Special Report

Performance of Precast and Prestressed Concrete in Mexico Earthquake

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Note: This report is based upon the author's observations during a visit to Mexico, October 13-17, 1985, on behalf of the Prestressed Concrete Institute.

The extreme severity of the earthquake and major aftershock that hit the west coast of Mexico, September 19 and 20, 1985, caused the collapse of several hundred multistory buildings in Mexico City [about 400 km (250 miles) away from the epicenter]. An estimated 10,000 people lost their lives and countless more were injured. In addition, a quarter million people lost their homes.

Most of the collapses were reinforced concrete framed buildings in the range of six to fifteen stories. Five of the collapsed buildings contained precast concrete components as part of their structural systems. Many buildings and parking garages in Mexico City utilizing precast concrete elements withstood the earthquake without distress.

In Lázaro Cárdenas [about 30 km (19 miles) from the epicenter], large fully precast buildings in the fertilizer plant resisted the earthquake exceptionally well. Also, throughout the country and within the cities, the concrete bridges withstood the earthquake without damage.

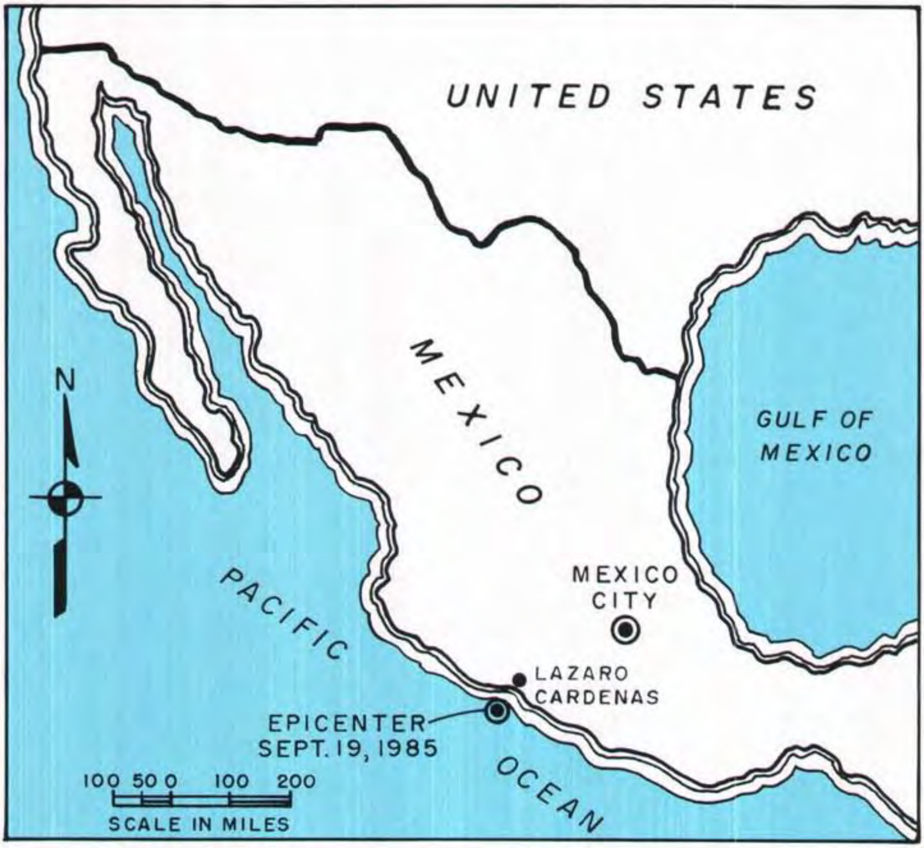
This report presents the author's observations of the performance of precast and prestressed concrete during his visits to Mexico City and Lázaro Cárdenas. However, prior to getting into this discussion, it is necessary to describe the unique seismological aspects of the earthquake and the resulting overall damage.

Reports on the performance of precast and prestressed concrete structures (most of which were composite) in Mexico during the earthquake of September 19, 1985, and the severe aftershock that struck on the subsequent day.

SEISMOLOGICAL ASPECTS

The earthquake that hit Mexico at 7:19 a.m. on September 19, 1985 had the epicenter about 30 km (19 miles) off Mexico's Pacific coast (see map). Within 36 hours, at 7:38 p.m., there was an aftershock emanating from the same general epicentral region. The quakes registered Richter magnitudes of 8.1 and 7.5, respectively.

In Mexico City, 400 km (250 miles) away from the epicenter, the underlying firm soil



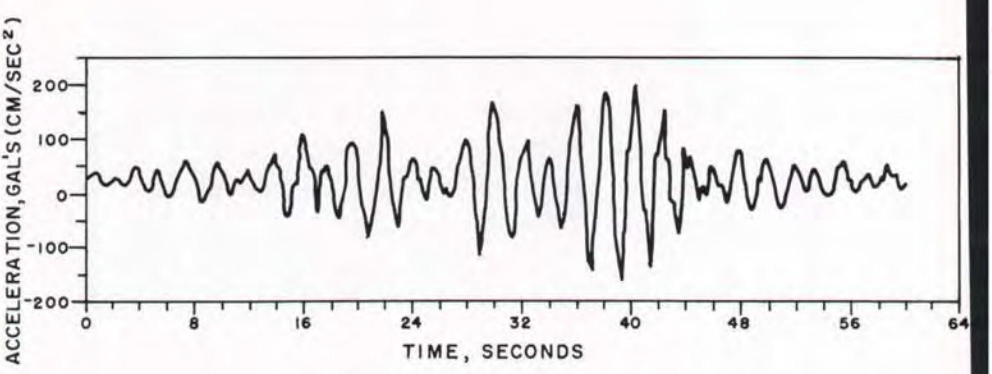


Fig. 1. Accelograph record of September 19, 1985, S60 E, SCT Station, Mexico City.

recorded a maximum acceleration of less than 4 percent of gravity with predominant long periods since the short period components of an earthquake are usually filtered out at relatively short distances from the epicenter. In sections of the city, located in the hills, the earthquake was only mildly perceived. The layers of soft sedimentary materials of the filled in lake bed upon which much of Mexico City is founded, however, amplified the bedrock accelerations very significantly.

