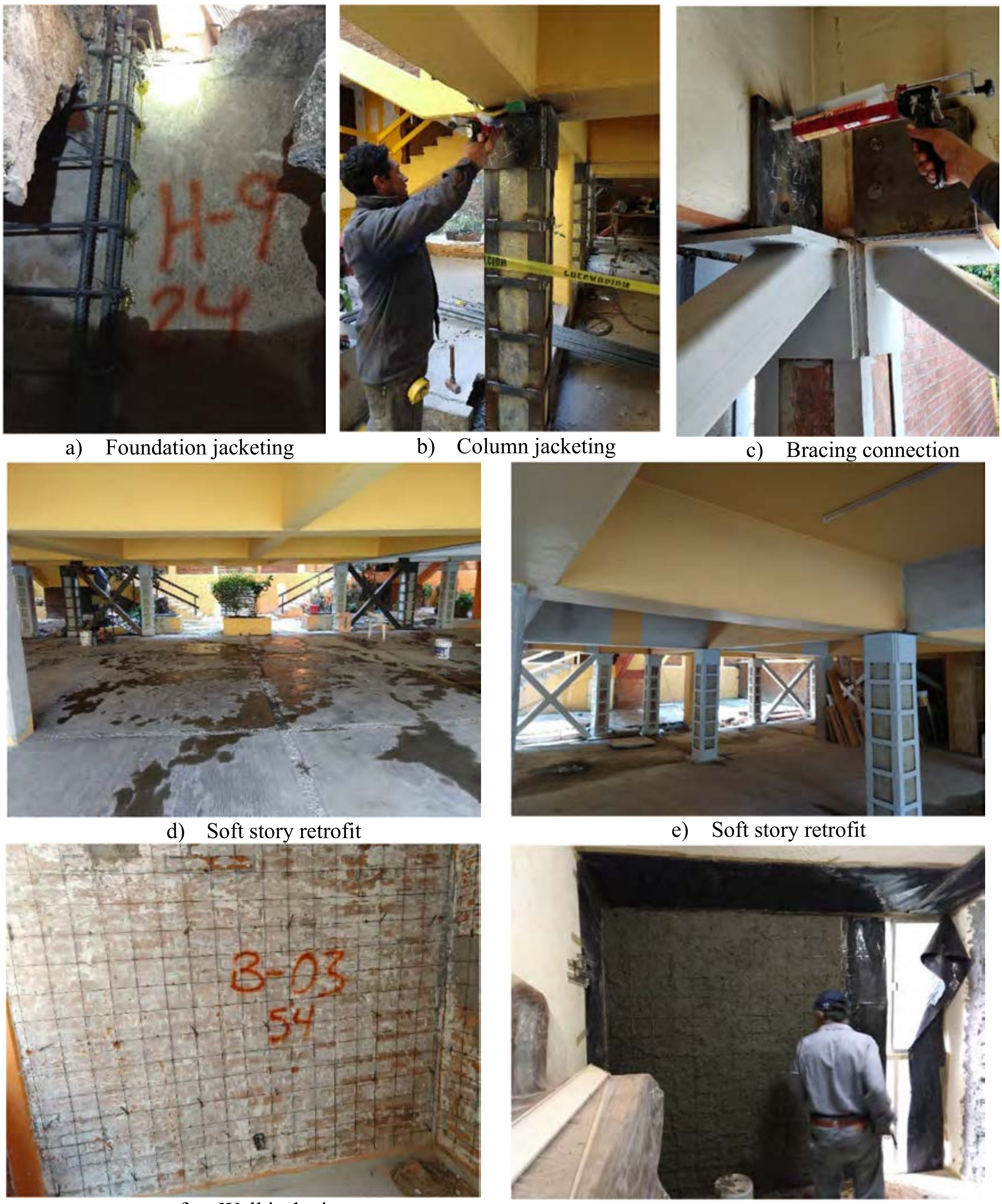
Then, an using public funds from the reconstruction program, an integral retrofit was planned to use in most of the damaged buildings of this housing complex. All buildings must satisfy the strength and deformation demands of the new seismic building code for Mexico City that was published in 2017. Then, the retrofit plan considered the following aspects. The soft story problem should be corrected, but the whole structure should also be strengthened, as well as its foundation.

a) Façade
b) Soft first story view
c) Damage in first story columns
d) Damage in some firs-story beams

Figure 86: Observed damage of Los Girasoles III housing complex (Rancho San Lorenzo street apartment buildings, during the September 19, 2017 earthquake. All pictures taken from reference [57].

The cross sections and reinforcement of the columns of the foundation box were increased using RC jackets (Fig. 87a). All first story columns were jacketed using latticed steel jackets (Figs. 87b to 87e). Concentric X-braces were placed in both orthogonal directions at the first story, to reduce the soft and weak story potential (Figs. 87c to 87e). For the damaged beam sections at the first story, carbon fibers were placed in the regions nearby beam-column joints (not shown). Finally, existing masonry walls above were jacketed using a welded-wire mesh (Figs. 87f and 87g), covered with mortar 2 cm in thickness (Fig. 87g). Careful reports of the construction process with clear, illustrative pictures are available [58].

