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FIELD OBSERVATIONS IN MEXICO CITY AFTER THE SEPTEMBER 2017 PUEBLA-MORELOS EARTHQUAKE

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Abstract

This paper shows the main reconnaissance observations from Mexico City after the September 19th, 2017 Puebla-Morelos Earthquake (7.1 M_w). It presents opinions and photographic illustrations of the seismic culture, the response of society and institutions, and the main factors that affected the structural performance of buildings.

It was noticed a great organization from authorities, professional societies and academia for the primary assessment of a vast number of buildings affected by the earthquake. Most of this effort has been documented by different institutions and findings are now of public access on the web. It is remarkable the strong seismic culture in Mexico, as seen in the early warning system, the periodic evacuation practices, the signposting of safe meeting places, the retrofitted buildings, and specially, the sensibility of the population about their seismicity and the importance of being prepared.

As expected in México, some of the main factors that affected the structural performance of buildings were the site effects, the failure of foundations, and the pounding to adjacent buildings. Staircases and the "non-structural" infill walls inducing failures due to soft story, captive column and torsion, as well as failure of connections are some of the unwanted influential elements that can be noticed. It was observed that many of damages were not specific from this event, but accumulated damage from previous earthquakes, even in repaired and retrofitted buildings. Finally, it was worrisome having seen many recent and under construction buildings with structural typologies that coincided with those of the most damaged buildings.

Talking about resilience, after the crisis had gone, and despite the positive early assistance, many people were unable to afford the great costs of repairing and retrofitting their buildings, specially condos. More than a year after the earthquake, there were still seen restricted safety zones around many buildings, and the worst news is that some of those buildings had been repaired and retrofitted after previous earthquakes, but they were back out of service. This is an issue that requires more attention because of its social impact.

Keywords: 2017 Mexico Earthquake; building damage; non-structural masonry; foundations; retrofitted structures

1. Introduction

On September 19th, 2017, an earthquake 7.1 M_w stroked Puebla and Morelos states of Mexico, at an epicentral distance of 120 km from Mexico City. This event caused more than 300 fatalities and hundreds of severely damaged buildings including at least 40 collapses.

A reconnaissance visit to Mexico City was held from September 28th to October 13th, having the opportunity to volunteer, among other national and international teams, in the evaluation brigades coordinated by the College of Civil Engineers of Mexico (CICM) and the Mexican Society of Structural Engineers (SMIE). Within this framework, the interior and exterior inspection of 20 severely damaged buildings was carried out; additionally, independent assessments throughout some districts of the city were performed.

The main objective of the visit was to gather information for a doctoral research in progress about performance, repair, and retrofit of masonry infilled moment resisting frames, therefore, this paper emphasizes this topic. However, other subjects of general interest are also mentioned. A photographic review with corresponding opinions is presented regarding the seismic culture, the response of society and institutions, and the main factors that affected the structural performance of buildings.

2. Seismic culture

Mexico has a deep-rooted seismic culture; despite the extreme damages and collapses in some sectors, the earthquake did not take them by surprise, since the population has been prepared for these events. It should be pointed out the up-to-date codes; the high academic, professional and institutional proficiency demonstrated by prior preparedness and emergency management; signaling of escape routes and meeting points in case of emergencies, almost in every building; the emergency policies developed by the security committees in condos and companies; the number of buildings that have been retrofitted to increase their capacity against earthquakes, including several with cutting edge technology such as energy dissipation devices, many with local development; finally, the early warning system as an icon of the culture of seismic prevention in Mexico. Fig. 1 shows some of the seismic culture elements that can be found in different spots of the visited areas.

Fig. 1 – Examples of elements of the seismic culture: meeting points and early warning system

3. Emergency response from community and authorities

As usual in these tragic events, there was a spontaneous reaction of people. At the first minutes after the shake, dwellers took the streets collaborating in everything within their reach: rescue of victims, first aid, logistical support, among others. Likewise, civil and military authorities promptly acted. The first days of our visit, some people commented us that they did not feel a firm and timely institutional response, arguing that many of the rescues were made by the neighbors themselves. Despite having heard these complaints, it was observed a great organization and response from involved institutions.

