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MEXICO EARTHQUAKE OF SEPTEMBER 19, 2017: CORRELATION BETWEEN SITE EFFECTS AND STRUCTURAL DAMAGE

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Abstract

A destructive intraslab earthquake occurred in September 19, 2017 (Mw 7.1) caused significant damage and hundreds of human losses not only in the epicentral area, in the States of Morelos and Puebla, but also in Mexico City and in the State of Mexico. Only in Mexico City itself, around 230 people died. The intensities recorded in some areas of the city, especially in zones with soil periods around 1.0 sec, were relatively high, even surpassing spectral values of 1.0g; the vertical component, due to the proximity of the earthquake, was unusually high for Mexico City.

The 2017 earthquake raised questions that are critical to understand the seismic vulnerability and resilience of the city, and they are partly answered in this paper. Using all 77 accelerometric stations in the city, the directionality effects and amplification pattern of the seismic intensities are characterized, as well as the correlations of the structural characteristics of the buildings with the site effects. To analyze and understand the structural behavior of damaged buildings, a comprehensive statistical analysis of the damages is shown, including not only the structural types and the year of construction, but the main structural problems identified (structural pathologies) such as irregularities both in elevation and plant, soft story and pounding, among others. The building damage database was constructed with 2125 reports of buildings carried out by universities and engineering associations after the earthquake, of which, 543 had severe damage. It is also included the information of all buildings with no damage in the city thanks to the cadastral information provided by the Mexico City government, as well as post-earthquake inspections, and visual inspections using Google Street View. A full study of selected neighborhoods, which compares similar buildings with and without damage, is included, yielding relevant statistical information of which pathologies cause more damage and even collapses.

Keywords: Mexico City, soft soil, collapsed buildings, seismic intensities, September 19

1. Introduction

The September 19, 2017 (Mw 7.1) was an intraslab earthquake, whose epicenter was located at approximately 120km from Mexico City, near the border between the states of Puebla and Morelos to the south-east of Mexico City and at a depth of 57km. Exactly 32 years after the September 19, 1985 earthquake, once again, Mexico suffered significant damage and hundreds of human losses. Severe damage was reported in Mexico City, Morelos, Puebla and in the State of Mexico [1] . In Mexico City, 44 buildings collapsed and around 800 buildings were severely damaged. Only in Mexico City, 230 people died [2]. The intensities recorded in some areas of Mexico City, especially in zones with soil periods between 0.5s and 1.8s, were relatively high, even surpassing values of 1.0g, and the vertical component, due to the proximity of the earthquake, was unusually high for Mexico City. In the Roma Norte and Hipódromo districts, located close to downtown, in the Cuauhtémoc municipality, 14 buildings collapsed in an area of approximately 1.0 km^2. This area has historically reported structural damage after intense earthquakes (1957, 1979, 1985, among others). However, in the same districts, many other structures remained unharmed despite apparently having similar structural characteristics. So, what causes one structure to be damaged, while another, with very similar characteristics, remains undamaged by the action of the same ground motion? What structural pathologies are the most critical to be considered in the seismic-resistant behavior? What kind of structures should be prioritized in risk mitigation plans?

This article focuses on the structural characteristics of the buildings that suffered damage in the most affected area in Mexico City during the September 19, 2019 Mexico earthquake. The main objective is to study the influence of structural pathologies and site effects on the structural behavior using real statistical data obtained after the 2017 earthquake in Mexico. In this article, we begin by analyzing the main recording seismic demands, including pseudoacceleration and directionality effect analysis; for this, the seismic records of 77 accelerometric stations have been used. Then, to analyze the structural behavior of damaged buildings, a comprehensive statistical analysis of the damage reported is shown, including an analysis of the main structural problems identified.

