STRUCTURAL DAMAGE CAUSED BY
THE 1976 GUATEMALA EARTHQUAKE

By
METE A. SOZEN
and
JOSÉ ROÉSSET

A Report to the
NATIONAL SCIENCE FOUNDATION
(Research Grant AT A 74 22962)

UNIVERSITY OF ILLINOIS
at URBANA-CHAMPAIGN
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MARCH 1976
At the request of the Committee on Natural Disasters, the Panel on Earthquakes dispatched an inspection team consisting of Mete Sozen and Jose Roesset to Guatemala City to report on the effects of the recent earthquake on engineered structures. Attached are their preliminary field notes which are being distributed to persons concerned with earthquake engineering. A complete detailed report based on the team's findings will be issued in the near future.

Nathan M. Newmark, Chairman
Committee on Natural Disasters
15 February 1976

PRELIMINARY NOTES ON STRUCTURAL DAMAGE CAUSED BY
GUATEMALA EARTHQUAKES OF 4 AND 6 FEBRUARY 1976

by

Mete A. Sozen* and Jose Roesset**


Guatemala City - See map. Population 814,000 in 1964 census with a density of approximately 1,000 persons per sq. mile. Projected (1976) over one million. City grew by 85% between 1950 and 1964. Elevation 5,000 ft. Surrounded by mountains, including a few active volcanoes, and serrated by ravines.

Soils - To 10 or 15 meters: clay changing to silty sand. To 100 meters: volcanic ash. Allowable soil pressure from 15 tons/m$^2$ to 30 tons/m$^2$. Ninety degree cuts.

Structural History - As would be expected, nonengineered construction dominates the one- to three-stories category. (50% of housing substandard according to Guatemalan 1964 census.) City also has two dozen buildings in the 10- to 25-story range. Almost all were well designed and well built in the 1960's and 1970's. Many buildings four to nine stories. Most well conceived, some very poor. No building code. When used, ACI 318 with chronologically pertinent

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zone-3 requirements. ACI 318-71 not yet popular because of obfuscation factor. Deformed bars with few exceptions. Grade 40 (current construction tends to 60). Concrete 3,000 - 5,000 psi. Frame, in various disguises, is the norm. The waffle quite common in heavy construction. Relationship between architect and engineer difficult to comprehend. Possible cases of architect changing structural scheme or elements during construction.

Seismic History - City demolished previously in a series of quakes which started in December 1917 and continued into 1918.

"Great" Earthquakes

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Earthquakes of 4 and 6 February 1976 - Major damage caused on 4th but that on 6th had considerable influence. In fact, structural damage increased daily at a perceptible rate to 14 February. Epicenter of 4 February event (3AM) was still uncertain (Latitude 15.7° - Longitude 89.2°, ?) but location of surface fault, inaccurately sketched on map, makes epicenter unimportant. Observed relative motion along the fault 60 to 120 cm. Magnitude 7.5 (from surface waves?). May have lasted about 30 sec. The event on 6 February was not as strong but did cause additional damage. Ground motion not measured for either quake. Reportedly, instrument out of order for first (no paper). Second occurred when
it was being reloaded. One seismoscope record south of city, salvaged by Chuck Knudson, may provide an indication of maximum acceleration.

**Mercalli** - VIII to IX (our estimate)

**Cost of the damage** - Not yet established in the city (February 14). Figures of $600,000,000 to $800,000,000 have been mentioned (to be compared with G.N.P. of $1,500,000,000 in 1967). We think that there is more damage to buildings than meets the eye. Cost of repair will depend critically on the selected design earthquake and how rigidly a code will be enforced. Local engineers and authorities calm, not ready to rush to a punitive code.

**Soil Effects** - If the ground motion varied throughout the town as a result of soil depth or properties, it was not observed by the authors. There was a marked change in the extent of damage from the north to the south end of town, at least in the districts visited, but this could be attributed to the quality of construction and distance from the fault, in that order.

**Soil Failures** - There were slides at the top edges of ravines (very steep) and severe cracking indicating imminent slides. Many houses destroyed as a result. Aftershocks caused additional slides. Major slides along highways (reportedly) covered several cars at a time (especially the major event of 6 February).

**One- to Three-Story Buildings** - Adobe, brick, bahareque (adobe or brick reinforced by wood frame usually having X-bracing). Reinforced brick in a few instances. Primitive timber roof truss. Tiles or corrugated steel sheet roof covering. Performance of adobe worst. Destruction not uniform. Typically, house at block corners demolished if adobe. Some blocks lost 30%, some less than 10%. Did not see a completely destroyed block in the city but others did. Reported loss of approximately 60,000 dwelling units in this category. Intact survival of an impressive number of units in this class (adobe, etc.) makes one wonder if the sustained acceleration in Guatemala City could be over 0.25g.

**Four- to Nine-Story Buildings** - Except some disastrous examples of probably non-engineered construction, all in the frame class with the horizontal element typically hidden in the thick slab (the weight problem compensated by voids or waffle). Problems in the lower end of this class primarily with
"captive columns" (columns partially or totally stiffened by nonstructural walls, in one case by a steel cabinet) failing in shear. At least three total collapses and many on the brink. Problems in the upper end (of this class) with flexibility (architecture in shambles) and apparent "exhaustion" (large steel strains and therefore cracks) of slab at column connections. Permanent displacements.

**Moderate-Rise Buildings** - Heavy construction. Well built. Typically long spans (8m or more). Waffle slabs predominant. Frames. Structural walls. One steel frame (the highest at 22 stories, in final stages of construction). Problems in a few instances with transverse reinforcement in R/C girders and short connecting beams. In one case, excessive movement of intact frame destroyed the brick skin although the structure was fine. Serious inclined cracking observed in one major column (2.3 by 2.3 meter column, 0.5 mm cracks). Guard said cracks existed previously, but were smaller in width. Series of failures in the first-story elements of an external R/C truss stiffening a building.