In clear contrast with the integral retrofit plan described above, a partial strengthening using latticed steel jackets at the first story columns only was implemented for the 6-story Anaxágoras apartment buildings (Fig. 88). These buildings were originally constructed in the 1970s with a RC moment frame supporting a flatslab at the first story only, and confined masonry walls and RC flatslabs only for the stories above. These two buildings experienced damage during the September, 1985 earthquake, and were only locally repaired in the damaged, boundary RC columns at the first story, by attaching an open box column nearby. The described repairment was not good enough, as during the September, 2017 earthquake, the buildings were damaged again. Shear damage was observed in the first story columns at the front of both buildings, plus diagonal tension damage in several walls above the first floor. Despite the described damage for the 2017 earthquake, all the strengthening these buildings have had is the one shown in Fig 88. The damaged first-story columns and beams were jacketed using latticed steel jacketing, and damaged masonry walls above were only locally repaired. Then, the soft story problem is still present in these buildings!



a) Foundation jacketing

b) Column jacketing

c) Bracing connection

d) Soft story retrofit

e) Soft story retrofit

f) Wall jacketing

g) Wall jacketing

Figure 87: Integral retrofit of Los Girasoles III housing complex (Rancho San Lorenzo street apartment buildings), using steel bracing, jacketing of foundation elements, walls and carbon fibers. All pictures taken from reference [58].

5.9 Other retrofit solutions

In the field of seismic retrofit there is always room for innovation, so sometimes “new” solutions are implemented. Unfortunately, some of these solutions do not seem to have been well and integrally conceived. The first author wants to highlight a solution that, in his humble opinion, it was not integrally conceived. This corresponds to the 8-story Guanajuato apartment building, which was constructed in 2002. The original building had a CC-FS system, where the flatslabs are the modern version, where large and wide Styrofoam blocks are used. This building is highly irregular, as: a) it is slender, b) it has an I-shaped plan layout and, c) it has a soft first story potential. During the September 19, 2017 earthquake, this building was red targeted. The building experienced extensive interior and exterior damage in walls, and in the column-slab joints, due to its excessive lateral flexibility. This building was retrofitted by increasing the lateral stiffness using eccentric steel bracing. That part of the strategy seems adequate. However, and as it can be noticed, the potential problem that the first author detects is that the braces are eccentrically connected at half-story within the columns (Fig. 89c). Unless an excellent detailing work and local strengthening of the columns have been done (unknown), this strategy is potentially dangerous, as a shear failure may be induced in the supporting columns. As it can be observed, the eccentric connection to the existing slab was done using reduced-section plates (Figs. 89b and 89c). Then, the first author is not very optimistic about the required care that it should have been taken for a connection in the middle of a column. Besides, was it necessary? It would not have been better to use a more traditional bracing solution?

a) May 2019 b) May 2019

Figure 88: Local strengthening of the first story and beams columns of Anaxágoras apartment building using latticed steel jackets.

a) March 2018 b) May 2019 c) May 2019

Figure 89: Atypical retrofit strategy for the Guanajuato apartment building using eccentrically connected steel braces at the middle of story columns and at the flatslab floor system

5.10 Anti-seismic painting

As described before, in the Mexican structural design community, it is known as "anti-seismic painting", the rehabilitation solutions for buildings damaged during strong earthquakes, where damaged elements are either only locally repaired using resins or mortar, and/or damaged materials are replaced. As the locally repaired buildings as described above are painted afterwards, with a color different from the one that may recall people the developed damage (mental health therapy), that it why this strategy is known as "anti-seismic painting".

The use of anti-seismic painting is allowed in buildings which experience only reduced, local damage, primarily in non-structural elements, and it is not related to the excessive flexibility of the structural system. That it is where the application of anti-seismic painting is a reasonable, quick solution. A good example of this type of allowed anti-seismic painting is the one applied for the Melchor Ocampo corner apartment building (Fig. 90). This building only experienced a localized façade spalling at the fourth story (Fig. 90a) during the 2017 earthquake, and it was not reported with damage in the official city damage survey.

a) October 2017 b) March 2019

Figure 90: Rehabilitation of Melchor Ocampo corner apartment building by fixing the local spalling damage and a new paint.

However, "anti-seismic painting" should not be allowed in buildings where the observed earthquake damage, although primarily observed in infill walls and non-structural elements, is clearly due to existing weaknesses of the structural system, like large lateral flexibility. Unfortunately, this fact is not always recognized by engineers and owners (particularly), so they want to apply anti-seismic painting right away. In a previous section, the authors already described a case study where a medium size earthquake led to switch from an original "anti-seismic painting" solution, to an integral retrofit scheme: the Romero de Terreros and Patricio Sanz apartment building (Fig. 59). Unfortunately, there are more cases where "anti-seismic painting" should not have been used and allowed. The authors just show two more clear cases.