2. Seismic demands of September 19, 2017 earthquake

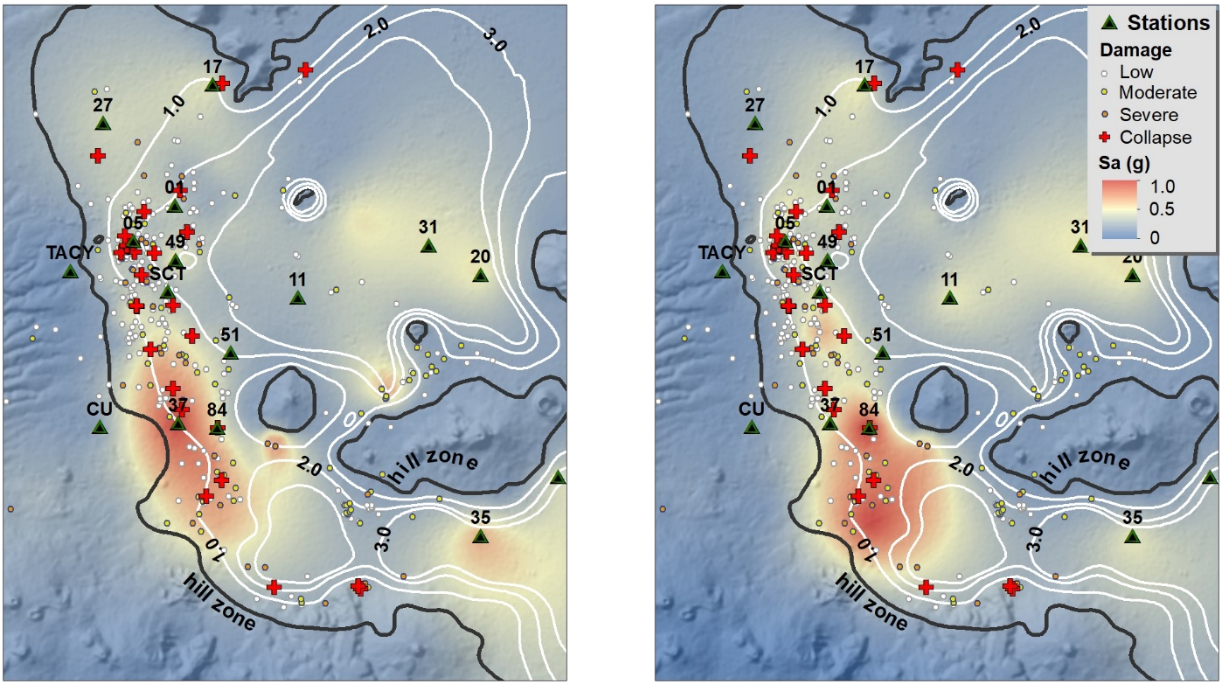
Fig. 1 shows the distributions of pseudoacceleration intensities (Sa) for the geometric mean of both orthogonal components recorded for September 19, 2017 earthquake and for single-degree-of-freedom (SDOF) systems with periods T=1.0, 1.5, 2.0 and 3.0s, together with the location of damaged buildings (from moderate damage to total collapse). The charts also include the dominant soil periods for the basin of the Valley of Mexico (contour lines). The soil of Mexico City is very particular and has been studied for several decades. For some frequencies, the amplification can be up to 500 times with respect to the expected amplification at long epicentral sites [3]. A large part of Mexico City is located on the ancient Texcoco lake, therefore in certain areas of the city, the clay deposits depth reaches several tens of meters. Sites at the lakebed zone near the international airport zone (stations 20 and 31) reach dominant periods over 5.0s with very large amplifications with respect to the hill zone.

As shown in Fig. 1, the zones with soil periods between 1.0 and 1.8s had the largest intensities, even reaching values of Sa~1.6g in station 84 (Tg=1.4s), coinciding roughly with the zones with reported damage. Although there is a strong correlation between intensities, soil dominant periods (soil amplifications) and damage, for certain zones, such as the downtown (Tg~2.0s) is not enough to explain the severe structural damage pattern of the area (shown inside the circle in Fig. 1c). Figure 1d exhibit that intensities for periods larger than 3.0s are smaller, and slight damage was to be expected in those areas; however, the second and third vibration modes (with periods between 0.6 – 1.5s), presented relatively high intensities, as shown in Fig. 1b, so the damage was considerable due to the contribution of these modes.

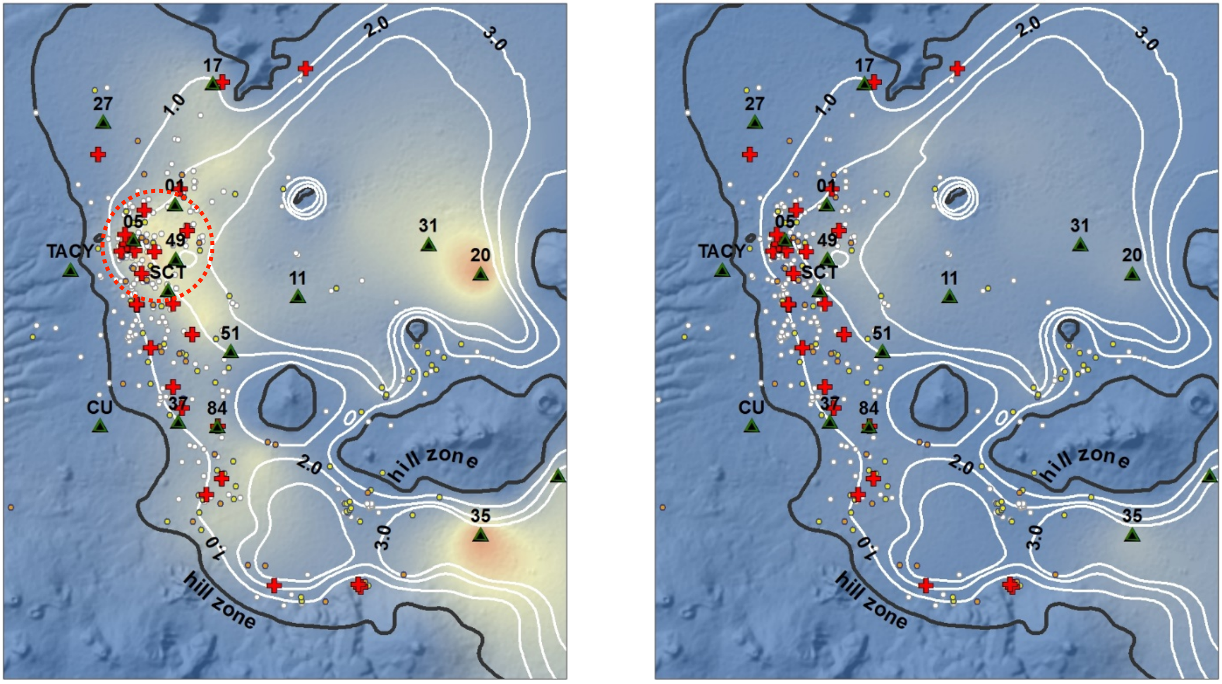
3. Damage statistics for the September 19, 2017 earthquake