**Bridges** - One bridge on a curve, down (about 30km from town). A prestressed concrete bridge on tall columns (post-tensioned main span, approx. 120 meters) in place but must have moved "sideways" at least six inches during quake. A steel bridge also on tall columns (main span approx. 100 meters) off its supports, resting partially on abutment.

**Miscellaneous Observations** - Ground motion in town must have been less than in Managua or San Fernando. (70, maybe 90%, of "El Centro" with possibly a relatively depressed response in the nearly-constant-acceleration range).

(1) One of the major buildings has connecting girders, carrying primarily earthquake effects, which vary continuously in depth (by a ratio of over two) from one column face to the other! (2) One of the collapses was initiated by "nonstructural" facade walls terminated at the failure level. Situation exacerbated by a variation in stiffness in the horizontal plane again introduced by nonstructural elements (the coup de grace being delivered by lack of adequate transverse reinforcement in the columns). (3) The other two collapses (and many other imminent ones) are due to unsympathetic symbiosis of structural and nonstructural elements.
The Guatemala experience should make us look to our R/C buildings with transverse reinforcement proportioned before the current "exorbitant" requirements. There is, of course, the hope of discovering that the ground motion in the city was so high as to be nonrepeatable or that the web reinforcement provided was below the threshold, but neither speculation holds much promise on the basis of available evidence.

The observed responses of the steel structure and at least two (which we inspected in detail) of the major R/C structures (all three of recent vintage) were impeccable. We were told that one of these two R/C structures (19 stories) was designed with all the earthquake force assigned to the structural wall, despite the presence of a hefty frame.

Because of the close similarity of the structural types and design procedures in Guatemala to those in the U.S., detailed analysis of their experience is essential, despite the lack of a strong-motion record.
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INTRODUCTION

This report has been prepared to provide a preliminary description of the response of engineered construction in Guatemala City to the earthquakes of 4 and 6 February 1976 as evaluated from our observations made during the period 8 to 14 February 1976.

The technical information contained in the report is limited primarily to photographic evidence. No quantitative analysis is included. We believe that an early release of the available information will be of value to emphasize some of the structural phenomena which do not need analysis and to put into perspective the level of damage experienced in the city.

ACKNOWLEDGMENTS

We acknowledge the cooperation and invaluable help received from the Camara Guatemalteca de la Construccion through the Committee for Damage Evaluation. Special thanks are due to Engineers Victor Chang Liang, Pablo Gutierrez, Juan José Hermosilla, Rodolfo Hermosilla, Luis Felipe Mérida, Hector Morzon, and Roberto Solis.

We visited Guatemala City for the Panel on Earthquakes (Chairman: P. C. Jennings), Committee on Natural Disasters (Chairman: N.M. Newmark) of the Commission on Sociotechnical Systems of the National Research Council. This report has been reproduced with support from the National Science Foundation (Grant ATA 74-22962).
GUATEMALA CITY

Guatemala City (Fig. 1.1) has served as the capital of Guatemala since 1773 when Antigua, the previous capital, was severely damaged by an earthquake. From 1821 to 1839, it was the capital of the United Provinces of Central America. Since 1839, it has been the capital of the Republic of Guatemala, which covers a mountainous area of 42,000 sq. miles.

The population of the city was established as 813,696 with a density of 991 persons per square mile in the 1964 census. It is estimated that the current population is well over a million. Guatemala City grew by 85 percent from 1950 to 1964.

The city is located approximately 1000 miles almost directly south of New Orleans at an elevation of 1500 meters in the Valley of the Hermit (approximate latitude and longitude: 15° by 91°).

GEOLOGY AND SOIL CONDITIONS

The geology of Guatemala (Fig. 1.1) shows a marked difference between the southern part of the country (including all the Pacific Coast), composed of relatively young materials (late tertiary and quaternary), and the northern part where basal rock (paleozoic and mesozoic) is exposed and folded extensively. The line of demarcation between these two parts runs east-west almost exactly along the Motagua River fault, where the epicenter of the earthquake has been located and a left lateral motion of 60 cm to 120 cm has been observed over some 175 km.

Four main geomorphological regions are normally considered. The first two, corresponding to the southern part of the country (where
Guatemala City is located) consist of a chain of volcanoes and volcanic rocks (late Tertiary) running south-east, and the coastal plain resulting from erosion of these mountains (Quaternary). These two regions extend themselves into El Salvador.

The third region, corresponding to the central and north-central part of the country, is a prolongation of the mountain chain in southern Mexico, but the orientation changes from south-east to east in Guatemala. This mountain chain is formed of granite, serpentinite and schists, with another fold of sedimentary rocks in the north.

The northernmost part of the country (fourth region) is a sedimentary basin of cretaceous origin which was probably at one time part of the Gulf of Mexico.

In addition to its great geological interest because of the volcanoes, there is in Guatemala a large number of long, straight fault traces. While the shape of these faults would suggest a "strike-slip" type of motion, historically only "dip-slip" motions had been reported. In the present earthquake, however, as mentioned above, a significant left lateral motion has been observed along the Motagua River fault.

Guatemala City is located on a plateau surrounded by mountains, including four active volcanoes, and serrated by very deep ravines. The basic soil is made of volcanic ash and pumice, down to at least 100 m. The top 8 to 15 m are the result of weathering of the volcanic ash, with the expected gradual transition from clay (of a brownish color) and sometimes organic silts (dark) to silts (yellowish to red), silty sands (yellowish, light brown or white) and sands (gray, pink or beige).