The 10-story, Calzada de Tlalpan commercial building, built in the 1970s is very flexible, as it has a CC-FS system, a long rectangular plan, is very slender, and it has a soft story potential. As a consequence of this lateral flexibility, all perimeter infill walls were clearly damaged during the 2017 earthquake (Figs. 91a and 91b), as well as in the interior. Nevertheless, the owner quickly ordered to apply anti-seismic painting, according to Google Maps, works were in progress in January 2018 (Fig. 91c). Most likely, this building will experience important damage again in a future moderate or strong earthquake.

a) September 2017 b) September 2017 c) January 2018 (Google)

Figure 91: "Rehabilitation" of Calzada de Tlalpan commercial building using "anti-seismic painting".

a) October 2017 b) October 2017 c) January 2023

Figure 92: "Rehabilitation" of Río Ebro apartment building using "anti-seismic painting".

The 9-story Río Ebro apartment building was erected in 1975 and it has a CC-FS structural system and masonry infills and façade walls. This building has the following structural irregularities: a) soft story potential, b) very slender and, c) asymmetric location of walls for stairs and elevators. During the September 19, 2017 earthquake, this building experienced substantial shear damage in all exterior masonry walls (Figs. 92a and 92b), and in many interior walls [59]. The first author was very surprised that anti-seismic painting repairing works were already in progress less than a month after the earthquake struck (Figs. 92a and 92b). Later, this author learned that the owners had the "expert" opinion, from an engineer with expertise in construction, that all the building had was "non-structural damage", so this building was "green". Then, he recommended the use of anti-seismic painting. City officials only acknowledge this fact [59].

It is clear that this engineer did not understand that the developed damage was due to excessive lateral flexibility, and that this building needed a more integral solution. The anti-seismic painting was finishing in early 2018, and the building looked like the more recently taken picture (Fig. 92c). Again, this building is prone to experience substantial damage again in future medium and strong earthquakes, as its weaknesses were not corrected.

6 CONCLUDING REMARKS

Mexico City is frequently affected by the action of moderate and very strong earthquakes from different seismic sources. For that reason, the Mexican structural design community has a long experience in the application of different retrofitting and strengthening techniques of seriously damaged buildings. In this paper, the authors tried to offer a detailed, honest review of how the most common retrofitting and strengthening techniques applied before the September 19, 2017 earthquake performed, including good and bad performances. These observations were strengthened with the statistics of an inventory of 112 previously retrofitted buildings which experienced from light damage to collapse. Only 46 of these buildings experienced severe structural damage or have been already demolished. It is worth noting that it was found that in only 18 rehabilitated buildings, the selected rehabilitation strategy was an important part of the observed severe damage.

It was observed that the seismic retrofitting of buildings using integral techniques which significantly modify the dynamic properties and lateral strength of the retrofitted building, such as the addition of steel bracing, exoskeletons, RC shear walls, macro-frames, post-tension steel (PTS) cable bracing and hysteretic energy dissipation devices (HEDDS), worked well in general. Observed performances were satisfactory when buildings were part of integral retrofit and strengthening strategies, where all key elements were locally strengthened (or added) at all stories, and care was taken to move the building out of resonant responses with the site, and connections with the original structural system were carefully implemented. Unsatisfactory performances were observed in partial retrofitting/strengthening projects, particularly when buildings were not adequately moved out of potential resonant responses, or connections were not well executed.

The dominant retrofit and strengthening techniques that are being used nowadays in Mexico City to rehabilitate buildings damaged during the September 19, 2017 earthquake were also shown and discussed. The authors emphasized those retrofit strategies that seem adequate. However, they also expressed their concerns regarding some of the observed solutions, particularly those solutions that, in their humble opinion, do not look good enough to improve the seismic safety of the subject repaired buildings. It is worth noting that in the humble opinion of the authors, some of these short-sighted solutions may be related to designs of unexperienced engineers in the field of structural strengthening and retrofit. On this regard, City authorities of Mexico City in particular, and city building authorities worldwide in general, should understand the need and importance on setting mandatory minimum standards and mandatory peer-review of retrofitting/strengthening of seriously damaged buildings, to authorize retrofit projects after strong earthquakes. In addition, the responsible of such projects and peer review panels should be composed of highly qualified and certified engineers, no "newcomers" eager to participate in "such opportunities", when they lack relevant experience and valuable knowledge. The safety of the people and cities cannot be jeopardized by allowing that inexperienced engineers would take such difficult decisions alone.

Finally, it can be concluded that the amount of severe damage detected in Mexico City in retrofitted buildings during the September 19, 2017 earthquake can be partially explained with the spectral intensities of the recorded ground motions when putting into context to those considered by the design spectra of the seismic codes used for the retrofitting projects, as discussed in detail elsewhere [1]. Then, a serious analysis and criticism should be done in the earthquake engineering community worldwide regarding minimum seismic requirements and criteria for future seismic rehabilitation projects. It should be evaluated if collapse-prevention design scenarios are still good enough, or serious steps should be taken to move forward to resilient-based seismic design of retrofitting projects, in order to minimize building damage, additional reparation, retrofit debris (which adversely affects the environment), as well as to improve and speed societal recovery.

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