ENGINEERING LESSONS TAUGHT BY EARTHQUAKES

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SYNOPSIS

The authors review some of the lessons they have observed in recent destructive earthquakes.

INTRODUCTION

"Experience keeps a dear school," said Benjamin Franklin in Poor Richard's Almanac, "but fools will learn in no other." And the eminent seismologist Charles Richter said "From Mallet's time to the present day, reports have confirmed, in melancholy repetition, the obvious fact that defective construction will not withstand an earthquake." Engineers take to the field after every destructive earthquake to document its engineering effects. What do we learn? Let us hope we accomplish more than just reaffirmation of Richter's assertion. Having paid the staggering social costs of destructive earthquakes we would be fools indeed if we refused to learn the lessons nature has offered us. Reviewing recent disastrous earthquakes, we find a number of lessons amply displayed.

GEOLOGIC HAZARDS

Time after time, geologic effects have dominated in the destruction wrought by earthquakes. Peru offers the most dramatic recent example, where an avalanche triggered by the earthquake buried the city of Yungay and over large areas of the city of Chimbote subsidence and ground liquefaction were prevalent. In the Alaska earthquake destructive slides occurred in several locations in Anchorage, many of them attributed to liquefaction of sand lenses imbedded in the clay underlying most of the city. The names L Street, Fourth Avenue, Government Hill, and Turnagain bring vivid memories of destruction. Ironically, the hazard was known and documented in a Geological Survey publication five years earlier, when many of the destroyed areas were still undeveloped, but that knowledge was unheeded. It was too easy to believe that remote hazards are not real hazards, and that disasters always occur somewhere else. Time and again buildings on soft ground have been damaged more extensively than comparable buildings on firm ground. Adapazari, situated in an alluvial basin, is a good example. Structures built on the alluvium of the city were damaged considerably more than those built on firmer ground nearer the

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epicenter. Not only is there more damage, but these sites are also more sensitive to distant earthquakes. A factory in the alluvial valley at Bursa, some 130 kilometers from the epicenter near Gediz, suffered damages which indicated an intensity level equal to the intensity in the epicentral region.

In some cases, man has altered geologic hazards and possibly created new ones. In recent years we have come to recognize that seismic activity in the vicinity of dams may increase as the reservoir is filled. Koyna is situated in a seismically stable region of the Indian peninsula. Earthquakes were rare before Koyna Dam was built, but tremors were felt frequently after filling began. Then in 1967 a destructive earthquake occurred at Koyna. The coincidence is too much to attribute to chance. The reservoir was apparently the trigger, although not the underlying cause.

Geologic hazards are sometimes readily apparent, but usually not. Microzoning is yet in its infancy. If we are to take advantage of the lessons of experience at all, we must recognize that geologic hazards often exist, and adequate subsurface explorations and assessment of geologic hazard must accompany the planning of any major project.

SOFT STORY

In multi-story buildings the ground story is often more flexible than the upper stories, sometimes intentionally and sometimes not. Upper stories are usually stiffened by structural or nonstructural walls and partitions, and ground stories are often open, with the number of walls and partitions held to a minimum in order to provide maximum flexibility in the use of the building. Outside walls are often glass show windows on the street side. The result is a rigid box atop a flexible ground story. The predictable earthquake behavior is shown in Fig. 1, a building in Skopje. Another graphic example was the 10-story Palace Corvin apartment building in Caracas. The front half which had small stores, with partition walls, at the ground floor, remained standing while the identical rear half with automobile parking, no partition walls, at the ground floor, collapsed.

The soft ground story is not without its proponents; indeed, some have advocated the use of a soft ground story to limit the inertia forces imparted to the structure above. In effect, this uses the ground story as a structural fuse. To be useful, a fuse must be expendable; ground stories are not. Experience should have taught us to avoid the soft story.

SHEAR FAILURE OF CONCRETE COLUMNS

Reinforced concrete columns subjected to transverse forces may ultimately fail in flexure or in shear, two basically different types of behavior. Flexural failure occurs by crushing of the concrete on one side, accompanied by tension yielding of the steel on the other side. It is basically ductile in nature, and flexural capacity of the member is maintained far beyond the distortion at which failure commences. Shear failure, on the other hand, occurs by yielding of the stirrups or ties or by tension fracture of the concrete between them. Shear failure is basically brittle; when it occurs the member loses its capacity to resist shear. The difference in behavior was shown dramatically in the columns of Olive View Hospital in San Fernando. The corner columns, Fig. 2, were tied and failed in a brittle manner. The intermediate columns, Fig. 3, are spiral columns and retained their load-carrying capacity through equally large deformations.

