Engineering Features of the Recent Mexican Earthquake

by James L. Beck and John F. Hall

The unique mid-level collapse of the hotel shown above may have resulted from a discontinuity in the structural system. This case presented quite a dilemma for the demolition crew, because the hotel is leaning over a row of undamaged apartment buildings in the rear. The leaning portion of the structure was finally removed piece by piece.

THE EARTHQUAKE OF SEPTEMBER 19, 1985 produced the worst earthquake disaster in Mexican history. Mexico City, although not devastated, sustained a huge blow in which as many as 10,000 lives may have been lost. About 250,000 people, of a population of 18 million, lost their dwellings, and more than 300 multi-story buildings either collapsed or were seriously damaged. Public buildings, such as schools, hospitals, and some government housing projects, were particularly hard hit, resulting in a large loss of life.

Transportation and communication systems, on the other hand, fared well. The subway and the international airport were functioning again soon after the earthquake. Long-distance telephone transmissions were interrupted because of the collapse of the office building housing the equipment, but the local telephone system still worked. Utilities also suffered only minimal damage. Water supplies eventually ran short because of damage to the distribution pipelines in the eastern and southeastern regions, but electrical power continued to flow to most of the city. The collapsed Regis Hotel was the source of the only major fire from gas leakage, although a number of smaller fires broke out elsewhere.

The earthquake occurred at 7:18 a.m. on Thursday and had a Richter surface wave magnitude of Ms=8.1. A large aftershock of magnitude Ms=7.5 followed on Friday evening. The main shock was centered 250 miles from Mexico City on the Pacific coast, near the town of Lazaro Cardenas on the border between the states of Michoacan and Guerrero (figure 1). The rupture zone extended for about 125 miles parallel to the coast along a tectonic feature called the Cocos subduction zone, which stretches for more than 1,000 miles along the Pacific coast of Central America. This feature is the source of many large earthquakes that have shaken the central and southern parts of Mexico in this century, including the 1957 Acapulco quake (Ms=7.5) and the 1979 Petatlan event (Ms=7.6), both of which produced serious damage in Mexico City.

In this subduction zone, part of the floor of the Pacific Ocean, called the Cocos plate, is being forced under the landmass of Mexico, which lies on the North American plate. This is happening at a rate of about three inches per year. This relative motion builds up large strains at the interface of the two plates where they are locked, and the earthquakes result from episodic release of the strain energy by localized rupturing of the interface. Primarily on the basis of this simple physical model, some seismologists had anticipated that a major earthquake would eventually occur in the area of the recent event. They had labeled this area the Michoacan seismic gap, because it had not ruptured completely for more than 70 years, while neighboring regions had produced earthquakes several times during this period. For the same reason, a major earthquake is expected to occur eventually in the Guerrero gap, which lies between the rupture zones of the 1979 Petatlan and 1957 Acapulco earthquakes. In such an event, structural damage is likely to occur once again in Mexico City.

We visited Mexico City 12 days after the September earthquake and spent four days walking around the city observing the damage to buildings. Although we found it informative, there are limits to what we could learn in this way. The collapsed buildings, for example, left little visual evidence of the weaknesses that had precipitated their collapse, and it was difficult to gain entry to seriously damaged buildings to inspect their interiors. But what really stood out was the extent of the damage to modern multi-story buildings, which is perhaps unprecedented. A survey by engineers from the National Autonomous University in Mexico City (UNAM) revealed that buildings of 6 to 15 stories sustained most of the damage. Distribution of severe structural damage throughout Mexico City, based on this survey, is shown in figure 2. Most of the damage is confined to those areas of the city that are on the dry lake bed. The Aztecs originally founded their city on an island in this ancient lake.

Ironically all of the old colonial buildings and the majority of the old low-rise buildings built before the introduction of a modern building code in 1957 apparently survived the earthquake with little damage. This surprising result demonstrates an important principle in earthquake-resistant design. Whether or not damage occurs depends not so much on the absolute strength of the structure as on its strength relative to the seismic attack imposed by the earthquake. The seismic forces generated in a structure depend on both the amplitude and the frequency content of the ground shaking. Because the ground motion on the lake bed was of a long-period nature, multi-story structures, which have long fundamental periods of vibration, experienced a seismic attack many times larger than that felt by low-rise buildings, which have much shorter natural periods. This resonance phenomenon accounts for the concentration of damage in buildings 6 to 15 stories high.