At the Communications and Transportation Center (SCT Station) in the city, instruments measured over 20 repetitions of almost steady state pulses of between 5 and 20 percent of gravity as can be seen in Fig. 1. The pulses came at a rate of every 2 seconds. Total duration of severe shaking was about 60 seconds. Such a long duration of intense motions has not been experienced in previously documented earthquakes.

Also, the peak acceleration of this record was more than twice that experienced in Mexico City's previous most severe earthquakes. The shape of this record resembles more of a response curve than that of a typical accelograph, thus indicating the specific seismic response characteristics of the particular depth and make-up of the lake bed fill.

Fig. 2 shows the spectral accelerations calculated from the SCT Station accelograph. This spectra is compared with the El Centro (1940) spectra which has become a standard for comparison.

Also shown for comparison are the spectra recommended in ATC-3.* As can be seen from the graph, accelerations in the period range between 1.5 and 3.0 seconds generated by the Mexico City event are considerably higher than those generated by other events.

The corresponding calculated amplitude of the soil displacement of the SCT record is up to ±20 cm (± 8 in.) from the initial position.

At another location in the city the acceleration pulses came every 3½ seconds (because of a different depth and make-up of soft deposits) with a maximum acceleration of about 12 percent of gravity.

The earthquake intensity was assessed on the Modified Mercalli scale to range between V and IX in the various parts of the city.

In Lázaro Cárdenas, on Mexico's west coast located about 30 km (19 miles) from the epicenter, the intensity was estimated as IX on the Modified Mercalli scale. The peak accelerations recorded in the epicentral region were 17 percent of gravity for a duration of 40 seconds with predominant frequencies in the 0.2-seconds range.

* "Tentative Provisions for the Development of Seismic Regulations for Buildings" by Applied Technology Council, associated with SEAOC.

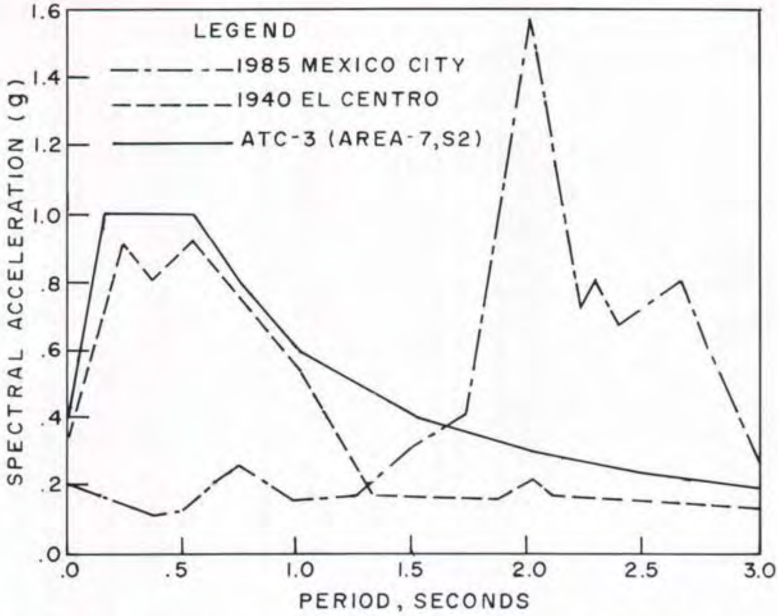


Fig. 2. Elastic response spectra for 5 percent damping. Courtesy of Englekirk and Hart Inc., Los Angeles, California.

OVERALL DAMAGE

As a result of these unusually long and intense earthquake motions, about 180 buildings collapsed and 85 were severely damaged and designated for immediate demolition in Mexico City.* Most of the severe damage was concentrated in several sections of the city within the filled-in lake bed.

The majority of these 265 (180 + 85) buildings were in the six to fifteen-story range. Categorized by structural types: 143 of these were concrete frames; 85 flat plates or waffle slabs with or without filler blocks; 10 structural steel frames; 17 masonry construction; and 10 of other structural types.

Classifying these buildings by their age:

- 69 were constructed prior to 1957
- 149 between 1957 and 1976
- 47 constructed after 1976

* According to a preliminary report issued by the Institute of Engineering at the National Autonomous University of Mexico.

This age division corresponds to the different code requirements in force at these particular time periods (see section on Building Codes below).

The most severe losses were in concrete construction (228 buildings out of 265) which is the predominant construction material in Mexico. Of these, 52 were built before 1957, 133 were built between 1957 and 1976, and 43 were constructed since 1976.

It appears that many frame buildings collapsed predominantly due to shear failures of columns resulting from large interstory distortions with the slabs "pancaking" one on top of the other (Fig. 3). In some flat slab buildings the primary failure appeared to be punching shear in the slabs around the column periphery with the columns protruding several stories high above the pancaked floors (Fig. 4).

There were numerous instances of a group of upper slabs collapsing with the remainder of the structure left standing (Fig. 5). There were also cases where a group of stories

Fig. 3. Pancaked multistory building.

within the height of the structure collapsed while leaving intact several stories above and a number of stories below (Fig. 6).

The disastrous effects in Mexico City resulted from resonance between the numerous, intense 2-second pulses of the earthquake and buildings having a period of vibration in the 2-second range.

