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SOM

PRELIMINARY OBSERVATIONS IN THE AFTERMATH OF THE SEPTEMBER 19, 2017 PUEBLA–MORELOS EARTHQUAKE

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Keywords
earthquake
seismic
structural
engineering

Abstract

In the wake of the devastating Central Mexico earthquake on September 19th, 2017, a team of SOM engineers traveled to Mexico City to contribute to post–disaster recovery efforts.

Shortly after the 7.1 magnitude earthquake struck, three structural engineers based in SOM's San Francisco and Los Angeles offices—Abel Diaz (SEAOSC), Patrick Murren (SEAONC), and Samantha Walker (SEAONC)—set out to document building damage and provide technical support to local structural reconnaissance efforts. Edward Guerra, Associate Director at SOM, and architect Adrián Gracia, Design Director at Cuatro44, joined the team. Both Guerra and Gracia reside in Mexico.

One of the first international teams of engineers on the ground in Mexico, the group documented building damage patterns before the crucial work of cleanup and rebuilding began. The team also assisted local officials in assessing critical and significantly damaged structures. The information gathered is being shared with the Earthquake Engineering Research Institute (EERI) in support of its mission to mitigate earthquake risk around the world. The team is also documenting its findings to be presented to educators, students, architects, and structural engineers, both in the United States and in Mexico. In addition, through collaboration with university researchers, a damage identification tool that utilizes photo recognition is being developed, with the intent to systematize and expedite the assessment of damage for large inventories of damaged buildings in future earthquakes.

SOM has organized reconnaissance teams in the aftermath of several major earthquakes, including the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, the 1995 Kobe earthquake, and the 2008 Sichuan earthquake. On each mission, the information gleaned from documentation, combined with the research conducted by numerous organizations and professionals involved in post–disaster recovery efforts, is intended to help cities become more resilient against seismic events in the future.

32 Years Later

A few hours after the annual national earthquake drill that commemorates the anniversary of the great Michoacán earthquake —which struck Mexico City on September 19th, 1985 and resulted in more than 10,000 reported deaths—a magnitude 7.1 earthquake struck Central Mexico, producing violent shaking throughout Mexico City, killing more than 300 people, and causing more than 40 structures to collapse.

The epicenter was located in Ayutla, near Puebla, and approximately 150 km southeast of Mexico City. Fortunately, the Mexican earthquake early warning system (Sistema de Alerta Sísmica Mexicano) had been triggered, providing roughly 20 seconds of warning in Mexico City and allowing thousands to evacuate buildings prior to the arrival of the earthquake's strongest shaking. The significant duration of the ground motion typically lasted no more than 30 seconds in the hill zones surrounding Mexico City, but extended beyond 90 seconds in some areas inside the Mexico City basin. The longest ground shaking correlated with the most heavily damaged neighborhoods of La Condesa and Roma (CIRES).

Damaging Soil Amplifications

Located in the volcanic belt of the Mexican subduction zone, Mexico City is subjected to both interplate (epicenter at plate boundary) and intraplate (epicenter inside the continental plate) earthquakes. The M8.0 1985 Michoacán earthquake was an interplate event where the seismic waves traveled more than 350 km before reaching Mexico City. The M7.1 Central Mexico earthquake was an intraplate event. Despite the different nature of these earthquakes, the damage from both occurrences correlated with soft soil amplifications and resonance with site periods in the lake bed zone that magnified the relatively modest input accelerations.

In the 1985 Michoacán earthquake, resonance for long site periods in the lakebed produced amplifications in spectral accelerations that, in some cases, exceeded 10 times the peak ground acceleration in the period ranging from 1 to 5 seconds. This explains the numerous collapses of high–rise buildings during that earthquake (Ordaz, et al.).