Even if the seismic attack on high-rise buildings was much stronger than that on low-rise buildings, the question still remains: Why did so *much* damage occur in the taller buildings? There were probably common factors operating. Poor-quality materials, poor workmanship, and a lack of adherence to the earthquake building code may have played a

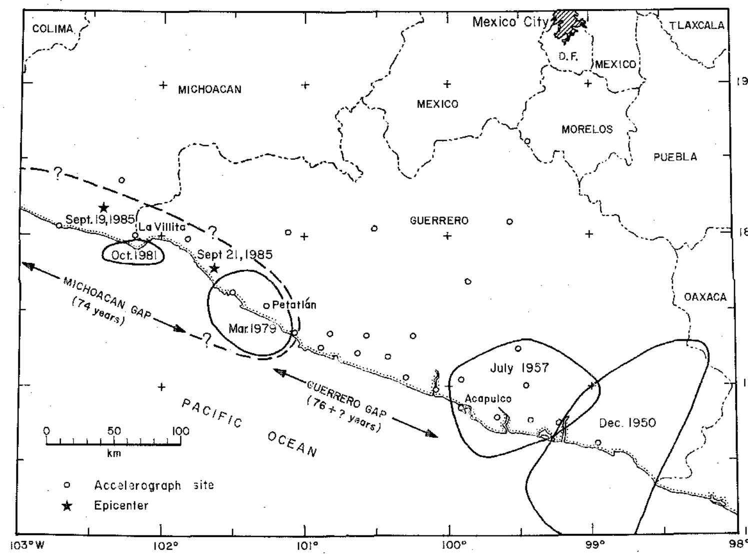


Figure 1 (above): Map showing the preliminary epicenters of the main shock and largest aftershock relative to Mexico City. The estimated rupture zones of the September earthquake and some earlier events along the Cocos subduction zone are also shown. This figure is adapted from a report on the coastal accelerograph array by Brune and Prince and their colleagues.

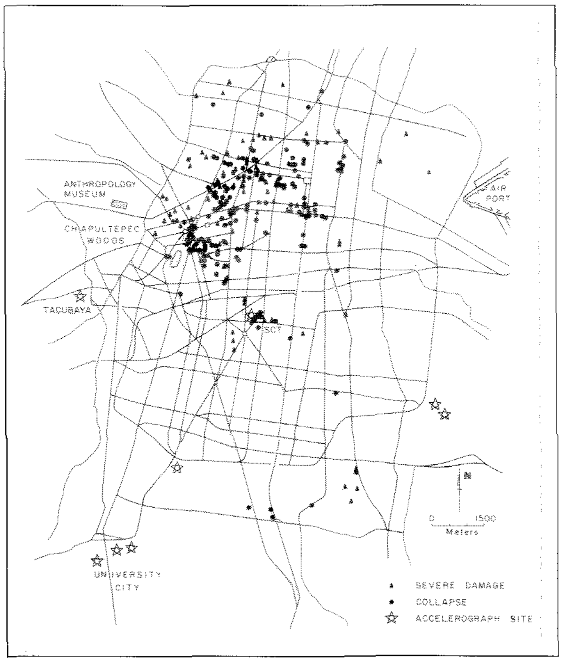


Figure 2 (left): Distribution of severe structural damage and sites where records of the strong ground shaking were obtained. Only some of the major streets of Mexico City are drawn. Damage is confined to areas on the old lake bed.

role in some cases. In our opinion, however, the main reason for the extensive damage was that the intensity of shaking on the lake bed was not anticipated.