The maximum possible shear in a reinforced concrete column is the sum of the ultimate moment capacity at each end divided by the effective length. In many cases it is possible to avoid shear failure simply by proportioning the column to accommodate this amount of shear force.

STRUCTURAL EFFECT OF NONSTRUCTURAL ELEMENTS

The nonstructural element is somewhat misnamed. Any element in a structure affects the behavior of the structure unless it is built in such a way that it remains undeformed throughout the response of the structure. Window glass is often mounted so the sash can deform without straining the glass. "Nonstructural" unit masonry partitions are usually built in contact with the adjoining structural frame, and even though they are not relied upon to provide strength to support the structure, they do provide strength up to their capacity if they are deformed by the structural response. The school buildings of Chimbote utilized reinforced concrete frame structures in which some of the columns were restrained by masonry walls. Whether the strength of the walls was considered in the design or not, it gave the columns a very short effective length and correspondingly high shear forces. The columns failed in the brittle type of shear failure mentioned earlier, as shown in Fig. 4.

CONNECTIONS

In general it is easier to design structural members than the connections that join them. Yet members seem to get the greater share of the designer's attention. In much of the U.S. it is the custom for the engineer to specify the type of structure and the details of the structural members quite strictly, but to allow the builder or fabricator considerable freedom to choose the connection details best suited to his own facilities and practice. To a degree this makes sense, but it also imposes the requirement that the engineer appraise the performance capacities of the connections to be used, and to be sure they are adequate to meet the requirements of the structure. This is risky. Most fabricators and builders envision the function of the connection as transmitting the forces associated with gravity loads. Seismic forces are apt to be the farthest thing from their minds. The Permanente cement bin in Anchorage, Figs. 5 and 6, is an extreme example. The columns were securely X-braced, and the bearing plates were firmly anchored to the concrete pedestals. Alas, only a token weld attached the column to its bearing plate. The connection was entirely adequate for gravity load and probably for wind also, but it was worthless for seismic force.

Examples of connection failures abounded in Anchorage. The Alaska Sales and Service Building, Fig. 7, was precast concrete. The structural members were adequate, but the connections were weak. Many of the structural members survived the fall to the ground and were salvaged for use in the rebuilt structure, in which the connections were more generously proportioned.

In its ultimate behavior, the structure must absorb or dissipate the energy imparted to it by the earthquake. Energy dissipation involves structural deformations beyond the elastic range. Generally members can be proportioned to exhibit ductile behavior well beyond the elastic range, but connections are more limited. Hence it is desirable to keep the connections elastic, and throw the inelastic behavior into the main members. Whenever feasible, connections should be proportioned to develop the ultimate force that can be transmitted to them by the members they join.

Another connection troublemaker is the connection of mechanical equipment to the structure. Elevator counterweights are often dislodged from their guides during an earthquake, machinery slips off its blocks, emergency batteries are thrown off of the shelves on which they are stored, and pipes and conduits are ruptured because there are no expansion joints to accommodate differential movement of different wings of a building. The problem is not designing the connection, but just recognizing the function adequate connections would serve in an earthquake.

SEISMIC OVERLOADS

Most seismic building codes require that structures be designed to withstand specified equivalent static lateral forces without exceeding specified stress limits. It is recognized that the specified static lateral force is considerably less than the actual dynamic forces that would be induced in the structure by the earthquake. We rationalize this by saying that after all, the structure is designed on an elastic basis and the materials can tolerate deformations far in excess of those corresponding to the design stresses. Within limits the rationale works; however, it may be misleading, for the seismic force may act in either direction, and may augment or counteract the effect of gravity loads. A good example is Koyna Dam, a straight concrete gravity dam. Its cross-section, shown in Fig. 8, has an unusual break in the slope of the downstream face because an unanticipated planning change required switching from a two-stage construction operation to single stage after construction had begun. Under normal service load the vertical stress is compression throughout the entire section for any reservoir level. With the reservoir full, the upstream compressive stress is small, especially opposite the break in slope of the downstream face, and the lateral seismic force reduces this further. Computing the effect of the extreme lateral force specified by the seismic code, one finds the upstream face to be in compression for the full height, albeit a small compression opposite the break in slope of the downstream face. This is shown in Fig. 8.

