STRUCTURAL RECONNAISSANCE FINDINGS OF THE 2017 MEXICO CITY EARTHQUAKE

BY
RACHEL G. CHANDLER

SENIOR PROJECT REPORT

Submitted in partial fulfilment of the requirements for the degree of Bachelor of Science in Architectural Engineering at California Polytechnic State University – San Luis Obispo, 2018

San Luis Obispo, California

Senior Project Advisor:

Anahid A. Behrouzi, PhD

Abstract

The author of this document is an undergraduate student at California Polytechnic State University - San Luis Obispo (Cal Poly) who was deployed to Mexico City to participate in reconnaissance efforts October 27th to November 4th, 2017 as part of a larger group of academics and professionals. The work was funded through a National Science Foundation (NSF) Grant #1811084 “The Effects of the 2017 Central Mexico Earthquake on Reinforced Concrete Buildings” with the overarching objective of collecting data on reinforced concrete building damage for understanding and further improving the seismic performance of these structures and the resilience of communities.

This report details structural damage seen in the 2017 Mexico City Earthquake and conclusions made from analysis of damage data related to: building characteristics, geotechnical zones, and peak spectral accelerations. The document focuses on three case study buildings documented and observed by the author to illustrate common types of severe structural damage observed in Mexico City:

- Pounding damage due to buildings built within proximity to one another.
- Damage to columns due to vertical stiffness irregularities leading to soft stories.
- Torsional damage due to reentrant corner irregularities.

Specifically this report examines distributions of story height, age of buildings, design irregularities as related to damage levels/failures seen after the 2017 earthquake and any available data from pre and post 1985 earthquake investigations. The major lessons learned were how damaging irregularities in a structure can be as well as the impact code benchmarks have in the progression of structural engineering for areas with high seismicity. These preliminary analyses indicated a need for more investigation in the area of sustainable and economical retrofit possibilities for soft story structures as well as additional experimental tests on unreinforced masonry retrofit solutions.

Table of Contents

List of Figures

1.0 Introduction

1.0.1 Role in 2017 Mexico City Reconnaissance

This report summarizes observations from the September 19th, 2017 Puebla Earthquake related to damages that had occurred to modern and retrofitted reinforced concrete buildings in Mexico City. The author was responsible for documenting damage via photographs, and documenting the descriptions of the building which was then analyzed to identify the key factors that are believed to contribute to most of the significant structural damage in this earthquake.

The reconnaissance work was funded via a National Science Foundation (NSF) RAPID grant #1811084. The objective of this grant was to send in teams to study reinforced concrete building damage in Mexico City after the 2017 Puebla Earthquake. The reconnaissance team members for the October 28th – November 4th, 2017 mission included:

- Rachel Chandler – Graduate Student at California Polytechnic State University, San Luis Obispo & Author of paper
- Garrett Hagen – Design Engineer at Degenkolb Engineers
- Sergio Breña – Professor at University of Massachusetts-Amherst
- Mario Rodriguez – Professor at Universidad Nacional Autónoma de Mexico (UNAM)
- Michael Kreger – Chair & Professor at University of Alabama
- Shane Crawford – Doctoral Student at University of Alabama

In Chapter 1 a spectral accelerations overview of the Mexico City Earthquake will be provided. Chapter 2 provides a description of seismicity and geological characteristics. Chapter 3 introduces the building case studies from sites visited and investigated by the author. Chapter 4 contains analysis of the building data collected by the NSF Rapid team after the 2017 Puebla event including age, number of stories, structural irregularities, damage type, and severity. Chapter 5 describes the conclusions from the data collected and analysis provided in Chapter 4. Appendix A provides an additional insight into the author’s experience through a reconnaissance blog written during the reconnaissance trip. Appendix B is a response to fellow student questions that were asked after the reconnaissance trip.

1.0.2 Spectral Accelerations Overview

1.0.2.1 Map from USGS Puebla, Mexico PGA

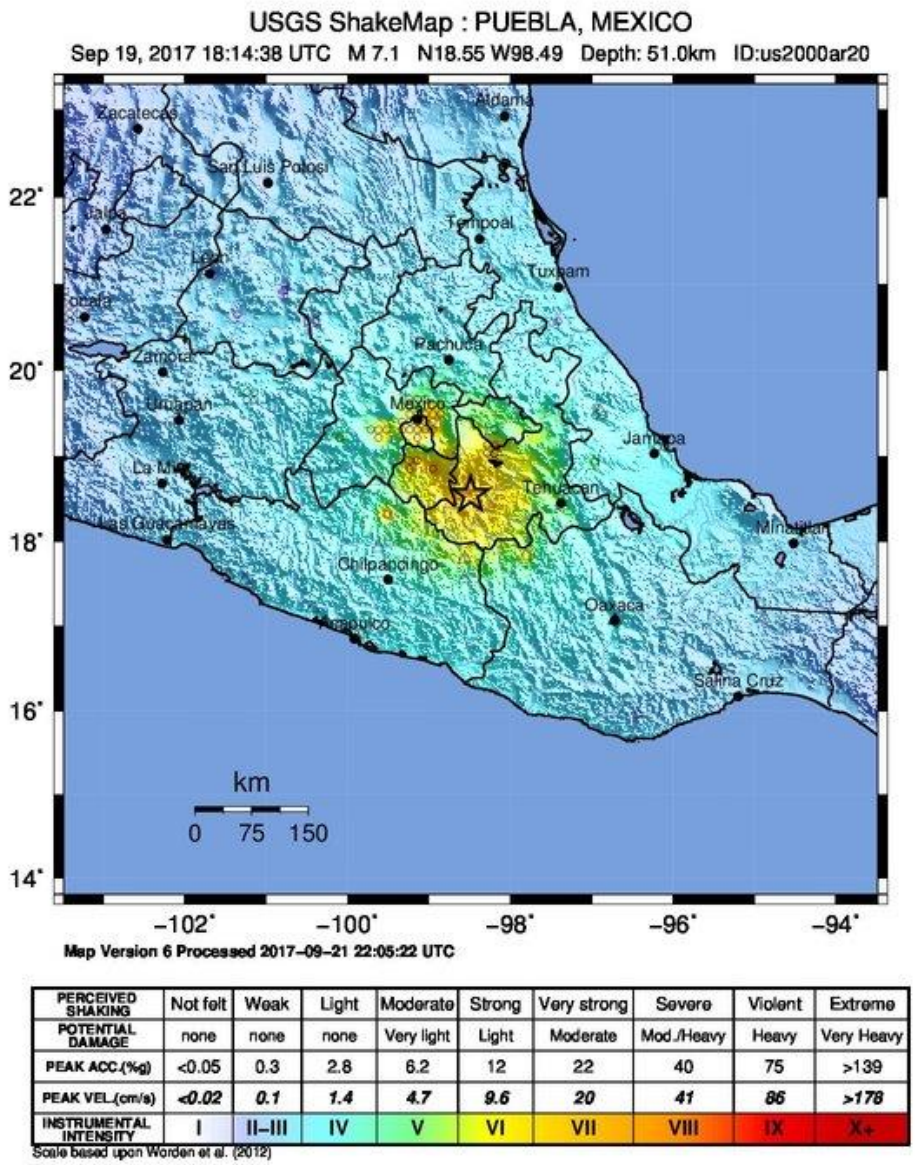


Figure 1: September 2017 Puebla Earthquake PGA Map (USGS, 2017)

In Figure 1, the map shows the peak ground accelerations (PGA) that were recorded during the 2017 Puebla Earthquake near Mexico City were consistent with strong shaking, and light to moderate structural damages.

2.0 Seismicity and Geological Characteristics

2.1 Mexico City Earthquakes

2.1.1 General Description of 2017 Puebla, Mexico Earthquake

On September 19th, 2017 an earthquake with a moment magnitude, M_w of 7.1 and a strong shaking of about 20 seconds, damaged the structures of Mexico City (Mayoral et al., 2017). The epicenter of the earthquake was approximately 60 km (37.3 mi) southwest of Puebla, Mexico, and 120 km (75.5 mi) southeast of Mexico City, Mexico (USGS, 2017). The earthquake occurred at a depth of 57 km normal to the fault near the point of curvature of the Cocos plate. There were over 80 strong ground motion instruments recording the event throughout Mexico City as shown in Figure 2. According to the Earthquake Engineering Research Institute (EERI) geotechnical team that performed a rapid response effort, the strong ground motion produced exceeded a VII Intensity Level in Mexico City, shown more precisely in Figure 3 than previously in Figure 1. This intensity is based off the Modified Mercalli Index (Mayoral et al., 2017).

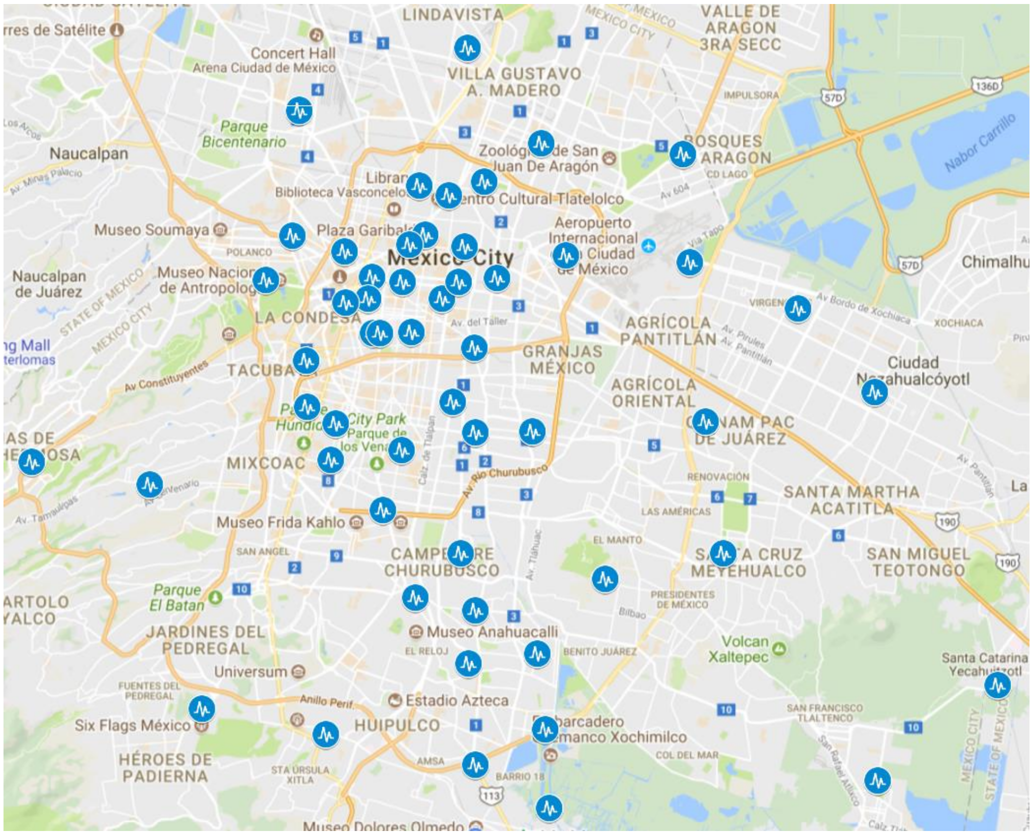
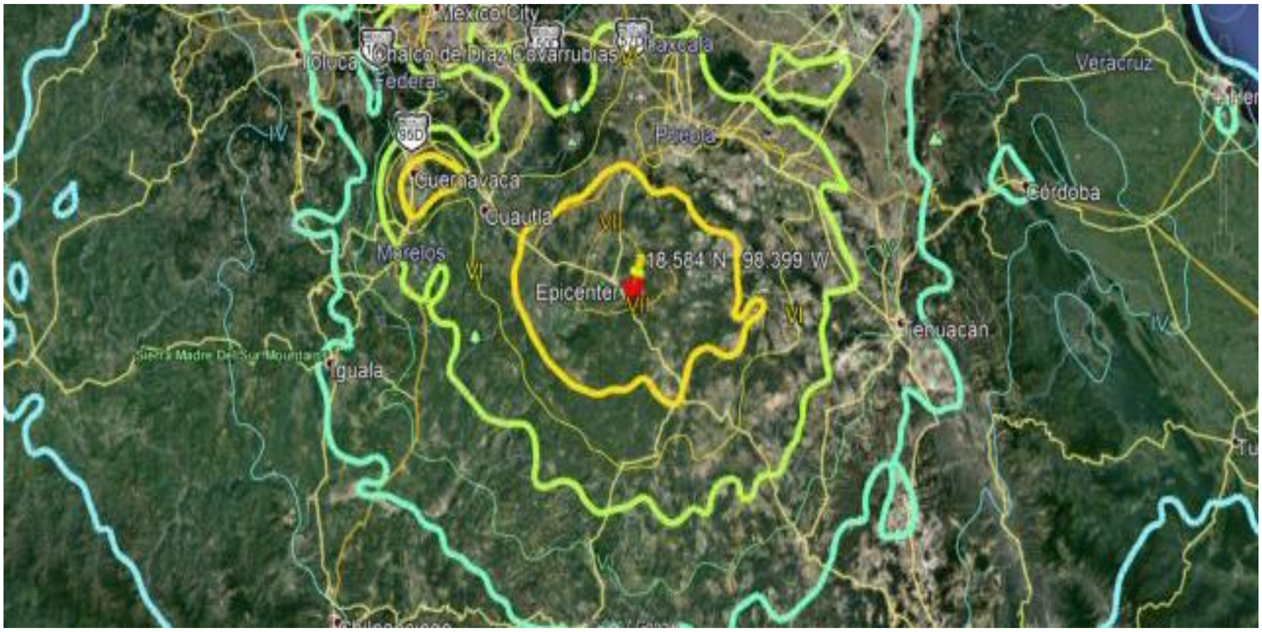


Figure 2: Location of Acceleration Stations in Mexico City (USGS, 2017)



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 3: Map Showing the Epicenter and Intensity Levels of the 2017 Puebla, Mexico Event (USGS, 2017)

2.1.2 General Description of 1985 Michoacán, Mexico Earthquake

In examining the recent 2017 earthquake, engineers and the population of Mexico are reminded of the 1985 Michoacán Mexico earthquake. On September 19th, 1985 an earthquake with an M_w of 8.0 and a strong shaking of about 13 seconds, significantly damaged structures in Mexico City. The earthquake occurred in the Pacific Ocean off the coast a distance of more than 350 km (217 mi) from the city, in the Cocos Plate subduction zone, and according to the accounts after the earthquake, over 2,000 buildings were damaged with the earthquake's ground motion at a depth of about a 27.9 km (17.3 mi) (Spence, 1986). This earthquake's ground motions produced a VII intensity level (USGS, 2018).

2.1.3 Site Seismicity

The seismic risks of Mexico City are related to four potential earthquake sources described in Tellez et al. (2005). These include: subduction, intermediate depth, continental and local earthquakes where subduction earthquakes occur more frequently and can cause more violent ground motions in the valley of Mexico City. The subduction waves produce long period motions which are amplified with the clay type soil within Mexico City (Tellez et al., 2005). In the September 19th, 2017 earthquake subduction occurred where the Cocos plate moved below the North American plate. In Figure 4 the relationship between the Cocos plate and the North American plate is depicted. The interpretation from the USGS data suggests that the earthquake occurred at the elbow of the Cocos plate (USGS, 2017).

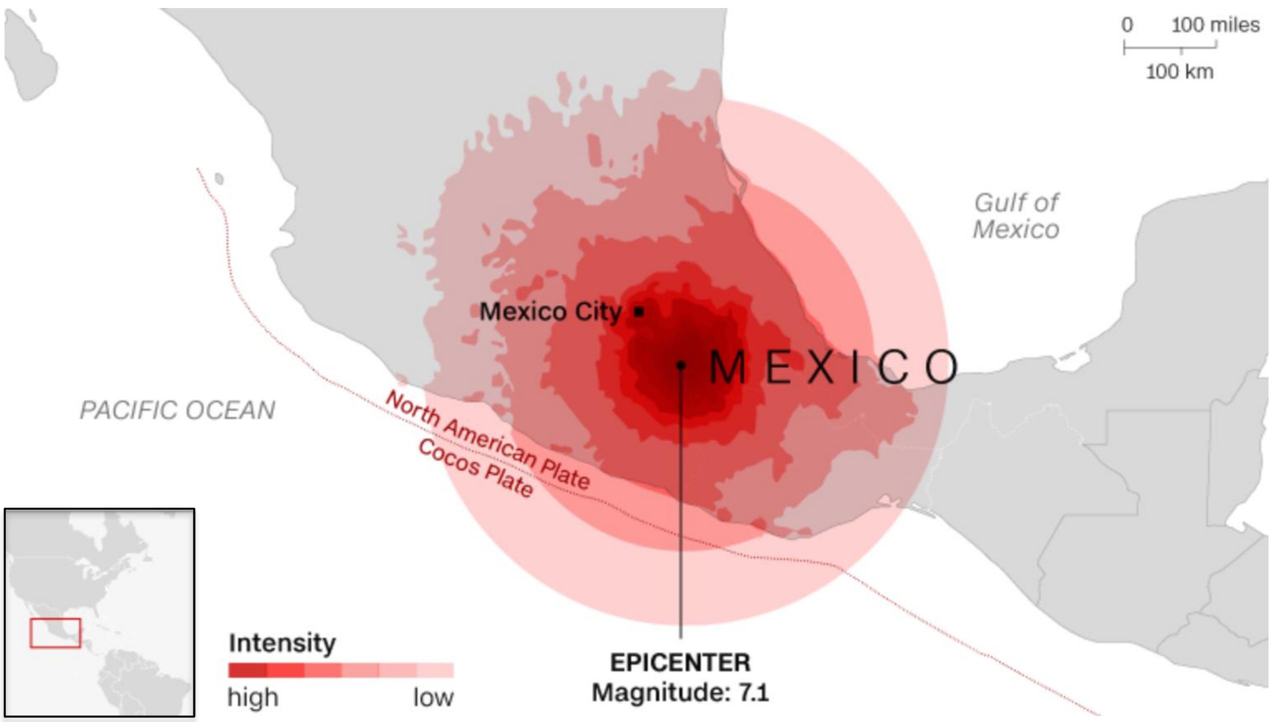


Figure 4: Cocos Plate in Relation to the North American Plate
(USGS, 2017)

2.1.4 Measured Response from 2017 Puebla, Mexico Earthquake

2.1.4.1 Spectral Acceleration Responses near Case Studies

In Figures 5-7 the recorded spectral acceleration data is shown for the nearest stations to the case study buildings described in Chapter 3. The different color lines in the below figures represent the spectral accelerations in the north east (NE) and North West (NW) directions. The simplified curve shown below in black represents the design spectra in that zone. These graphs come from the acceleration stations scattered throughout Mexico City – positions shown in Figure 2.