Before the earthquake, the seismic provisions of the building code for Mexico City would have been considered adequate by most engineers familiar with the principles of earthquake-resistant design. It was known from earlier strong-motion earthquake records obtained in Mexico City that the ground motion is substantially altered by the sediments of the lake that once existed there. A soft clay layer 50 to 100 feet thick, which underlies the city in the area where the damage was concentrated, acts like a narrow-band filter that greatly amplifies the ground motion over a narrow frequency range. The building code took this into account by assigning the largest earthquake design forces to structures in the period range from 0.8 to 3.3 seconds, which were to be built on the lake bed. In contrast, U. S. codes take advantage of the fact that all strong-motion records obtained in this country show that the energy in the spectrum of the ground motion peaks at shorter periods, so the design forces prescribed in the code usually decrease for building periods longer than about 0.3 seconds.

But no one anticipated the amount of amplification of the ground motion in the old lake sediments. A strong-motion record obtained at the SCT site (Ministry of Communications and Transportation) on the lake bed shows a ground acceleration history of long duration, which peaked at 17 percent of gravity and whose frequency content is dominated by a component with a period of two seconds (figure 3). In contrast, the ground motions recorded on firm ground in Mexico City show a broader frequency content and exhibit peak accelerations in the range of 3 to 4 percent of gravity, a factor of 4 to 5 less than at the SCT site. An example of a firm ground record is shown in figure 4, which is from an accelerograph at the Seismological Observatory at Tacubaya on the western side of the city. The SCT record was published two days after the earthquake by Professor Jorge Prince and his colleagues at UNAM, and it plays an important role in establishing quantitatively how strong the ground shaking was on the lake bed. Unfortunately, this record was the only one obtained within the area of damage in the city, but ground motions of a similar general character probably occurred throughout the area.

We believe that the amplification on the lake bed is primarily due to a resonant buildup of seismic waves within the thick clay layer just beneath the surface. Because of this resonance, the duration of the incoming seismic waves is a very important factor in controlling the degree to which the ground shaking amplitudes build up. We feel that this is one of the important reasons why the recent earthquake was more destructive in Mexico City than other large earthquakes that

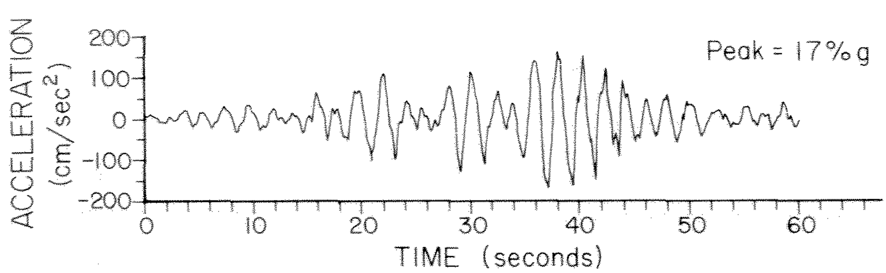


Figure 3: Ground acceleration in the east-west direction at the SCT site on the old lake bed.

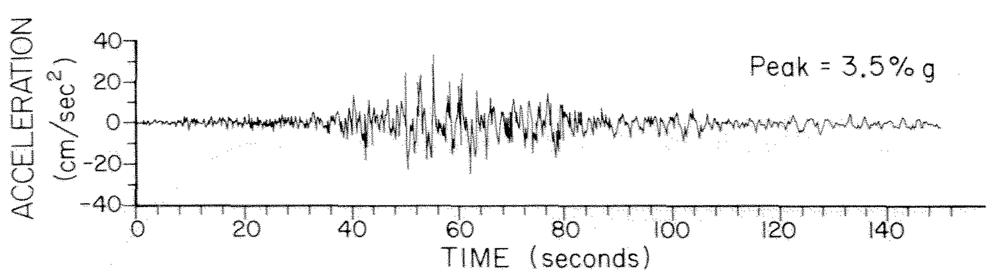


Figure 4: Ground acceleration in the east-west direction at the Seismological Observatory, Tacubaya, which is on firm ground. Note that the time scale is half of that in figure 3.