It was also witnessed a great support from professional associations of engineers, architects and academics, as well as many private companies from different sectors. It is opportune to highlight the work of the CICM together with the SMIE in the organization of voluntary crews for technical support to the affected population. A control center was installed in the facilities of the CICM, managing the unconditional support of Mexican and international, engineers and architects, professionals and students, who inspected in a record time a vast number of buildings, providing expert guidance to the owners and/or users, wile documenting field data to be used in future research. Several teams were organized based on the expertise of the volunteers, and the information was processed in real-time and made public from early October 2017 in a web page designed for this purpose (https://www.sismosmexico.org/). Fig. 2 shows a representation of the control center at the CICM, including distinctive elements of the organization, such as the badges for the evaluation teams, and the use of smartphones to transferring geo-located information to be processed in real time.

Fig. 2 – Organization of the evaluation teams of the CICM & SMIE

4. Factors that conditioned buildings damage

4.1. Site Effects

To talk about earthquakes in Mexico City is to talk about the site effects. In fact, this was one of the most commented topics by professionals and academics. It is known that Mexico lies on sediments over an old lagoon, and therefore, the effects of amplification of seismic shaking at certain vibration natural periods are very large. One of the most commented features about the site effects was that this time, the closer intraplate earthquake generated effects different from that of 1985, which epicenter was between the plates of Cocos and North America, much more distant. For the 2017 Earthquake, the named "transition zone" with shallower sediments and a slightly stiffer ground were more affected. Fig. 3 shows the differences in the location of the collapsed buildings on 1985 vs. the new collapses on 2017, warning that previous experiences should not be considered as a recipe.

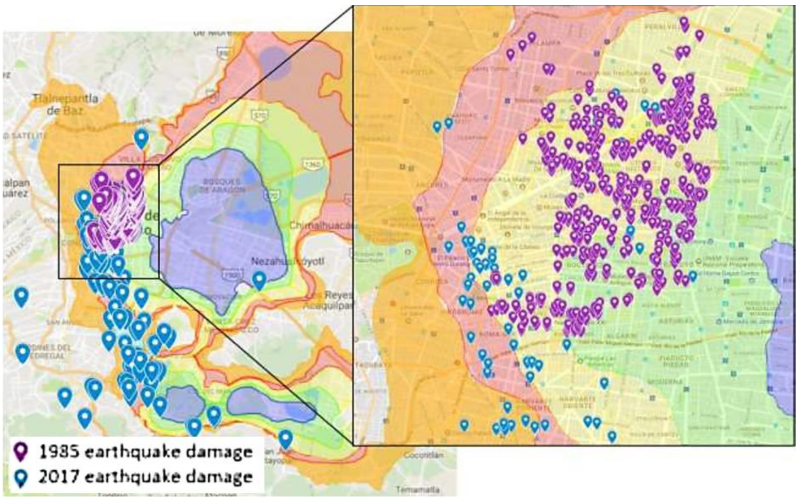

Fig. 3 – Comparison of the location of collapsed buildings during Sept. 1985 and Sept. 2017 [1]

4.2. Failure of foundations

Another common concern in Mexico is the failure of foundations. The first building visited caused us alarm because of its leaning (Figs. 4a-c); later on, it was perceived how the Mexican culture coexists with the settlements of foundations and how *Pisa Towers* are spread throughout the city.

Other examples are buildings with recessed doors, where people must go down-stairs to get in; emblematic buildings such as the Sears Tower (Figs. 4d,e), which was already inclined and apparently leaned more during this earthquake. In this last building of two independent structures, the joint cover was observed following the shape of the original inclination. In some of the inspected buildings, cracks on ground reflected the settlement of the structure (Fig. 4f). Sidewalks and pavements were also seen highly damaged (Fig. 4g).

As said before, it is obvious that Mexican engineers and population have a tolerance towards the settlement of foundations much greater than that from people of any other part of the world.