Frame buildings in the twenty-story range (concrete or steel) entered the earthquake with a 2-second period and were immediately severely excited by the 2-second pulses. Note that the customary design formula for the period of a frame building is 0.1 second per story.

Shorter concrete frame buildings in the six to fifteen story range (the range where most of the collapses occurred) entered the earthquake with natural periods of 0.6 to 1.5 seconds. These initially stiffer structures gradually became more flexible and lengthened their periods due to cracking and yielding in sequential sways until their period of vibration reached 2 seconds. These

Fig. 4. Columns protruding above pancaked floors failed in punching shear of a flat slab multistory building.

Fig. 5. Collapsed upper stories.

Fig. 6. Collapsed middle stories.

Fig. 7. Building sunk relative to sidewalk.

buildings then came into resonance with the 2-second pulses causing their collapse.

The extremely long duration of the earthquake collapsed buildings which could have survived a lesser number of earthquake pulses.

Hammering of neighboring buildings not separated by proper seismic joints caused damage in many instances. Particularly, where adjacent buildings were of different heights, the lower building created a buttressing effect and caused a damaging whiplash of the protruding part of the taller neighbor.

While flexible buildings had the tendency to collapse in a "pancake" manner due to column failures resulting from large interstory distortions, a case of a very stiff building was observed which developed extremely high overturning moments and tilted over in its entirety, pulling the friction piles from the ground.

There were also cases of soil subsidence causing a building to settle as a block by about a third of its ground story (Fig. 7).

Buildings containing shear walls performed generally well, offering a better damage control to nonstructural elements by limiting the drift during the earthquake response.

An important observation is that an overwhelming majority of the buildings located in the area of maximum damage, even those in the period range susceptible to this earthquake, fared extremely well. In most cases, collapsed buildings were surrounded by others which went through the earthquake undamaged (Figs. 8 and 9).

BUILDING CODES

Before 1957, the Mexican Building Code had no special detailing requirements for seismic design and specified a lateral design force of 0.025g. After the 1957 earthquake, the lateral force requirements were gradually increased.

In the 1976 Code a higher lateral design

Fig. 8. Most buildings behaved well.

Fig. 9. Most buildings behaved well.

force requirement was specified. The detailing requirements introduced in the 1976 Code are less stringent than the requirements of ACI 318-83, Appendix A.

Following the 1985 earthquake, emergency regulations were introduced increasing considerably the lateral force requirements and specifying stricter rules aimed at increasing the rigidity of buildings to reduce drift, limiting plan eccentricity to reduce torsion, improve inspection requirements, and other provisions. These emergency regulations will eventually, after careful scrutiny, become part of the Mexican Code.

PRECAST PRESTRESSED CONCRETE PRODUCTS

Currently, there are about ten manufacturers of precast prestressed concrete products in Mexico City, two of which produce exclusively architectural precast concrete.

Structural Precast Concrete

The producers of structural precast concrete manufacture a variety of standard components such as single tees, a variety of double tees [2 m, 2.5 m and 3.0 m (6.6, 8.2, and 9.8 ft), hollow-core slabs (Spancrete, Dycore and Spiroll), thin precast prestressed plates to be used for composite slabs, small precast beams used with concrete filler blocks for spans up to 6.1 m (20 ft), all types of beams for custom designed industrial plants, columns on an individual order basis, mostly up to five stories high (only occasionally up to nine stories), standard and special bridge girders and other complex shape elements for special projects.

In recent years, precast concrete manufacturers have been using portable precasting plants at the sites of major projects to avoid long distance hauling of large precast elements.

The prestressing industry annually uses

between 7000 and 8000 tons of prestressing wires and another 7000 tons of prestressing strands.

Only a very small percentage of buildings in the center of Mexico City utilize structural precast concrete. Most of the precast buildings are outside the center of the city. Within the city, use of cranes for erection of large elements is difficult in the narrow streets with heavy traffic. Several multistory parking garages have been built with precast elements, some of them in the area of maximum damage.

About 40 percent of bridges in the Mexico City area are constructed with precast prestressed members using substantial amounts of cast-in-place concrete to tie the bridge components together in order to achieve a behavior similar to that of monolithic concrete.

It should be noted that the awareness of the engineering community of the seismic problem has resulted in using precast elements in buildings with cast-in-place concrete to create composite action. All structural slab elements (single tees, double tees, hollow-core slabs, and small beams with fillers) are used with a cast-in-place reinforced concrete topping.

The connections between slabs and beams and beams and columns are cast in place with the reinforcing bars mostly welded. In rare cases, post-tensioning is used to create connections between beams and columns. In the majority of city buildings using precast elements, the columns are cast in place. Only rarely were shear walls used in these buildings.

Architectural Precast Concrete and GFRC

There are about 1000 buildings up to fifteen stories in height in Mexico City clad with architectural precast concrete panels (Figs. 10 and 11).

Currently, there are about a dozen buildings in Mexico City in which glass fiber reinforced concrete (GFRC) was used as backing for the facing concrete in architectural precast panels. Two of the buildings are in the twenty-story range, the remainder are four to five stories in height. The performance record of these GFRC panels over their 4 to 5 year life is satisfactory. None of these buildings are located in zones of earthquake damage.

PERFORMANCE OF STRUCTURES WITH PRECAST COMPONENTS

This section presents the author's observations of the performance of structures using precast concrete components in Mexico City and Lázaro Cárdenas.

Mexico City

Buildings — Throughout Mexico City there is a significant number of multistory residential and commercial buildings and parking garages constructed with precast elements, although they represent only a small percentage of the buildings in the city. There are also many single-story and two-story schools built with precast elements.