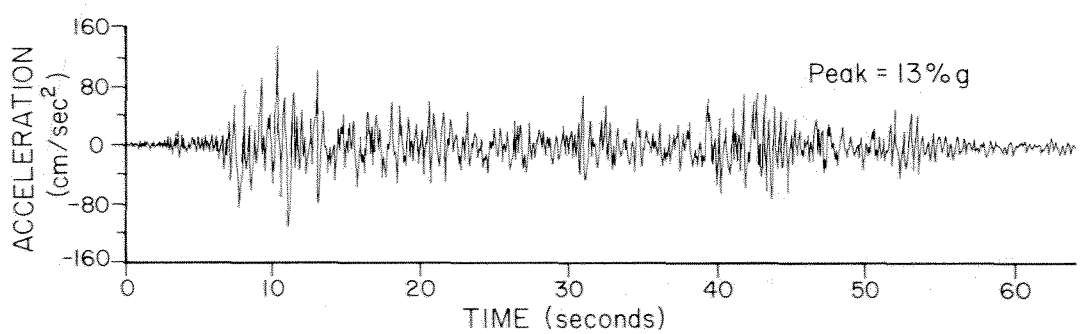


Figure 5: Ground acceleration in the north-south direction at La Villita near the center of the rupture zone on the Pacific coast.

have occurred in the Cocos subduction zone in the last 50 years. The ground shaking lasted longer because the recent event had a longer source duration than previous events in this zone. In fact, long-distance seismograph records from Caltech's Seismological Laboratory indicate that the September event was actually two large earthquakes — one 40 seconds or so after the other. Further support for this comes from some of the strong-motion records obtained in the epicentral region from an accelerograph array installed as part of a joint U.S.-Mexico project headed by Prince of UNAM and Professor James Brune of UC San Diego. For example, the La Villita record from the center of the rupture zone shows a second burst of stronger shaking about 40 seconds after initial triggering of the instrument (figure 5). Notice that the peak acceleration for this record is about 13 percent of gravity, lower than at the SCT site in Mexico City more than 200 miles away. This low value is consistent with peak accelerations of less than 20 percent of gravity exhibited by other accelerograph records obtained over the fault zone, which explains why severe damage was not widespread in the coastal regions.

The longer duration of the main shock on September 19, compared with earlier earthquakes, helps to explain the greater amount of destruction in Mexico City. First, the ground motions had more time to build up to large amplitudes by resonance within the old lake sediments. Second, once structural damage is initiated, it tends to worsen progressively as the number of large-amplitude cycles increases. So for longer shaking, more damage will accumulate.

In addition to the common factors for the widespread damage to high-rise buildings (figures 6 and 7 provide further elaboration), each damaged building showed its own particular weak points. Some of the weaknesses that we observed during our visit are illustrated in the photographs on the following pages. These do not include the cases, such as the General and Juarez Hospitals, where loss of life was high. These sites had been largely cleaned up by the time we arrived.

To structural engineers, the Mexican earthquake was a huge experiment, albeit a tragic one, which has provided invaluable data on the behavior of multi-story buildings in strong, long-period ground shaking. The earthquake is sure to stimulate much research, particularly studies of the phenomenon causing the amplification exhibited in the strong-motion records from the old lake bed compared with those on firm ground. Also, the strong-motion records obtained from the coastal accelerograph array are one of the richest sources of data available of the shaking in the epicentral region of a large subduction zone earthquake and are sure to receive much study by both earthquake engineers and seismologists. The earthquake engineering group at Caltech is planning to cooperate with colleagues from the Institute of Engineering at UNAM in a program to install a more extensive accelerograph array in Mexico City, which will also monitor structural response. The likelihood of future earthquakes shaking the city, particularly in the Guerrero gap, makes this an important project.