The following statistics summarize the information gathered from the Institute of Engineering (UNAM, National Autonomous University of Mexico) and the ISCDF (The Institute for Buildings Safety of Mexico

City). The damage database has 2125 inspected buildings reports, of which 543 had severe damage. The characteristics of the buildings were obtained from the cadastral records of Mexico City, as well as post-earthquake-enhanced inspections, and from visual inspections using Street View®.



a) Sa for T=1.0s b) Sa for T=1.5s



c) Sa for T=2.0s d) Sa for T=3.0s

Fig. 1 – Pseudoacceleration maps for the September 19, 2017 earthquake for different periods. a) 1.0s, b) 1.5s, c) 2.0s and d) 3.0s. The damaged buildings are shown with a red cross

A total of 44 buildings had a partial collapse and 39 a total collapse. After detailed inspections, it was determined that 93 buildings must be demolished (so far, only 42 buildings have been demolished). This section summarizes the main characteristics of the 543 buildings with severe damage.

After the September 19, 1985 earthquake, the seismic regulations for Mexico City became much stricter, hence the earthquake-resistant performance of buildings built before 1985 is weaker than recent structures. After the 2017 earthquake, from the total of structures reported with severe damage, close to 80% were built before 1985. Looking at the whole city and analyzing the cadastral information, the pre-1985 damaged structures represent 0.31% of all structures in México City, while post-1985 damaged structures represent 0.08% of the cadastral.

Due to the characteristics of the 2017 earthquake, the damage was mainly concentrated in structures between 1 to 9 stories, which represent about 80% of structures reported with severe damage. The damage is also linked to the zone of the city, since the site effects in the lakebed of the Valley of Mexico change in a few dozens of meters. Figure 2 shows the damage distribution given by the Municipality. As can be seen, the most affected municipalities are Benito Juarez and Cuauhtémoc.

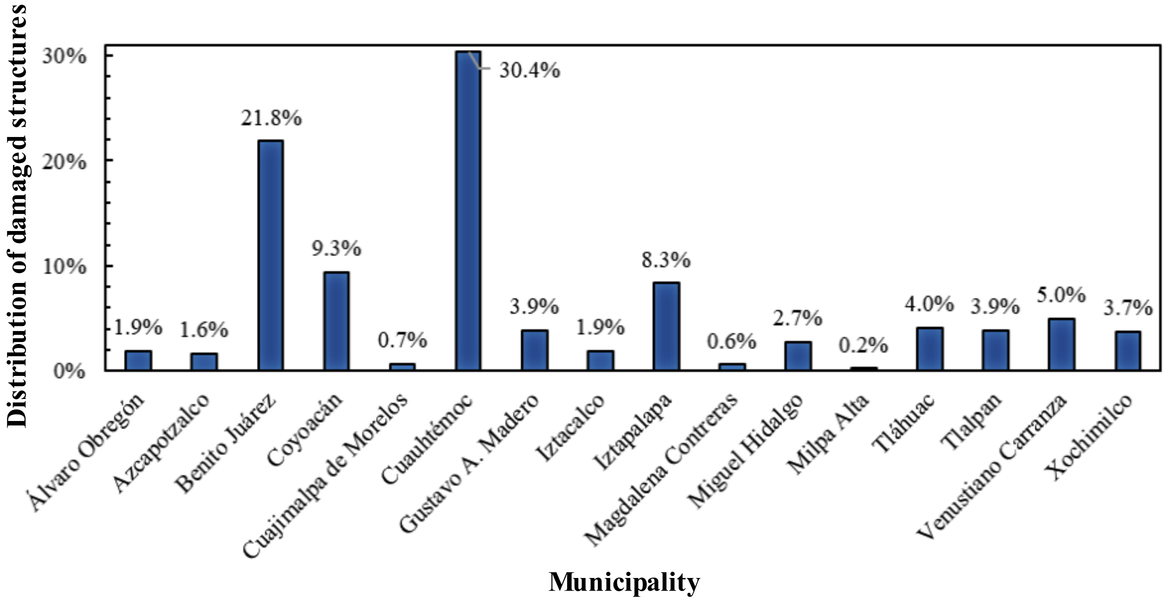


Fig. 2 – Distribution of damage reported in 2017 earthquake according to the municipality

On the other hand, by analyzing the buildings with severe damage in the database, it is possible to note that most of the damaged structures were built between the ’70s and the ’80s. During this period, a lot of the buildings were structured with concrete flat slab systems, which during the 1985 earthquake showed to be very vulnerable. Fig. 3 shows the distribution of severely damaged structures according to the structural type. As shown in this figure, more than 45% of the flat slab system structures suffered severe damage. Unfortunately, concrete flat slab structures have been an inadequate structural type for cities with high seismic activity, due to the inability of the flat slab to transmit moments and shear forces to the columns. During the 1985 earthquake, more than 80 structures with flat slab system collapsed.