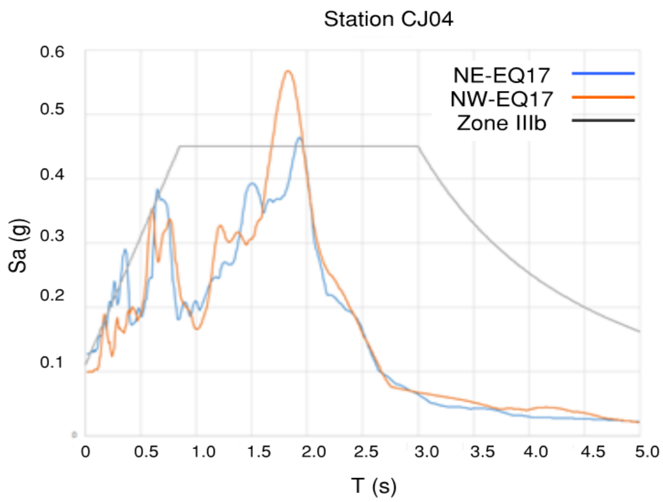


Figure 5: Multifamiliar Juárez II Station Spectral Acceleration Data - Near Tehuantepec 153 (USGS, 2017)

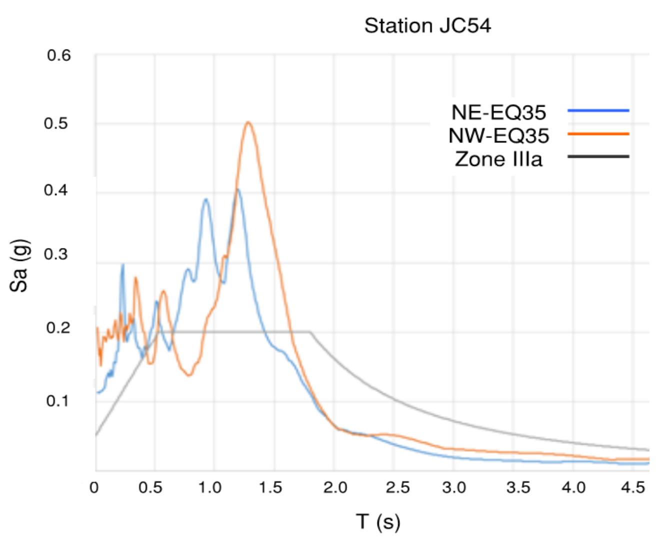


Figure 6: Parque Jardines de Coyoacán Station Spectral Acceleration Data –
Near Rancho San Lorenzo 54 (USGS, 2017)

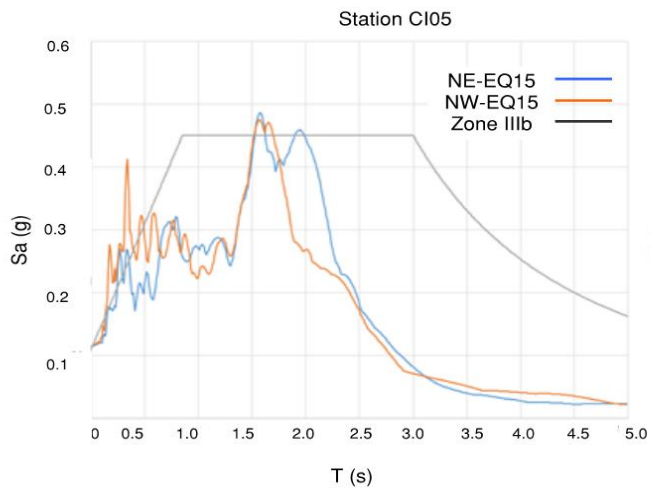


Figure 7: Roma Station Spectral Acceleration Data - Near Avenida México 55 (USGS, 2017)

2.1.5 Geotechnical Characteristics

Based on ground motion recordings, the rock ground motions resulted in resonance in the transition zone soils (Zone II) and lake bed zone (Zone III) described in Section 2.4.1. This resulted in a large horizontal spectral acceleration response at a recorded period estimated between 0.8 and 1.5 seconds. Most buildings observed that were built within soil Zone II and Zone III experienced severe ground motions. Specifically, for reinforced concrete structures, those lacking in proper construction and/or detailing requirements for current building codes, experienced the most severe damage from the ground motion within those soil zones (Hutchinson, 2017).

With respect to ground motions, recordings from soft rock showed a much higher frequency content in the 2017 event than in in the 1985 earthquake. The rock ground motions resulted in resonance in the transition zone soils (Zone II) and lake bed zone (Zone III) described in Section 2.3.1 (Mayoral et al., 2017).

The UNAM investigative teams noted that soil characteristics greatly influence foundation performance in areas of heavy structural damage. Seismic induced settlements were prevalent in Mexico City ranging from 1 to 15 cm (0.4 to 5.9 in) in the free-field soils around end-bearing pile structures. There were also many cases that involved tilted structures (1 to 3 degrees) in Mexico City due to the plasticity of the clay soils. Other soil deformations observed by the UNAM teams included slope instability and ground subsidence cracks. Cracking can result in significant decreases in soil stiffness and shrinkage can produce differential displacements at the foundation which can result in movement and damage to the structure above (Mayoral et al., 2017).

2.1.5.1 Soil Zones

The soil in Mexico City has a unique effect on the performance of structures and distribution of damage. The subsoil in the Valley of Mexico is generally divided into three main soil zones: the hill zone, transition zone, and lake bed zone. These zones were formed because Mexico City and the surrounding areas are in an old lake basin that is made up of the former Texcoco Lake and the Xochimilco-Chalco Lakes (Mayoral et al., 2017). These lakes have disappeared over time due to underground water extraction and land reclamations in the area. Thus, the outskirts of Mexico City have become a hard soil and rock formation, and the central part of the city is built upon soft clay deposits. Figure 8 shows the three main soil zones as well as further sectioned off soil zone layers that correspond to the depths of the clay deposits within that layer.

- The hill zone, Zone I, is comprised of volcanic tuff soils. This soil zone has high strength and is considered incompressible.
- The transition zone, Zone II, is characterized by a layer of clay deposits confined by a semi-compacted sand layer above and below. This soil condition can lead to an amplified ground motion within the transition zone soil layers between the very soft and hard soil layers.
- The lake bed zone, Zone III, contains deep clay layer deposits which have high compressibility and water content of (100-500%) (Tellez et al., 2005). These layers are intermixed with firm strata found 20-35 m (65.6-114.8 ft) deep into the lake bed and are the material that bearing foundation piles are built atop.

As a note, the lake bed zone (Zone III) is where most of the structural damage occurred and where the author and affiliated reconnaissance team focused their data collection in the late October 2017 mission.

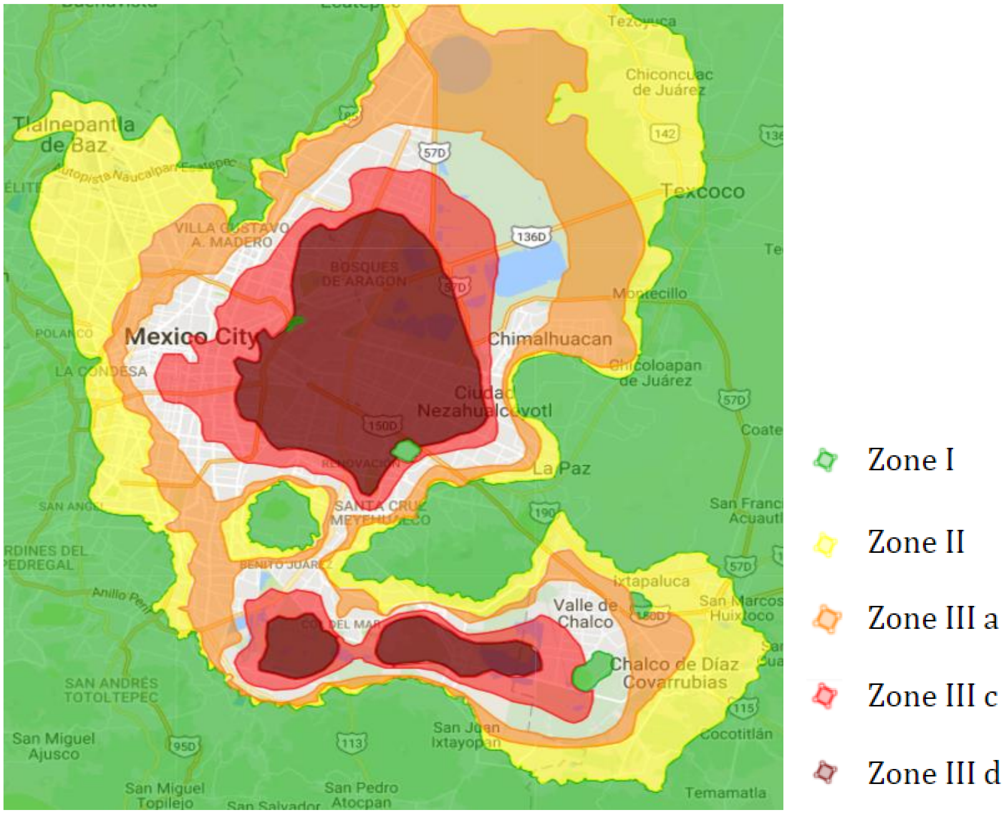


Figure 8: Zone Representation of Mexico City (Maps, M. 2018)

2.1.5.2 Geotechnical Description

The soil within Mexico City has a unique dynamic response and is nearly elastic. Studies have shown that the soils that make up Mexico City show no significant reduction in shear modulus and no significant increase in the damping ratio under seismic conditions (Mayoral et al., 2017).

During the 1985, 8.1 M_w Michoacán Earthquake a recorded peak ground acceleration on the lake bed, soft soils - Zone III, was five times larger than the corresponding peak ground acceleration on the hills, rock soils - Zone I (Mayoral et al., 2008). Zone III has been extensively studied since the 1985 event because of its unique properties of clay deposits.

Typical soil profiles are found in Figure 9. The center and right graphs represent the typical soil profiles for Zone III soil conditions. The left graph represents the typical soil profile for Zone II soil conditions according to (Mayoral et al., 2017). These graphs show the first 7.9 m (26 ft) of clay with a certain shear wave velocity. When an earthquake wave interacts with this type of soil, the earthquake waves are dissipated within the clay. With hard bedrock, the waves reflect and can magnify the seismic waves.

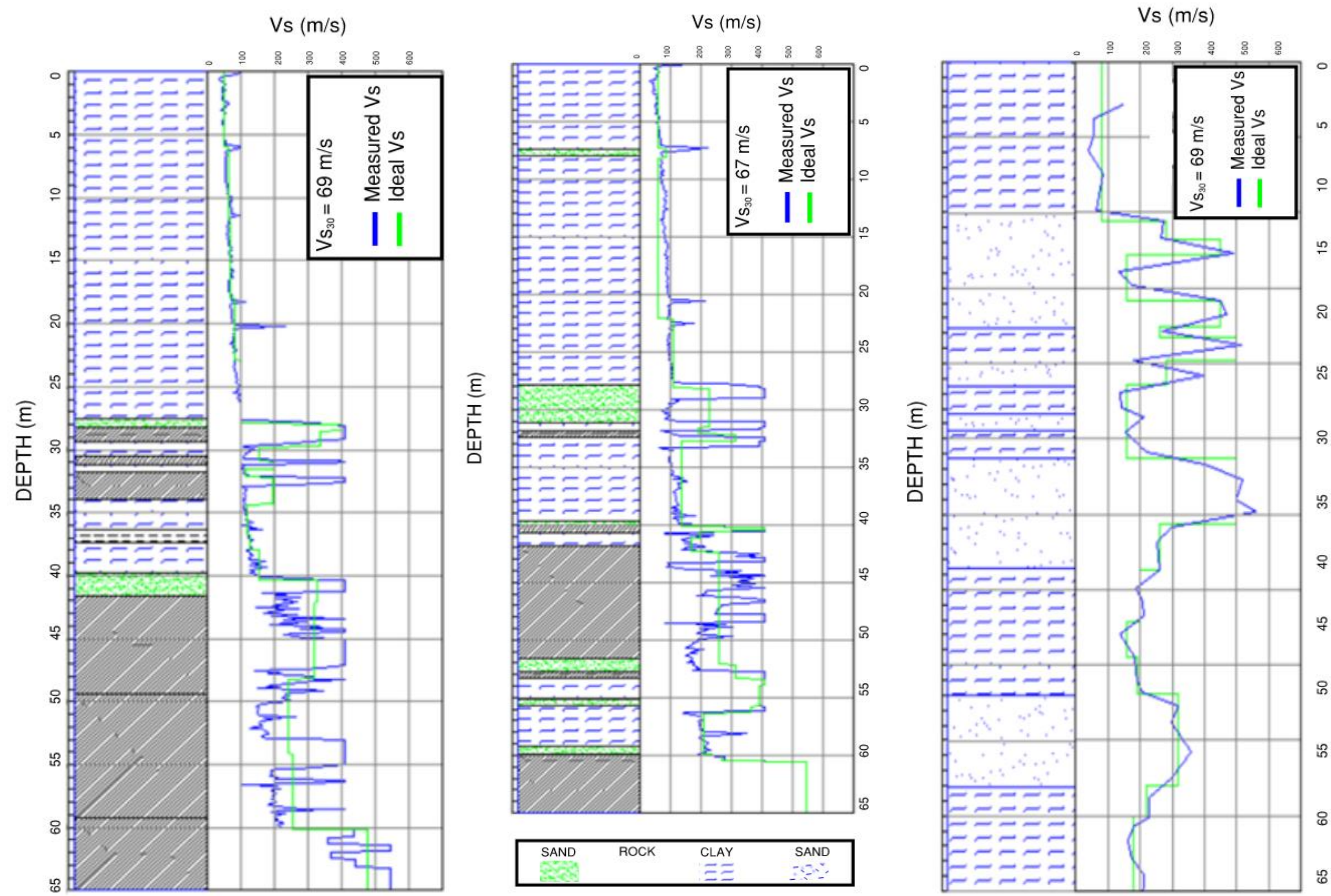


Figure 9: Zone II & III Soil Profile (Mayoral et al., 2017)

2.1.6 Building Damage Distribution with Respect to Soil Zones

A variety of buildings in Mexico City were damaged in the 2017 Puebla earthquake: new, old, retrofitted, commercial, and residential buildings. Commonly this included unreinforced masonry or pre-1985 buildings that do not comply with post-1985 seismic code requirements.

Observations of damaged structures were compiled into a database by two structural response teams from UNAM-GEER deployed September 24-30 and September 29-October 6, 2017 (USGS, 2017). There is approximately a total of 340 damaged buildings in the database. The buildings that were visited by teams are represented by red markers in Figure 10. Official reports released in late November 2017 indicated that a total of 38 buildings had collapsed, 340 buildings were identified as high-risk buildings, and 273 buildings were found to be partial risk buildings (Mayoral et al., 2017). A damage survey by structural engineers revealed that a number of collapsed buildings had been erected in the 1960s and 1970s with unreinforced masonry walls confined by non-ductile concrete frames. It is noted that structural damage was primarily located in the west and southwest transition Zone II and lake bed Zone IIIa and IIIb. Within each of these areas, there were large horizontal spectral acceleration response at periods of 0.8 to 1.5 seconds (Mayoral et al., 2017).

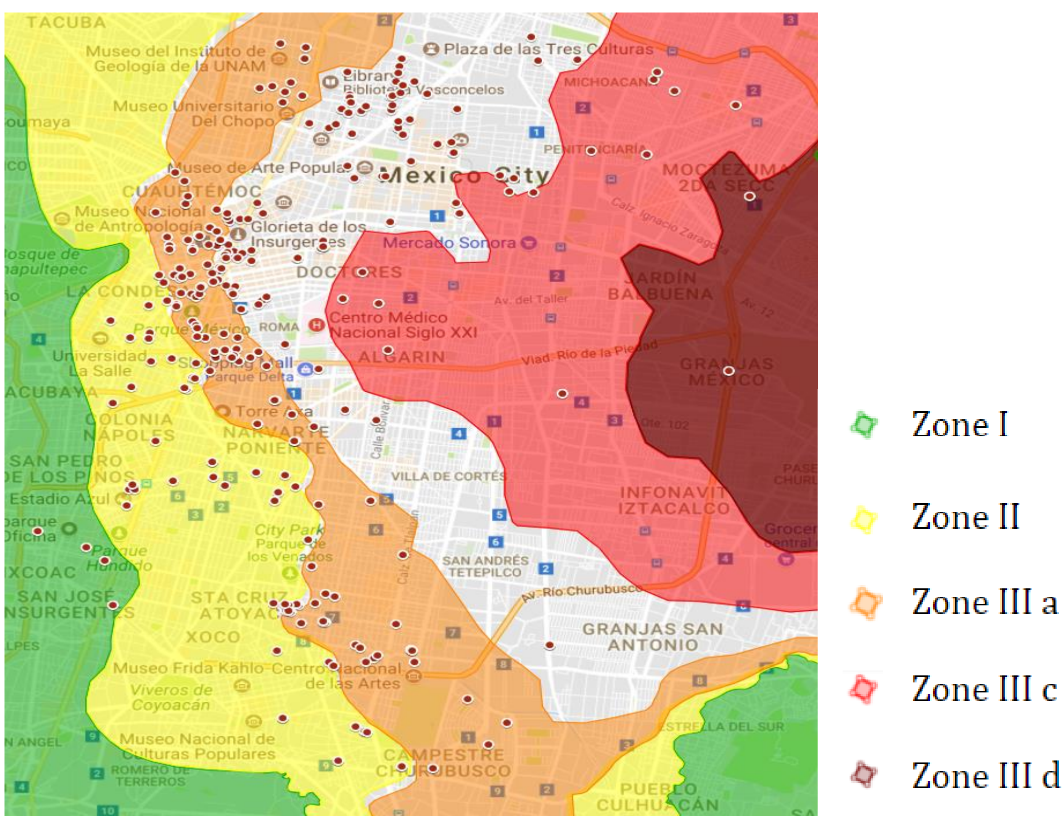


Figure 10: Distribution of Damaged Buildings in the 2017 Puebla Earthquake

2.1.7 Observations during the October 2017 Reconnaissance Trip

The reconnaissance team the author served on visited a total of 68 building sites during October 27th to November 4th, 2017. 38 of which were structurally damaged based on external visual inspection, 23 of these damaged buildings were subjected to a more detailed investigation, and 7 were determined as not structurally damaged. Buildings with five to eight stories experienced more severe damage. The main structural damage observations from the investigations of reinforced concrete buildings after the 2017 Puebla Earthquake were the following:

- Pounding damages to the lateral system due to close proximity neighboring structures;
- Soft story effect due to ground floor parking garages and openings created by discontinuous columns and/or walls;
- Torsional reentrant corner irregularity due to shape and orientation of building;
- Short column due to construction and detail designs not being adequate;
- Shear critical columns due to insufficient amount of transverse reinforcement in column;
- Weak connectivity between members due to inadequate detailing and construction methods; and
- Deep beam, slender column damages due to poor reinforcement detailing and design.