The Koyna earthquake was recorded in the dam. The effect of gravity plus the computed first mode of response to the recorded earthquake is also shown in Fig. 8. This shows a computed tension in the upstream face well in excess of the tension capacity of the concrete. The dam fractured at that location and extensive repairs had to be undertaken.

Another potential problem area from seismic overload occurs in exterior columns of tall buildings, where the overturning effect of seismic forces may more than offset gravity load effects, leading to tension in columns. Perhaps the best example of this is the Petunia II Apartment Building in Caracas, shown in Fig. 9. These column tension forces require proper splices for steel columns and appropriate reduction in flexural strength in reinforced concrete columns.

GROUTED WALLS

We have gained a valuable lesson from our experience with grouted masonry walls. The State of California requires that masonry walls in certain buildings be grouted to meet specified standards. For concrete block walls the essence of the requirement is that the cores of the units be reinforced with vertical bars and filled with grout. Figure 10 shows block walls at the Juvenile Hall in San Fernando after the 1971 earthquake. A surface fracture of the ground ran through this facility and damage was extreme. We leave it to the reader to imagine what might have happened to this building if these had been unreinforced block walls. The merits of grouting are clear.

DISASTER PLANNING

A final lesson offered by nature has thus far not been adequately heeded. When an earthquake strikes there is immediate response by government at all levels, from municipal to federal, by international organizations, the Red Cross, UNESCO, and foreign governments, depending on the severity of the disaster. The first needs are medical aid for the injured, adequate communications, essential utilities, and fire protection for the disaster area. Plans for meeting these emergency needs have usually been made in advance, for they pertain to any type of disaster. Failure to provide for these needs can be catastrophic.

Reconstruction starts immediately, and almost invariably moves faster than new planning. Buildings are replaced in kind in the same locations. Adobe buildings with mud roofs are replaced by adobe buildings with mud roofs. Damaged concrete is removed and replaced. Relief is administered according to immediate need rather than maximum ultimate benefit. Disaster plans are needed immediately when the event occurs, and then it is too late to make them. Experience has shown the need for advance planning for disaster, but we decline to acknowledge it. We would do well to heed Franklin's admonition.