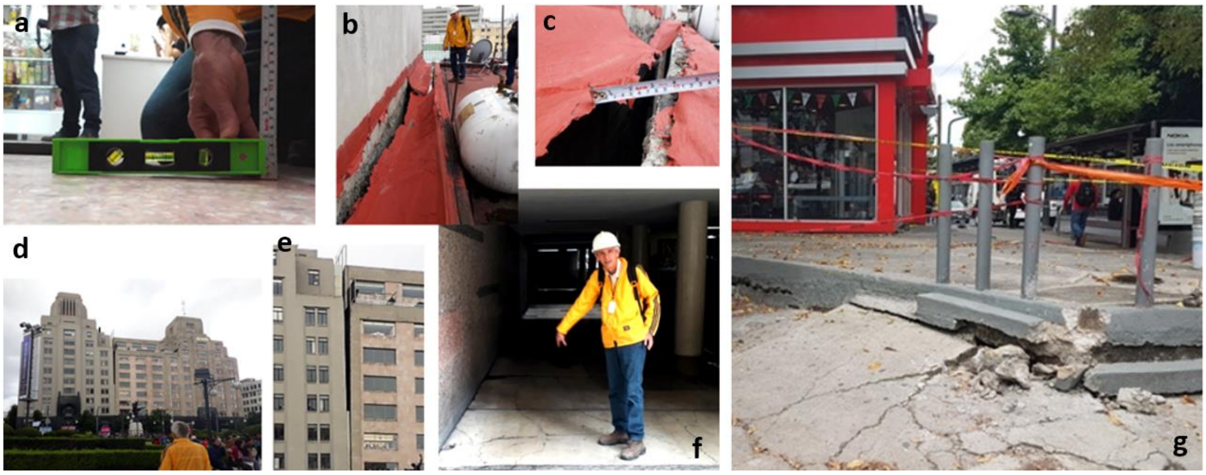

Fig. 4 – Geotechnical and foundation-related damages

4.3. Pounding to adjacent buildings

Another important issue was the pounding between buildings. Fig. 5 shows a med-rise building adjacent to a lower one; this is a critical condition because when they collide, they tend to concentrate a huge deformation demand over this point. The left picture of the figure exposes the residual leaning of the top stories of the building. The middle picture shows the building's extremely damaged rear face. Additionally, a two-story mechanism is observed, evidencing a soft/weak story after the infills and the structural members failed. Finally, the right picture exhibits the failure of one of the columns. Months after, this building was demolished.

Fig. 5 – Damages due to pounding of adjacent buildings

4.4. Project, reference codes, construction, and maintenance

Most collapsed and heavily damaged buildings were in old pre-code constructions, but there were also recent and retrofitted structures severely damaged.

Differences between the on-site dimensions and specified dimensions in drawings; additional stories not considered in the project; thick, heavy flooring added in refurbished apartments; and other deviations from the original project, are examples of irregularities found in the inspected buildings.

There was also noticed corrosion damages in the main structural members of some buildings, caused by constructive deficiencies and lack of maintenance.

Fig. 6 – Deviations in dimensions; added overweight; corrosion damages

4.5. Detailing and connections

The building in Fig. 7 may have had cumulative deficiencies conditioning its collapse. The sections of the structural members of the lateral resisting system look weak, but for the purpose of this paper, it is opportune to emphasize the failure of connections of the steel brace to the rest of the structure. Sometimes, the type of bolts for static or dynamic loads are misunderstood, and even bolts suitable for low stress-high cycle fatigue of machinery are wrongly used for the extreme loads - low cycle fatigue as in earthquakes.

Fig. 7 – Detail of connections in one of the collapsed buildings

4.6. Stairs

Stairs usually provide an extra stiffness that may attract a large portion of the lateral forces, causing two negative consequences: the first is the failure of the stairs themselves, and the second is the modification of the dynamic response, causing torsion in plan, and damages to other structural members.

Figs. 8a-e show a building having a very significant torsion due to the presence of an eccentric stair at the south, which induced severe damage to the columns located toward north, away from the center of stiffness (stairs); it can be noticed the residual drift and the cracks in columns (8d,e). Then, Figs. 8f,g display extreme damage to stairs, which compromised the scape routes of another mid-rise building.