In the 2017 Central Mexico earthquake, the closer proximity to the epicenter and different frequency content of the seismic event produced higher peak ground accelerations, averaging up to 0.3g in the lakebed. Amplifications were predominant in site periods between 1 and 2 seconds, reaching spectral accelerations of approximately 0.6g+ in the significantly damaged area of La Condesa (CIRES). Therefore, collapses occurred most frequently in low and mid–rise buildings. The reason for soil amplification at shorter periods for this earthquake may be explained by the different frequency content of the incoming seismic waves due to the different source to site distance, as well as potentially by basin effects, to be confirmed by future investigations.

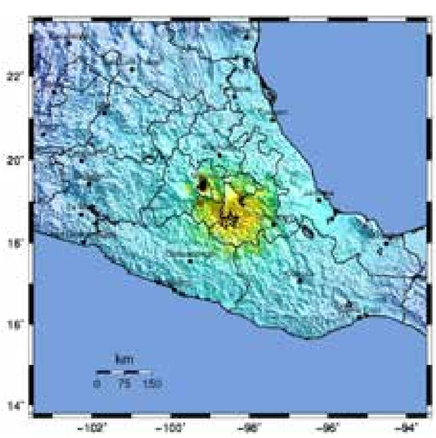


Fig. 1: Epicenter and shaking intensity for the M7.1 Central Mexico Earthquake (USGS).

Fig. 2: Overlay of damaged buildings during the M7.1 Central Mexico earthquake (red dots, Verificado19s) and extent of the lakebed soft clay and transition zones (Mexico City Building Code).

Founded on a Raft

Mexico City was initially founded as an Aztec city on an island in the old Lake Texcoco. The growth of the city inside the Mexico Basin in the following centuries, to its current population of 26 million in the greater metropolitan area, drained the lake and produced an overuse of water leading to consolidation and compaction of the clays that had formed the lakebed in the past. Over the last 100 years, regional subsidence has been well documented to reach 11 meters in some areas, and current rates still reach 30 cm/year in some neighborhoods of the city (Martinez–Gonzalez, et al.).

This subsidence, combined with the extremely soft nature of the sedimentary layers in the lakebed, has required foundation systems compatible with these two mechanisms. Fully compensated foundations (those in which the weight of the building equals the weight of the excavation) are common in Mexico City, where the building essentially becomes a “raft” that floats on the soft soil, producing small differential settlements. For heavier structures in which compensation is not possible, a raft with friction piles is often utilized, designed to settle at the same rate as the regional subsidence. Failures due to excessive settlement and foundation rotation are regularly observed after earthquakes in the region, and the M7.1 Central Mexico earthquake was not an exception.

Reconnaissance

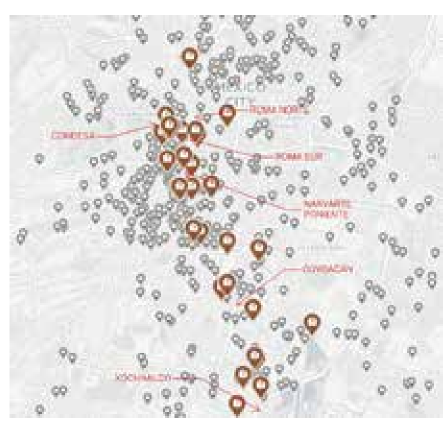
Beginning less than 48 hours after the Central Mexico earthquake, the authors performed a three–day reconnaissance of affected structures in Mexico City with the dual goals of documenting earthquake–related building damage and, as possible, assisting local authorities in their efforts to evaluate damaged buildings and get residents back in (or out of) their homes and businesses safely.

The reconnaissance focused on heavily–affected neighborhoods, including Condesa, Roma, Narvarte Poniente, Coyoacán, and Xochimilco. Given these neighborhoods’ general alignment in the southwestern portion of the city, Mexico City newspapers (Arvizu) noted these areas formed an “eje de la desgracia” or “axis of misfortune.”