4. Influence of structural pathologies on building damage

Other structural characteristics that defined the damage pattern presented in the 2017 earthquake were the structural pathologies. These pathologies modify the structural response in a negative way, aggravating the demands and causing more damage. Around 70% of buildings with severe damage had at least one structural pathology.

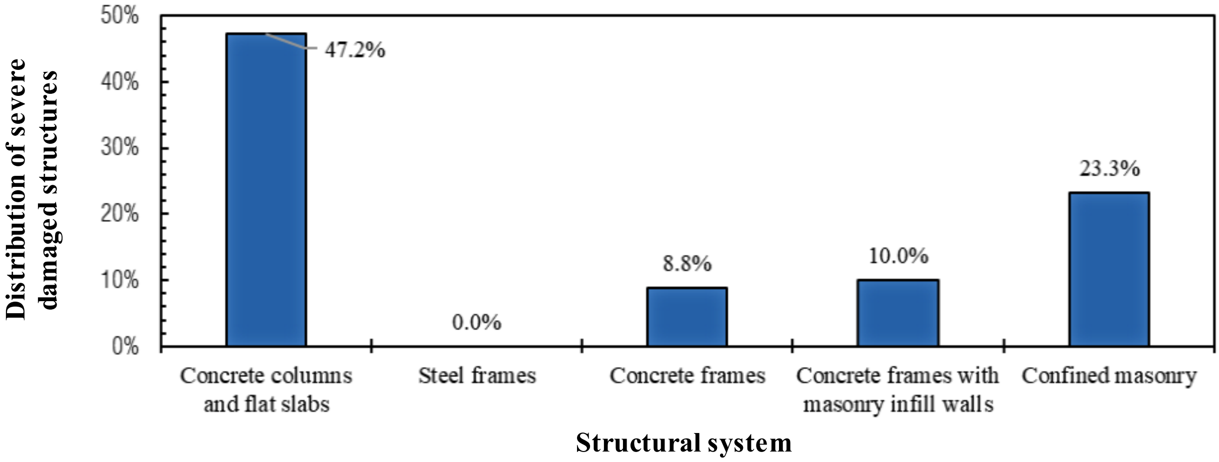


Fig. 3 – Distribution of structures with severe damage according to the structural system

The structural pathologies that were presented in most of the damaged buildings were a) corner effect, b) pounding, c) soft story, and, d) plan irregularity. Structures with pounding represented 21% of the severely damaged buildings; unfortunately, this situation is very common in Mexico City. The soft story, which has caused several collapses around the world, represented 29% of the structures with severe damage. A structural pathology very common in most buildings is the plan irregularity; this problem is reflected in the 45% of severely damaged structures. It must be noted that building with severe damaged had more than one structural pathology at the same time.

4.1 Description of the case study: Roma and Hipódromo districts in Mexico City

The metropolitan area of Mexico City has 16 municipalities, of which the Cuauhtémoc municipality was the most affected after the 2017 earthquake (~ 33% of the total damage reported in the city). This area also suffered significant damage during the September 19, 1985, earthquake, since this area has historically been very populated and has the older buildings in the city, including Tenochtitlán, built more than 700 years ago. Within this municipality are the Roma and Hipódromo districts. About 30% of the total collapsed buildings were reported in these areas.

For the analysis of the structural behavior and the influence of the structural pathologies on the damages reported in Mexico City during the 2017 earthquake, a database of 1923 buildings in Roma and Hipódromo districts was gathered. The damage level of buildings was classified into four categories, shown in Table 1.

Table 1. Classification of structural damage

Damage level	Description
Low	Light damage usually reflected in non-structural elements
Intermediate	Additionally, small cracks occur in structural elements
Severe	Large cracks in structural elements and large deformations. This type of damage compromises the stability of the structure
Collapse	Collapse of the structure during the earthquake or required demolition

The delimited area of the case study is shown in Fig. 4. Since the intensities in the lakebed zone area of Mexico City vary significantly over short distances ([3],[4]), for this case study, the accelerometric station CI05 was taken as the center or a rectangle area of 500m each side; the strong ground motion within this area was considered to be roughly the same at all points. The damage levels in the structures were adopted as an equivalent-damage index (ID), depending on the dynamic response at different levels of seismic intensity.

The structures were classified into four damage levels: 1) Low damage (0 < ID < 0.05), which corresponds to light damage that does not affect the integrity of the structure. 2) Intermediate damage (0.05 < ID < 0.30), where fissures in structural elements are evidenced. 3) Severe damage (0.30 < ID < 0.60), with significant deformations in structural elements and 4) collapse (0.60 < ID < 1.00), with partial or total structural collapse.