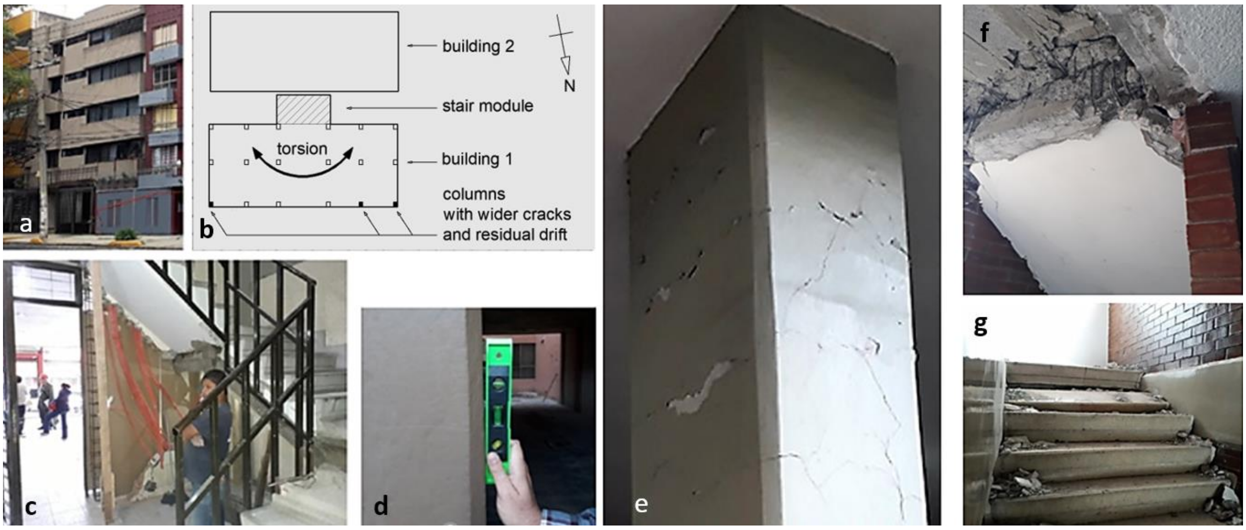

Fig. 8 – Torsion induced by stairs (a to e); extreme damages and obstruction of emergency exit (f, g)

4.7. Non-structural masonry walls (infills)

Despite the warnings in codes and specialized literature, it is still common to consider the "non-structural" masonry walls in models only as weight and mass; and even more, to build those walls without the proper isolation from the structural members. Again, this event reflects how this practice ends up compromising the structural performance of buildings.

A repeated cause of collapses was the soft-story due to ground open story, but that was not only seen when evident in the original configuration of the building, but also in upper stories after the masonry walls started to fail, losing their contribution to the stiffness of those stories, which was more likely to occur in cases of pounding between adjacent buildings (Fig. 5 above and Fig. 13 below). The captive column was also determinant in some failures, and also a concentrated damage on beams and slabs as a sort of "captive beams" or "captive slabs" (Figs. 9a,b). Another issue was the widespread damage to masonry walls themselves, even in buildings with no structural damage, showing how the deformation capacity of those stiff – brittle elements is not compatible to the expected drift of a typical moment resisting frame. Figs. 9c-f show an example where the walls fall toward the outer and inner side of the building, compromising the way out and the life-safety performance objective. Finally, adding to section 4.2 above, it is probable that some of the failures of foundations that ended in leaned buildings, were related to the stiffening effect imposed by the infills, which undoubtedly increases the base reactions foreseen in the project.