Although the majority of these buildings are in areas which suffered little damage, many buildings using precast elements are located in zones of severe damage. Inspection of many of them in the area of severe damage showed little or no damage. Some of the inspected buildings and parking garages are described in Appendix A.

Five of the 265 collapsed or most severely damaged building structures contained precast elements.

Inspection of the remains of two of these collapses — the six-story Maternity Ward at the General Hospital (Figs. 12 and 13); and the partially collapsed seven-story public parking garage at Carranza Street (Figs. 14 and 15) — showed many connections between columns and beams intact. The remains and positions of the pancaked slabs suggested that collapses were caused by failures unrelated to the precast elements or their connections. Thus, the earthquake performance of these buildings was similar to those of monolithic concrete frames.

Fig. 10. Architectural precast concrete cladding.

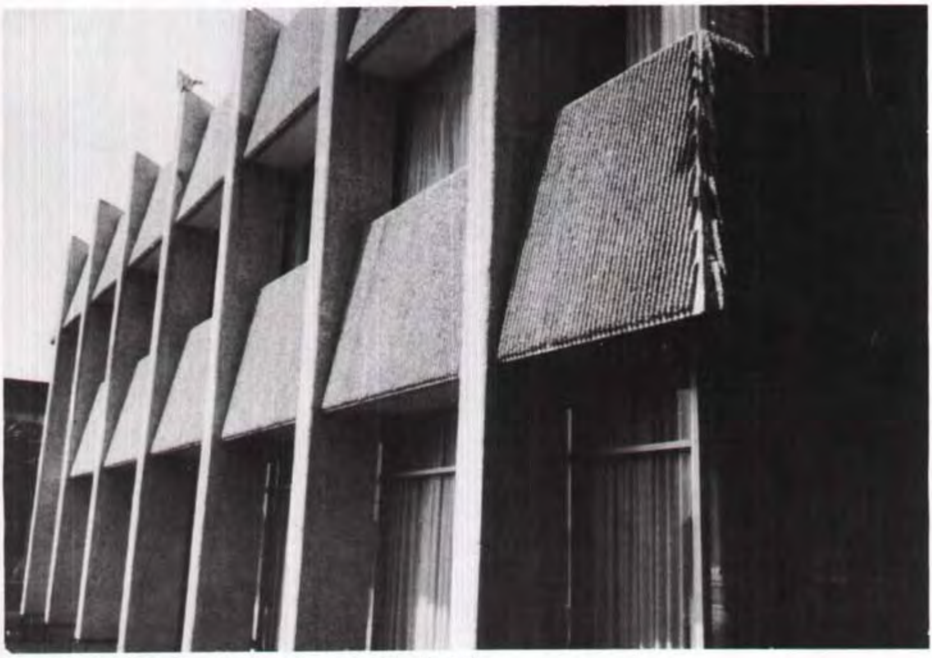


Fig. 11. Architectural precast concrete cladding.

Fig. 12. Remains of six-story Maternity Ward, General Hospital.

Fig. 13. Remains of six-story Maternity Ward, General Hospital.

As can be seen in the figures, the Maternity Ward used double tee slabs with 5 cm (2 in.) topping, while the parking garage used topped hollow-core slabs. The Maternity Ward was a free standing structure and column failures might have been the primary cause of collapse. The parking garage stood in the middle of the block squeezed in between neighboring structures; hammering against the adjacent structures might have caused the failure.

The remains of the other three collapsed buildings using precast components could not be inspected since they had been cleared by October 12, 1985.

Bridges — It is worthwhile to mention that none of the concrete bridges in Mexico City, whether cast in place or precast, suffered any damage during the earthquake. Also, there were no official reports of bridge failures from the interior of the country.

Architectural Precast Concrete — Of the more than 1000 buildings clad with archi-

Fig. 14. Partially collapsed seven-story public parking garage at Carranza St.


Fig. 15. Detail showing partially collapsed seven-story parking garage at Carranza St.

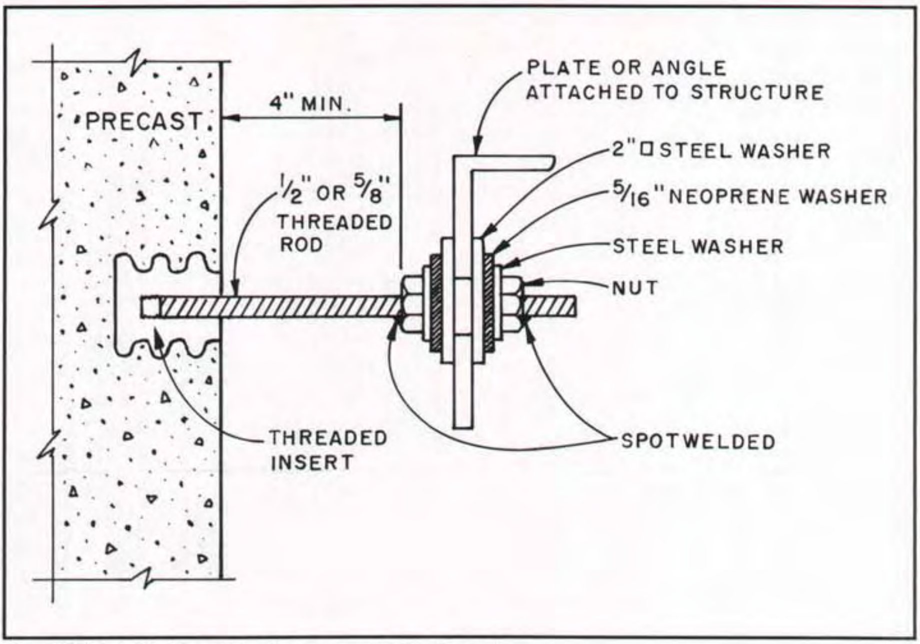


Fig. 16. Detail of architectural panel attachment.