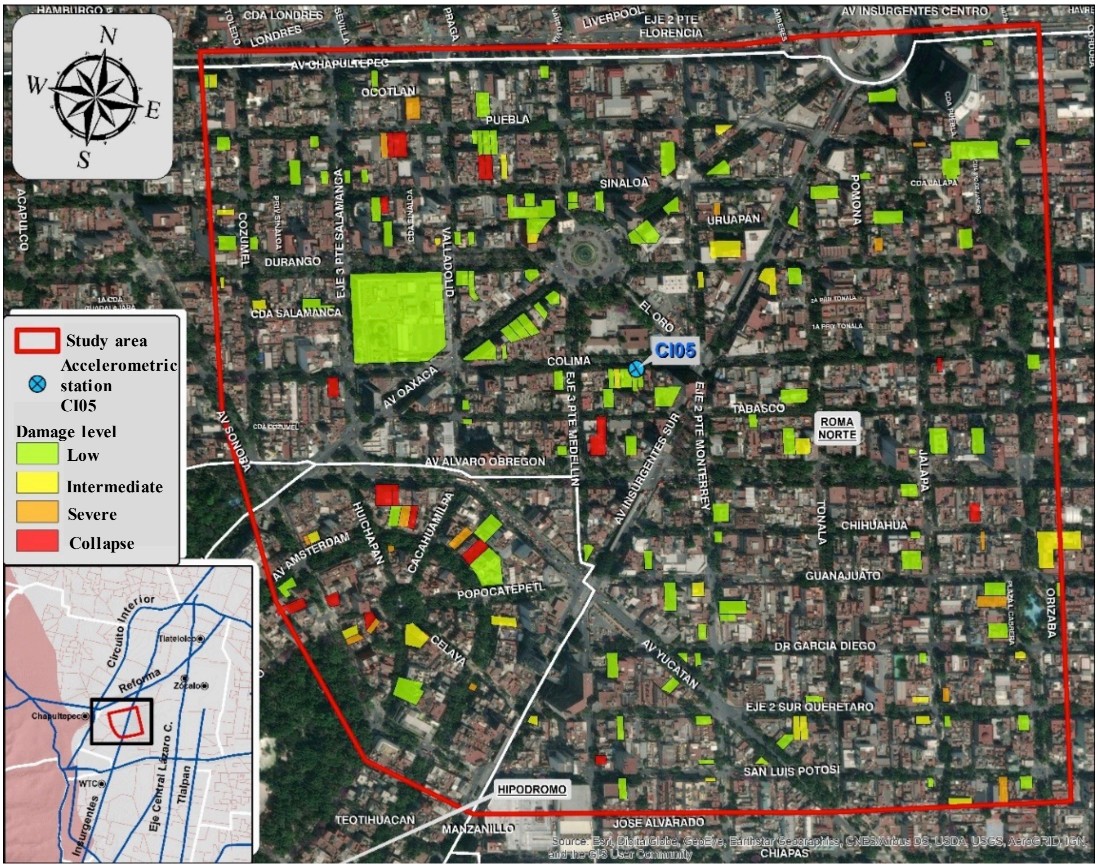


Fig. 4 – Map of the area of study showing the location of the accelerometer station CI05 and buildings with different levels of damage

Figure 5 shows the pseudoacceleration demands (Sa) for station CI05 for both horizontal components of motion and for the corresponding geometric mean; this geometric mean is the demand used in this work hereafter. As can be seen in Fig. 5, the demands for both orthogonal components are similar for most periods, so using the geometric mean would not exclude directionality effects.

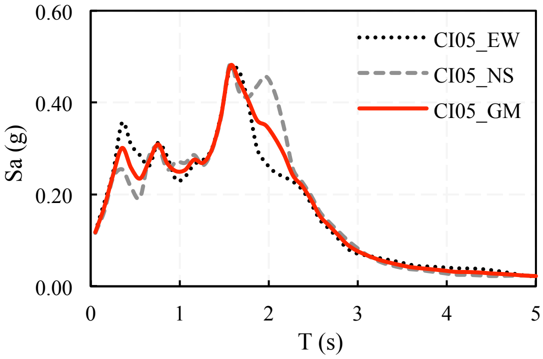


Fig. 5 – Pseudoacceleration spectra for station CI05

In the area of study shown in Fig. 4, 1923 buildings were found, 91% of which were not damaged, while less than 1% had partial or total collapse.