While this profile is typical, the actual soil properties, degree of plasticity and water content change appreciably in different parts of
of the town. Depth to dense sand may vary from 1 or 2 m to 8 or 9 m, increasing generally from the northern part of the city (zone 2 and north of zone 1, Fig. 1.2) towards the southern part of zone 1. It is about constant in zones 9 to 15 (somewhat deeper in zone 12). Water content is higher in zone 8 particularly, as well as in parts of zones 9, 12 and 14.

Spread footings with tie beams or strip footings are the usual type of foundations in the city. Allowable soil pressure is estimated at 15 to 30 tons/m$^2$. Ninety-degree cuts are frequent along highways.

Soil conditions played a clear role in some of the failures and damage. There were slides at the top edges of the ravines and many houses were destroyed as a result.Slides were also numerous along highways, many of them caused by the aftershock of Friday, 6 February, and it was reported that several cars had been buried. Large cracks in the ground and soil settlement could be observed in various parts (particularly across some highways). A television transmitting station on top of a mountain had a foundation failure. There was no evidence, however, of soil amplification.

**SEISMIC HISTORY**

Guatemala has had a long history of earthquakes and its capitals (La Antigua first and Guatemala City since 1773) have been destroyed in the past.

Earthquakes in Guatemala (affecting Guatemala City) have been classified into two main categories:
1. Earthquakes related to volcanic activity which occur in swarms with an average duration of three to four months. The largest event is rarely the first one and its magnitude is normally under 6.5. They are, however, of shallow focus and they cause considerable destruction within a radius of 30 km from the epicenter. They tend to have a high frequency content and the intensity depends strongly on the soil conditions.

2. Larger coastal earthquakes with magnitudes up to 8 but a focal depth of 40 kms. They tend to have longer periods and they have not been historically destructive.

Guatemala City may experience from five to seven strong motion earthquakes per century. The largest one was probably that of 4 January 1918, part of a series of shocks which started in December 1917 and which destroyed the city. The next strongest earthquake was that of 6 August 1942, with a magnitude of 7.75 and an epicentral distance of 137 km (of the coastal type). The maximum acceleration in the city was estimated at 0.07 to 0.16g, the first figure being considered more reliable.

In May 1947, a Montana instrument was installed at the Observatorio Nacional by the U.S.C.G.S. Reportedly eight to ten motions have been recorded, the largest one corresponding to the earthquake of 23 October 1950, also of coastal origin, epicentral distance of 109 km and magnitude 7 (recorded acceleration 0.037g).

A recent seismic risk study conducted in relation to the design of the Incienso bridge had indicated for the maximum credible earthquake in the city a magnitude of 6.5, epicentral distance of 25 km, maximum ground acceleration of 0.25g, predominant frequency of 2 to 3 Hz and a return period of 200 to 400 years. A return period of 50 years was estimated for an acceleration of 0.10g.
It would appear that the earthquake of 4 February 1976 does not belong in either of the two categories mentioned above. The epicenter seems to have been located near the Motagua River fault some 100 kms northeast of the city and lateral motion has been observed along the fault (from 60 to 120 cm) extending over 170 km.

The following is a list of some of the major earthquakes in Guatemala from 1530 to 1942.

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It was reported that a small foreshock was felt by some on the night of 2 February 1976. The main earthquake occurred some 24 hours later, on 4 February at approximately 3 a.m. There was serious damage and general panic in the capital. Between 500 and 600 aftershocks took place in the next few days, the main one occurring on Friday, 6 February around noon. At least four of the aftershocks during the period 8-14 February caused perceptible shaking of buildings.

As could be expected, some confusion existed originally as to the location of the epicenter of the main shock. The local observatory had placed it out south of the town, in the general area where most damaging earthquakes had occurred in the past. The U.S.G.S. placed it northeast of the city. This general location, with slight corrections, was finally accepted when the motions reported before were observed along the Motagua fault. The epicenters of the ensuing aftershocks were also located in the neighborhood of the fault. A Richter magnitude of 7.5 was assigned to the event of 4 February and about 5.5 to the second. (The first shock was rated at 7.9 by the U.C. Seismological Laboratory at Berkeley.)

The instrument at the observatory was not operational for either of the two major events (out of paper in the first case, in the process of being reloaded in the second). As a result no strong motion records are available. Two seismoscopes were located at the University (southwest of the city), one in the basement, the other in the top floor. The seismoscope records are currently being interpreted by the U.S.G.S. Seismological Field Survey.

Damage caused by the main shock was particularly severe in the central part of the country, with complete destruction of all the towns immediately
to the north, northeast and northwest of Guatemala City. The percentage of destruction tapered off slowly toward the northeast (90% at El Progreso, 60 to 80% at Zacapa), and very fast toward the south and particularly the southwest. The second event of 6 February caused substantial additional destruction and a large number of slides along highways.

In the absence of any instrumental data at the time of writing this report, maximum accelerations and frequency content of the motions can only be estimated on the basis of the observed damage in the city. The maximum acceleration does not seem to have been too large, probably on the order of 0.20g. There was on the other hand evidence of large motions and many cases of hammering between buildings with adequate gaps between them. This would suggest a relatively long predominant period for the earthquake. Mercalli intensity seemed to be larger in the northern part of the city (estimated at VIII).