The reconnaissance occurred shortly after the earthquake when substantial resources from the military and Protección Civil agencies were directed toward rescuing people still trapped in collapsed structures. Along with the response from authorities, building officials, and professional organizations, the outpouring of civilian volunteer support observed was extraordinary. The SOM reconnaissance team partnered with a local professional architecture organization, Casa del Arquitecto, in assisting city building officials (DRO, or directores responsables de obra / directors overseeing the work) in their efforts to assess critical or severely damaged structures.

Typical forms of building construction, structural systems, and observed damage and failure modes are summarized in the following sections. This article reflects a selection of representative cases from the SOM reconnaissance and does not intend to draw overall conclusions beyond the noted observations.

Fig. 3: Diagrammatic representation of the regional subsidence mechanism in Mexico City (Kimmelman).



Right:
Fig. 4: Official Mexican government map of damaged (gray) and collapsed (brown) structures (Mexican Government). The neighborhoods observed by the SOM reconnaissance team are indicated in red.

Fig. 5: The SOM reconnaissance team during a visual observation of damage in the Condesa neighborhood (SOM).

Fig. 6: Confined masonry frame with St. Andrew's cross bracing (SOM).

Typical Building Construction

The overwhelming majority of structures that the SOM reconnaissance team observed were constructed from combinations of concrete, masonry, and brick used in both structural and nonstructural applications. The buildings observed ranged from one to approximately 10 stories tall, with the majority having two to four levels. Concrete frame structural systems with and without confined masonry or brick infill walls were common for shorter structures less than four stories tall. Taller structures also used concrete or masonry shear wall systems. Confined masonry frames sometimes employing units arranged in St. Andrew's cross bracing configurations were observed in some instances in taller mid–rise structures.

In almost every instance, buildings were constructed either in direct contact with neighboring structures or with little separation, leaving vulnerability to pounding damage. Architectural flashing over gaps between structures was commonly observed where separation had been provided.

Popular tourist neighborhoods such as the Historic Center and Polanco sustained very little damage.

Nonstructural damage modes such as cracked glass, spalling of plaster and brick facades, and collapse of parapet walls and canopies were among the most frequently observed types of damage. Usually, it appeared that damaged nonstructural elements and facades were either not properly designed to withstand deformation–induced demands or not properly detailed to allow

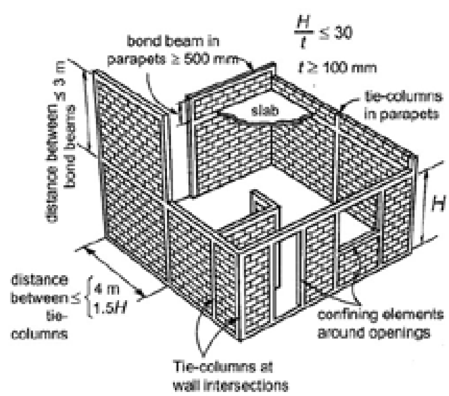


Fig. 7: Typical confined masonry construction (Alcocer, et al.).

for slip and provide release from such demands. Numerous cases of cracked or shattered glass, spalled plaster, and cracked or collapsed masonry facades were documented, including in more modern buildings. Additionally, in multiple cases, it was observed that portions of facades had cracked or collapsed due to pounding impact from neighboring structures.

Fig. 8: Deformation–induced diagonal shear cracking of a masonry panel detailed integral with the lateral frame system (SOM).

Failures of confined masonry walls were also common. This system, frequently used in Mexico City, is composed of reinforced column and beam frame members and a lightly or even unreinforced masonry wall. The reinforced end members provide confinement for the masonry infill and enhance the ability of the wall to act as a shear load–bearing panel. Failure in the masonry panel can occur due to shearing and out–of–plane collapse (in occasions caused by pounding), both of which were observed in the field either in isolation or in combination. Panels that experienced diagonal shear cracking and failure in the mortar posed additional out–of–plane falling hazards in subsequent aftershocks. In some cases, diagonal cracking was observed to have extended into the vertical concrete elements.