4.2 Analysis of the influence of structural systems on observed damage

To understand the level of seismic resilience of the structures that were damaged in Mexico City, a statistical analysis of damaged structures was carried out, by identifying different structural pathologies. In the case study area, there was the collapse of the building located in Álvaro Obregón 286, an office building of 7 levels, structured with RC (Reinforced Concrete) columns and flat slabs, built-in 1958. In the same zone, 63 buildings between six to eight were found and analyzed (damage viewer, ERN, 2017 [5]). Those buildings had different damage levels and structural typology. Having structures of similar height, delimited in a small area to reduce differences in the site effects, allowed focusing on the influence of the structural configuration and the pathologies of each building. These 63 buildings were classified into four structural types: 1) flat slabs, 2) Reinforced concrete frames (RC frames), 3) RC frames with masonry walls and, 4) steel frames. Figure 6 shows the comparison of damage between the four structural types. Each symbol corresponds to a structural system and the number above each one corresponds to the number of structures of each structural system, indicating the total number of buildings in each damage level. The blue band corresponds to the accelerations demanded by the structures according to its estimated period (which depends on the structural type) and the spectra of station CI05. Figure 6 also shows typical vulnerability curves for the full range of intensities for the four structural types and the mean curve. These vulnerability curves were constructed with analytical models and calibrated with the statistical data for the acceleration demands of the acceleration band of Figure 6. As can be seen in this figure, most of the structures suffered only minor or intermediate damage (55 structures), six had severe damage and two structures collapsed. The buildings with severe damage were those of RC frames and flat slabs, while the collapses occurred in the flat slab buildings. The most vulnerable structural system was by far flat slabs, while less vulnerable systems were steel frames and dual systems.

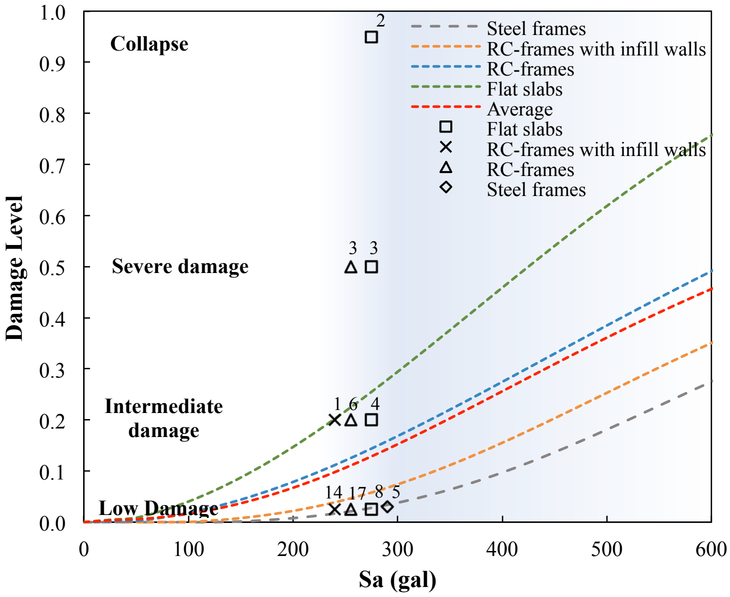


Fig. 6 – Comparison of damage levels of the four structural types studied [10]

4.3 Analysis of the influence of two structural pathologies on the damage pattern

Additionally, to better understand the structural performance of damaged structures, the main pathologies in the buildings were gathered: a) corner effect, b) plan irregularity, c) irregularity in elevation, d) pounding, e) soft story, f) short column effect and g) previous damage, Fig. 7 shows the damage levels for buildings with a flat slab structural system (seventeen buildings), together with the pathologies found in each building of this structural type. In the same figure, each square represents a building, and the number above each one indicates the number of pathologies found in that building. The vulnerability curves, empirically constructed from the observed data, and affected by the influence of the pathologies are presented. As can be seen in this figure, although the flat slab system itself has a high vulnerability, the level of damage increases considerably with the number of structural pathologies. Although the structural system defines the seismic behavior of the structure, it is clear that the structural pathologies my affect this behavior by very large factors. Therefore, to assess correctly the seismic resilience of any building, it must be analyzed comprehensively, considering in a realistic way the pathologies that affect its behavior.

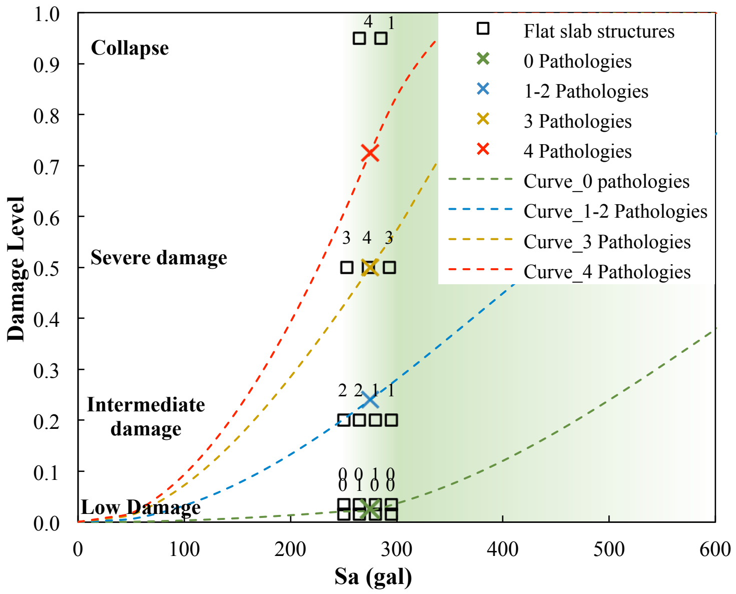


Fig. 7 – Damage levels only for buildings with a flat slab structural system, and the influence of pathologies on the structural performance [10]

From these results, two pathologies that frequently occurred in severe damage buildings, were analyzed in detail: a) corner effect and b) soft story.