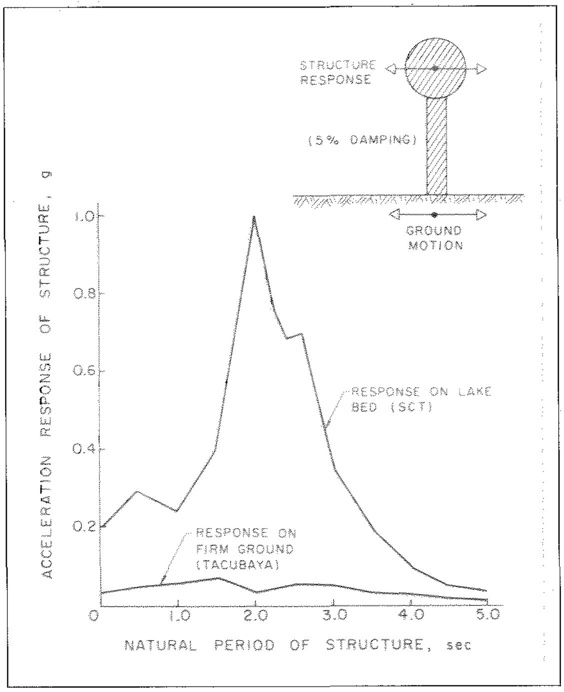


Figure 6: The engineering significance of earthquake ground motion is revealed by the response spectrum, shown here for the Tacubaya and SCT ground motions. A response spectrum shows the maximum response to the earthquake reached by an elastic mass-spring oscillator (i.e. an idealized building) as a function of the vibrational period of the oscillator. The SCT ground motion excites a much larger response than does the Tacubaya motion, especially when the period of the oscillator is near the predominant two-second period of the SCT ground motion, because this is when resonance occurs. Since the fundamental period of vibration of an N-story building is given by N/10 seconds, buildings in the 15-to-30-story range located on the soft clay layer should be most vulnerable.

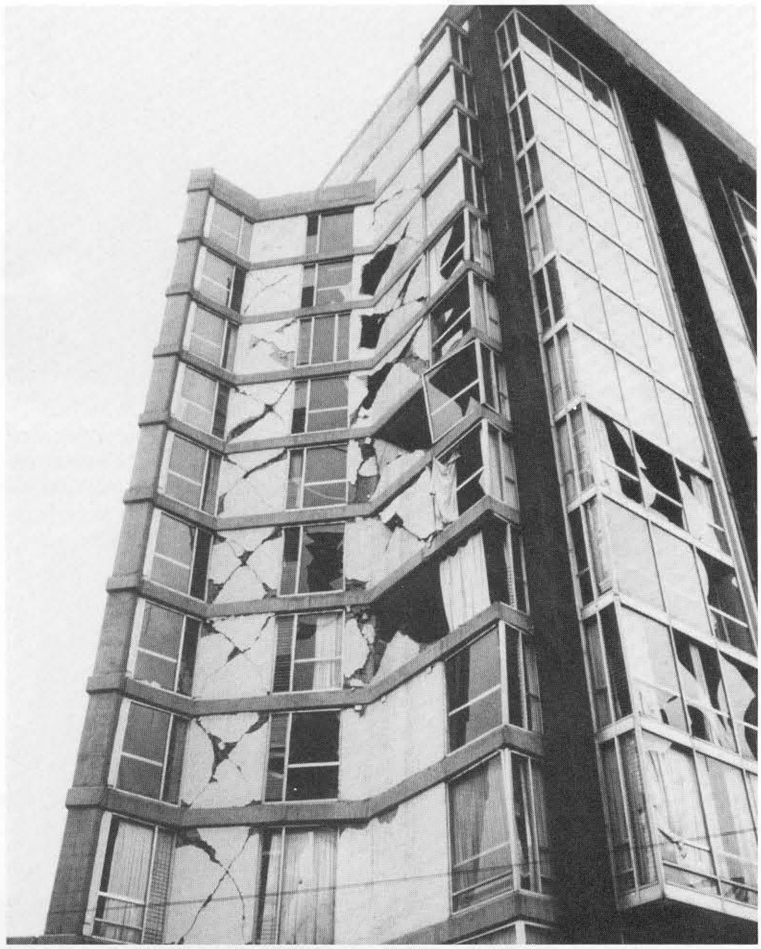
Number of stories	Percent of all buildings located in the damaged area that either collapsed or suffered severe damage.
1 to 2	2
3 to 5	3
6 to 8	16
9 to 12	23
13 to 15	22
16 to 22	? (3 total buildings)
more than 22	0

Figure 7: As seen from the table, the most vulnerable buildings were somewhat shorter than predicted by the response spectrum. This difference can be attributed to nonlinear effects; as yielding takes place, a building softens, and its fundamental period of vibration increases. Thus, during the earthquake an eight-story building may enter a resonant condition as its period increases toward the two-second period of the ground motion. On the other hand, a much taller building may leave a resonant condition as its period increases.