A number of buildings were observed to have residual drifts after the earthquake, relatively easy to identify without the use of any surveying equipment given the minimal separation between structures. There were also instances where lack of plumbness was observed, most likely due to differential settlement related to the regional subsidence in the Mexico City clays. Residual drift issues could sometimes be distinguished from settlement issues either by partial loss or damage of architectural flashing that had previously covered building separations, or by impact damage due to pounding.

Clockwise from top left:

Fig. 9: Damaged glass cladding on an office building along Paseo de la Reforma (SOM).

Fig. 10: Collapse of confined masonry panels (SOM).

Fig. 11: Facade damage due to building pounding (SOM).

Fig. 12: Example of building with post–earthquake residual drift (SOM).

Fig. 13: Nonstructural brick facade failure at a shopping mall near Coyoacán (SOM).

Observations from Collapsed Buildings

Partial and full collapses were observed at buildings that appeared to have structural deficiencies such as soft stories, structural irregularities, and discontinuous or incomplete lateral load paths. Where observed, these shortcomings typically occurred in mid–rise structures between 4 and 12 stories tall. While observed damage, on a city–wide scale, tended to be concentrated in the neighborhoods where these observed structures were located, it is noteworthy that in each of the cases observed shown below, adjacent structures showed little or no damage. While soft soil in these neighborhoods, as described earlier, may have exacerbated ground accelerations, the collapses and substantial damages documented here likely owed more to structural deficiencies than to locally poor soil conditions.

Soft story mechanisms were occasionally observed. A pancaking collapse of a mid–rise structure was observed in the Hipódromo neighborhood, close to Parque México. At one end of the structure, the top two stories had completely sheared off from the vertical support. At the other end, the top two stories were still resting on a column where concrete had crushed, the longitudinal bars had buckled, and confining tie reinforcement was not visible from the street. It was observed that the failure occurred at the level where the roof of the adjacent structure was located. Given the relative lack of damage elsewhere in the structure, it is possible that the neighboring structures, without adequate seismic separation, provided an unintended inflection point at the collapsed story, trigging a shear failure in the vertical elements where the soft story collapse occurred.

Structures at block corners that appeared to be affected by torsional irregularities were also common among the documented collapses, as observed for a building located adjacent to the Parque México. Two orthogonal sides of the four–sided structure were entirely composed of a form of masonry wall; the other two sides had frame configurations and were located at the block corner. When observed, the building appeared to have twisted due to this irregularity. The building was both leaning on the neighboring structure with pounding damage visible, and leaning away from the street, as evidenced by comparing the profile of the structure with its apparently plumb neighbor. Damaged columns, including shear–related failures at the corner columns subjected to pounding impact from neighboring structures, were observed.

A collapsed building was observed in the Roma Sur neighborhood, roughly a block away from Avenida de los Insurgentes, a main traffic artery through the area. When observed, neither the mode that triggered collapse nor the original size of the building was evident. A subsequent review of a Google Street View image of the building prior to collapse revealed that the structure was much taller than expected and that a wall facing the street appeared to be discontinuous. However, it could not be conclusively determined whether the wall was structural. Further, both in– field observations and other pre–collapse images suggested that the building had a structural system with reinforced concrete columns. Other reconnaissance teams documented common occurrences of failures of reinforced concrete column and flat slab structures (Galvis, et al.), where collapse may initiate through a punching shear failure in the

Fig. 14: Soft story partial collapse of a mid–rise structure observed in the Hipódromo neighborhood (SOM).

Fig. 15: Corner building near Parque México with apparent torsional irregularity leaning on its neighbor on the verge of collapse (SOM).

slab to column connection. Though also unable to be confirmed in this case, a punching shear failure in a flat slab may have precipitated the collapse.

Two neighboring buildings—one collapsed and one severely damaged—were observed in the Valle Centro neighborhood. Significant damage in the corner vertical support of the building still standing was observed. When observed, the structure was supported by temporary steel shoring posts in an attempt to prevent collapse.