4.3.1 Corner effect

The geometry of the structure at the perimeter strongly influences the building's seismic behavior. If there is wide and irregular variation in strength and stiffness around the perimeter, the center of mass will not coincide with the center of stiffness, therefore, torsional forces will generate and cause the building to rotate around the center of resistance [6]. This condition is commonly presented in corner buildings where these structures in Mexico City have flexural facades facing the street, and the other two sides, have infill walls linked to columns; this architectural solution produces a strong, and sometimes very strong, stiffness irregularity [7].

In Mexico City, during the 1957 earthquake, 40% of the reported damages happened in corner buildings [8]. Later, in the 1985 earthquake, 42% of all collapsed buildings were at a corner [9] and, during the 2017 earthquake, at least 44% of the reported damage were corner buildings [7].

In this work, corner effect is classified in three levels depending on the number of walls on the sides facing the streets:

- ➢ Null effect. Buildings located at a corner but with a symmetric perimeter.
- ➢ Low affect. Buildings located at corners with two facades formed predominantly by walls or sturdy columns.

- Strong effect. Buildings located at corners with two facades formed predominantly by thin columns.

According to the information of corner buildings collected in the area of study (Fig. 4), 246 buildings were not damaged, 51 suffered light damage, 14 intermediate damage and 6 severe damage or total collapse. Although buildings with corner asymmetry had severe and total damage, this pathology was not decisive when evaluating the entire universe of buildings, since many buildings have corner asymmetry but not suffered damage.

Fig. 8 shows the average damage of buildings according to the assigned level of corner asymmetry. It can be seen that, for the total of buildings in the case study zone, even with null corner asymmetry, there is 1.4% of average damage (this value is very similar to the average loss of all the area of study and it is due to other pathologies and characteristics that caused damage) while buildings with high corner asymmetry represent 4.5% of damage. It is very clear that there is a strong correlation between corner asymmetry and damage: having a strong corner asymmetry increased the observed damage by a factor of 3.2.

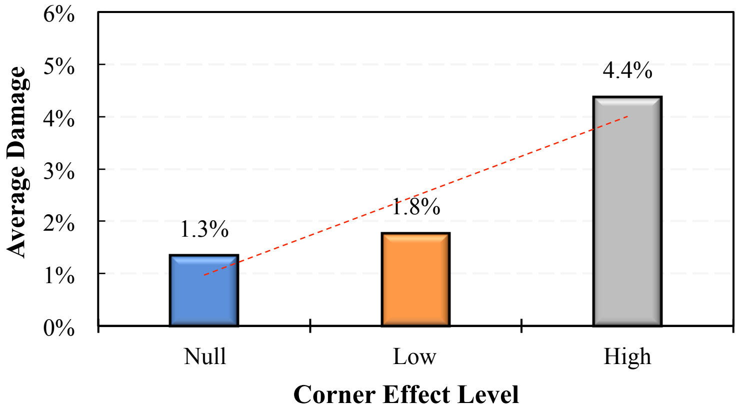


Fig. 8 – Statistics of average damage on corner buildings according to the level of corner effect [10]

4.3.2 Soft story effect

Of all 33 buildings with severe or total damage in the case study zone, 10 (30%) had a soft story pathology. According to the database, 275 buildings had first soft-story (FSS), of which 229 had no damages, 28 suffered minor damages, 8 intermediate damages, and 5 severe damage or total collapse. This pathology had a higher impact in the damage statistics than the corner asymmetry. There is a very strong correlation between FSS and damage: having a high FSS increased the observed damage by a factor of 7.3.

Fig. 9 shows the average damage in buildings according to their level of FSS. As it is observed, there is a considerable increase in the average damage depending on the level of FSS; damage goes from 1.2% when there is no FSS to 8.8% when buildings have an intense FSS effect.

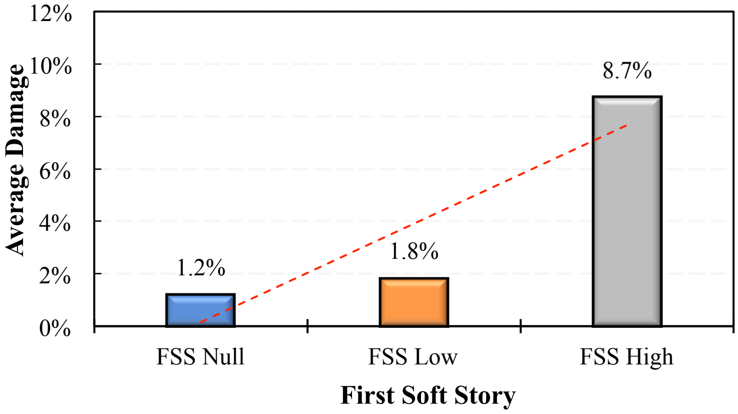


Fig. 9 – Statistics of average damage on buildings damaged by the earthquake according to the assigned level of first soft story [10].