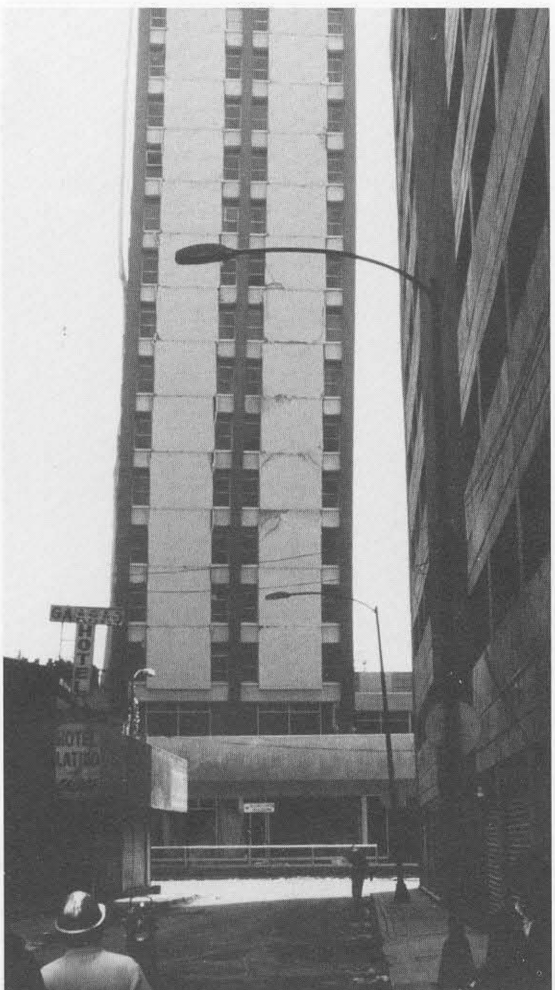
In design, ductility is interrelated with strength because if the strength of a building is too low, then the ductility demanded by an earthquake is very high. In Mexico City, lack of strength was evident in the columns of many buildings. When such buildings survived, they did so by narrow margins.

Most of the buildings that suffered full or partial collapses probably lacked ductility, that is, the ability to undergo considerable yielding without losing strength. Since even the best built buildings yield during strong ground shaking, ductility is essential to avoid collapse, especially for long-duration earthquakes when a number of yield cycles occur. In reinforced concrete construction, proper detailing and placement of the steel reinforcing bars is an important element in providing ductility. Perhaps with longer bar anchorages and extra hoops to confine the concrete, the school shown above would have safely survived the long duration of the Mexican earthquake.

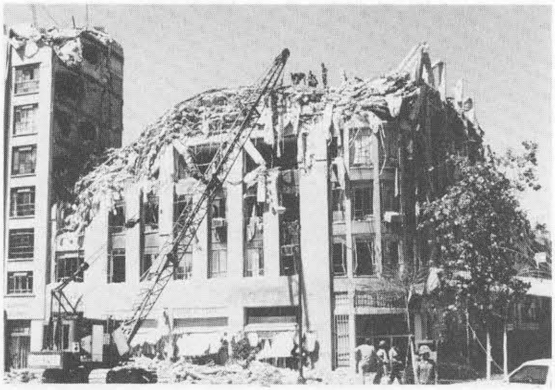
Only one of the original three sections of the Nueva Leon apartment building, a twin to the building in the background, remains standing (right, foreground). The close-up (below) of the remaining section reveals weak columns, a number of which failed.