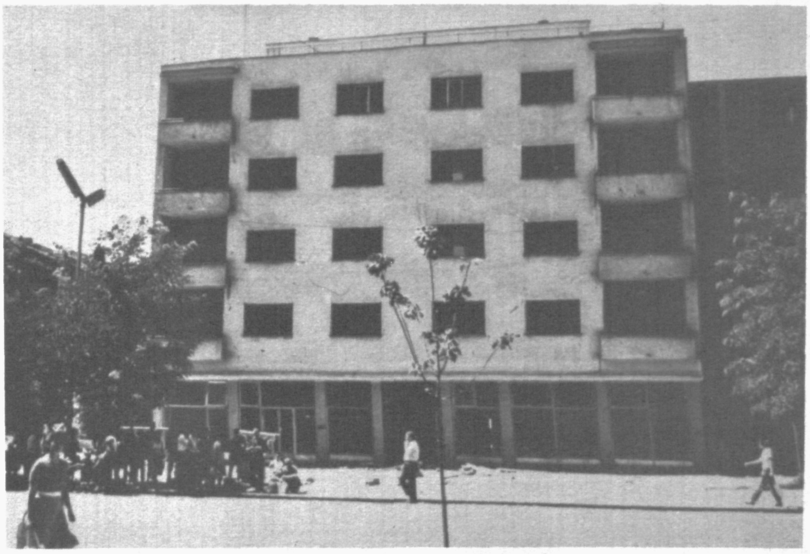


Fig. 1. Soft ground story, Skopje

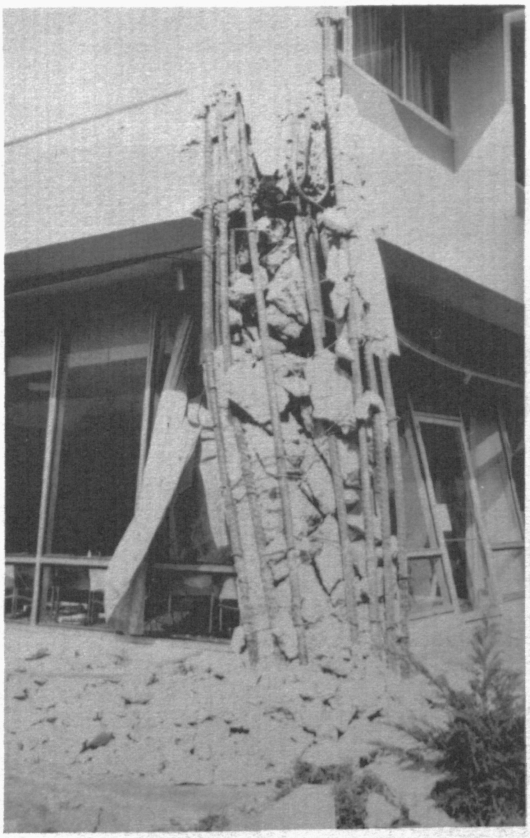


Fig. 2. Brittle failure of tied column, San Fernando

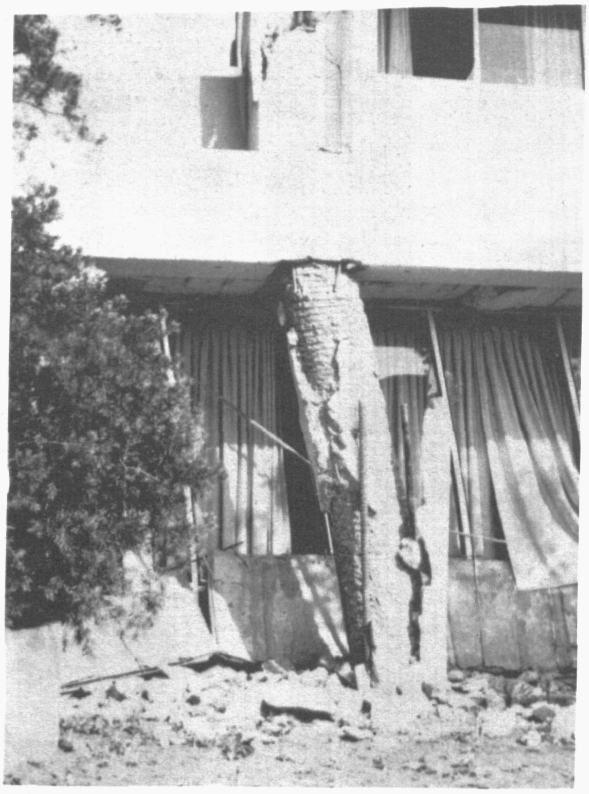


Fig. 3. Ductile behavior of spiral column, San Fernando

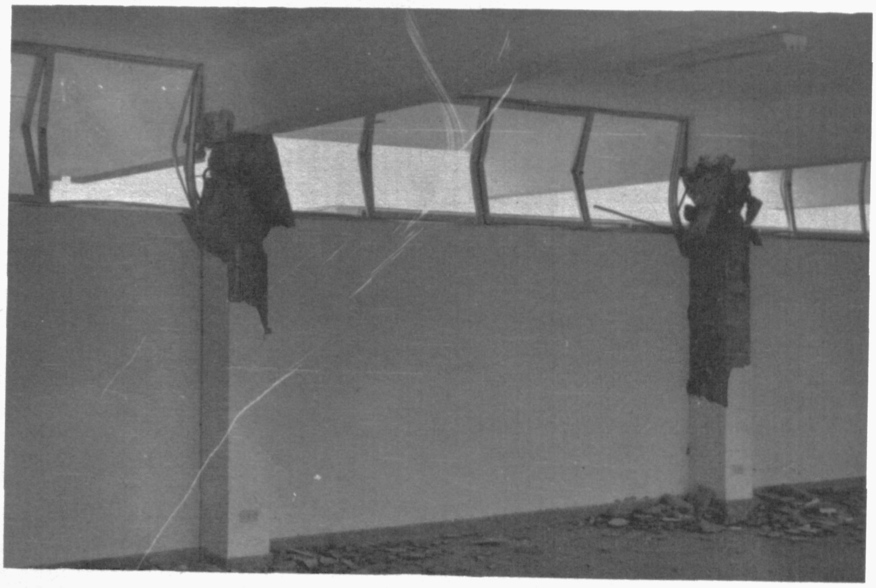