Fig. 17. Panel attachment detail.

tectural precast concrete panels, many were in the zones of severe damage. The architectural cladding panels performed very well during the earthquake (Figs. 10 and 11).

It is customary in Mexico to attach architectural panels by welding the insert plates at the bottom of the panel to the structure and to use the detail shown in Fig. 16 at the top of the panels to allow for relative movements of the panels due to thermal and shrinkage effects of the panels, in addition to shrinkage and creep of the columns. This detail also allows for frame distortions due to wind or earthquakes without damaging the precast panels. Fig. 17 shows a picture of this detail.

There were only two cases of poor performance of architectural cladding during the earthquake. In the case of the six-story "Seguros la Republica," a number of panels pulled away several inches at their upper flexible connections after some bolts sheared off. The lower welded connection of the panels remained intact and kept the panels from falling off the building. The original connections were re-established after the earthquake by removing the sheared bolts and installing new ones.

The other case was that of the twelve-story building at the corner of Nuevo Leon and Campeche Avenue in which the upper three, two-story architectural panels fell off the building during the earthquake. Those were U-shaped panels, 1.20 m (4 ft) wide and 25 cm (10 in.) deep, that covered the two columns at an expansion joint and were attached to only one of the two columns to permit the joint to function. Apparently, during the earthquake the joint opened wider than the space provided, thus throwing off the panels.

In a number of instances, where significant nonstructural damage to multistory buildings attested to interstory distortions, the architectural cladding of these buildings remained fully intact. This stability indicates that the detail shown in Figs. 16 and 17, which was used in these buildings, provided sufficient distortion capacity to allow the distortions of the structure without damage to the panels.

Lázaro Cárdenas

The seismic performance of a number of very large, fully precast industrial buildings in the fertilizer manufacturing plant in Lázaro Cárdenas, under construction since 1978, is of particular interest due to their proximity to the epicenter of the earthquake [about 30 km (19 miles)] and due to the recorded strong motions there as described previously.

One of the reasons prestressed concrete was selected for these structures was the need for protection against corrosion, which is a usual requirement in the environment of chemical plants. At this fertilizer plant there were three giant horizontal industrial "A-frame" silos* (Fig. 18). The fourth is now under construction. Each of the three-hinged silos measures 68 × 280 m (224 × 918 ft) in plan and is 28 m (92 ft) high at its apex.

The silos, described in more detail in Appendix B, consisted of two 44.7 m (146.6 ft) long precast prestressed channel beams tied together by post-tensioned beams under the floor.

There were also two-story plant buildings; one three bays and the other two bays wide. The roofs consisted of simply supported, channel section, precast prestressed beams spanning 25 m (82 ft). See Appendix B for more detailed descriptions of these buildings.

At the location of the precast plant buildings the ground movements were extremely violent. In some locations inside and outside of the buildings fine granular soil was shooting out during the earthquake like geysers, creating large mounds up to 1 m (3.3 ft) in height.

Within the two-bay building, the previously level, slab-on-grade became wavy (Fig. 19), inducing a difference in elevation of 1 m (3.3 ft) between the lowest and highest points. The middle row of columns settled relative to the exterior rows registering

* "Giant Precast Silo for Storing Fertilizers Built in Mexican Port," by José Ma. Riobóo, PCI JOURNAL, V. 27, No. 4, July-August, 1982, pp. 108–119.

Fig. 18. Giant horizontal silo.

measured differentials up to 60 cm (24 in.). There was also extensive damage to the roadway running along the storage building with the roadway settling in some locations up to 50 cm (20 in.).

Both the giant silos and the plant buildings performed very well during the earthquake. Only a very few purlins had fallen off their supports in the silos. In the two plant buildings several beams shifted on their supports and only two beams (out of 60) exhibited slight shear cracking (Fig. 20) in addition to some minor repairable distress and dislocation.

This exemplary performance of the precast elements, despite the large differential settlements, was a result of the statically determinate structural configuration in which differential settlements do not cause additional moments or shears. This structural system with corresponding details allowing rotations without loss of support contributed to the excellent performance during the earthquake.

OBSERVATIONS

1. The disastrous earthquake off Mexico's Pacific coast on September 19, 1985 and the aftershock on September 20, 1985, having Richter magnitudes of 8.1 and 7.5, respectively, caused an amount of destruction in Mexico City, 400 km (250 miles) away from the epicenter, never before experienced in the western world in modern times.

2. Accelerations of only 4 percent of gravity were registered on firm ground around the city. These were amplified to 20 percent of gravity by the soft layers of the filled-in lake bed. The earthquake was also of unusually long duration consisting of twenty 2-second pulses which caused disastrous resonance with structures having periods of vibration in the 2-second range.

3. Some 265 multistory buildings, most of them ranging from six to fifteen stories, collapsed or were severely damaged. Most collapses of concrete structures appeared to have occurred due to large interstory distortions causing shear failures of columns.

Fig. 19. Slab waves 1 m (3.3 ft) high.

Fig. 20. Shear crack in roof beam.

4. As in previous earthquakes, buildings containing shear walls performed well, offering better damage control by limiting drift, and thus also reducing the danger of collapse.

5. The choice of a structural system with sufficient overall stiffness cannot be overemphasized. In concrete structures the overall rigidity can be provided either by incorporating shear walls or by column and beam sizes to result in adequate stiffness. Providing for a given seismic intensity, a level of strength consistent with the degree of available ductility will ensure survival in an earthquake. However, the best detailing of members and connections cannot compensate for an inadequate structural system.

6. There are many buildings and multistory parking garages using precast components in Mexico City (some in the areas of severe damage) which withstood the earthquake without damage or distress.