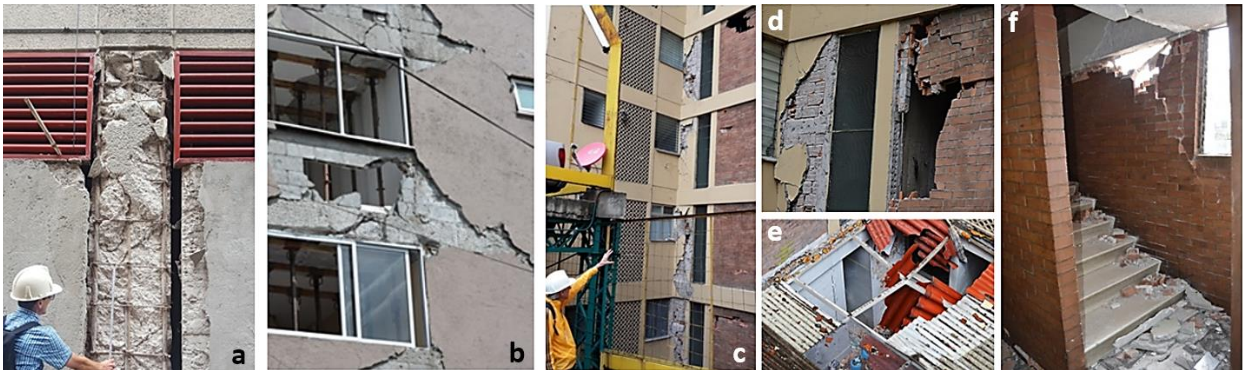

Fig. 9 – Damages related to masonry infills

Fig. 10 shows schemes of observed typical performance patterns: a) the common assumptions of walls in models, only weight and mass; b) the expected performance considering free deformation of the structural members without infills; c) Soft Story (open ground story) in the original configuration of the building; d) Captive Column in the original configuration of the building; e) Soft Story induced after infills fail; f) Captive Column induced after infills fail; g) failure of foundations due to increasing base reactions, resulting from the stiffening imposed by the infills; h) generalized damage and collapse of portions or the entire walls, subjected to great deformations if the structure develop the expected drift capacity. These patterns have been widely seen after recent earthquakes in other countries, affecting not only old pre-code buildings but also new buildings. More details have been presented by this paper's author in previous WCEE [2] [3].

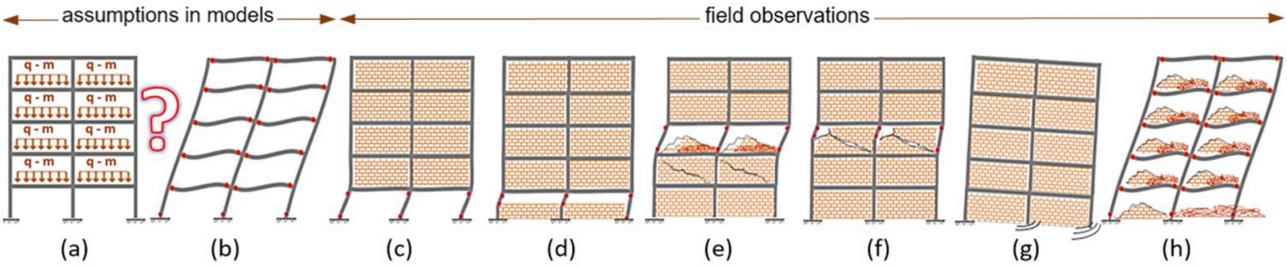

Fig. 10 – Schemes of typical performance patterns of MRF with infills

4.8. Repaired and retrofitted buildings

As Mexico City has suffered various destructive earthquakes, many buildings have been repaired and retrofitted. Fig. 11 exhibits some examples: a) additional beams added to reduce the "H" shape irregularity of the building in plant; b,c) additional damping and stiffness device (ADAS) for energy dissipation; d,e,f) ; "X" steel braces added to the RC moment resisting frame; g) shear RC walls added to a RC moment resisting frame.

Many of these solutions performed well during the 2017 earthquake, but some inappropriate behaviors were noticed. Figs. 11d-f reveal cracks due to tensile stresses in columns, and the sliding of the connection instead of the nonlinear deformation of the steel braces. Then, Fig. 11g illustrates the failure at joints due to lack of continuity of the longitudinal rebars in the added RC wall.