3.0 Introduction to Case Studies

From the reconnaissance work done in late October 2017, three case studies were chosen for further exploration. The case studies are outlined below:

- **Case 1, Tehuantepec 153:** exhibited successful performance in the 2017 earthquake with a retrofit completed after the 1985 earthquake.
- **Case 2, Rancho San Lorenzo 54:** contains a soft-story irregularity.
- **Case 3, Avenida Mexico 55:** contains a soft-story and reentrant corner irregularity.

3.1 Case Studies

3.1.1 Case 1, Tehuantepec 153: Retrofit from the 1985 Earthquake

3.1.1.1 Building Description

Tehuantepec 153 (19.40484, -99.16329) is a 7-story apartment building constructed in 1979 which is located on Tehuantepec between Mendellín and Calle Monclova, shown in Figure 11. This C- shaped building has parking on the ground floor and an approximate floor area of 215 m^2 (2,314.24 ft^2), on upper stories this area is divided into two apartment units separated by the center elevator core and stairs.

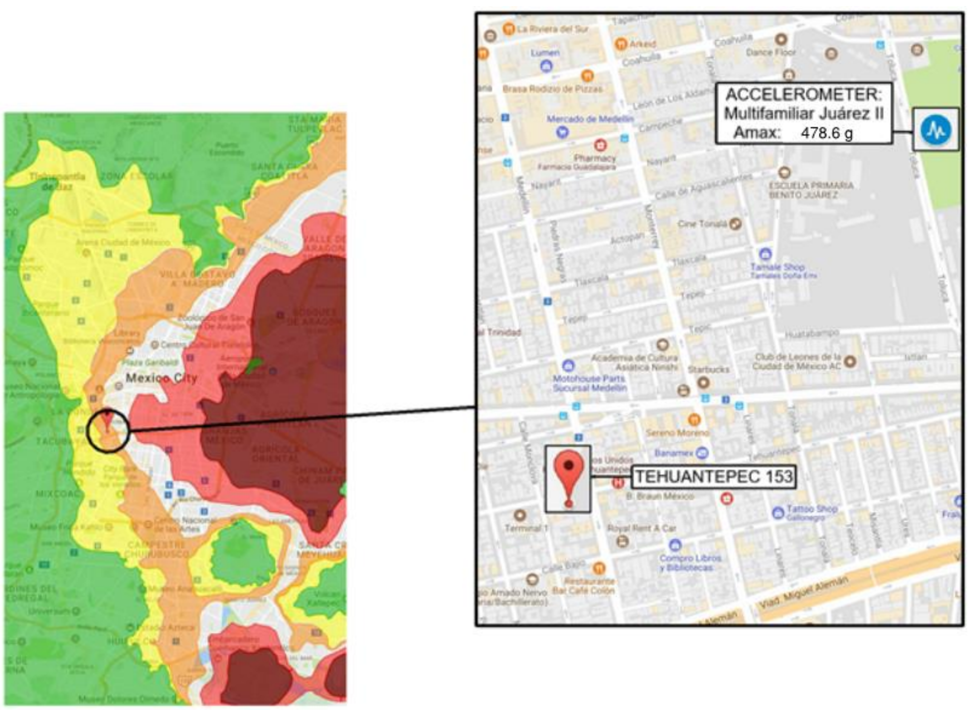


Figure 11: Location of Tehuantepec 153

The main lateral force resisting system in the building is comprised of four reinforced concrete frames on lines 1-4 in Figure 12. Two continuous 15cm (5.9 in) thick reinforced concrete walls were built around the elevator core and stairwell on lines 2 and 3. Figure 13 shows the reinforced concrete beams that were added after the 1985 earthquake to reduce torsional effects on the building. The first floor consists of a waffle slab supported on reinforced concrete columns. The foundation as noted by (Aguilar et. Al, 1996) is a grid and slab system on friction piles. Figure 14 provides an exterior view of the building.

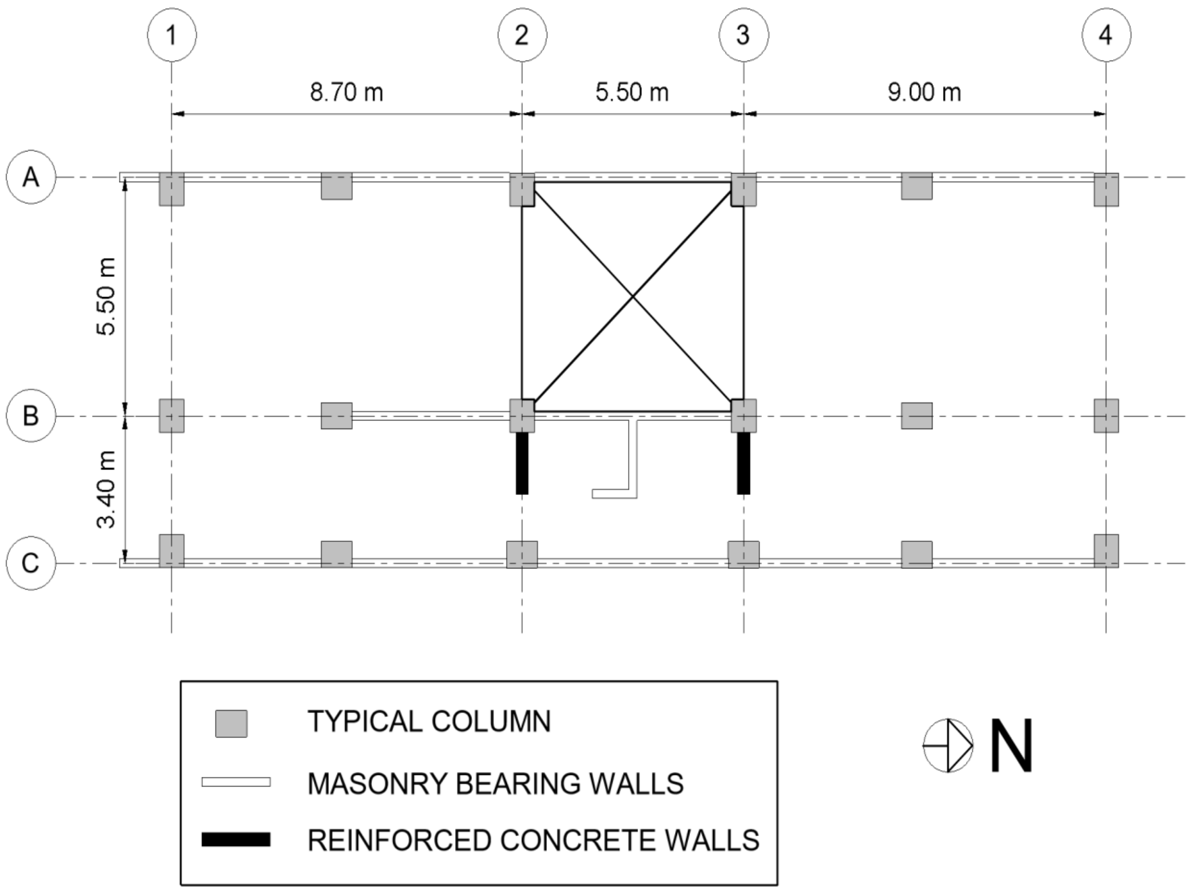


Figure 12: Building Plan Level 1

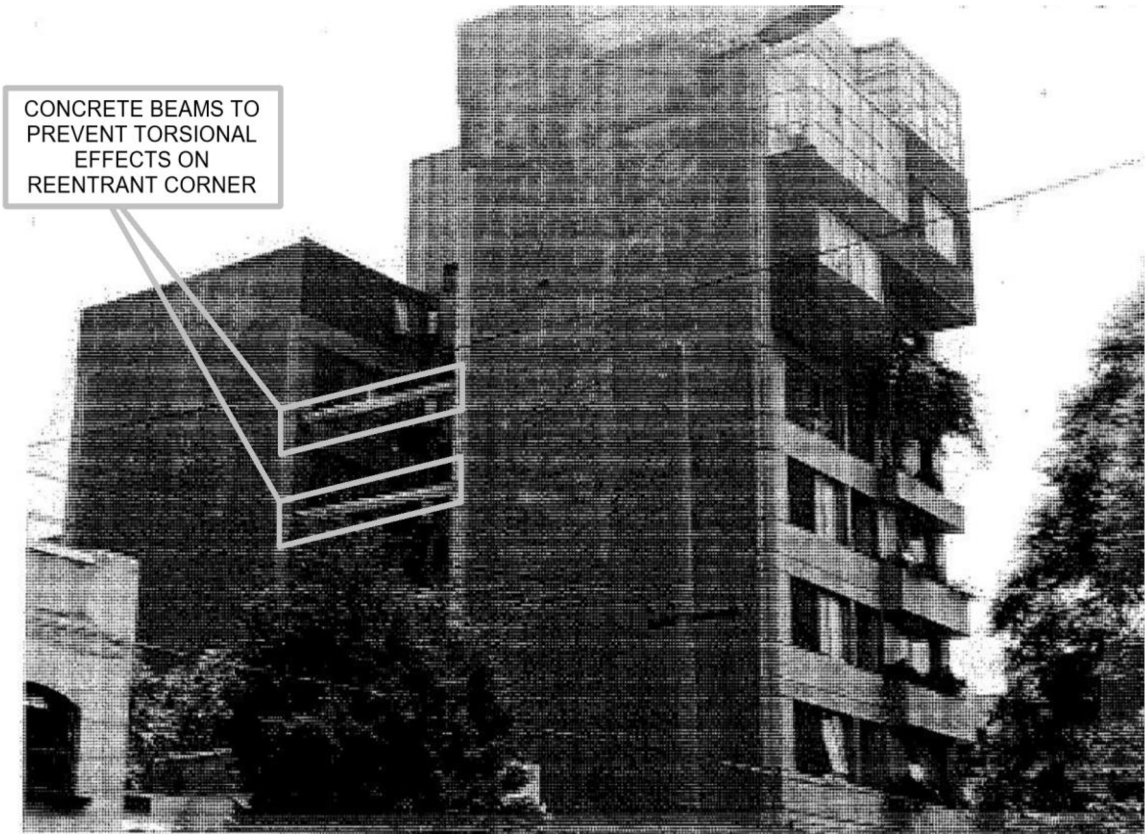


Figure 13: Building Profile (Aguilar et. al, 1996)

The major vulnerabilities identified in this structure were:

1. Vertical irregularity at first floor parking where walls/columns included on other story levels are discontinued;
2. Torsional irregularity due to the separation gap (reentrant corner) located in between the two apartment units; and
3. Irregular floor plan that resulted in rocking action between the two units.

Pounding between adjacent buildings was common in the 2017 Mexico earthquake; however, visual inspection of this building indicates minimum clearances of at least 2 ft (0.6096 m) on each side, thus avoiding this damage type.

Figure 14: Exterior View

3.1.1.2 Code of Practice

The design code practice at the time of original construction was the 1976 Mexican code that included seismic provisions and a set of complementary technical requirements for the design and construction of Mexico's most common building materials (wood, masonry, concrete, and steel). In a summary of the Mexican building code history, Aguilar et. al (1996) states that after the 1985 earthquake an emergency code was published to assure that building repairs would be resilient in the future. Changes included:

- The seismic coefficients were increased to account for different soil conditions;
- The peak ground accelerations (PGA values) for soft soils were increased;
- The strength reduction factor for columns were decreased when ductility factor used was > 2;
- Minimum tied column dimensions were increased to 30 cm (11.81 in);
- Spacing between column ties was decreased;
- Distance of unrestrained longitudinal bars in columns was decreased to < 15 cm (5.91 in);
- Ties in a column required to be ≥ #3 bars;
- For flat slab designs 75% of the longitudinal reinforcement had to be embedded into the column;
- Live loads were doubled due to partial/full collapses in the 1985 earthquake due to overloading; and
- More stringent requirements were instituted for the design of foundation piles to limit differential settlement as well as other updated provisions on minimum separation between buildings, connection detailing, and construction.

3.1.1.3 Performance in 1985 Earthquake & Subsequent Retrofit/Repair

Aguilar et. al (1996) states that the damage in Tehuantepec 153 after the 1985 earthquake was concentrated in the masonry walls on all levels, mainly in the E-W direction. The unreinforced masonry walls, not being designed as part of the lateral force resisting system, saw the most damage in the structure. The E-W direction unreinforced masonry walls had seen damage to the plaster and several diagonal cracks were apparent. Most boundary elements adjacent to the masonry infill presented cracking and spalling of concrete cover. The concrete walls in the stairwell core showed severe cracking at all story levels. There was a local failure along the exterior unreinforced masonry wall on line A due to a cyclic rocking movement of the frame on line 2 perpendicular to the wall. The N-S direction experienced less damage due to the large continuous walls on lines A and C in Figure 12. There was no apparent pounding damage with adjacent buildings.

The retrofit repairs consisted of an overall strengthening of the lateral system. In the E-W direction, four reinforced concrete frames were added on lines 1-4 in Figure 12. The cross section of existing beams and columns were enlarged to increase strength and stiffness. Longitudinal and confinement reinforcement was added into the beams and columns to improve ductility. An analysis of the foundation deemed it adequate for demands of the new load path. Damage to the masonry walls were repaired with wire mesh and shotcrete on both faces of the walls. To reduce torsional effects due to the reentrant corner, the beams shown in Figure 12 were added on line A on floor levels 4 and 5 to provide additional torsional stiffness. The cracks found in the concrete walls around the stairwell core were epoxy injected. In addition, there were reinforced concrete walls added around the elevator to strengthen the building's lateral stiffness. To ensure that the retrofit be sufficient, the design was analyzed as a framed structure and this provided enough capacity for resisting lateral earthquake load. Additional details on the retrofit for Tehuantepec 153 can be found in the Aguilar et. al (1996) report.

3.1.1.4 Current Performance in 2017 Earthquake

The damage after the 2017 earthquake was, like the 1985 earthquake, concentrated primarily in the masonry walls on all levels. The unreinforced masonry saw moderate shear cracking and spalling, shown in Figure 15. There was no pounding damage with adjacent buildings. The frame of the structure appeared to have a ductile response based on the numerous flexural cracks in all first-floor columns shown in Figure 16. Through their exterior evaluation of the building, the reconnaissance team noted that the foundation had experienced uplift seen in Figure 17. Due to movement of the exterior masonry walls perpendicular to the reinforced concrete frame on line A, columns experienced significant cracking from the rocking motion of the building. Repeated rocking of the building – uplift and impact with the ground – resulted in significant cracking to the concrete columns. Specifically, there were flexural cracks at the top and bottom of N-S faces of columns indicative of plastic hinging. On the E-W faces there were flexural cracks on N-S faces and tension-shear cracks of columns highlighted in Figure 18 and 19. Further inspection of the columns yielded a typical crack width measurement of 0.30 mm (0.013 in) for columns on lines 2-4. Like in the 1985 earthquake, the N-S direction had a more ductile response due to the continuous walls on lines A and C in Figure 12.


Figure 15: Shear Cracks through Masonry Infill Walls and Beam


Figure 16: Column Damage Seen on Line 5 in Figure 12

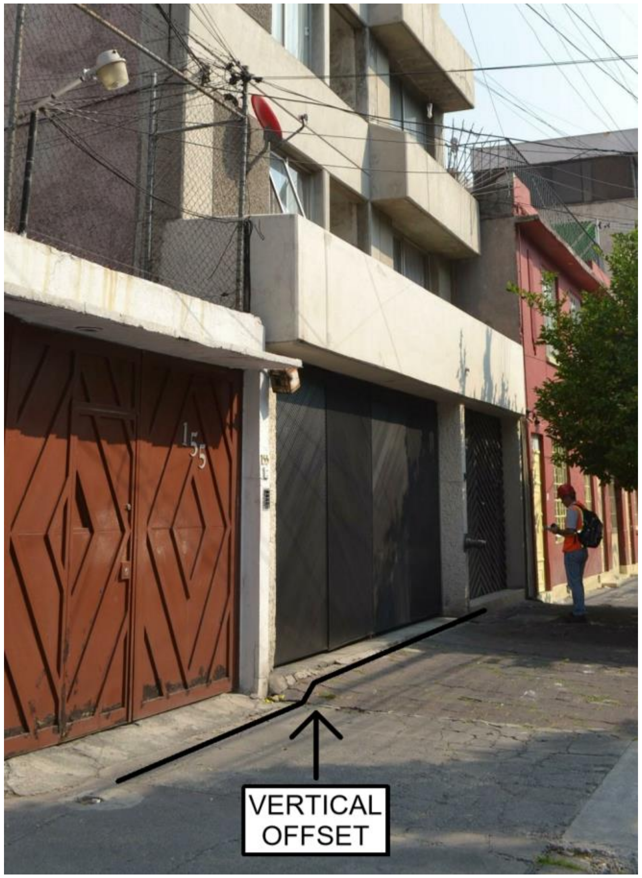


Figure 17: Vertical Offset of Foundation

Figure 18: Exposed Foundation Damage

Figure 19: Column Damage Seen on Lines 2, 3, and 4 in Figure 12

3.1.1.5 Lessons Learned

The team concluded that the overall performance of the building was ductile. This is significantly better than the building's performance in the 1985 earthquake, and is likely a result of generally increasing column strength by enlarging the column cross sections, adding in reinforced concrete walls and increasing the strength in both directions. Thus, the Tehuantepec 153 post-1985 retrofit proved largely a success.