7. Five multistory buildings (one parking garage among them) using precast components suffered total or partial collapse. These were composite structures using a substantial amount of cast-in-place concrete. Inspection of the debris suggests that the reasons for failure of these buildings were the same as for the concrete frame structures and were not related to the use of precast prestressed components.

8. Of the 1000 buildings clad with architectural precast concrete panels, many were in the area of the city in which severe damage occurred. In many distressed buildings, the architectural panels showed no distress due to the flexibility of their attachment details. Only two buildings had some distress of architectural panels.

9. The twelve buildings ranging from two to twenty stories clad with GFRC panels were not in the area of earthquake damage.

10. Forty percent of Mexico City bridges are built with precast concrete components. None of the bridges (cast in place or precast) suffered any damage.

11. In Lázaro Cárdenas [30 km (19 miles) from the epicenter] a number of fully precast and prestressed large industrial structures performed extremely well during the earthquake despite considerable ground movements. The four three-hinged giant silos with beams of 44.7 m (146.6 ft) in length lost only a few purlins. In a plant building the simply supported beams spanning 25 m (82 ft) experienced only a few minor shear cracks in two (out of 60) beams despite differential column settlements of up to 60 cm (2 ft).

In conclusion, it should be emphasized that this report presents primarily the author's observations of the performance of precast and prestressed concrete structures in the Mexico Earthquake. Because of time and financial limitations, it was not possible to obtain an in-depth technical perspective on seismic performance that includes cause and effect relationships. Nevertheless, the author believes that the opportunity exists to conduct a comprehensive study of the behavior of not only the hundreds of failed buildings but also the thousands of structures that survived this unique earthquake undamaged. Such a study would be of immense value to researchers, engineers and code writers, enabling them to incorporate this experience into better designed structures in the future.

ACKNOWLEDGMENTS

The author appreciates the assistance of the Mexican National Association of Prestressers and Precasters during his visit. Particular help was received from Mr. Mario Fastag of Pretesca Group, Mexico City, producers of architectural precast concrete and GFRC and from Mr. Aurelio Zugasti of Ticonsa, manufacturers of the precast components for the fertilizer plant in Lázaro Cárdenas.

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APPENDIX A — BUILDINGS IN MEXICO CITY

The following is a description of some of the buildings inspected in Mexico City after the earthquake:

— Eleven-Story Apartment Building
— Seven-Story Parking Garage
— Four-Story Parking Garage
— Abraham Ayala Gonzalez Auditorium
— Ten-Story Parking Garage
— Five-Story Parking Garage

Eleven-Story Apartment Building

This structure, which is located at No. 210 Amsterdam Avenue (Fig. A1), was built in 1979 using Spancrete hollow-core slabs with a 5 cm (2 in.) topping. The columns are cast in place. In the lower five stories, concrete block masonry partitions were used, and in the upper six stories, the partitions were of gypsum drywall.

No structural damage was observed on this building except for cracking in the stairs at the junctions of inclined stair slabs and the horizontal landings. Cast-in-place stairs usually act as vertical trusses with high rigidity, and not until the stairway is damaged does the flexible frame participate in lateral resistance. There was moderate to extensive diagonal cracking in the concrete masonry partitions (Fig. A2) in both directions; however, no cracking was observed in the gypsum partitions.

Seven-Story Parking Garage

This structure, situated at Moreno and Quantaneros Streets, is located in an area of the city where moderate damage oc-

Fig. A1. Eleven-story apartment building on Amsterdam Avenue.

Fig. A2. Cracking of masonry partitions in adjacent building.

Fig. A3. Seven-story parking garage at Moreno Street.

curred during the earthquake (Fig. A3). The structural system has three 17 m (56 ft) spans of prestressed single tees supported on inverted tees on the interior and L-beams at the exterior ends. These in turn are carried by precast concrete columns. Cast-in-place concrete is used generously to tie the precast elements together to create frame action for lateral resistance.

Architectural precast concrete spandrel panels are attached to the structure all around the periphery. There are no signs of distress in the garage, although there is ample evidence of distortions during the earthquake as seen in the cracked buttressing wall at the entrance to the garage (Fig. A4).

Fig. A4. Cracked buttressing wall at garage entrance.

Four-Story Parking Garage

This structure is located at Antonio Anza and Cuauhtemoc Avenue (Fig. A5) across the street from the General Hospital collapses and adjacent to the Multifamily Housing Complex collapse. The lower story of the parking garage is used for commercial space and the upper three stories for parking.

The structural system: the slabs spanning 15 m (50 ft) used 60 cm (2 ft) deep double tees with 5 cm (2 in.) reinforced concrete

Fig. A5. Four-story parking garage in the zone of maximum damage.

topping supported on inverted T-beams which rest on precast columns with large capitals. There are seven 15.25 m (50 ft) bays longitudinally and seven 11 m (36 ft) bays transversely.

The column to beam connections are cast in place with protruding bars and bars inserted through round cores left in the columns. The lateral resistance in the transverse direction is provided by the inverted tees interacting with the columns to create frame action. In the longitudinal direction (in the direction of the double tees) heavy, 1.1 m (3 ft 8 in.) wide beams on all column lines provide frame action with the columns. There are circular ramps at the center of the structure.

The fascias on all floors around the periphery of the parking garage are curved architectural precast concrete panels. Except for several very minor separation cracks in the ground story between the masonry filler walls and columns (Fig. A6), there is no sign of any structural distress in this structure which is located in an area of most severe damage.