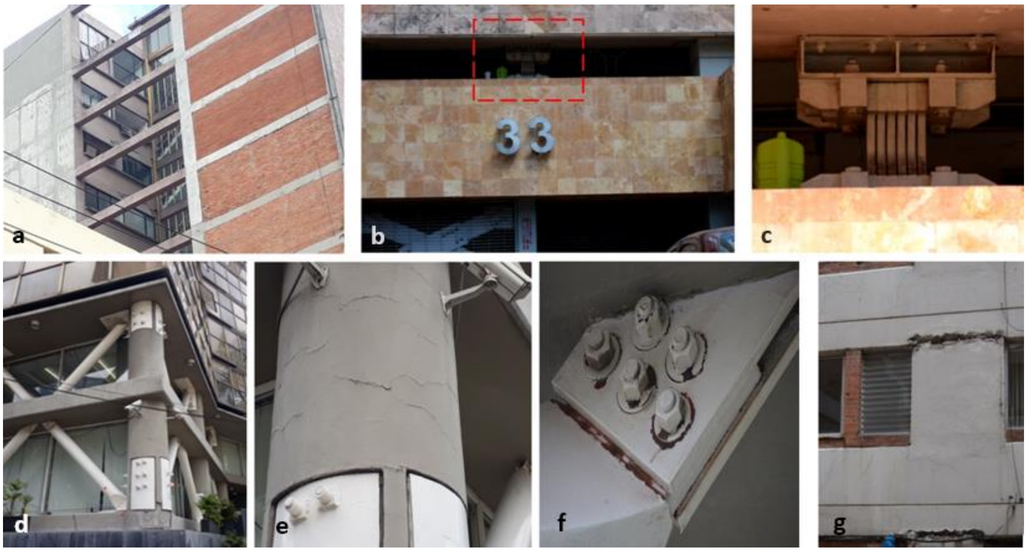

Fig. 11 – Examples of retrofitting techniques and their performance

Some partial repairs of structural members that were probably damaged by previous earthquakes were observed, but with no evidence of a global retrofit of the building, which can cause catastrophic consequences as those described in Point 5 below.

4.9. Pre-existing/accumulated damage

The pre-existing damages made very difficult to obtain a clear diagnosis in many buildings, since many of the visible symptoms were due to the accumulated damage and not lesions originated in this event. This is something to keep in mind, since a damaged structure will always be closer to reaching its collapse limit state. Fig. 12 shows a before and after picture of a building where pre-existing damages might have been underestimated, resulting in insufficient repair or strengthening.

Fig. 12 – Pre-existing damage: Ago. 2014 (left) [4]; after 2017 earthquake (right)

5. Multi-factors conditioning the collapse of one building

Fig. 13 displays a collapsed building in Roma district, were soil profile is the same as that of most collapses, showing the relevance of the site effects. The main cause of this collapse might have been the pounding to the adjacent building. It was also noticed a strong torsional trend induced by the "H" shape with wide open areas in plan, a central stiff stair module, and the irregular distribution of the “nonstructural” masonry walls, which were complete height at rear facades and partial height (windows) on facades towards the street (Figs. 13a,b). The collapse mechanism was in a soft and weak upper story, once the structure and the masonry walls failed after hitting the adjacent building.

The furthest column from the stiffness center (Fig. 13d) had a confining strengthening of steel shapes (probably a repair of damages by previous earthquakes). This reinforcement stiffened the body of the column and concentrated tensions at the ends (joints), where the collapse sequence probably begun (column coincides with the corner of maximum displacements due to torsion in plan). If it is confirmed that the reinforcement of this column was in response to damages from previous earthquakes, it alerts about the importance of retrofitting the whole building, balancing the stiffness, strength and ductility, and solving the core causes of damages, instead of being limited to the repair of only the damaged elements.

Fig. 13 – Collapse of a building due to the overlap of multiple factors

6. Codes and academia vs. professional practice and societal judgments

Mexico counts with up-to-date codes and a robust academia and professional societies, but, as in other places, some projects are in hands of engineers who are far from being part of this excellence.