A partially collapsed department store was observed in the Coyoacán neighborhood. Both substantial racking damage and a partial collapse were observed in different parts of the store structure. Residual drift of an overhang at an entrance to the store resulted in the racking of the relatively small gravity columns providing support. A shear crack in the masonry wall above the overhang suggested that the overhang structure was supporting lateral forces, whether intended or not. Though the small ground–level columns did not appear to be adequate to prevent residual drift of the overhang, their limited lateral capacity may have prevented further collapse.

The remainder of the department store structure appeared to be an unconfined masonry wall, providing both gravity and lateral support. With the exception of a partially collapsed portion where mattresses and other heavy merchandise had been stored, the structure appeared relatively undamaged. A partially damaged panel immediately adjacent to the collapsed portion showed diagonal shear cracking, suggesting that the wall panels may have failed first due to lateral demands, then subsequently collapsed under gravity demands with the loss of structural integrity. It is also possible that the above–average mass in the collapsed portion, related to the heavy storage, may have played a role in the partial collapse.

From top right:

Fig. 16–17: Collapsed building in the Roma Sur neighborhood, before and after (Google Street View and SOM).

Fig. 18: Building adjacent to a collapsed structure in the Valle Centro neighborhood being propped by steel shoring posts (SOM).

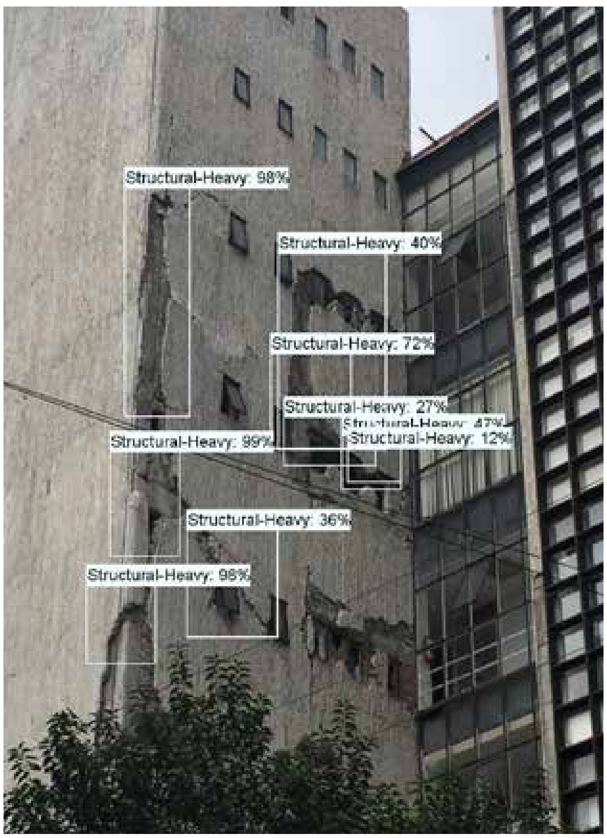
Fig. 19: Partially collapsed department store in Coyoacán with residual racking of small ground level gravity columns (SOM).

Technological Documentation and Assessment of Building Damage

The observations from this reconnaissance are being shared with the engineering community through organizations such as the Engineering Earthquake Research Institute (EERI). Part of this collaboration includes uploading in–field photos to the EERI Virtual Clearinghouse. In this database, photos are manually catalogued as either (1) structural or (2) non–structural, and the level of damage is indicated (either light, medium, heavy, or severe). The photos and information uploaded to the database are freely available online.

In an effort to enhance post–earthquake reconnaissance capabilities, SOM teamed up with software developer Anthony Sarkis to develop a prototype machine learning-based tool to document and assess building damage from photographs. Once calibrated and tested, photographs could be rapidly catalogued using this tool with more detail and less subjectivity than would be performed manually.