Total losses due to the earthquakes are obviously very high. The last tentative figure of dead reported during the stay of the authors approached 20,000 (some 4,000 in Guatemala City). A total of 60,000 dwellings had been destroyed in the city. Rescue and food distribution operations were carried out generally in an expedient and orderly way and by 11 February, a week after the main shock, activities in the city were almost back to normal (although many buildings had been evacuated for precautionary measures). An emergency committee was inspecting all public buildings and private engineers had organized themselves through the Camara Guatemalteca de la Construcción (Chamber of Construction) to conduct detailed inspection of all private buildings.
STRUCTURAL HISTORY

It is natural to expect a considerable range in type and quality of construction in a city of over one million people which grew rapidly over the last quarter century without any regulations for structural design. Against that backdrop, the most striking feature of the construction in Guatemala City is the "weight" of engineered construction, or the sizes of structural elements, in such buildings, which reflect emphatically the concern of the builders for earthquake effects over and above satisfying minimum requirements.

Most of the moderate-rise construction in Guatemala City is of recent origin, concentrated around Centro Civico (Fig. 1.2) and strung along Reforma Avenue toward the southern part of the city. The concentration around Centro Civico may be seen in the background of Fig. 2.5 (viewed from the north) and in Fig. 2.6 (viewed from the west.) Examples of buildings along the Reforma are also seen in Fig. 2.7 and 2.8. There are approximately two dozen buildings having from ten to twenty stories in Guatemala City.

Buildings having four to nine stories occur randomly throughout the city with relative concentrations near the Parque Central and Centro Civico. Various examples can be seen in Fig. 2.1 through 2.6.

We have been told that the structural components of buildings in both of the above classes would have been typically sized by a structural engineer. All but one of the taller buildings had reinforced concrete structural elements with a mode design compressive strength of 4000 psi for recent construction with 3000-psi concrete used in the footings. There were cases of the use of 5000-psi concrete in structural elements carrying
compressive forces. Except for a few examples of Grade 60, Grade 40 deformed bars (imported from Mexico or El Salvador) were used in recent construction, although the current trend is toward Grade 60 bars. Plain bars, sometimes mixed with deformed bars, were observed in some of the older buildings.

For details of reinforced concrete construction, ACI Building Codes were used as a guide. For most of the recent buildings, the version used was ACI 318-63. ACI 318-71 is not yet generally used.

Lateral forces were taken from the chronologically relevant SEAOC documents.

The structural steel for the 19-story (plus three basements) Finance Ministry Building was fabricated by a subsidiary of Bethlehem Steel Co. We have been told that this building was designed for a base shear of eight percent of its weight at working stresses.

For almost all of these buildings engineering appeared very good, according to the best state of the art practiced at the time they were designed. Construction was also generally of good quality. There were only a few isolated instances where we encountered inadequate quality control of construction and materials (a new wing of the General Hospital San Juan de Dios, the Tikal Building and a couple of three-story buildings).

Flexible type construction (reinforced concrete frames or columns with waffle slabs) predominated, with very attractive but damage-prone architecture. Large span cantilevers were frequent, with solid brick walls at their tips starting from the second or third story. Only three major buildings were found to rely primarily on structural walls for lateral resistance walls, the Banco de Guatemala (with a shear wall core designed to take the full lateral load), the Edificio El Cortijo, near
the Reforma, and a building (Fig. 2.7) in final stages of construction.

Unreinforced adobe dominated the low-rise construction. Such buildings were sometimes reinforced with timber posts and lintels stiffened by x-bracing, the system being called "bahareque." Both types, adobe and bahareque, are used with large perforations for windows and doors. When used for small businesses, the front wall is reduced to two columns. The roof is typically supported by a light timber truss, the cover being provided by corrugated iron or simple tiles. Middle-class residences used concrete slabs for roofs and floors, supported by block walls with some reinforcement or very light reinforced concrete or masonry columns. Two- and three-story construction often had frames with infill walls. A view of low-rise construction near the airport is shown in Fig. 2.9.

SOIL FAILURES

The city is delimited on almost all sides by steep ravines (Fig. 7.2 and 7.3) the slopes of some of which are sites for residential construction (Fig. 7.1). A large number of small slides took place along the edges of the ravines (small in relation to those which occurred along highways north of the city, obliterating the routes for lengths of as much as 50 meters at a location.) Wide cracks indicating the imminence of a new series of slides were visible at almost all city boundaries. Minor slides occurred continually during the period we were in Guatemala City. Figure 3.1 shows a two-story residence destroyed by a slide. Note the minimal shaking damage to the house next door.

Figure 3.2 shows the transmitter house for a television station (Channel 3) located on top of a hill (elevation, 2400 meters) northeast of the city. The rigid reinforced concrete box was supported in a rather
small central base made up of four 50 by 50-cm reinforced concrete columns on individual footings. Articulations which appeared to be Mesnager hinges were between the box and the columns. Rocking forces evidently caused uneven settlement of the columns, the settlement exceeding 35 cm for the southeast column (on the left in Fig. 3.2). Because of the distortions, the column shells had spalled locally at the articulations, with extensive loss of the shell of the southeast column and damage to the filler walls between the columns. Failure of the building was due clearly to a foundation failure, which resulted from the architectural planning and possibly from the location of the building at the edge of a rather steep slope. (No cracks were observed on the slope.)

GENERAL PATTERN OF DAMAGE

Old buildings such as the Mercado Central, the Cathedral and several churches in the center of town (zone 1), suffered varying degrees of damage. The towers of the Cathedral were inclined (in opposite directions) and cracked and the facade was damaged: there was talk of demolishing the building. The churches of Santa Rosa and Capuchinas had the top of the walls (which sustained the roof) partly collapsed. The dome of the church of La Merced was displaced. In the Mercado Central some of the heavy adobe walls were cracked and partially collapsed. The walls of the Instituto Central de Varones (brick building also in zone 1) had collapsed carrying with them the roof.