3.1.2 Case 2, Rancho San Lorenzo 54: Vertical Irregularity – Soft Story

3.1.2.1 Building Description

Rancho San Lorenzo 54 (19.30926, -99.12563) is a 5-story building is located on Rancho San Lorenzo Street in the southern part of the Mexico City lake bed zone as shown in Figure 20. It was constructed in 1983 as a 5-story apartment complex building with parking on the first floor as seen in Figure 21. The buildings to the right and the left of Rancho San Lorenzo 54 are the same height and floor plan.

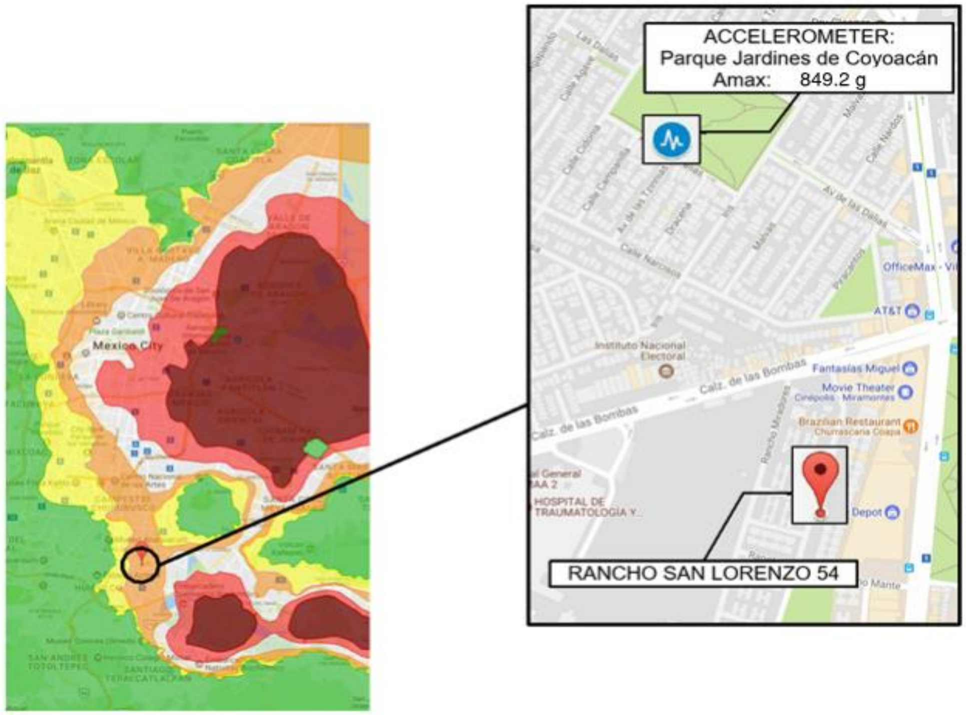


Figure 20: Location of Rancho San Lorenzo 54

Figure 21: Exterior View

The main lateral force resisting system is comprised of a reinforced concrete frame with unreinforced masonry infill walls. There was a section of the building in which the reconnaissance team did not have access to document or collect data as noted in Figure 22.

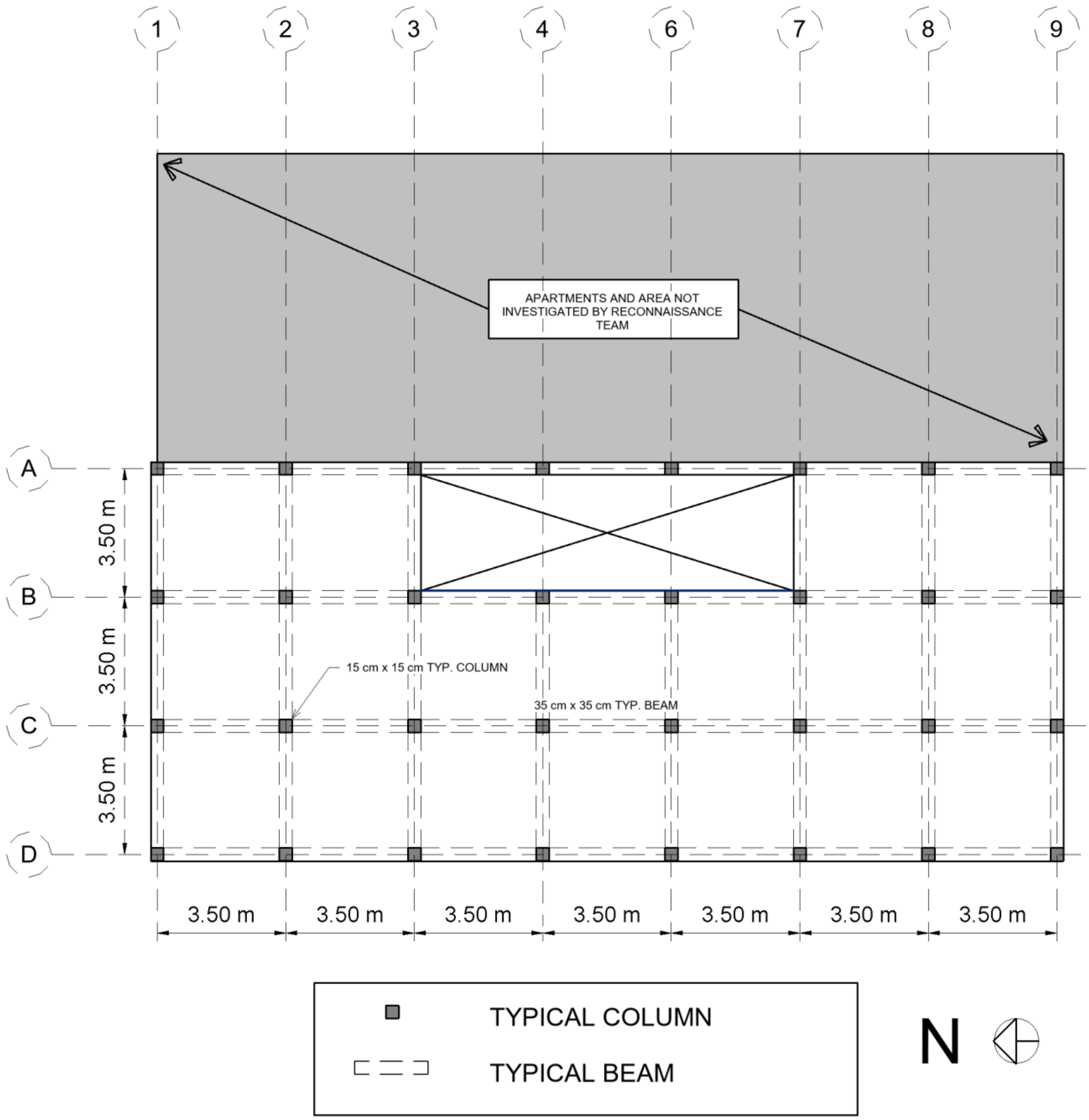


Figure 22: Sketch of Building Plan Level 1

The major vulnerabilities identified in this structure were vertical irregularity at the first floor and torsional irregularity located in the center of the floor plan. The vertical irregularity/soft story results from walls and columns that are terminated at the first floor (above the parking level) as shown in Figure 23. The full-height cutout in the center of the building creates a reentrant corner irregularity as shown in Figure 24.

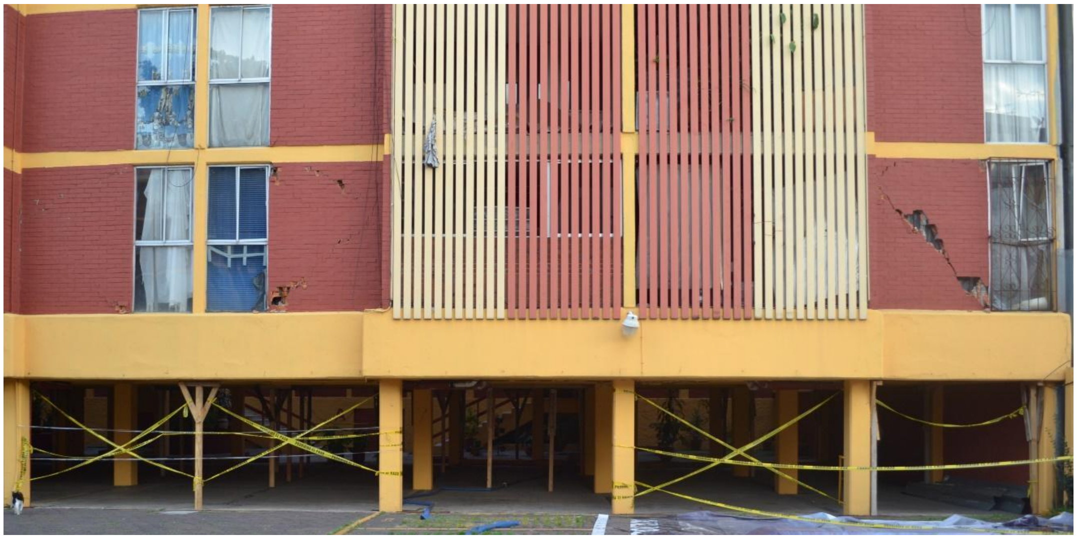


Figure 23: Exterior View of Soft Story Irregularity

Figure 24: Reentrant Corner Torsional Irregularity

3.1.2.2 Code of Practice

Refer to description in section 3.1.1.2.

3.1.2.3 Performance in 2017 Earthquake

The damage after the 2017 earthquake was concentrated primarily in the masonry walls on all levels as highlighted in Figure 25 and 26. There was no pounding damage with adjacent buildings that could be observed. The deep spandrel beams experienced spalling of concrete and the rebar was exposed as shown in Figure 27. In addition, the frame of the structure appeared to have shear cracking damage on the E-W faces of columns at the first-floor level, as seen in Figure 28. There was also shear damage to the columns on the outside frame at floor level 2 as seen in Figure 29. Further inspection of the columns on the first floor yielded a typical crack width measurement of 0.10 mm (0.004 in) for columns on lines 3, 6, and 8. These cracks were thought to have occurred due to the soft story irregularity and insufficient ties within the column. The overall performance of the building was poor. Visual inspection of one of the first-floor apartments led to the cataloging of severe masonry infill damage in the apartment walls as shown in Figure 25 and 26. Severe damage to all masonry walls and shear damage to columns has made the building unfit to occupy for the time being until a retrofit has been performed.

Figure 25: Shear Cracks through Masonry Infill Walls Exterior View

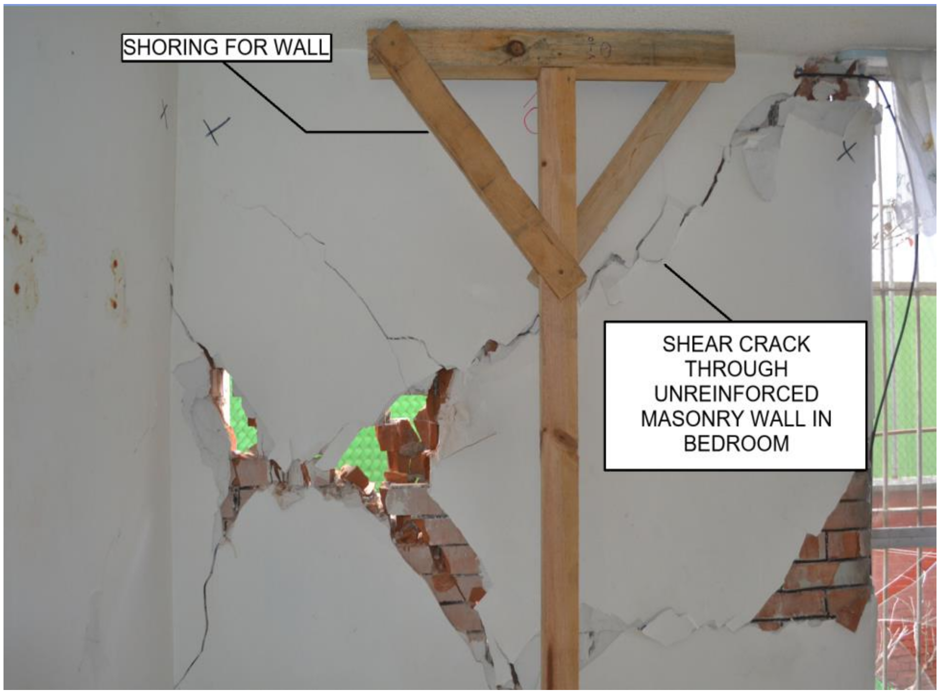


Figure 26: Shear Cracks through Masonry Infill Walls inside Apartment

Figure 27: Exposed Rebar from Concrete Spalling in Deep Spandrel Beam (Located on line A in Figure 12)

Figure 28: Shear Cracking on First Floor Columns

Figure 29: Shear Cracking in Columns (Typical on Exterior Line D)

3.1.2.4 Lessons Learned

The team concluded that the overall performance of Rancho de Lorenzo 54 was poor. The nonstructural damage to the masonry infill walls throughout the building was severe. The shear cracks on the columns observed make this building an unsafe structure. The primary lesson learned with Rancho de Lorenzo 54 is that a building with soft story and reentrant corner, can experience severe damage to the structure if not sufficiently designed.

3.1.3 Case 3, Avenida México 55: Torsional Irregularity – Reentrant Corner

3.1.3.1 Building Description

Avenida México 55 (19.41436, -99.16855) is a 10-story building located on Avenida México in the central part of the México City lake bed zone as shown in Figure 30. This building is on the corner of Calle Ladero and Avenida Mexico. This structure was located on the perimeter of the Parque México. It was constructed in 1979 as a 10-story apartment complex building with a small parking area on the first floor as seen in Figure 31.

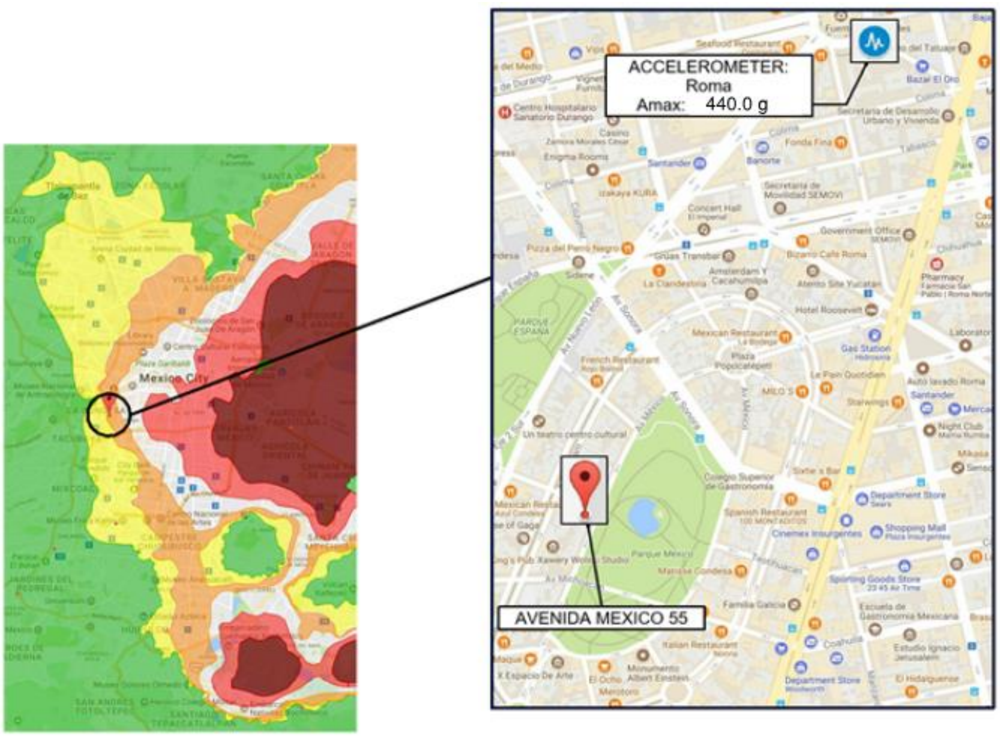


Figure 30: Location of Avenida México 55

Figure 31: Exterior View

The main lateral force resisting system is comprised of a reinforced concrete frame with unreinforced masonry infill walls. A concrete core around the stairwell and elevator provided additional lateral strength as shown in Figure 32.