Hundreds of photographs will be uploaded to the EERI database and other databases from various Mexico City reconnaissance teams. In addition, in the aftermath of a major earthquake, local communities typically develop large databases of building damage that cannot always be rapidly evaluated by experts. The intent of the machine learning-based tool is to make the photo cataloguing process for these databases not only more uniform and efficient, but also more comprehensive. For example, rather than assigning one single damage type and severity to each photo, the tool would be able to separately catalogue and assess different parts of the photo, automatically. Through machine learning, the ability of the tool improves with the more photos that it processes. Other possible information that could be extracted from this tool includes the building material, the type of structural system, and the building height.



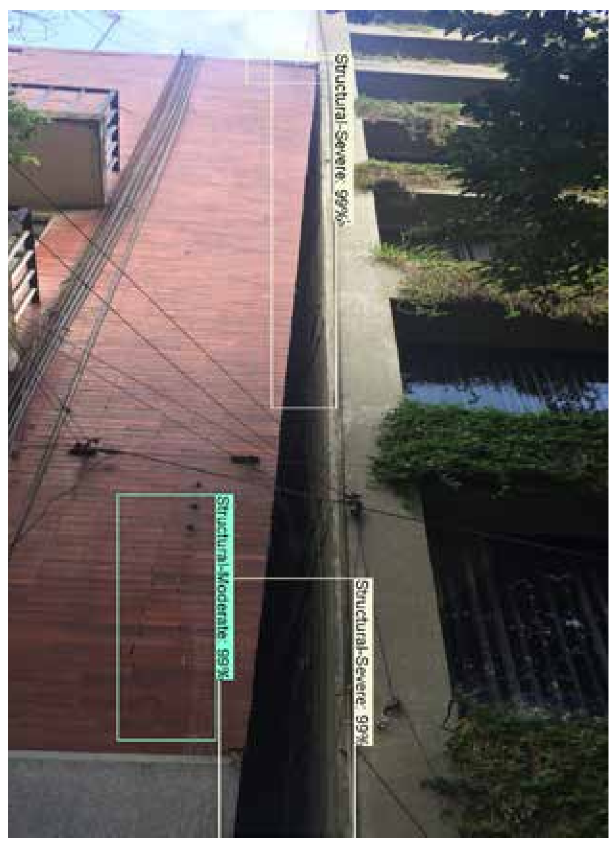


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Fig. 20: Enlarged map showing the location of data uploaded by the SOM reconnaissance team to the EERI Virtual Clearinghouse (EERI).

Fig. 21–23: Examples of damage cataloguing using the photo recognition tool (SOM).

Conclusions and Next Steps

Overall, the damage caused by the 2017 Central Mexico earthquake was found to be localized, even within the most heavily affected neighborhoods. The following types of building damage were generally observed by the SOM reconnaissance team:

- Nonstructural damage in elements that did not seem to be properly designed for deformation–induced demands or allowed to accommodate movement;
- Failures of confined masonry walls;
- Failures in corner buildings subject to irregular loading;
- Pounding damage;
- Residual drifts;
- Partial and full collapses of buildings that appeared to exhibit soft stories, structural irregularities, or possible punching shear failures in flat plate and concrete column systems.

SOM has organized reconnaissance teams in the aftermath of several major earthquakes, including the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, the 1995 Kobe earthquake, and the 2008 Sichuan earthquake. The objective of these trips is to observe damage and apparent building behavior, to try to understand and explain the reasons for observed damage and to share the information gathered with other building professionals, researchers, and organizations in order to improve the state of knowledge on building performance in earthquakes so that cities can be made more resilient in the face of these natural disasters.

The information that the SOM team gathered from the 2017 Central Mexico earthquake reconnaissance mission is being shared with the engineering community through organizations such as EERI and the Structural Engineers Association of California (SEAOC). The team is also documenting its findings to be presented to educators, students, architects, and structural engineers, both in the United States and in Mexico. In addition, SOM teamed up with software developer Anthony Sarkis to develop a prototype machine learning-based tool to document and assess building damage from photographs in order to enhance post– earthquake reconnaissance efforts.

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