Abraham Ayala Gonzalez Auditorium

This building, located at the General Hospital (Fig. A7), was constructed about 8 years ago, with a seating capacity of about 1000. The roof of the auditorium consists of

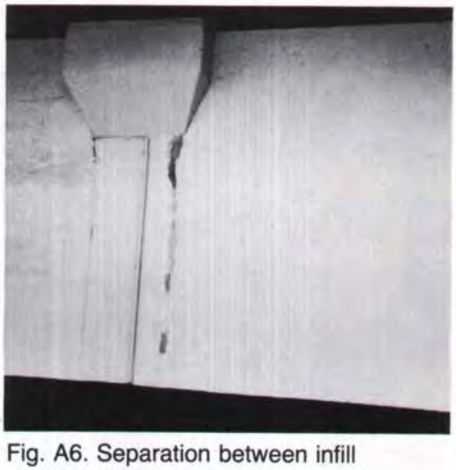

Fig. A6. Separation between infill masonry and frame.

Fig. A7. Abraham Ayala Gonzalez Auditorium.

single tees spanning up to 25 m (82 ft). There is no sign of any distress whatsoever in the structure.

Ten-Story Parking Garage

This structure, which is situated on Flamingo Avenue is located in an area of the city which underwent considerable damage (Fig. A8). All around the garage are severely damaged structures, some with several upper stories collapsed. In the adjacent block two steel structures (the twenty-one and thirteen-story Pino Suarez Office Buildings) collapsed and their twenty-one-story steel neighbor is several feet out of plumb, as seen in Fig. A8. The structural slab of the garage consists of precast prestressed double tees with a 12.2 m (40 ft) clear span supported on 1 m (3.3 ft) wide inverted tees and cast-in-place concrete columns.

Fig. A8. Ten-story parking garage on Flamingo Avenue. In background is the tilted twenty-one story steel structure.

In the direction parallel to the double tees, there are cast-in-place beams on the column lines to create frame action with the columns for lateral resistance. There is a significant number of concrete walls around the periphery. This ten-story parking garage does not show a single sign of distress.

Five-Story Parking Garage

This structure is located at the corner of Alliende and Equador Streets. The east half of the building is cast-in-place concrete while the west half of the structure was switched to precast concrete for economic reasons. The precast part uses prestressed concrete channels with a 5 cm (2 in.) topping, precast beams and precast concrete columns five stories high. No signs of distress could be observed in this building.

Several other buildings using precast components were also inspected. However, they were located in areas in which no damage was registered to them or to any other types of construction.

APPENDIX B — STRUCTURES IN LÁZARO CÁRDENAS

The following is a description of the inspected industrial structures built of precast concrete components at the fertilizer plant in Lázaro Cárdenas:

— Giant Silos
— Three-Bay Building
— Two-Bay Building

Giant Silos

Three giant precast concrete silos (a fourth is now under construction) for storing fertilizer of pitched (A-frame) sections (Fig. B1) were constructed since 1978; each one measuring 68 m (224 ft) in width and 280 m (918 ft) in length and 28 m (92 ft) in height.

The three-hinged A frames [every 9.4 m (28.7 ft)] consist of two precast prestressed channel beams 44.7 m (146.6 ft) long with a maximum depth at midspan of 1.8 m (5.9 ft). The two channel beams are tied at the footing level by post-tensioned beams. The spread footings have sockets to receive the main beams. At each of the three hinges, neoprene plates are used to allow for rotation.

The length of each silo is subdivided into three segments by expansion joints. L-shaped precast prestressed purlins receive the as-

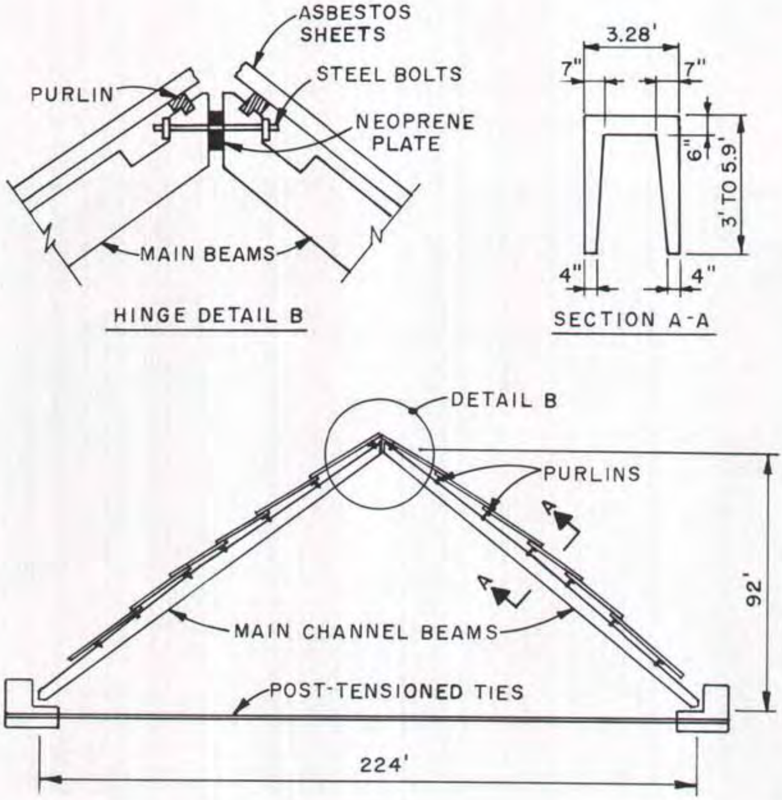

Fig. B1. Section of silo and details.

bestos structural sheets. To provide wind and seismic bracing, similarly shaped purlins have been arranged diagonally between the three-hinged arches to create horizontal trusses for one-third of the length from each end of the silos.

As a result of the earthquake, only a very few purlins have fallen off in these four silos. Also, some of the columns of the longitudinal wall near the outside abutments settled up to 10 cm (4 in.) leaving a gap between these columns and the main beams. The silos withstood this earthquake remarkably well.