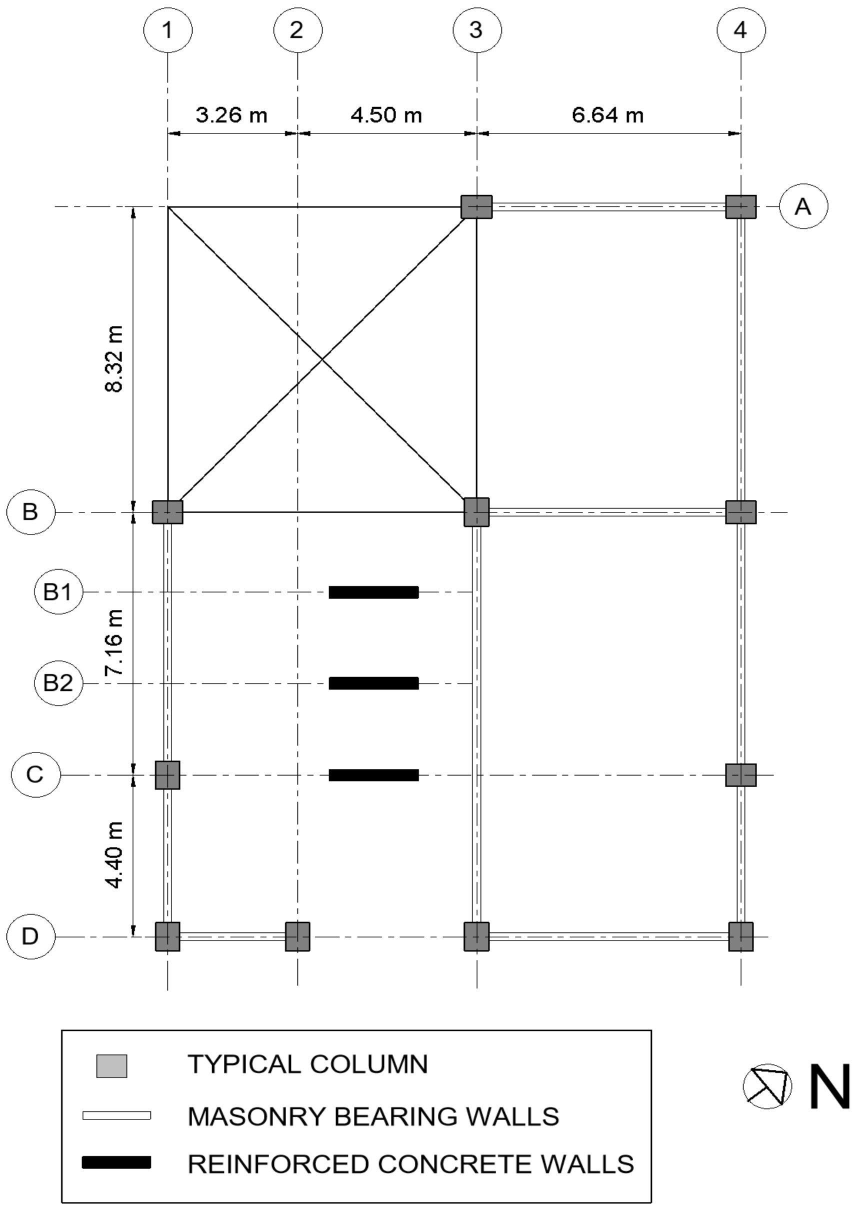


Figure 32: Sketch of Building Plan Level 1

The major vulnerabilities identified in this structure were vertical irregularity at the first floor and torsional irregularity continuous along height of the building. The vertical irregularity at the first floor is created by discontinuous walls and columns at the first floor in between lines 3 and 4 in Figure 32 that results in the soft story shown in Figure 33. The reentrant corner in the top left of the building's floor plan seen in Figure 36 creates a torsional irregularity.

Figure 33: Exterior View of Soft Story Irregularity

Figure 34: Reentrant Corner Torsional Irregularity

3.1.3.2 Code of Practice

Refer to description in section 3.1.1.2.

3.1.3.3 Performance in 1985 Earthquake & Subsequent Retrofit/Repair

The reconnaissance team interviewed the apartment owner who indicated that after the 1985 earthquake the only damage to the structure was to the concrete core in the center of the buildings – repaired by epoxy injecting all cracks.

3.1.3.4 Performance in 2017 Earthquake

The damage after the 2017 earthquake was concentrated primarily in the masonry walls on all levels as highlighted in Figure 35 and 36. This was a result of the epoxy injected concrete core being weakened from the previous 1985 earthquake. As shown in Figure 37, the epoxy injections were along significant lengths of the wall. With the concrete core weakened, the reinforced concrete frame experienced greater torsion and pounding forces from neighboring buildings as seen in Figure 38. The deep spandrel beams experienced shear cracking as highlighted in Figure 39. The frame of the structure saw a shear crack to the bottom column on line 3-D as shown in Figure 40. This shear crack was not present in the same column on 3rd or 5th floor. This shear crack formed due to the story forces being increased with the torsional movement of the frame. Visual inspection of 3rd and 5th floor apartments led to the cataloging of severe masonry infill damage in the apartment walls as seen in Figures 40 and 41. Severe damage to all masonry walls and shear damage to columns has made the building unfit to occupy for the time being until a retrofit has been performed. The overall performance of the building was poor.

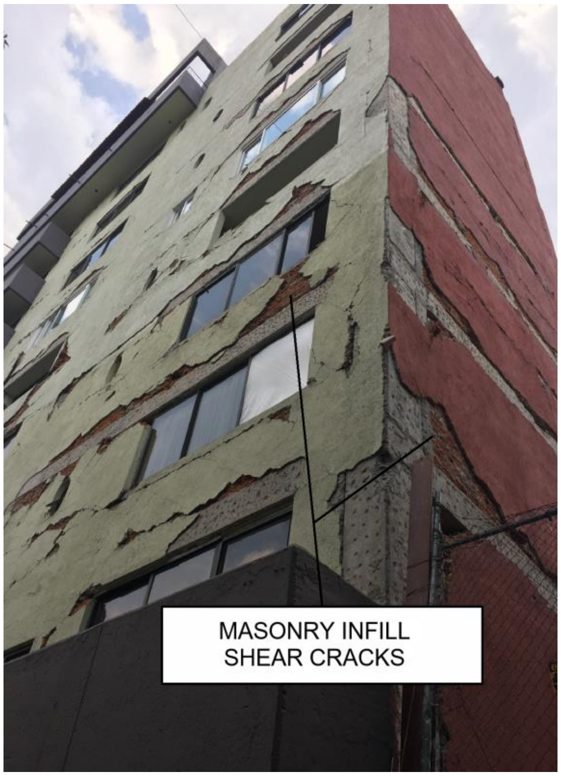


Figure 35: Masonry Infill Exterior Wall Damage (Line 1)

Figure 36: Masonry Infill Exterior Wall Damage (Line 3)

Figure 37: Epoxy Injections for Concrete Core (Line B1)

Figure 38: Pounding Damage (Line B)

Figure 39: Beam Cracking (Line B)

Figure 40: Column Shear Crack (Line 3-D)

Figure 41: Shear Cracks through Masonry Infill Walls in Kitchen 3rd Floor

Figure 42: Boundary Element Exposure due to Masonry Infill Wall Spalling in Bathroom 5th Floor

3.1.3.5 Lessons Learned

The team concluded that the overall performance of Avenida México 55 was poor. The nonstructural damage to the masonry infill walls throughout the building was severe. The shear crack on the column on line 3-D, highlighted in Figure 40, would need further investigation to determine if it affects the strength of the column. The amount of structural damage to the reinforced concrete frame observed suggests this building is an unsafe structure. The primary lesson learned with Avenida México 55 is that when designing a soft story with a reentrant corner, there will be severe damage to the structure if not sufficiently designed.

This case study was chosen because of the investigative teams' ability to enter the building and gain a better understanding of the structural as well as the non-structural damage on the interior of the building. Because this building is a corner building the torsional forces created a more intense level of damage than case study 2 where the building was restricted from rotations on both sides – having apartment complexes directly to the right and left of the case study.

4.0 Building Damage Analysis and Findings

4.0.1 Introduction to Damage Analysis

The following data analysis summarizes 118 buildings investigated by all teams collaborating on the National Science Foundation (NSF) rapid project – 68 buildings were visited and documented by the author and the remaining 50 were buildings visited by other teams.

4.0.1.1 Age Comparison

Figure 43 shows a total of 118 buildings investigated, the reconnaissance team was unable to determine the age of 37 buildings (31%) buildings. Of buildings with known age – 28 buildings (13%) were pre-1960, 55 buildings (38%) were 1970-80, and 8 (6%) were post-1980.

One consideration with the distribution of ages was the code used for the design of each building and how shortcomings in past codes could have led to observed damage. The introduction of general seismic design provisions was in 1976. And more detailed seismic provisions came after the 1985 earthquake. For more information regarding these seismic provisions refer to the description in section 3.1.1.2.

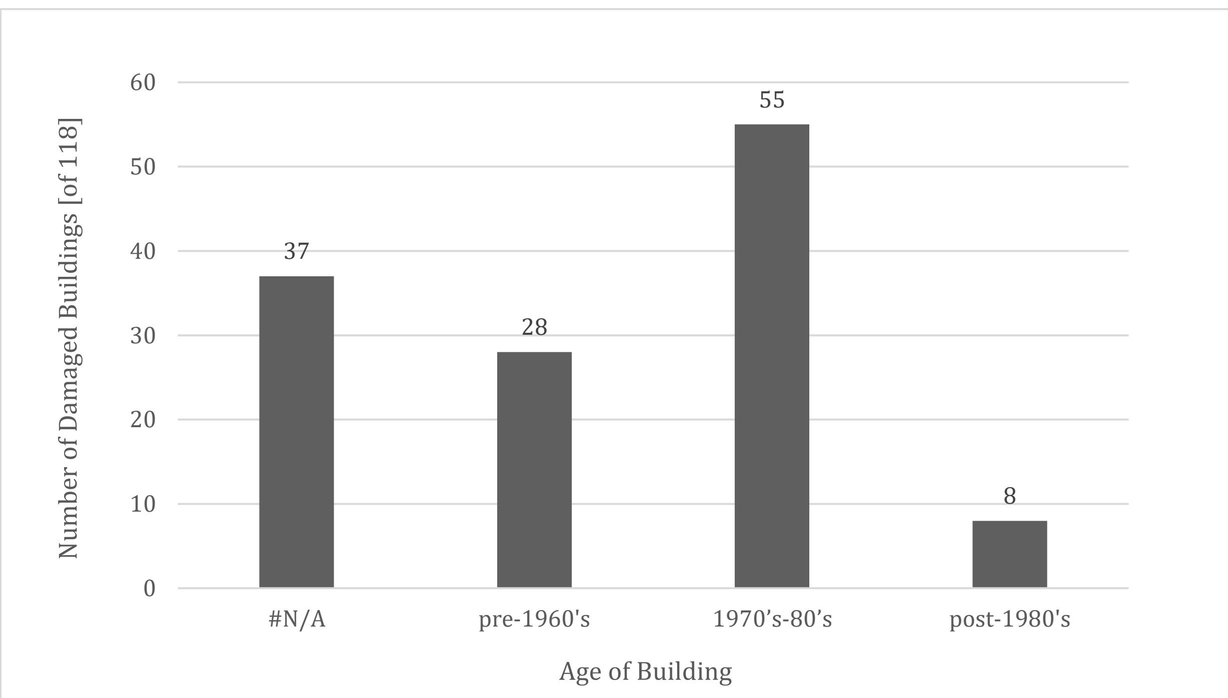


Figure 43: Age of Building Comparison

4.0.1.2 Number of Stories in Building Comparison

For the 118 buildings investigated the average height was 7-8 stories. The reconnaissance teams often had to estimate the below-ground levels of the building. Figure 44 shows a total of 118 buildings investigated. Of buildings investigated 29 (24.5%) buildings were ≤ 4 stories, 51 (43%) buildings were 5-8 stories, 26 (22%) buildings were 9-12 stories, and 11 (9%) buildings were > 12 stories.

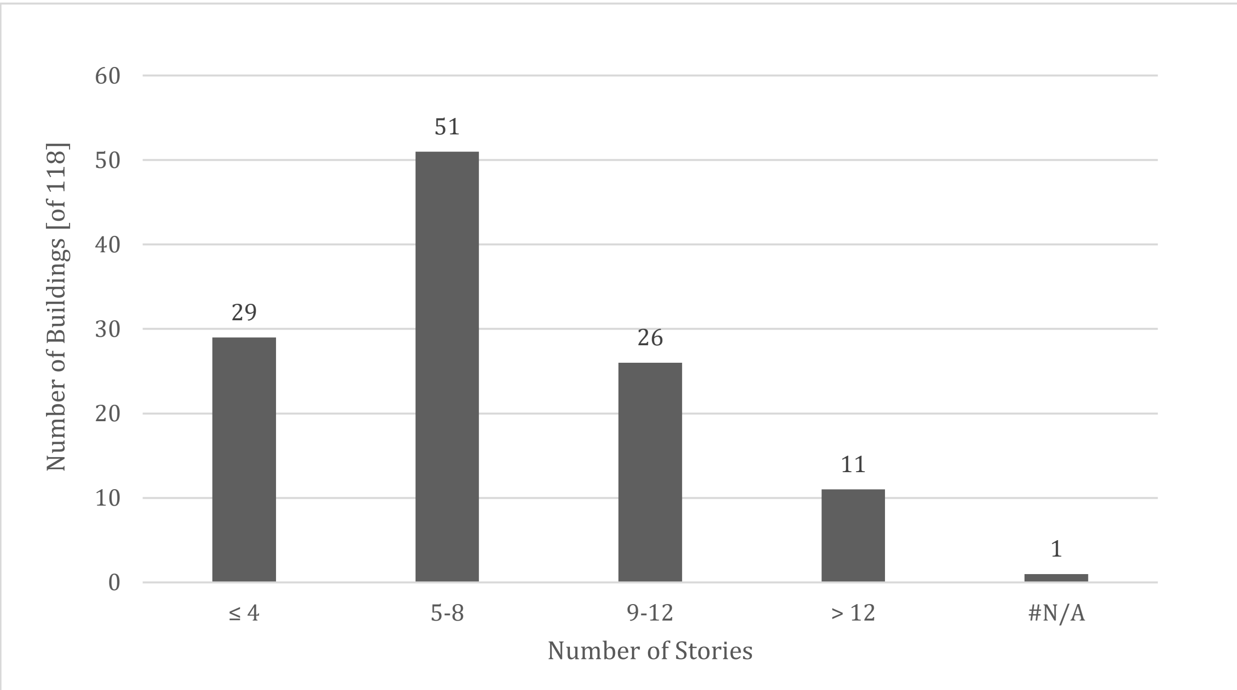


Figure 44: Story Height of Buildings

4.0.1.3 Irregularities Comparison

The most common types of irregularities within the buildings investigated were soft stories, vertical irregularities, captive columns, discontinuities, torsional irregularities, and corner building damage. On occasion, the reconnaissance team was unable to enter buildings, in which case damage is based on the best knowledge due to access to the buildings. There were 37 (31%) buildings that had damage due to having soft stories, 9 (7.5%) buildings that had damage due to having vertical irregularities, 24 (20%) buildings that had damage due to having captive columns, 7 (6%) buildings that had damage due to having a discontinuity, 8 (7%) buildings that had damage due to having torsional irregularities, and 29 (24.5%) buildings that had damage due to being a corner building. Figure 45 shows the irregularities found in the buildings investigated.

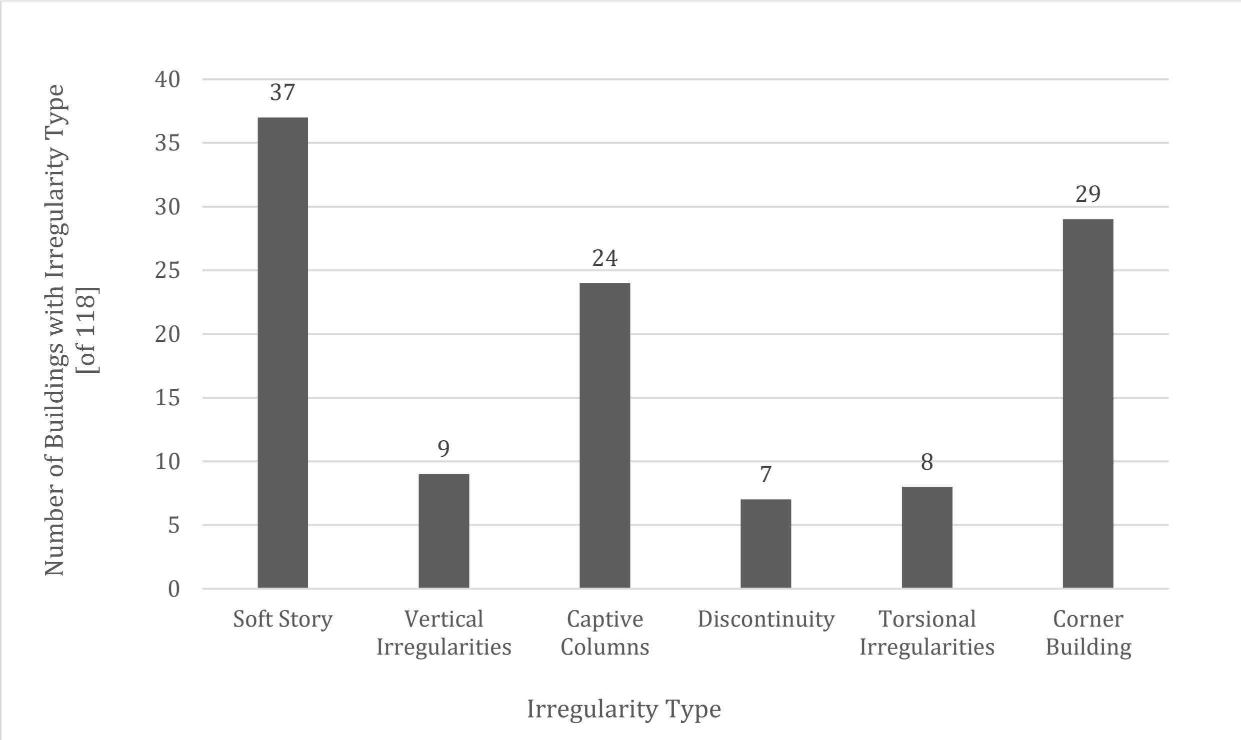


Figure 45: Irregularity Type Comparison

4.0.1.4 Comparison of Damage Type and Damage Severity

Types of failures documented were splice failure, crushing, buckling, pounding, shear failure, and joint failure. In Figure 46 there were 118 buildings investigated of those 38 (32%) buildings experienced shear failure, 14 (12%) crushing failure, 13 (11%) buckling failure, 10 (8.5%) pounding failure, 7 (6%) splice failure, and 5 (4%) joint failure.

With respect to the damage levels of the buildings seen, many saw severe damage in both N-S and E-W directions in both masonry infill and the reinforced concrete frame or wall systems. When the reconnaissance team investigated each site, the level of damage was described in three distinct categories: severe, moderate, and light:

- In reinforced concrete structures it is considered severe damage if there are visible local structural failures to the structure.
- In masonry infill walls it is considered severe damage if there are wide and through cracks in walls and joints between panels.
- In reinforced concrete structures it is considered moderate damage if there is spalling occurring within the structure.
- In masonry infill walls it is considered moderate damage if there are cracks in walls and joints between panels and/or flaking of large pieces of plaster.

- In reinforced concrete structures it is considered light damage if there are only hairline inclined cracks and/or flexural cracks within the reinforced concrete structure.
- In masonry infill walls it is considered light damage if there are hairline cracks and minimal flaking of plaster.

In Figure 47, of the 118 buildings investigated 75 (63.5%) buildings had severe reinforced concrete damage, 76 (64%) buildings had severe masonry infill damage, 13 (11%) buildings had moderate reinforced concrete damage, 24 (20%) buildings had moderate masonry infill damage, 22 (18.5%) buildings had light reinforced concrete damage, 18 (15%) buildings had light masonry infill damage, 58 (64%) buildings had no reinforced concrete damage, and 47 (40%) buildings had no masonry infill damage. The aforementioned damage occurs in either or both cardinal directions (N-S and/or E-W).