An example of damage diversity was provided by the General Hospital San Juan de Dios, with a combination of buildings of different ages. The old part, some 25 years old, was made of brick walls with timber trusses and a tile roof. Damage was generally limited to cracking and falling of
plaster from the walls and ceilings. Although this wing was evacuated, no serious structural damage was apparent. A new wing finished two years ago was made of concrete columns with waffle slabs and large cantilevers. There was considerable damage to the heavy brick partitions and to the structure, with crushing at the top of several columns (poor quality construction). A more recent pediatric wing (finished one year ago) had practically no damage.

While there were some spectacular partial failures of engineered buildings (such as the Hotel Terminal or the Liceo Javier) and in a few cases structural and nonstructural damage could be easily observed from the street (El Camino Real, Cruz Azul, or the Clinicas Medicas at the end of the Reforma), in general most engineered buildings showed little sign of any distress from the outside. Almost all of them had, however, some nonstructural damage and a substantial number showed after closer inspection structural cracks, often in the beams (Ritz Intercontinental, Camara de Industria, Edificio Reforma Obelisco, etc.) It was apparent that lateral displacement of the structure had been large, certainly into the inelastic range of response, in all cases. An unusually large number of cases where two buildings with a separation of a couple of inches had banged against each other could be observed. The Finance Ministry building, for example, had the main steel tower and a smaller reinforced concrete wing with a separation of six inches between them except at a few points where the gap was only two inches. Hammering between the two buildings occurred at these points at the third floor level.

Definition of a Mercalli intensity is clearly very subjective. It depends particularly on whether buildings which were well engineered in the 50's and early 60's can still be considered today as specially designed.
A large fraction of small adobe, brick and bahareque one- or two-story houses survived the motion well in zone 1. On the other hand destruction of this type of building was very severe in other zones. As pointed out above, the ensemble of the engineered buildings in the city suffered an important amount of damage. Cracks in the ground were abundant in some parts of town. It is our opinion that a modified Mercalli intensity of VII is the minimum value which can be reasonably assigned to some parts of the city and that VIII is more realistic on the whole. (An intensity of IX could be claimed in certain zones).

Damage to Buildings in the One-and Two-Story Class

The reported loss of 60,000 residential units was in this group of predominantly nonengineered construction. In the parts of the city visited by the writers, destruction seldom amounted to a third of a given block. Typically, ten percent of a block was heavily damaged, districts in the more modern south part of the city having even a smaller average for houses seriously damaged, as a result of quality of construction and, possibly, distance from the causative fault. Damage intensity was reported to be particularly high in zones 3, 5, and 7 (Fig. 1.2).

In the one- and two-story group, the record was much better for bahareque than for plain masonry, whether adobe or brick. Failures of adobe buildings appeared to have resulted from out-of-plane rather than in-plane forces, a result which may be related to the light roof structures (Fig. 4.1 and 4.3) which were not heavy enough to generate large inertia forces but for the same reason did not restrain the walls.

Lightly reinforced block construction, despite the heavy concrete floor and roof slabs, typically survived with wall cracks indicating serious in-plane forces and shattered windows witnessing the distortion.
An impressive number of low buildings of plain masonry construction came through with barely a crack suggesting that the repeated "short-frequency" acceleration pulses in the city might not have exceeded 0.25g.

**Damage to Buildings in the Three- to Seven-Story Class**

There were a few notable collapses in this group, notable not because of their unusual features but rather because of their having been observed before and the strong likelihood of their being observed again.

Figures 5.1 through 5.5 describe the failure of the Otutlan Church. It would seem that a minimal increase in cost of the structure, resulting from the expense for adequate splices, could have saved the church.

The Javier Highschool (Liceo Javier) was the seat of another recurring failure mechanism which has been observed too many times before in the Caribbean as well as in other areas of the world. Figures 5.6 through 5.8 show the collapsed portion of the school buildings while Fig. 5.9 and 5.10 illustrate the primary cause of the failure. The reinforced concrete column, bounded by "nonstructural" walls, attracts considerably more shear than intended (because of increased overall stiffness of the structure and increased relative stiffness of the "captive" set of columns) and fails in shear because of lack of sufficient transverse reinforcement to develop its flexural strength in plastic hinges forming at the ends of a much shortened clear height. The condition shown in Fig. 5.9 is noteworthy because it illustrates that the wall need not fill the entire bay. Figure 5.10 demonstrates that a discontinued partition wall can create the same effect. Friction between the wall and the floor may suffice to wedge the wall. A more extreme example is provided in Fig. 5.11. The light ornamental enclosure around the staircase frame provided sufficient rigidity and strength to tear the column from the roof slab.
A rather routine demonstration of the captive column was provided by a three-story building on Seventh Av. (Fig. 5.12). Identical failures were encountered in buildings of similar characteristics in various other parts of town.

A more sophisticated example of the captive column was observed in two five-story apartment buildings. Details of the column shear failure are illustrated in Fig. 5.13 and 5.14. While in the photograph (Fig. 5.13) the inclined crack is visible only in the left column, these cracks existed in various widths in all but one of the edge columns in the first and second stories. It is evident that the nonstructural infill wall transformed the interior bay of the edge frames into a structural wall which may actually have been beneficial to the comportment of the buildings during the earthquakes. However, the concentrated distortion of the wall over the height of the slit window initiated the shear failure of the columns.

The most dramatic collapse in Guatemala City was that of the six-story Hotel Terminal (Fig. 5.15 through 5.20). The building can be described as a four-story tower on a two-story base which covers a larger area in plan. The tower frame had only one bay in the short direction. This bay was stiffened appreciably in the top three floors by end walls required by the architectural plan (Fig. 5.15 and 5.16). Thus, the third floor, immediately on top of the larger two-story base, was transformed into a flexible link in the vertical plane. To aggravate an already bad condition, the location of the kitchen on the north end of the building in the third floor placed an infill wall at that end (Fig. 5.16 and 5.18) plus other walls around the stairs (Fig. 5.17) while the south frames were left completely open because of the dining hall. The frames around the dining hall thus were
made the flexible link twice, in the vertical and horizontal planes.