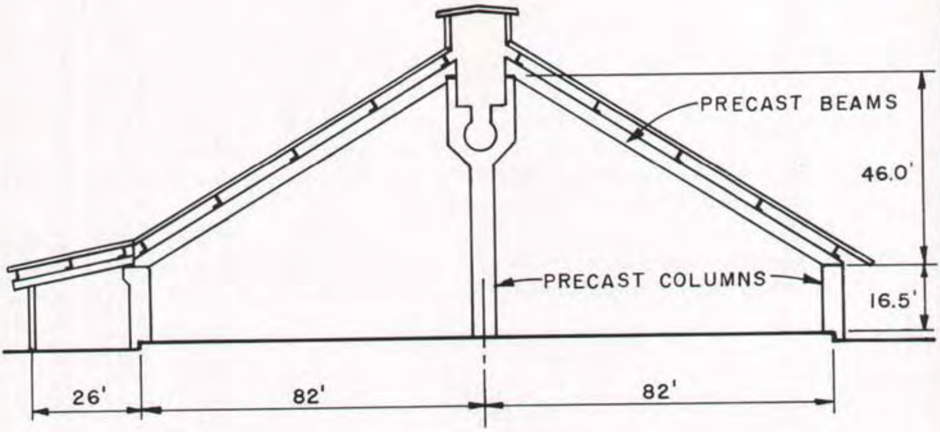

Fig. B2. Section of two-bay building with lean-on bay.

Fig. B3. Middle column row of two-bay building.

Three-Bay Building

A three-bay building (two bays and a lean-on) 58 m (190 ft) wide and 120 m (394 ft) long was recently completed. The two bays each span 25 m (82 ft) (see Fig. B2). The sloping, simply supported precast prestressed roof beams have channel sections similar to those of the giant silos shown in Fig. B1.

Also, purlins and asbestos roofing are similar to those in the giant silos. The columns are precast concrete. While the side columns are 5 m (16.5 ft) high, the 19 m (62 ft) high middle row columns are split at their top 4.5 m (15 ft) into a fork-like shape to receive conveyors and the two roof beams (Fig. B3).

The lateral resistance is provided by the four rows of columns acting as cantilevers. During the earthquake, several of the sloping roof beams shifted on their supports by as much as 20 cm (8 in.) (Fig. B4). Measured after the earthquake the exterior longitudinal walls shifted and the width of the building increased by 10 to 12.5 cm (4 to 5 in.). Also, large mounds of thin material were driven through the slab-on-grade joints in a geyser-like fountain.

Two-Bay Building

A two-bay building 50 m (164 ft) wide and 120 m (394 ft) long, also recently completed, has a slightly sloping roof with similar simply supported channel section precast prestressed roof beams, purlins and asbestos structural sheets as the other buildings. The massive precast concrete columns resting on spread footings and acting as cantilevers provide the lateral resistance for the structure.

During the earthquake, the movement of the ground caused the initially horizontal slab-on-grade to become wavy with differentials from the lowest to the highest point of more than 1 m (3.3 ft) as can be seen in Fig. 19.

Some columns of the middle row settled causing differentials relative to the exterior columns up to 60 cm (24 in.). Roof beams

Fig. B4. Beam shifted 20 cm (8 in.) at top of column.

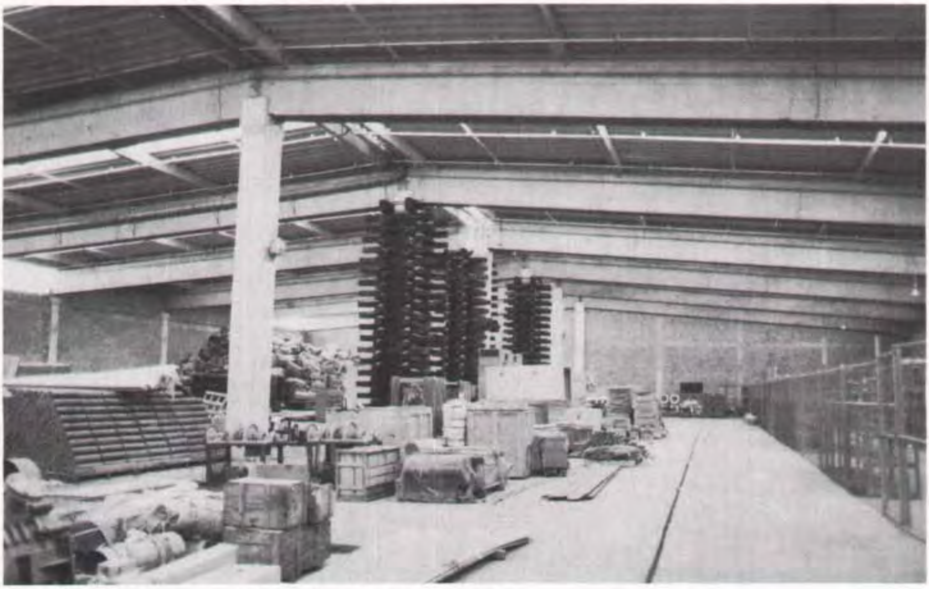

Fig. B5. Temporary cribbing for repair of support.

at three column locations required temporary cribbing (Fig. B5) so that the beam seating could be repaired. However, not a single structural element suffered serious distress or collapse.

A free-standing 5 m (16.4 ft) tall end wall of this building is out of plumb by 50 cm (20 in.) and will have to be replaced.

The exemplary performance of the precast concrete structures despite the large differential settlements was the result of the statically determinate structural configuration in which differential settlements do not cause additional moments or shear.

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NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by September 1, 1986.