It is worth mentioning that Mexico has various high-rise buildings with pretty interesting architecture which might be controversial. Fig. 14 shows some of them having irregularities that would be in any “not to do” list in earthquake prone areas. It must be noted that no news about some of these buildings having damages was heard. These emblematic structures are always in hands of highly qualified firms and it is expected an up-to-date – well-detailed project, regardless the evident irregularities that for sure were taken into account. For some low to middle-rise buildings it might be seen the other side of the coin, as some promoters pressure for a cheap-fast project, which might mean accepting less qualified professionals.

Fig. 14 – Typical high-rise buildings in Mexico City

Two middle-rise buildings under construction are shown in Fig. 15. The one at the left looks too close to the adjacent buildings, which might conduce to pounding. The one at the right exhibits the masonry infills without the properly insulation from the main structure, and without evidence of having been considered as part of the structural system. These configurations are widely referred as vulnerable, and may induce damages as those described in sections 4.3 and 4.7 above.

Fig. 15 – Buildings under construction – Left: too close to the adjacent buildings
Right: with infills neither properly insulated nor connected to the structure

Another concern during the inspections of the affected buildings was the presence of some contractors already making repairs, concentrating on stairs and partitions, but underestimating some structural damages in columns and beams that were detected by our team. One of the locations where this happened was the building shown in Figs. 8a-e above. Our appreciations were reported to the engineers in charge.

Later on, interacting with the residents of some buildings, we found out their expectations on what should be contemplated in a good project. One of them showed us a picture of his apartment, recently painted before the earthquake, which can be compared to the condition after (Figs. 16a,b). In another building, some people were moving out after seeing minor cracks in "non-structural" masonry walls; even though the building had been inspected by different engineers agreeing in the opinion that cracks didn't represent any issue for its safety. Figs. 16c,d show the sound condition of a robust columns and beams in this building; then, the minor cracks in walls, which caused panic to residents to the point of making them to move out.

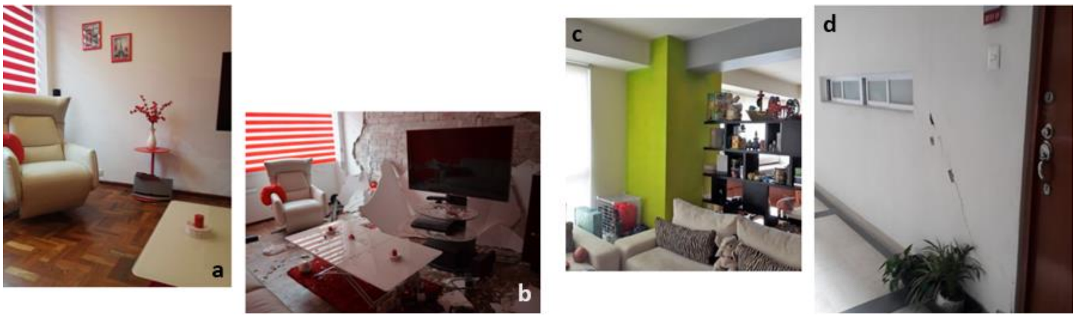

Fig. 16 – Damage to "non-structural" masonry walls. What should be acceptable

The precedent paragraph leads to think about the current criteria in many codes, which still focus on life safety and collapse prevention limit states, but pay less attention to the acceptable damages, especially those related to non-structural components and content. Both examples presented in Fig. 16 might have, by far, exceeded the performance objectives for the intensity of this earthquake, but still that is something too difficult to understand and accept by the owners and residents of those buildings. It would be appropriate to review the levels of damage that codes accept today, both for new constructions and for repairs or retrofits.

7. Resilience

The priority after the earthquake was to rescue people in collapsed buildings; all society and media was thoughtfully following this activity (Fig. 17a). At the end of the third week, another stage was observed: hopes of rescuing people alive cease, and emphasis on restoring the operation of the city is increased. By that time, some people had already begun to despair since whole streets are closed, and many cannot return to their homes, their jobs, their daily lives, realizing that the road to recovery will be a long journey.