The collapse of the columns in the dining hall area occurred in stages. According to eyewitnesses there was a major lurch of the building during the main event of 4 February. Partial destruction of the columns (possibly limited sliding along inclined cracks) were "felt" about 20 minutes after the main shock. However, the columns were still supporting the upper three stories. Complete collapse of the story took place during the 6 February shock. The reported progressive mechanism fits in with the hypothesis of shear failure of the columns as does the structural state of the building before the earthquakes. However, the conditions of the failed columns (Fig. 5.19 and 5.20) do not permit irrefutable diagnosis. Furthermore, there was little permanent distortion of the fourth-floor slabs in the horizontal plane, which does not discount, but also does not confirm the existence of torsional instability suggested by the distribution of "nonstructural" walls. There were, however, inclined cracks in the third row of columns (from the south end of the building) at the failure level. The columns on the north end were intact.

Hotel Terminal was designed in the late fifties when the requirement of providing sufficient shear strength in columns to resist the shear corresponding to flexural hinges at both ends had not been publicized and certainly not required. But it would appear that the shear failure resulting from lack of heavy transverse reinforcement was the culmination and not the trigger of the overall failure mechanism which must be related to the distortion of the structural action by architectural requirements.

Damage to Moderate-Rise Buildings

Two buildings, which may also be seen in Fig. 2.2, in which lateral-load resistance was provided primarily by frames, comprising columns and
thick flat slabs (hollow), are shown in Fig. 6.1 (Horizontal 1, eight stories) and 6.2-6.3 (Cruz Azul, eleven stories). Both buildings survived the earthquakes without collapse (slab failures seen in Fig. 6.2 were caused by impact of walls falling from upper floors). Both ended up with permanent displacements. Both had serious architectural damage.

It could be said that the architectural damage was prescribed by the choice of the structural scheme: a relatively light frame. The amount of inelastic response in the "beam" elements was indicated by cracks, near the columns, having residual widths of approximately 0.8 mm going all the way through the depth of the slab. The structures were, in effect, successes in relation to the implicit design philosophy. They had ridden out a moderately strong motion by developing moderate "ductility." Whether the design criterion is a desirable one is debatable. A more plausible demonstration of this design criterion was provided by a medical clinic building on the Reforma south of Centro Civico (Fig. 6.4). The eleven-story building had a moderate core and a relatively heavy frame comprising tied columns and thick waffle slabs. The structure survived the earthquakes with barely a scratch but the brick skin of the building and the partition walls had enough cracks and failures in them to make the local journalists use photographs of the building as an example of a critically damaged structure.

The structural failures in the ten-story building of the Hotel Camino Real (Fig. 6.5) are only of narrow interest because of the special "lattice" or "perforated shear wall" that was used to resist shears in the long direction of the building which was curved in plan and had an expansion joint in the middle of the long dimension. The hotel was built in two stages, the top five stories having been added after about eight years.
following the initial construction in 1966. Structural walls and frames resisted the lateral loads in the short dimension of the building.

The struts forming the lattice on the convex face of the building are shown in Fig. 6.5 and 6.6. In this face, failures occurred in all struts in the first story inclining from west (top) to east (bottom). The location of the failures near the joints indicates influence of bending and/or splices. A closeup is shown in Fig. 6.7. The struts measured 50 by 18 cm as built in cross section and the strut shown was reinforced by four No. 8 bars at the corners and by a combination of No. 6 and No. 5 bars at mid-section near each long face. The No. 3 ties had 90-deg. bends with 8-diameter extensions. The minimum strength of the concrete was reported to be 5000 psi. The struts on the concave face of the building are shown by the overlapping photographs in Fig. 6.8 and 6.9. There was only one strut failure (Fig. 6.8).

It must be noted that although some elements of the perforated wall or lattice had failed, the architectural details of the building were in good condition.

The 15-story (plus two basements) Camara de Industria building (Fig. 10) has a central tower supported by four main core-like columns (Fig. 6.10a and b) and a structurally integral rear portion which uses a structural wall (Fig. 6.10c) for lateral forces in one direction. An interesting structural feature is the connecting girder of variable depth (Fig. 6.10c) at the first-floor facade, a configuration which stiffened one of the main columns with respect to the others leading to a complex of residual inclined cracks with thicknesses of the order of 0.5mm in that column. (According to a security guard in the building, these cracks existed before 4 February but were much finer). Figure 6.11 shows the
inclined cracks on both sides of one of the girders framing into a main column.

Bridges

Figures 7.1 and 7.2 show the Incienso bridge which crosses a ravine on the north side of the city. It is a prestressed concrete bridge with a main span of approximately 120 m. Hammering damage at the meeting points of the approach spans and main girder indicated total maximum relative movement of approximately 30 cm in the transverse direction but a permanent relative displacement of only 2 cm.

The Ascuncion bridge, a steel girder, had a permanent lateral displacement of about 40 cm because of the girder being shifted off its supports (Fig. 7.3).

The reported site of a bridge collapse (Aguas Calientes) approximately 25 km from the city, was not visited.

SUMMARY

A 7.9-magnitude earthquake associated with an approximately 175-km surface fault devastated central and eastern regions of Guatemala on 4 February 1976, causing heavy structural damage (Mercalli VIII) in Guatemala City, the capital of the country with a population of over one million. A particularly severe aftershock on 6 February 1976 caused additional damage in the city.