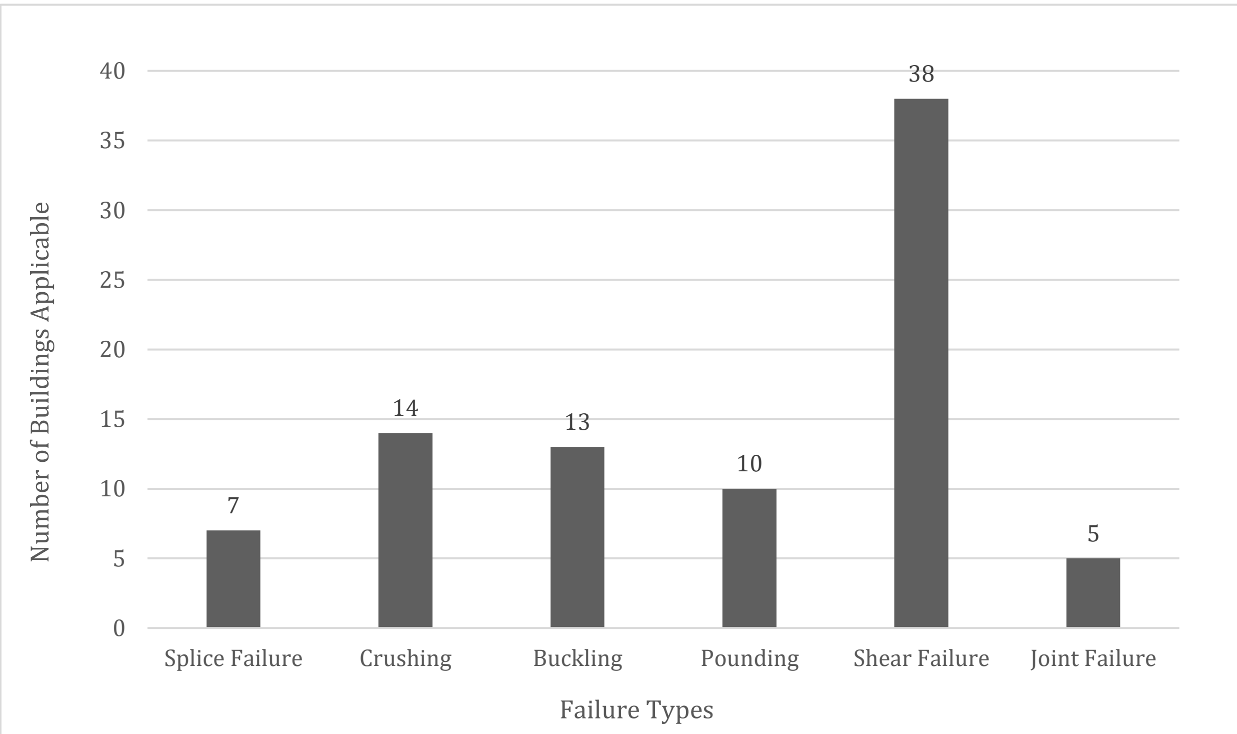


Figure 46: Failures Documented Comparison

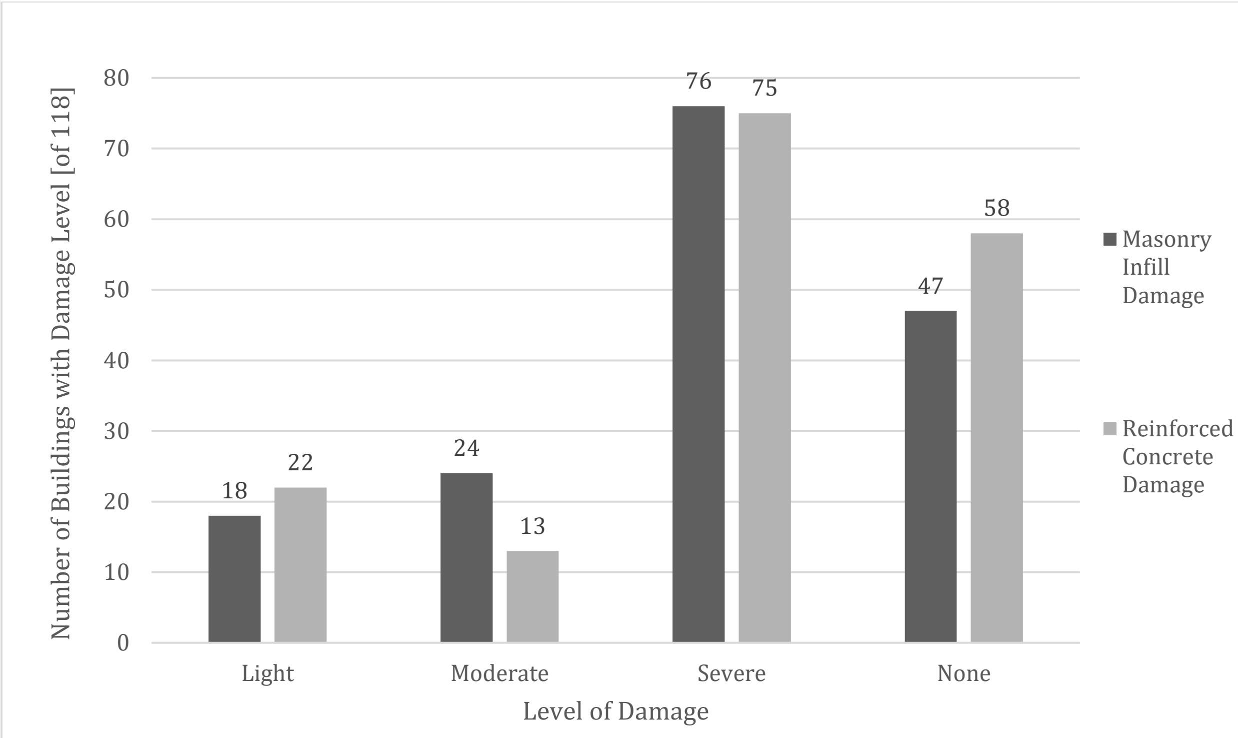


Figure 47: Damage Levels Comparison

5.0 Conclusions

The data analysis in Chapter 4 is – age of building, number of stories, irregularities investigated in the structure, damage levels/failures seen after the 2017 earthquake, and 1985 earthquake investigations.

Of the 118 buildings investigated, the most common ages of buildings were found built in the years 1970-1980. This is important to note as the buildings were designed and built before the 1985 benchmark code. Refer to the description in section 3.1.1.2 for further details regarding the 1985 code updates. Many of the damages and failures seen in these buildings were due to poor detailing and design irregularities in the structure as the older codes had very little information regarding seismic design or detailing. The most common damage pattern observed by the author was reinforced concrete shear failure – a brittle damage type often due to a lack of proper detailing. The key issues seen in the quantitative data for the investigated buildings – primarily soft stories, captive columns, and corner buildings – stem from a pattern of irregularities.

The major lessons learned from the reconnaissance experience and data analysis were how damaging irregularities in a structure can be when poorly designed; as well as the impact code benchmarks have in the development of structural engineering. These findings highlight how additional investigation in the areas of sustainable and economical retrofit strategies particularly for soft story structures retrofitting is needed to ensure better structural performance and improve community resilience for earthquake hazards in the future. Additionally the results from the 2017 Puebla earthquake indicate that solutions for unreinforced masonry need to be further developed for areas of the world where unreinforced masonry is the most common building type.

6.0 Acknowledgments

This project was a result of funding of a National Science Foundation (NSF) Rapid Grant #1811084. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

The team participating in the earthquake reconnaissance work consisted of Garrett Hagen – Design Engineer at Degenkolb Engineers, Sergio Breña – Professor at University of Massachusetts-Amherst, Michael Kreger – Chair & Professor at University of Alabama, Mario Rodriguez – Professor at Universidad Nacional Autónoma de Mexico (UNAM), and Shane Crawford – Doctoral Student at University of Alabama. The research work was supervised by Dr. Anahid Behrouzi – Assistant Professor at California Polytechnic State University, San Luis Obispo.

7.0 References

Aguilar, J., Breña, S., Del Valle, E., Iglesias, J., Picado, M., Jara, M. and Jirsa, J. (1996). *Rehabilitation of Existing Reinforced Concrete Buildings in Mexico City*. 1st ed. Austin, Texas: Ferguson Structural Engineering Laboratory.

Arroyo D., Ordaz M., Ovando-Shelley E., Guasch J., Lermo J., Perez C., Alcantara L., Ramírez-Centeno M. (2013). Evaluation of the change in dominant periods in the lake-bed zone of Mexico City produced by ground subsidence through the use of site amplification factors. *Soil Dynamics and Earthquake Engineering*, Elsevier, 44, 54-66.

Hutchinson (2017). "Geotechnical Impacts of the Sept 19,2017 Puebla-Mexico City Earthquake." Presentation.

Maps, M. (2018). *Mexico-Surveyed Bldgs – Google My Maps*. [online] Google My Maps. Available at: https://www.google.com/maps/d/u/0/viewer?mid= 1ySmFCwRv1nRzpkQwzBJS-DtQRPU&ll=19.37284421112858%2C-98.97269455056914&z=11 [Accessed 28 Mar. 2018].

Mayoral, J.M., M.P. Romo, L. Osorio. (2008). Seismic parameters characterization at Texcoco lake, Mexico. *Soil Dynamics and Earthquake Engineering, Elsevier*, 28(7), 507-521.

Mayoral, J.M., E. Castañon, L. Alcántara, S. Tepalcapa. (2017). Seismic response characterization of high plasticity clays. *Soil Dynamics and Earthquake Engineering*, Elsevier, 84, 174-189.

Mayoral, J., Hutchinson, T., Franke, K., Alcaraz, M., Arduino, P. and Asimaki, D. (2017). *Geotechnical Engineering Reconnaissance of the 19 September 2017 Mw 7.1 Puebla-Mexico City Earthquake.* 1st ed. [pdf] Geo technical Extreme Events Reconnaissance Association. Available at: http://learningfromearthquakes.org/2017-09-19-puebla-mexico/images/2017_09_19_Puebla_Mexico/pdfs/Geo-Reconnaissance-of-19-sept-2017-Mw-7.1-eq-v1.pdf [Accessed 29 Mar. 2018].

Spence, R. (1986). *The Mexican Earthquake of 19th September 1985.* Society for Earthquakes and Civil Engineering Dynamics (SECED). EEFIT, 1986. [online]. http://www.istructe.org/webtest/files/7f/7f000f69-45a1-4d9f-a479-ef5ef668fc2a.pdf

Tellez, M., Angulo, E. and Schroeder, M. (2005). *Accelerograms for building design for hard soil in Mexico City*. 81st ed. Mexico City: WIT Press.

USGS (2017). Executive Summary of M7.1 - 0 km NE of Ayutla, Mexico. Retrieved from https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20#executive. Last accessed on October 3, 2017.

USGS (2018). "M 8.0 - Michoacan, Mexico." (2018). Earthquake.usgs.gov, <https://earthquake.usgs.gov/earthquakes/eventpage/usp0002jwe#executive> (Aug. 20, 2018).

Appendix A:

Reconnaissance Blog

CAL POLY

Mexico City Reconnaissance

Rachel Chandler's Mexico City Reconnaissance Journal

Fourth-year undergraduate ARCE student Rachel Chandler is traveling to Mexico City to perform earthquake reconnaissance work from October 28 – November 4, 2017. There she will examine damaged structures after the recent 7.1 earthquake. Her personal accounts throughout the week will be recorded here on a day by day basis.

The journey began in early October 2017 when assistant professor Anahid Behrouzi was asked by Purdue professor Santiago Pujol to collaborate in a National Science Foundation (NSF) RAPID grant. The objective was to send a team to study reinforced concrete building damage in Mexico after the recent September earthquakes. After continuous communication between the teams at Purdue, Cal Poly, University of Alabama, University of Buffalo, UC-San Diego, and the NSF Programs manager, the project recieved pre-approval and the reconnaissance was in full swing!

Dr. Behrouzi notified Rachel Chandler of the opportunity and without a second thought she was on-board for a prospective date to ship out to Mexico City on October 28, 2017, for a week. With dreams of becoming an engineer that supports seismic design and natural disaster recovery in developing nations, Rachel knew this could be a career game-changer. By the end of the day she had made arrangements with all her professors and on-campus employer to carve out time for reconnaissance. Preparing to take time away from campus during Week 7 of the strenuous ARCE senior schedule is no small feat.

A busy week passed of procuring documents for an expedited travel approval from the International Studies office; gathering and purchasing reconnaissance tools; booking flights, shuttles, and hotel; securing a mentor – Degenkolb design engineer and Cal Poly alumni, Garrett Hagen- to accompany her into the field.

Below are her accounts of the process including her observations of reinforced concrete damage, community recovery, and cultural experiences.

In particular, thanks go to all of Rachel's on-the-ground reconnaissance mentors and team collaborators:

- Garrett Hagen, Design Engineer at Degenkolb Engineers
- Sergio Breña, Professor at University of Massachusetts-Amherst
- Michael Kreger, Chair & Professor at University of Alabama
- Mario Rodriguez, Professor at Universidad Nacional Autónama de México (UNAM)
- Shane Crawford, Doctoral Student at University of Alabama

We'd like to give a huge shout-out to everyone at Cal Poly. Thank you International Studies Office (Cari Vanderkar Moore and Azucena Perez) and Cal Poly Grants Office (Trish Brock and Susanne Gartner), as well as Al Estes, Mark Cabrinha, Erika Clements, Adriana Sousa for your help!

CAL POLY

Day 1: Arrival in Mexico City

The Journey Begins

OCTOBER 27-28, 2017

Around 4:15 pm on Friday October 27th, Rachel left San Luis Obispo to catch a shuttle at the Santa Maria Airport and then was onto to Los Angeles. After a brief stay-over with her family, she will fly out from LAX on Saturday morning to the Benito Juarez Airport in Mexico.

In hand for plane reading as she prepares for her first reconnaissance mission:

•ATC 20 a field manual on post-earthquake building evaluation

•ATC 78 discussing behavior of older non-ductile concrete buildings

•PMFSEL 96-3 describing retrofits to concrete buildings after the 1985 Mexico Earthquake

Traveling, Tacos, and Earthquakes

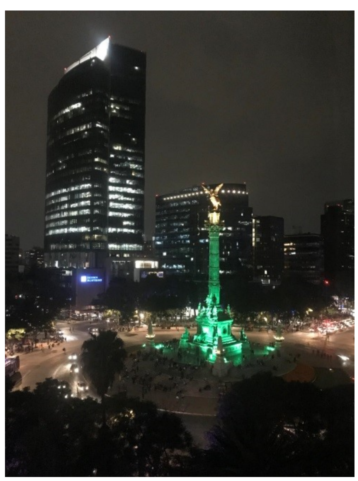
Saturday morning started with a 10 a.m. flight from LAX, nearly four and a half hours later I was through customs and on a shuttle to the hotel. The ride gave me a broader view of the building types in Mexico City and the tightly spaced construction reminded me of downtown Los Angeles where land is valuable. Many buildings had aged masonry walls (presumably unreinforced); however, being one story buildings they did not appear to have significant exterior structural damage, only deterioration due to weathering. I found it interesting that these buildings had giant car hoods and parts stored on their roofs. That was a new sight for me, certainly not a roof load you would consider in our ARCE design

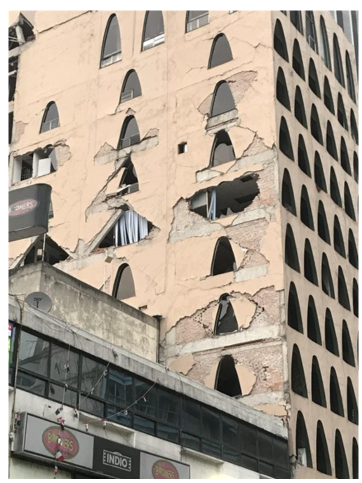
Arriving to the Sheraton Mexico City Maria Isabel Hotel, I settled into my room to find a great view from my window of El Ángel monument on Paseo de la Reforma, the main avenue that runs through the heart of Mexico City. After a short break, I met civil engineering professor Sergio Breña from UMass-Amherst for a dinner of authentic Mexican tacos and Queso con Chorizo (heavenly compared even to Southern Californian standards), during which we discussed the plan for tomorrow. Dr. Breña is one of the engineers that examined many buildings after the 1985 Mexico Earthquake and, for him, this trip is an opportunity to re-evaluate some of the same structures and compare their response to last month's earthquake.

My first in-the-field lesson from Dr. Breña took place on our walk between the hotel and the restaurant when he pointed out a water tank on a roof that had started to tip over and create stress cracks along the building. For the same structure, there were cracks along masonry partitions which seem to follow the diagonal braces as well as other cracking at the interface of beams and columns. While we did not go inside the building today, perhaps we will later in the week.

When it comes to reconnaissance, Dr. Breña says it takes lots of patience and a small team to navigate through the bustling Mexico City traffic. We will be leaving early tomorrow morning to get a start on work, and around noon expect to be joined by my primary mentor, Cal Poly ARCE alum Garrett Hagen from Degenkolb. I am extremely excited to be working in the field and learning alongside two very intelligent and gifted engineers.

So far I have seen the airport, the downtown street life, a damaged water tank, and the inside of a small Mexican restaurant. All to which, I am pleased to report, have exceeded my expectations in terms of the beginning of one great adventure.





CONNECT WITH CAL POLY

CAL POLY

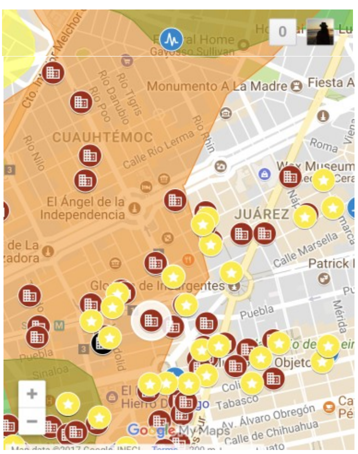
Day 2: Initial Wanderings and Observations

Initial Structural Damage Observations and Social Discoveries

OCTOBER 29, 2017

Today I woke up at 7 a.m. to the sound of loud Mexican music coming from the plaza outside my window. Not long after, I went down to the hotel lobby to meet up with Dr. Breña and our local host, Dr. Mario Rodriguez from Universidad Nacional Autónoma de México (UNAM). Dr. Rodriguez shared his theories about damage to buildings that experienced both the 1985 and 2017 earthquakes.