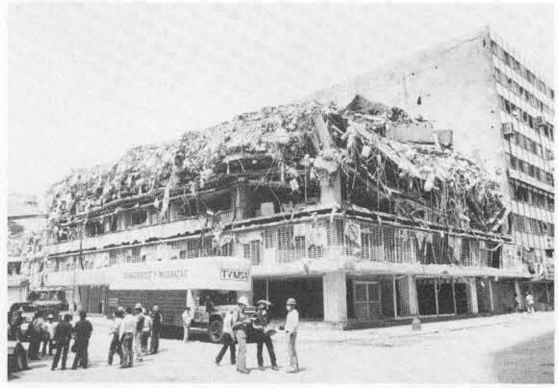


The use of unreinforced masonry to fill in exterior walls between reinforced concrete frames is a common construction practice in Mexico City. The masonry panels, being stiff, attracted a large share of the earthquake load and, being brittle, often failed. So these types of buildings were particularly susceptible to the effects of period elongation described earlier. In addition, use of masonry infills on three sides of a building, while leaving the front open, created a nonsymmetric distribution of stiffness, causing a torsional response that increased the stress on the structural elements in the perimeter of the building. The building above shows diagonal cracks typical of shear overstress.

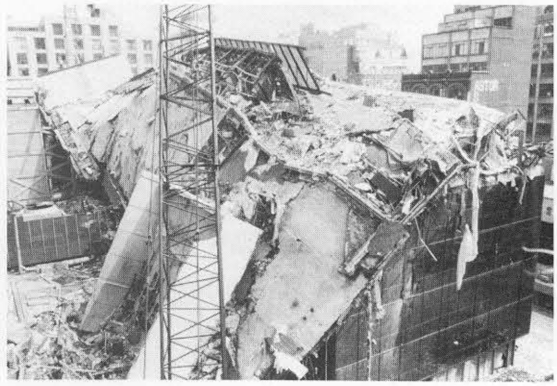


Steel construction is rare in Mexico City, yet one of the most spectacular examples of damage occurred to the complex of five steel-frame buildings at Conjunto Pino Suarez. The 21-story tower shown at left, one of three buildings that remained standing, is leaning six feet out of plumb at the roof level due to yielding which produced permanent interstory drift. To the right of this tower stood a fourth one, also 21 stories, that toppled onto a fifth tower of 14 stories, bringing it down as well. The toppled tower, shown above, which employed truss beams and box columns, overturned at the third-floor level. Failure may have been initiated in the trusses from buckling of the chords or in the truss-to-column connection by fracture of the weld.





An interesting characteristic of the damage in Mexico City is that a great number of buildings collapsed in their top stories, leaving the lower portion intact. Three examples are shown here. One possible reason for this behavior is that designers tapered the column sizes too severely in the upper stories, permissible if only gravity and wind loads act, but unwise for earthquake loads.



Flat-plate construction, consisting of reinforced concrete slabs and columns without beams, did not fare well in the earthquake. Inadequate shear strength in the slab-to-column connection resulted in pancake failures of the slabs with the columns remaining upright in many cases.

During the earthquake, buildings swayed back and forth; a 15-story building may have swayed as much as two feet at the roof level in each direction. Closely spaced buildings thus have the opportunity to damage each other through impact. These photos show examples of impact damage; the lower one suggests another reason why the top portion of some buildings collapsed.

***Most** multistory buildings in Mexico City are founded on piles. Those piles that are not long enough to bear on the firm stratum below the soft clay layer may have slipped downward during the earthquake. The result, as shown in the top photo, was a tilted building. Although the overturning failure shown in the lower picture appears to be foundation related, it was probably initiated by collapse of a corner column in the basement, which was then followed by uprooting of the pile at the opposite corner as the building overturned.*

***Below:** Even in the severely damaged areas of Mexico City, many buildings survived undamaged, some without even a single broken pane of glass. Why did some buildings fare well while others suffered? Were building collapses due to gaps in engineering knowledge or to sloppy design or construction? Is the building code adequate? These questions remain partially unanswered. Unfortunately, a lack of detailed documentation of the damage following the earthquake, the subsequent demolition and removal of many buildings without inspection or material testing, and the legal difficulty of gaining access to the structural plans of the buildings may prevent these questions from being completely answered.*