There has been no direct measurements of the ground motion in Guatemala City. A seismoscope record, not yet reduced, may give an indication of the maxima in the southern edge of the city. Judging crudely on the basis of damage to engineered and nonengineered structures, it
would appear that the spectral response to the motion in town could have been on the order of three quarters of that to the north component of the 1940 El Centro record with a relatively depressed portion in the nearly-constant-acceleration range of response.

The engineered construction in town was designed and built to resist strong ground shaking on the basis of recent concepts of earthquake engineering. Its overall record was excellent. The significance of the observed performance depends, of course, on how strong the ground motion was in the city.

Insofar as the behavior of engineered construction is concerned, three strong impressions emanate from a superficial inspection of the damage in Guatemala City:

*That architecture can destroy the structure was once again demonstrated in Guatemala City. Passing over the problem of changes introduced into the overall stiffness of a building by architectural decisions as being too abstruse for a general conclusion (Fig. 5.15-5.20), the much-too-obvious problem of the captive column (Fig. 5.6-5.14) must be flagged. It does not take analysis to reveal the captive column, often a feature of institutional buildings in temperate climates. It would seem incumbent upon local building authorities in earthquake-prone regions to identify these details in high-occupancy buildings and, as a minimum, inform the occupants of the risks involved.

*The long span (over 8m) frame girders of some of the moderate-rise structures developed critical inclined cracks suggesting that a larger amount of web reinforcement would have been appropriate. (In one case, these cracks might have been initiated by cut-off longitudinal reinforcement.) These phenomena should be studied and documented because of their possible impact on current detailing practice.
*As after the Managua experience of 1972, observations in Guatemala City (Fig. 6.1-6.4) raised questions about the economic feasibility of the "ductile frame" even though it was also demonstrated that if the frame is heavy enough, it can ride out an earthquake of moderate intensity with minimal damage to the architecture (Fig. 6.13). In contrast, responses of the few structures relying on walls for lateral resistance were consistently superior (Fig. 6.14).

The general features of the heavy construction in Guatemala City compare favorably with those of similar construction in the U.S. and elsewhere. Detailed analyses of the behavior of some of the buildings in Guatemala City are essential for improvement of current design concepts.
Legend for Fig. 1.2

1. Lo de Bran - Residential area. Puente del Incienso.
2. Hospital General.
3. Cathedral.
4. Cruz Azul, Camara de Comercio, Edificio Tikal, Edificio Horizontal, Edificio Herrera
5. Hotel Ritz Intercontinental
6. Civic Center: Ministerio de Finanzas, Banco de Guatemala, Corte Suprema, Tribunales
7. Camara de Industria
8. Hotel Terminal.
9. Hotel El Camino Real, Edificio Reforma Obelisco
10. Clínicas Médicas
11. Edificio TV 3, modern church
Fig. 2.1 Looking North from Hotel Ritz-Intercontinental (Heavy lowrise building, left background, is the National Palace. The dome on the right belongs to the Cathedral.)
Fig. 2.4 Looking Southwest from Hotel Ritz-Intercontinental (The volcano in center background is the Agua. The two peaks on the right are Fuego, an active volcano, and Acatenango.)
Fig. 2.5 Looking South from Hotel Ritz-Intercontinental (Highest building is the 19-story Ministry of Finance Building which marks the location of Centro Civico. Two peaked volcanic mountain in right background is the Pacaya which is currently active.)
Fig. 2.7 A New Moderate Rise Building to House Medical Clinics. (The steel tower is the "Torre Reformador.")
Fig. 2.8 The El Triangulo (left) and the Centro Americano
Fig. 3.2 Northwest View of the Transmitter House for Television Station Ch. 3 Located on a Hilltop (elevation 7700 ft) West of the City. (Note tubular conduit, straight before the earthquake, which emphasizes the settlement and tilt resulting from foundation failure.)
Fig. 4.2 Texture of Adobe Wall

Fig. 4.3 Fallen Parapet (Note absence of cracks, related to in-plane forces, in wall)
Fig. 5.5 Otutlan Church, Column Splices
Fig. 5.7 Javier High School, Detail of Failure (Note class room furniture supporting upper-story)
Fig. 5.9 Javier High School, Shear Failures in First-Story Columns (Note that (1) the partition wall is not solid and (2) inclined cracks in interior column have formed in both directions (x-pattern) while the inclined crack in the corner column indicates shear failure in one direction, the direction in which part of the column is stiffened by the wall.)
Fig. 5.10 Javier High School, Shear Failure in First-Story Column
(Note that partition wall does not bear on another column)
Fig. 5.11 Javier High School. Ornamental infill was stiff and strong enough to tear column away from roof.
Fig. 5.12  Shear Failures in Captive Columns of Three-Story Building
Fig. 5.13 Five-Story Apartment Building
Fig. 5.14 Inclined Crack in First-Story Column
Fig. 5.15 Hotel Terminal, Southeast
Fig. 5.18 Hotel Terminal, Third-Floor, Kitchen, North End
Fig. 5.19 Hotel Terminal, Third Floor, Dining Room, South End
Fig. 5.20 Hotel Terminal, Third-Floor, Columns
Fig. 5.21 Tikal Building
Fig. 6.1 Horizontal 1
Figure 6.2 Cruz Azul Building, Northeast
Fig. 6.6 Hotel Camino Real, Southeast
Fig. 6.10 Camara de Industria
Fig. 6.11 Camara de Industria, Girders
Fig. 6.12 Bank of Guatemala Building
Fig. 6.13 Supreme Court (foreground) and Tribunal Court Buildings
Fig. 7.4 Elevated Water Tank
APPENDIX

NOTES ON STRUCTURES VISITED AND OBSERVED DAMAGE

1. Lo de Bran - Residential area in zone 3. Two story private houses. Several located near the edge of the ravine failed because of slides. First floor collapsed. People sleeping in second floor went down with the house. No casualties reported.