We then navigated our way through the blocks of downtown Mexico City towards the concentration of damaged buildings shown in the annotated map (near Av. México and Ámsterdam). The red markers are buildings that have not yet been investigated, yellow markers have already been investigated, and black markers indicate collapses. Today we would focus on the red markers.



ABOVE: MAP OF EARTHQUAKE INVESTIGATION SITES

Much of the external damage to buildings was horizontal and diagonal cracking to unreinforced masonry infill, clearly visible in the images shown below (top row). Another common damage type was spalling along beams and columns that were subjected to significant stresses during the earthquake shown below (bottom row). Further investigation will be necessary to determine if repairs could be made using epoxy injection of cracks or strengthening of column members via jacketing.

CRACKING TO MASONARY INFILL(LEFT) AND CRACKING AND SPALLING OF BEAMS/COLUMNS(RIGHT)

This is about the time that Garrett Hagen joined up with us, and all stopped for a lunch of pollo con mango seasoning. At home, I am a practicing vegan, but I did not want to miss out on experiencing the culture during my travels.

The afternoon allowed me to practice my Spanish, as it turns out many locals like to tell their story and voice their concerns about the buildings they live in to a team of knowledgeable engineers. Some were even kind enough to let us into their homes or apartments to take notes of damage to interior columns and shear walls.

A case I found in particularly interesting was 55 Av. México where one side of the building had hardly any external damage, but the perpendicular side had masonry infill cracking at nearly every floor and plaster was spalling off in large sections. From the interior courtyard we also observed the causes of the irregular soft story suffered by this building: a reentrant corner and a large span without a continuous column to the foundation. This building had been rehabilitated after the 1985 earthquake with epoxy crack injections to the concrete core wall surrounding the stairwell at the center of the building. Last month's earthquake led to weakening of this wall system resulting in additional lateral and torsional demands on exterior columns. As an outcome, the front center column exhibits shear cracking at the ground level of structure, but we did not observe distress as we traced the column up to the third through fifth floors. It is likely damage is concentrated at the base of the structure due to the combined story forces which result in a significant base shear at the bottom floor.


55 AV. MÉXICO: UNDAMAGED VS. DAMAGED FACES OF THE BUILDING


LEFT: 55 AVE. MEXICO: CONCRETE CORE WALL SURROUNDING STAIRWELL (DARKER AREAS INDICATE POXY ADDDED AFTER 1985 EARTHQUAKE)

RIGHT: SHEAR CRACKING TO COLUMN AT BOTTOM LEVEL

During the course of our work today, I witnessed a Día de Los Muertos procession attended by many with painted faces and traditional attire. This event serves as a remembrance of those who have since passed on, including those from the recent earthquake. A park near our hotel also had giant skulls adorning the walkways for this special occasion.

CAL POLY

Day 3: Successful Retrofitting following 1985 Earthquake & Lessons on Cracks

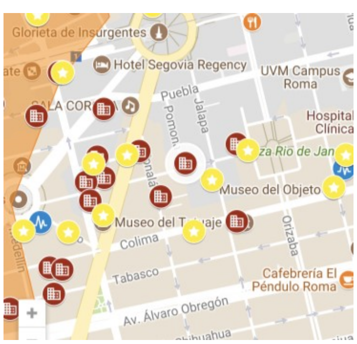
Successful Retrofitting & Lessons on Cracking

OCTOBER 30, 2017

Today we focused our efforts on a different area of Mexico City, near Colima and Calle de Durango (shown in the map below). One of our goals was to investigate retrofitted concrete buildings that Dr. Breña had previously investigated after the 1985 Mexico earthquake.

Halfway through the day we were joined by one of Dr. Breña's former students, Alex, who lives in the vicinity. He explained that after last month's earthquakes the task of assessing damage and tagging buildings fell to local architects, including university students. These investigators were instructed to tag damage based off crack width/extent which led to over-tagging damage.

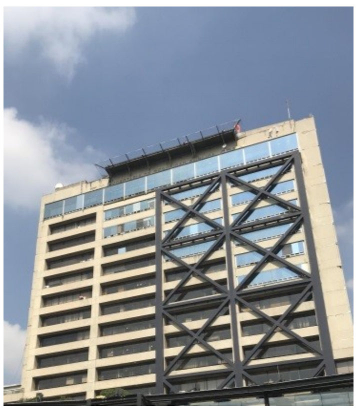
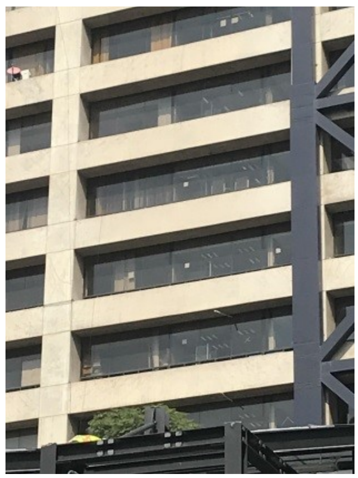
The rest of this blog post will discuss two case study buildings that had been retrofitted since the 1985 earthquake as well as lessons I learned about different crack patterns in concrete structures.



ABOVE: MAP OF REINFORCED CONCRETE BUILDINGS

How did the retrofitted buildings perform?

The first retrofitted building we investigated was the local police station which performed rather well with the addition of external steel bracing (shown in the images below). Still, the interaction between the original concrete structure and steel frame was apparent in hairline cracking in concrete beams/ columns where steel bracing was introduced. Based on our observations, we concluded that: (1) the location of more numerous or wider concrete cracks in the columns indicated which member (beams vs. columns) controlled in the concrete system, and that (2) connections between the concrete and steel systems at every other floor created a collector in the concrete beam on the intermediate story that was not tied into the steel bracing (as evidenced with the lack of visible cracking in these beams).

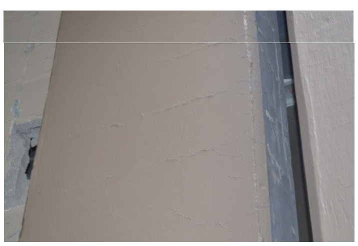
LOCAL POLICE OFFICE: RETROFIT WITH EXTERNAL STEEL FRAME

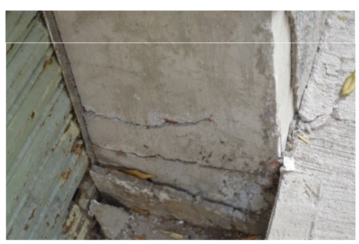
We also visited a local hospital building retrofitted with the addition of steel rods/anchorages for the beams up to the 6th floor and widening of columns to result in strong column behavior, per the strong column-weak beam seismic design approach. In the images shown below, the thin line (highlighted in red) are the steel rods and the end anchorage of these rods are housed in square box (highlighted in yellow) on the exterior face of columns. This building performed exceptionally well. The on-duty security guard informed us that during the earthquake there was some shaking of the building and slight uplift in the foundation shifting; however, overall the columns exhibited no visible signs of damage. This was probably the most successful retrofit seen today.

ABOVE: PERFORMANCE OF STEEL ROD/ANCHORAGE RETROFIT BETWEEN BEAMS AND COLUMNS (LEFT) & SLIGHT UPLIFT OF FOUNDATION (RIGHT)

What do different types of cracking mean?

Today's major lesson was what different cracking patterns can reveal about a damaged member. Typically, horizontal hairline cracks on a column result from tension or elongation due to building rocking or tilting. However, in some instances these cracks may just be movement or expansion of paint/plaster which requires further investigation to determine if the underlying concrete member experienced structural damage. Vertical cracking along a column can be an indicator that there is insufficient vertical reinforcement and that some movement in that direction has occurred. Diagonal cracking in columns is most likely a sign of shear failure, but again this can be misleading as cracks may only appear in the paint/plaster and be non-structural in nature.





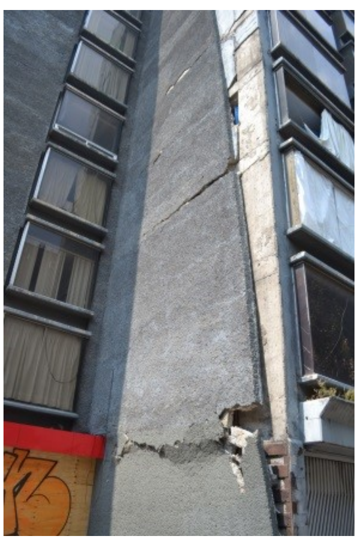
EXAMPLES OF COLUMN DAMAGE : CONCRETE CRACKING AND SPALLING

Beam cracking is slightly different. Horizontal cracking can provide insight into the load path for a concrete frame system: cracks along the length of beam may continue through the column-beam connection into the adjacent column and down to the foundation. Vertical cracks in beams generally result from bending due to flexural demands, while diagonal cracks are indicative of significant shear demand. Cracks that are initially vertical and become inclined suggest a combined shear-flexure response. Similar to column cracking, beams covered in paint/plaster that exhibit visible cracking may be non-structural with limited-to-no damage of the underlying concrete member, or they can be critical.

Additionally, a crack can be pre-existing from a past earthquake, these are normally epoxied and painted over. The following images show the difference between a large pre-existing crack that has been epoxy injected (left) and new crack which occurred on a similar wall (right, note black dots placed along crack).

EXAMPLES OF PRE-EXISTING EPOXY INJECTED CRACKS AND NEW CRACKS

Many buildings we have seen in the Mexico City area have a concrete frame system with unreinforced masonry (URM) infill. Significant failures of URM components are easy to distinguish as the plaster finish usually has significant cracking or has completely detached and is falling from the building. Concrete components tend to fare better because they have a more ductile response, such that they can carry significant loads at greater deformation demands than brittle URM walls. The images below illustrate an example of structural damage to concrete wall with exposed rebar (left), and non-structural damage to a cracked URM infill wall (right).



EXAMPLES OF DAMAGE TO CONCRETE WALL (LEFT) AND URM INFILL WALL (RIGHT)

CAL POLY

Day 4: Journeying Further South

Journeying Further South

OCTOBER 31, 2017

Today the team headed further south towards the center of the lake bed area. Yes, as it turns out Mexico City was once a lake in some areas! The surrounding rocky terrain slopes downward towards the city center and there are many subterranean rivers and canals that run in this direction. The neighborhood we visited today had a river flowing nearby and buildings in this area experienced significant structural damage; however, in some cases this damage is simply an indicator of ductile performance – a desired response from a seismic design perspective.

CHARACTERISTIC EXAMPLES OF CONCRETE DAMAGE

A building of particular interest was Tehuantepec 153. In one of his reports from the mid-1990s, Dr. Breña had documented its retrofits which consisted of the addition of an entire new concrete frame system. There were numerous cracks on both faces of most columns along the perimeter of the frame system. Upon further investigation, the cracks on the column faces in the east-west direction were concentrated at column ends to form a hinge-type mechanism. The opposite column faces exhibited uniformly distributed, horizontal flexural cracks which was likely due to the rocking or tilting of the building tower above these first-floor level columns. The photographs below show hinging at the base of the column (left), and distributed cracking along the full length of the column (right).


TEHUANTEPEC 153: VARIATION OF COLUMN CRACK PATTERNS BASED ON DIRECTION OF LOADING

During the investigation of Tehuantepec 153, we also observed exposed what appears to be a pile cap foundation underneath the previously described first-floor level column.


TEHUANTEPEC 153: FIRST-FLOOR COLUMN AND UNDERLYING EXPOSED FOUNDATION SYSTEM

We were very grateful to the gentleman who gave us a tour of the inside of his own apartment in the building to investigate interior damage(pictured left).

Further down the street, we came upon Manzanillo 114. While this building was not noted as damaged in our database, we happened to look through the window and notice shear cracking on an interior column. We were fortunate to meet with the apartment complex owner. He, along with several other residents, was able to share his account of being in the building during the earthquake. Further investigation of the property indicated that nearly all of the first-floor columns inside the garage had one column face with flexural hinging at both ends (below left), and the other face starting to show signs of shear cracking (below right). Other than crack pattern, an important metric that we collect is crack width using a crack width gage (below center). We also observed pounding damage from interaction with neighboring buildings. Our discussions with building residences led us to conclude that pounding against the adjacent buildings caused the shear cracks in the columns. Unfortunately, the issue of pounding noted at Mazanillo 114 was not an isolated case. In the area we were investigating today, many buildings were constructed on small land parcels and in close proximity to adjacent structures, resulting in structural damage when these buildings impacted each other during ground shaking.



MANZANILLO 114: (LEFT) COLUMN HINGING AT ENDS, (CENTER) SHEAR CRACKING, (RIGHT) COLLECTING CRACK WIDTH DATA(0.30MM)

As Día de los Muertos continues, more decorations and costumes appear in the city streets. The photograph below is a mural dedicated to the holiday.

CONNECT WITH CAL POLY

CAL POLY

Day 5: Damage Everywhere

Pounding Structural Damage and Dia de Los Muertos

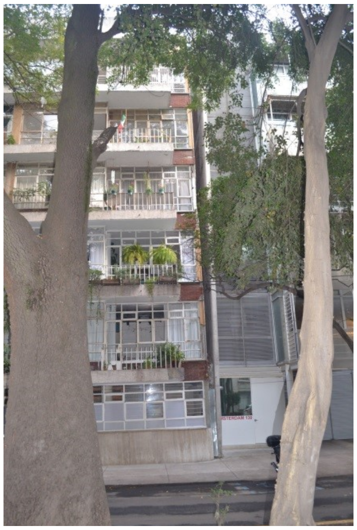
NOVEMBER 1, 2017

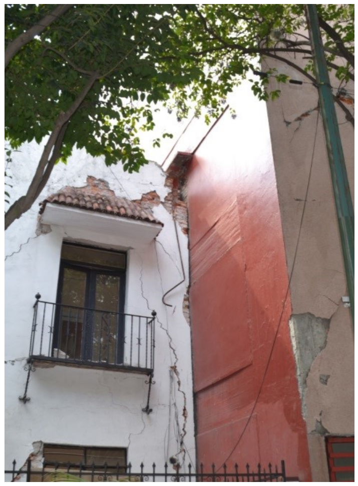
Today was a bit of a transition day for our reconnaissance team. Joining our team was Professor Mike Kreger from the University of Alabama and his graduate student Shane. Also, it was the last full day with Cal Poly alum Garrett Haggen from Degenkolb. We decided to revisit the Condesa neighborhood, the location of one of the main concentrations of building damage in the city, to show the new team members previous structures we had visited from my first day of reconnaissance work. Along the way we encountered buildings we had not investigated before, and were able to make new observations related to pounding between adjacent structures.

Lessons Learned about Pounding between Buildings

Pounding damage results from interaction between two more buildings located next to one another. These can be buildings of the same or uneven heights where they tilt into or impact each other during the earthquake ground motion. For buildings of uneven heights, we noted instances of pounding damage to the shorter structure, and more extreme cases where the taller slender structure collapsed due to a strong force applied repeatedly at or below its mid-height. To understand this failure scenario, consider the analogy where you are standing and a sharp force hits your legs over and over; eventually your upper body becomes unstable and you collapse.

A few, varied examples of pounding are shown in the photographs below. On the left image, there are two buildings of the same height separated by notable gap due to residual lean of one of the buildings after being displaced by pounding. In the center image, a short residential structure adjacent to a 10-story apartment complex experienced shear cracking through its masonry infill due to pounding, the taller building did not have notable structural damage. On the right image, the corner of a mid-rise building is making contact with a taller building. Fortunately based on the aspect ratio and relative heights of the buildings as well as duration and spectral content of the ground motion, there was limited damage from pounding between the structures.





OBSERVATIONS OF POUNDING BETWEEN BUILDINGS

Our investigations led me to conclude that relative displacements between buildings, and the gap provided to allow for these movements, are critical design considerations necessary to avoid pounding. Mexico City, like many metropolitan areas, has issues with structural pounding since property is valuable, land space is limited, and buildings are constructed in close proximity to one another. Through questioning the reconnaissance team leaders, I learned from Dr. Breña that pounding is not normally accounted for in design of buildings for dense, urban environments despite its potential to cause significant damage. Garrett also pointed out that when conducting post-earthquake investigation many teams only look for cracks and note the patterns/widths, but do not seek out the causes – such as the interaction between buildings that we saw yesterday which resulted in shear cracking in the columns.

Both Dr. Breña's and Garrett's commentaries tell me there is much to be done with transferring lessons learned about pounding from the field into codified seismic practice. I believe that this knowledge transfer is particularly important in conducting building retrofits since developing approaches to better predict and dampen the building interaction could help prevent pounding damage occurring in closely constructed buildings.

Tomorrow we head about an hour further south to the center of the lake bed area. This area experienced heavy damage due to its soil density and type. I look forward to investigating that area and hopefully learning some more about the city.

Cultural Reflections

Though I have been reporting signs of the Día de los Muertos holiday during the week, today officially begins the first day of the two day remembrance. We saw many altars dedicated to those who have passed on. One little girl came up to the group and invited us to look at her family's altar she helped create in the converted front room of their pool supplies shop. You could tell her deep pride in the altar when she broke out in a huge smile when we asked to take a picture of it.