Fig. 17 – Images of Mexico City, hours to years after the earthquake

One of the disrupted areas of the city was the "Zona Rosa", a neighborhood of great commercial activity where some blocks were closed due to various buildings at risk of collapse. This is an indication of how a single damaged building can force out of service a whole block of shopping centers, offices, and residential buildings having no damage. Fig. 17b above presents a banner with this message: *The merchants of Zona Rosa are kidnapped by the authorities that do not allow us to work due to the closure of the streets, and have not done the pending revisions in the buildings of the area. A solution is urgent!*

Bit by bit, routine starts getting back and people focuses on recovery. Hopelessly, after the crisis had gone, some of the buildings had to be promptly demolished, as the one in Fig. 5 above. Figures 17 c and d expose the same building, and then, the empty site after it was removed. Then again, many people were unable to afford the great costs of repairing and retrofitting their buildings, specially condos. More than a year after the earthquake, there were still seen restricted safety zones around some buildings, and others with the same emergency shoring installed at that moment (Figs. 17e,f), and the worst part is that some of those buildings had been repaired and retrofitted after previous earthquakes, but they were back out of service. This is an issue requiring more attention because of its social impact.

It is important to mention that media, and even this kind of research papers, always emphasize damages and collapses after an earthquake event, but the truth is that the majority of the buildings in the city didn't suffer any damage (Fig. 18). Earthquake failures are selective to vulnerable structures, either because they are located in places were the dynamic response is amplified or because of particular deficiencies in the projects, the construction, the operation and/or the maintenance of the buildings. There is also something related to chance, between the characteristics of the shaking in that specific earthquake and the possibility of activating the weak link of the structural system.

Fig. 18 – A view of Mexico City: not all was damages and collapses

To close this point, it is appropriate to refer some official documents were polices for recovery of buildings can be consulted, as the *Reconstruction Program for Mexico City* [5], and the *Standards for the Seismic Rehabilitation of buildings damaged by the Earthquake of September 19th, 2017* [6].

8. Research opportunities and information sources

This event has been widely documented, which offers great opportunities for the scientific community in multiple areas of interest. Listed below are some sources of information that can be consulted:

College of Civil Engineers of Mexico: http://cicm.org.mx/
Mexican Society of Structural Engineering: http://www.smie.org.mx/
Mexican Society of Geotechnical Engineering: http://www.smig.org.mx/
Engineering Institute – UNAM: http://www.iingen.unam.mx/
Site for the Mexico Earthquake (CICM) https://www.sismosmexico.org/
Earthquake Engineering Research Institute: http://learningfromearthquakes.org/

Social networks have also provided countless information, since Mexico City is a large metropolis with many people having access to smartphones and sharing their photos and videos on platforms such as Facebook, Twitter, Instagram, YouTube and WhatsApp, which also allows access to study widely documented damage patterns and many other topics.

9. Conclusion

This paper offered a series of field observations in Mexico City after the Sept. 19th, 2017 Puebla-Morelos Earthquake. Being Mexico a big metropolis, examples of good engineering and seismic culture have been presented, but also some others not so fortunate have been documented.

A multiplicity of factors conditioning the structural performance of buildings was observed: the site effects; the failure of foundations; the pounding to adjacent buildings; the failure of connections; the great influence of the stairs and the "non-structural" walls (infills) in the dynamic and structural performance, among others. It was observed that many of the damages were not specific from this event, but accumulated damage from previous earthquakes, even in repaired and retrofitted buildings. Finally, regardless of the fact that most of collapses were related to old pre-code buildings, it was worrisome having seen some recent and under construction buildings with structural typologies coinciding with that of the most damaged buildings.

This earthquake shows again to academics and professionals the importance of not only studying the design of new structures, but also attending the huge inventory of existing buildings that have already been constructed under codes that are today recognized as obsolete. In this sense, current trends in performance-based and resilience-based design are particularly important. Still more, it is essential to promote solid criteria on the overall configuration of buildings, as well as the relevance of the compatibility of deformations between structural members, connections, non-structural components, foundations, and adjacent buildings. These have usually been the main issues after this and many other earthquakes worldwide.

10. Acknowledgements

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