2. Mercado Central. Old building (zone 1) with heavy adobe walls (0.60 to 1m thick in parts). Timber roof with corrugated metal sheet. Partial collapse of some outside walls.

3. Instituto Central de Varones (zone 1) Brick walls collapsed bringing down roof with them.


6. Church of La Merced (zone 1). Dome displaced.

7. General Hospital San Juan de Dios (zone 1 toward zone 3). Combination of buildings of different ages. Evacuated, old part (25 years old) with brick walls and timber roof structure with tiles: plaster cracked and fallen from walls and ceilings. 15-year old wing with concrete columns. Cracks in partitions and brick walls. Lintel over one door broken. New 2 year old wing - Concrete columns with waffle slab and heavy brick partitions. Cracked partitions, crushing of top of several columns (bad construction). Pediatric wing (1 year old). 2 story building - no apparent damage.

8. Adobe, bahareque and brick low rise construction. Collapse of about 5 to 10% of these buildings in zone 1, serious damage to another 5 or 10%. More damage in other zones (3, 5 and 7).


11. Synagogue. Modern shell roof in 7th Avenue near Reforma. A small crack on one of the supporting legs of the shell. Internal structure with large slab resting on isolated columns (large cantilevers and spans). Some damage, hammering against shell. Damage at the staircase.

13. **Liceo Javier** - Modern private school (built 1963) 3 wings (3 stories). In one of the wings complete collapse of second floor over central part of building. Captive column problem. Collapsed story had classrooms. Third story dormitory. People in dormitory but no casualties. One person reportedly had time to step out of the room and into adjacent portion of building before collapse occurred.


15. Main building TV3 (southwest of town, near Otutlan Church). Concrete frame brick infills. Damage to staircase, cracked partitions. One broken captive column.

16. **Cruz Azul** (zone 1). Concrete columns with cantilevering waffle slabs. Flexural cracks on slab along edge of capitals. Breakage and falling out (in blocks) of exterior brick walls. Cracks in interior partitions. Elevator-staircase box separate tower. Hammering between two buildings. Gap between them widening at top (one of the buildings leaning away from the other).

17. **Edificio Horizontal Uno** - Similar to Cruz Azul and close by. Similar problems. Considerable interior damage.


19. **Torre Clinicas Medicas** (at the end of Reforma). Concrete columns, waffle slabs cantilevering. Almost no structural damage. Considerable damage to outside shell (brick walls and glazing on tip of cantilevering slabs), two interior partitions and two false ceilings (badly buckled).


21. **Camara de Comercio** (zone 1). Concrete frame with columns outside building. Longitudinal beams recessed (along facade). Short transverse beams framing into longitudinal beams and columns. Inclined (shear) cracks in short beams. Minor flexural cracks in columns. Cracking of brick walls in staircase box and substantial damage to exterior brick walls (particularly at the corners of the building).
22. Hotel Terminal. Collapse of one floor with (reported) progressive shear failure of the columns. Failure caused by a combination of reasons discussed in text.

23. Edificio Tikal (zone 1). Damage to 1st story columns (crushed) and to walls. Building with a long history of problems (construction interrupted for many years, finished only recently). Bad quality construction and materials.


25. Biltmore Hotel. Adjoining El Camino Real. Damage to some partitions, only moderate. Failure in shear of one column.

26. Hotel Ritz Continental (zone 1). Very little damage on the outside (falling of some marble from columns) Considerable damage to interior partitions in hours 4 to 7. Shear cracks on longitudinal beams on one side of building 14th and 5th floors and both sides on 3rd floor. Outside staircase with vertical metal struts buckled (situation progressing).


28. Camara de Industria. 15-floors reinforced concrete frame with combination of two-way and one-way slabs. Inclined cracks on two main columns at ground level. Elevator-staircase tower separate tower with shear wall on one side and short beams connecting to main building. Shear cracks in these short beams. Shear and flexural cracks in girders of main building.

29. Corte Suprema and Tribunales (Civic Center). Concrete columns and waffle slabs. Two buildings of different heights connected to each other. Joint between them with corrugated infill worked very well. Light damage in short building (Corte Suprema) to false ceilings, and cracked plaster. Some corner cracks in brick infill and cracks in architectural facade. No apparent structural damage. Tribunales building had only minor damage in brick walls of elevator and staircase boxes. Marble fell down from one wall of staircase box in the lower floors. Stiff building with L-shaped corner columns. No structural damage.

30. Banco de Guatemala (Civic Center) 15-story modern (12-year old) concrete building with waffle slabs. Elevator-staircase core designed as structural shear walls for full lateral load. No structural damage, very minor nonstructural damage with small cracks on brick walls adjoining elevator core from 9th floor up. Some cracks on outside walls of 6th floor. In an adjoining auditorium problems had been experienced during construction (cantilever deflected and had
to be propped by steel columns). Partitions were broken, one of the main beams had a serious shear crack (it existed as a hairline crack before but opened considerably during the earthquake) and the folded plate roof running transversely had cracks especially near the columns. Some of the ceiling panels had fallen down.


33. Incienso Bridge. Elegant prestressed concrete bridge in zone 3 (Lo de Bran). Very tall piers. Continuous central span and simply supported lateral spans. Considerable motion, hammering at joints and some permanent separation (less than one in.). Motion mainly longitudinal but also transverse. One abutment partly broken, pulled away by the longitudinal motion of the superstructure because of debris wedged in between.

34. Asuncion Bridge. Steel girders on concrete piers. Considerable lateral, transverse and torsional motion. Cracks on ground near one end of bridge with evidence of slides. Out of service.