DIA DE LOS MUERTOS ARTWORK AND ALTARS

CAL POLY

Day 6: Short Stories & Poor Building Configurations

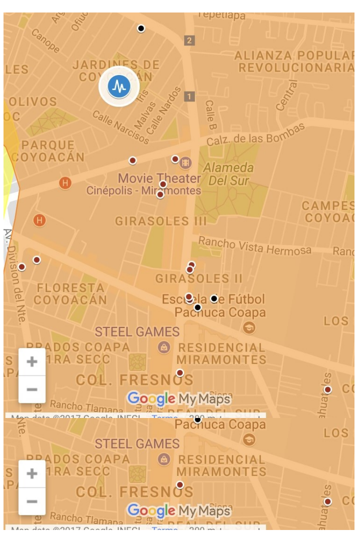
Structural Investigations & General Takeaways

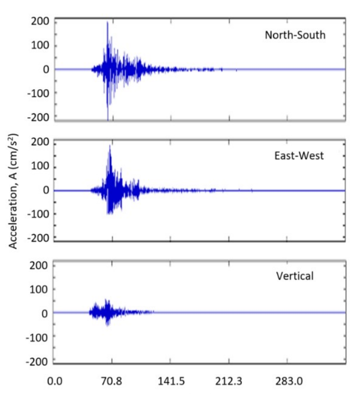
NOVEMBER 2, 2017

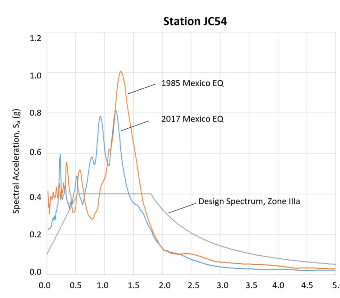
Today started like all of the other days except for one difference: we took a thirty-minute Uber ride south towards the mountains and then a 5-mile walk in the blistering heat to arrive at Av. Canal de Miramontes. In our database, there appeared to be many damaged buildings clustered in the vicinity and we wanted to investigate why that was the case. There we met up with Dr. Mario Rodriguez (who I met on Day 2), so he would show us the significant damage along certain streets in this area.

Seismic Recording Station: Reviewing the Records

Along Miramontes there are primarily residential buildings with an average height of 5-stories. The map below shows the nearest seismic recording station in Parque Jardines de Coyoacán (Station # JC 54) indicating a peak ground acceleration of 220 gals (1 gal = 1 cm/s^2), equivalent to about 0.22g. To the right of the map is the acceleration record from this station for N-S, E-W, and vertical motion. Note the significant spike in magnitude in the N-S direction nearing a time of 70 seconds. Also located below is a response spectra which plots of building period versus spectral acceleration S_a for the 1985 and 2017 earthquakes, as well as the design spectra for the site (orange, blue, and grey lines; respectively). It is important to note that how both earthquake spectra exceed the design spectrum.







ABOVE: PARQUE JARDINES DE COYOCAN AMAX: 220 GAL (LEFT), ACCELERATION RECORD (CENTER), RESPONSE SPECTRA (RIGHT)

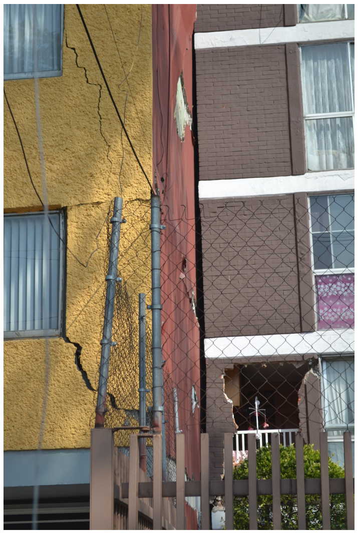
Structural Damage in Miramontes

There appeared to be a few factors that resulted in the concentration of building damage around Miramontes:

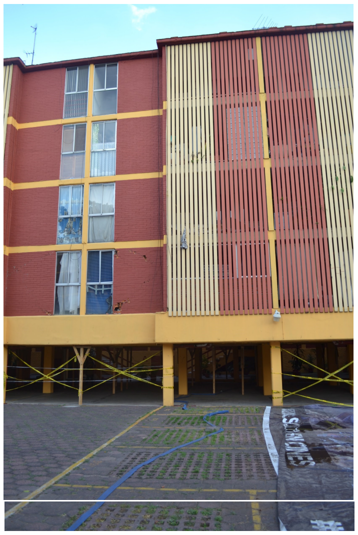
- the motion was predominantly in the N-S direction, same as the orientation of the street;
- the region is located on transition zone soil characterized by highly-compressive clayey layers alternating with sandy alluvial deposits; and
- many buildings exhibited designs with either soft stories or captive columns.

Our investigations of apartment buildings along Miramontes revealed wide shear cracks-to-partial collapse of masonry infill walls and significant structural damage to first-floor columns. The team concluded that the severe damage to masonry infill likely led to loss of stiffness in the building requiring the columns to carry considerably more demand. Dr. Rodriguez pointed out that despite the susceptibility of unreinforced masonry infill walls to severe damage, they are quite prevalent in Mexico due to their low cost, ease of constructability, and construction tradition of over a hundred years.

Further down the street we saw families moving out of a six story apartment building where columns had severe cracks and partial/complete collapse of masonry infill wall panels.



On the adjacent street, we found two nearly identical apartment complexes, differing only by the first floor design. The building shown on the right had continuous masonry walls, while that shown on the left had an open garage making it susceptible to soft-story behavior.




The apartment building, shown above on the left, exhibited shear and flexural cracks on columns and exposed rebar on its deep spandrel beams. The most important thing I learned from this case was that open first-floor garages have a tendency to reduce the building stiffness at this level where the shear force is the greatest.


Lessons From Today's Investigations

1. Be careful of first-floor soft stories with low stiffness particularly where shear demands are expected to be high. Use columns with larger cross-sections or more reinforcement so these members (and the story as a whole) can achieve a greater stiffness.
2. Unreinforced masonry infill is brittle and can experience significant non-structural damage. It should be noted that intact infill walls do add stiffness/strength to buildings with reinforced concrete frame systems and when these infills fail, stress will be redistributed to the frame and may lead to column damage.
3. Avoid designing short/captive columns that tend to fail in a brittle manner via shear as shown in the image below. If short/captive columns are unavoidable, they need to be designed to resist high shear demands using larger cross-sections or more closely spaced shear reinforcement.

CAL POLY

Day 7: Final Round

Final Round

NOVEMBER 3, 2017

During my last day out in the field, we were fortunate to journey slightly north of the Miramontes area from yesterday and investigate several buildings.

We started the morning at Zapata 285 which housed a book distribution company comprised of two structures: one was a reinforced concrete (RC) frame building and behind it a steel braced frame building with concrete beams and slabs. The RC frame exhibited significant structural damage including a separation crack to a front column and flexural damage to the concrete core wall system. Most of the masonry infill walls either had large shear cracks or suffered a partial-to-complete collapse. In comparison, the steel braced frame building performed well and the only visible damage was non-structural. The owner of the building was extremely informative and eager to help us learn from his experience during the earthquake.

ZAPATA 285: (LEFT) SEPARATION CRACK IN COLUMN, (RIGHT) TYPICAL DAMAGE TO MASONRY INFILL WALL

Later in the day, we came upon what I would consider both the most interesting and the most devastated (still-standing) building of the trip, Azores 609. This building had a classic seismic design deficiency: the first floor level was left susceptible to a soft story failure due to the use of incredibly slender columns (around 7.5 in x 13.75 in). Our team concluded that the damage progression during the earthquake consisted of several columns failing in shear in the weak-axis direction, and due to loss of their shear capacity they subsequently buckled under the gravity load of the building. We did note that the building floor plan appeared symmetrical about the entrance and there was similar damage pattern across the entire soft story. In the images below, you can see the precaution that was taken to carry the building gravity load via shoring.

AZORES 609: EXTENSIVE COLUMN DAMAGE REQUIRING SHORING (LEFT) SHEAR AND (RIGHT) GLOBAL BUCKLING

After returning from my last day in the field, the team spent time documenting our findings in forms developed by the American Concrete Institute (ACI) Reconnaissance Committee. With Dr. Kreger as the chair of the committee and Dr. Breña being funded by ACI, it was important that we track important data about the buildings that can later be analyzed to evaluate the current seismic provisions for the reinforced concrete building code that we use in the United States.

Today's interesting building finds was a great way to end the trip and my first reconnaissance experience. Tomorrow is my shuttle ride back to Benito Juárez airport, a flight to Los Angeles, a shuttle to Santa Maria, and a car ride to San Luis Obispo. Only one week from when I started, I will be back in the design labs of Building 21. Expect photo galleries and videos from the trip, coming soon.

Appendix B:

Response to Student Reconnaissance Questions

ARCE 444: Reinforced Concrete Design
Instructor: Anahid A. Behrouzi, PhD

Q&A for Rachel Chandler on the Mexico Reconnaissance Trip
October 28 – November 4, 2017

Disclaimer: *The following responses are from ARCE undergraduate student Rachel Chandler, written on Day 7 of her Mexico Reconnaissance Trip (November 3, 2017). Responses are unedited with respect to language and technical content. The views expressed here do not reflect the technical content of ARCE 444: Reinforced Concrete Design as instructed by Dr. Anahid Behrouzi or any formal texts/building code documents. Please relay technical clarification questions to Dr. Behrouzi or other ARCE faculty, for cultural and experiential questions follow up with Rachel.*

1. Luke: What is the status of these buildings for people being allowing inside of them? What kind of safety precautions are made to make sure nobody goes into a building that could collapse? How are buildings evaluated to determine if they are safe or not?
    a. Some buildings are considered evacuated, we saw some of the people moving out of their houses and apartments. Others, people are advised to move out but some stay because it is their only housing option. The local civil protection police will go and inspect buildings after the earthquake, they will then tag the building based off of cracks. Sometimes architecture students will actually go out and be given basic instructions which will sometimes give inaccurate tagging or overexaggerated tagging because of lack of training. The evaluation process is a scale of size of cracks.
2. Hailey-Rae: How many of the building have you seen that have had significant damage that are built to the standards that we design for? Are there obvious differences between buildings that are designed structurally "better" than others? (For example, do reinforced CMU walls see as much or behave similarly to non reinforced?)
    a. We design for different standards because Mexico uses their own building code. But they have adopted significant portions of the ACI-318 code. But it is definitely not the same. Also, the cost of building and construction is a huge factor on how they design here. They do have their own design spectrum that was noted and shown in the previous blog post.
3. Chris B: I saw on one of your posts that the fractured column you posted had its rebar buckling. Do you know whether the rebar buckled because the column experienced a much higher load than expected during the earthquake? Or did the rebar buckle because the stirrups/ties were not spaced according to code? Did you possibly measure the distance between the column ties and the # of rebar used so we can investigate the load that caused the rebar to buckle according to Euler buckling? Also, did the concrete on the column break off first, leaving the rebar exposed? Or did the rebar buckle, breaking the concrete?
    a. The concrete before it spalls off creates some sort of support, but is is more heavily strained more than the bar. So my best guess would be that the rebar started buckling after the concrete had spalled off. The tie spacing is awful here and is probably a huge contribution to some of the damages I have seen. We did not measure the spacing on this one specifically because there were not enough ties exposed. My best guess as to what happened would be that there was a hinge created at the bottom due to the tower above moving back and forth. Basically the column was being pulled and stretched and then compressed back and forth.
4. Teddy: In ARCE 372, John Lawson spoke about many 10-12 story buildings in Mexico City being heavily damaged b/c they hit their resonant frequency while shorter and taller buildings nearby were untouched. Are you noticing anything similar where a certain height range of building was particularly susceptible to damage?
    a. Yes, that is the first thing I noticed when looking at the acceleration graphs from local accelerometers. The height range I have observed is 5-10 story buildings.
5. Caleb: So I was reading about Day 1's findings and saw something that I am learning about right now in ARCE 451; Reentrant Corners. So I know that based on Reentrant Corner Irregularity that some design capacities must be increased by 25% such as collectors and connections. My question is based on your observations, were there any findings of weak connections and drags? I am also wondering based on experience of your coworkers, is

there any other special details that must be taken into account when you have a structure with an irregularity? Were there any unique observations you saw with the reentrant corner that you didn't see in other buildings?

   a. Reentrant corners were very common here going from building to building. However, none of my colleagues are aware of how engineers here design for that irregularity. These corners do make the building experience a lot of torsion especially if the building is a corner building.

6. Sophie: Overall, what were the main differences between buildings that did well in the earthquake and ones that didn't?
   a. Soft stories, short columns, pounding a corner building versus others, and the use of unreinforced masonry infill in corner buildings. But there are many other factors I am sure that can be determined with more investigation.
7. Cory: From my understanding of load flow through a concrete structure, a majority of the force will be focused where the stiffness is greatest. Would you say that it is common to see damage among pilasters along the wall? I would think that the embedded column within the wall would add stiffness compared to the rest of the wall and was wondering if this is how it behaves in the field.
   a. My understanding is that in these types of structures they use boundary elements that are not structural columns, but add in some stiffness to the system if any, very little. The masonry infill is not reinforced so that does terribly and fails in shear. Once the masonry infill walls fail, the columns receive the brunt of the load. Then the forces get dumped into the next strongest member.
8. Tanya: I was wondering if you felt like you were prepared to do damage assessments based on the classes we have taken so far or if you've been learning a lot from the engineers you are with. I find it really interesting that you are with an engineer doing assessments who has also done the same type of work during the 1985 earthquake!
   a. I was actually not really prepared at all for seismic analysis because I got put behind in my analysis flowchart. So I have yet to take 412 and 483. However in order to understand the way a building behaves, 371 and most design classes have prepared me for that part. I think once I take 412 and 483 there will be connections made and it will have a real world application for me which is what I am looking forward too. I have been learning a lot from the engineers and professors I have been with. Every day is something new and a review of what I had learned the previous days. Yes, both Mike and Sergio were assistant professors during that time period. It is great to hear their stories from back then.
9. Max: How did the epoxy retrofits from the 1985 earthquake perform? Did the epoxy hold or did that seem to be a weak spot during the most recent earthquake?
   a. The epoxy did great in that member, however the epoxy essentially weakened that member making the other members in the frame work harder and show damage. So overall I would say epoxy does great for the short term solution, but it creates that weak point in your structure which makes other members work harder and possibly fail.
10. Ricardo: How did the type of cracking vary between buildings? Or was there a type of cracking that was predominant in most of the buildings you visited? I assume the lateral systems used, the building heights, and the member functions all affect the type of failure and the observable cracking shape. Was there a lateral system that was more successful in preventing major cracking?
    a. Yes there are a lot of variables to answer your question. I would have to say there are three main types of cracks I saw (shear, tension, flexural). These all could be a result of pounding, the actual earthquake, faulty construction and details, or even a weakening during the previous earthquake. I would say the retrofits performed really well, so adding in steel bracing into a RC frame seemed to do really well.
11. Kyle: You said that one of the most successful retrofits was at the local hospital where they added steel rods and widen the columns, while other retrofits such as the steel bracing on the outside of the police station were also successful but there were visual signs of damage. Do you know what the city of Mexico is planning to do for

future retrofits and construction? And if what they have seen from this damage assessment be taken into account or will factors such as cost and ease of construction govern the new retrofits and designs?

   a. Making an educated guess from the way Mexico works and the way their engineers work, I would say that they will stick to what they know which is steel column jacketing, widening of the columns, adding in steel braces. They want to add more stiffness to the lateral system essentially. Cost is yes a huge factor. That is why I think they are not using reinforced masonry systems, they know what they know and don't want to spend more money that they don't have.

12. Zachary: I understand that there has been many instances of cracking but have you come across and instances of concrete columns crushing at the base due to free rotation of columns?
    a. I wouldn't call it column crushing necessarily. I believe it is a shear failure that occurs. You wouldn't see crushing unless you had significant tilting back and forth and that coming down of the column being a significant force through it and making it fail. But the cracks that we have seen are mainly shear or flexural cracking.
13. Jerry: What has been the biggest cultural takeaway for you? Has this experience made you more aware/ appreciative of your heritage? Also, what food would you recommend when in Mexico?
    a. Biggest cultural take away: Mexico City is very similar to Downtown Sacramento in terms of how it looks. I was expecting much less development as we went further away from the city center, but there was a community and a level of community development that surprised me. I also really liked how many trees they have incorporated into their communities and neighborhoods. Yes being here has made me more aware, I would like to someday visit my grandparents hometowns to see the difference. Recommended food for non vegans: queso con chorizo. For the vegans out there: chips and homemade guac for sure.
14. Chad: I've done some research on SPSWs and while they aren't common, they are very cool and work well for retrofits. Have you seen any buildings that were retrofitted with steel plate shear walls after the 1985 earthquake, or have Dr. Brena or Hagen said anything about using SPSWs to retrofit buildings damaged in the recent earthquake? If you see any, I would be interested in hearing about how they performed.
    a. The buildings that we focused on were only reinforced concrete buildings with steel bracing retrofits. I don't think that SPSW's are an economical solution for Mexico right now.
15. Brooke:
    Have you been using any sort of tool to measure and classify the cracks that you are observing? Also have you and your team observed any buildings that are non livable and had to evacuate?
    a. Yes, similar to the one Anahid passed around in class one day. It's a crack gage that measures the thickness of cracks in a column or wall. You hold it up and estimate which size is the closest. Yes, there have been many buildings we couldn't get into because the police was blocking us from entering.
16. Jeret: What kind of building codes are used for design in Mexico? Have they also adopted the IBC/ASCE? I was reading the part in your blog about pounding between buildings and was wondering if the Code there limits story drift to try to avoid things like this.
    a. They have adapted some of the ACI-318 code into their building spectrum. However there are a lot of inconsistencies. And in regards to pounding what ends up happening is (my own theory) that they don't multiply by that factor of R, they just calculate without that reduction factor. So I think that is where the buildings fail because of pounding.
17. Kenny: I didn't know that pounding is the interaction between 2 buildings located next to each other, is there a calculation procedure involved to determine the minimum distance between 2 buildings to avoid pounding?
    a. Yes, in 451 I believe we learned it to calculate the diaphragm deflection. It is a simple enough process, and actually is required in our building codes. Essentially when an earthquake hits, the buildings won't necessarily move in sync with each other, some have different periods which causes them to deflection differently.

18. Katie: I find it interesting that when designing structures that are very close to each other, the engineers in Mexico City do not take into account the potential for pounding. I feel like basic structural design tells you to look at the lateral deflection of the building that you are designing and if there is an existing building within that range of motion, you should probably change your design. I understand that Mexico City is a very densely populated area; however, I think that the longevity of a structure is more valuable than a few square feet of footprint.
    a. I totally agree with you. And I have asked some of the local engineers what they think and they have no idea what happens. I have a feeling that some of these buildings are very old and might've been before the age of newer codes which account for diaphragm drifts.
19. Jiaming: I think there is some property set back requirement in IBC or ASCE. Are they not meet the code requirement or is there any other reason led to the pounding problem?
    a. I don't know what happens, but I don't think it is calculated correctly or accounted for. Mike was going to ask another local engineer tomorrow while I am on my way back home so we shall see if there are any explanations, because I only have theories at this point.