4.3.3 Combination of pathologies: Corner effect and soft story

As shown in Figs. 8 and 9, the condition of FSS is far more critical than corner asymmetry. The cases in which both pathologies were correlated, and affected a given structure were also analyzed. An example of this is the building located in Medellín 176, which had FSS and corner effect. This building collapsed after the 2017 earthquake, and the buildings images, before and after the earthquake, are shown in Fig. 10.

Out of all damaged buildings, 4% presented both pathologies, 10% only have FSS, 13% only corner asymmetry, while the rest (73%), have other or null pathologies. Fig. 11 shows the average damage when the buildings have either one or both pathologies. As can be seen, the most critical condition is the combination where both pathologies are presented with the largest values, reaching an average of 31.7%, this means, total damage for one out of three buildings.

a) Before de 2017 earthquake b) during the 2017 earthquake c) After the 2017 earthquake

Fig. 10 – Photos of the building located in Medellin 176, before, during and after the earthquake. The building has both pathologies studied: corner asymmetry and ground weak story.

As it is shown in Fig. 11, 31.7% of the actual damage reported is presented in buildings that have high-intensity levels of both pathologies. Likewise, when buildings have a level high of one of each pathology, and low of the other one, the damage is also considerable (between 10.8 and 12.5%).

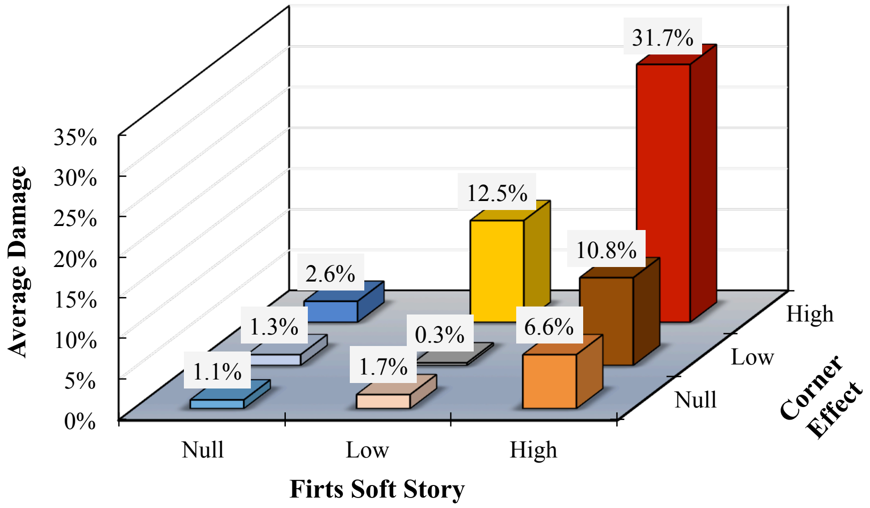


Fig. 11 – Statistics of buildings, which have either one or both pathologies in the area of zone [10]

4.4 Analysis of the resonance between the dominant soil period of the site and the structural period of collapsed structures

Figure 12 shows the relation between the estimated dominant period of the structure [11] and the dominant period of the site [3]. It can be seen that only one of all collapsed structures was in the line of resonance, but most of all structures were far from this line. It is also clear that no structure had a period larger than the site, which means this condition may put the structure in the safe side.

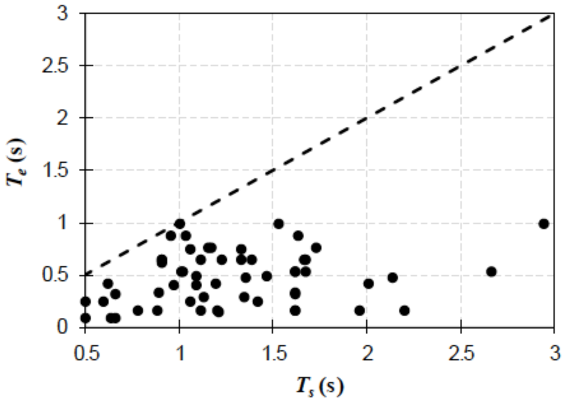


Fig. 12 – Relation between the dominant period of the site and the dominant period of the structure. The dotted line marks perfect resonance [12].

5. Conclusions

The September 19, 2017 earthquake caused a lot of damage to medium high-rise buildings, and a lot of data is available to better understand the site effects and the structural response. In this work, a studied area was surveyed, and the information of all buildings was gathered in order to study the statistics of two pathologies: ground soft story and corner asymmetry.

The statistics show clearly that there is a very strong correlation of the observed damage with the presence of these pathologies, increasing the expected damage by a factor of 3.2 and 7.3 for corner asymmetry and ground soft story, respectively.

There is also a very strong correlation between the observed damage and the presence of both pathologies. When both pathologies are present, the expected average damage is 31.7 per cent. This means that almost one out of three buildings had total damage if they had both pathologies classified as high.

6. Acknowledgements

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