Fig. 4. Columns restrained by adjacent walls, Chimbote

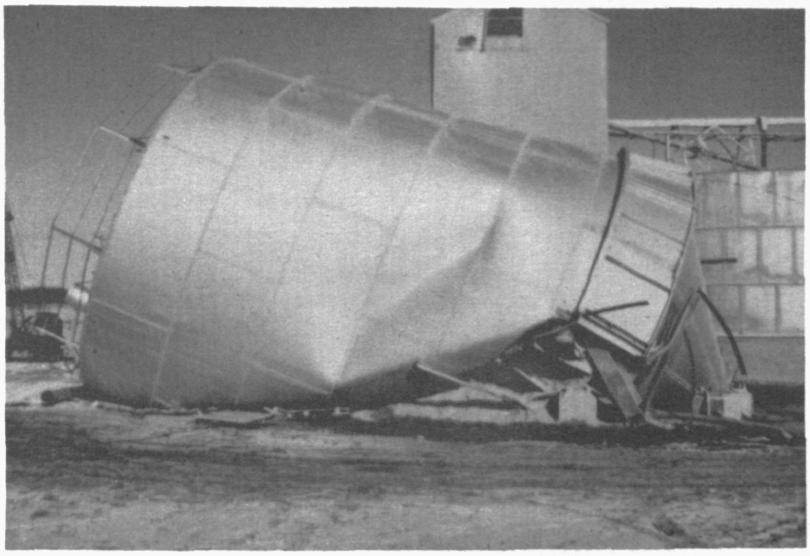


Fig. 5. Collapsed cement bin, Anchorage

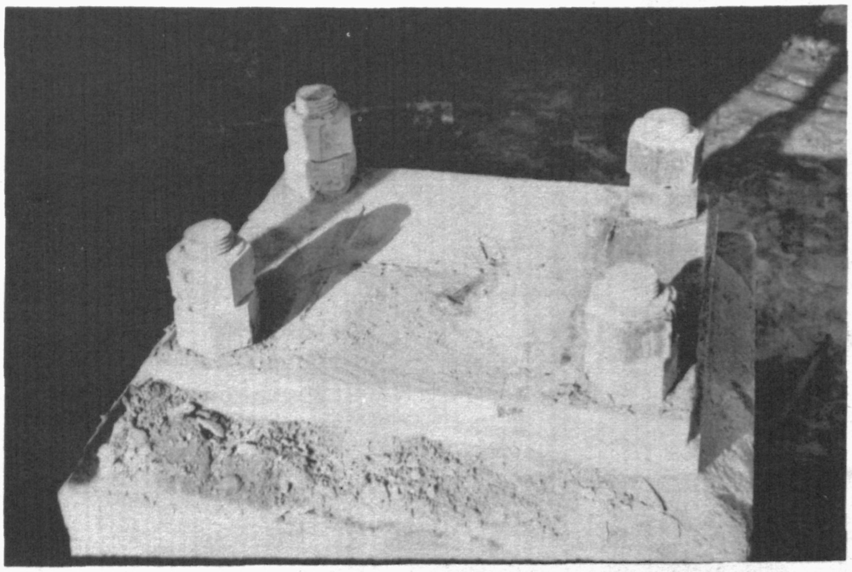


Fig. 6. Base plate for cement bin column, Anchorage

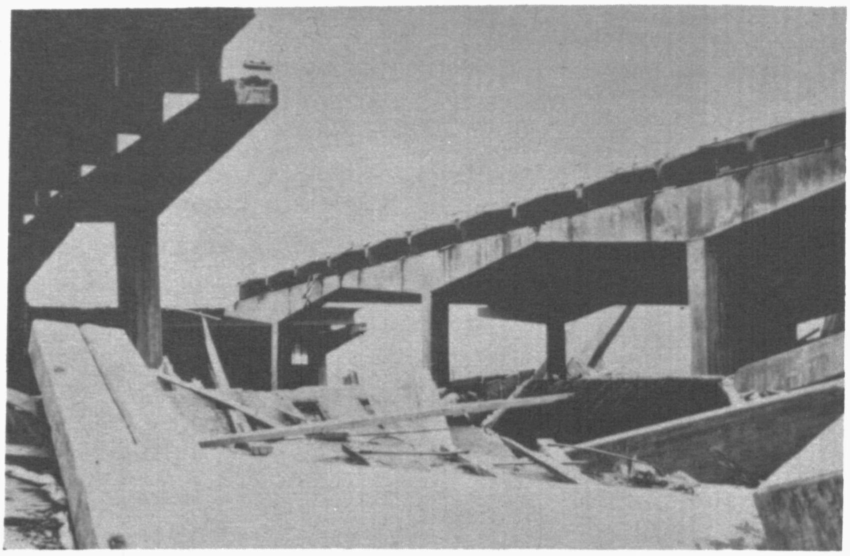
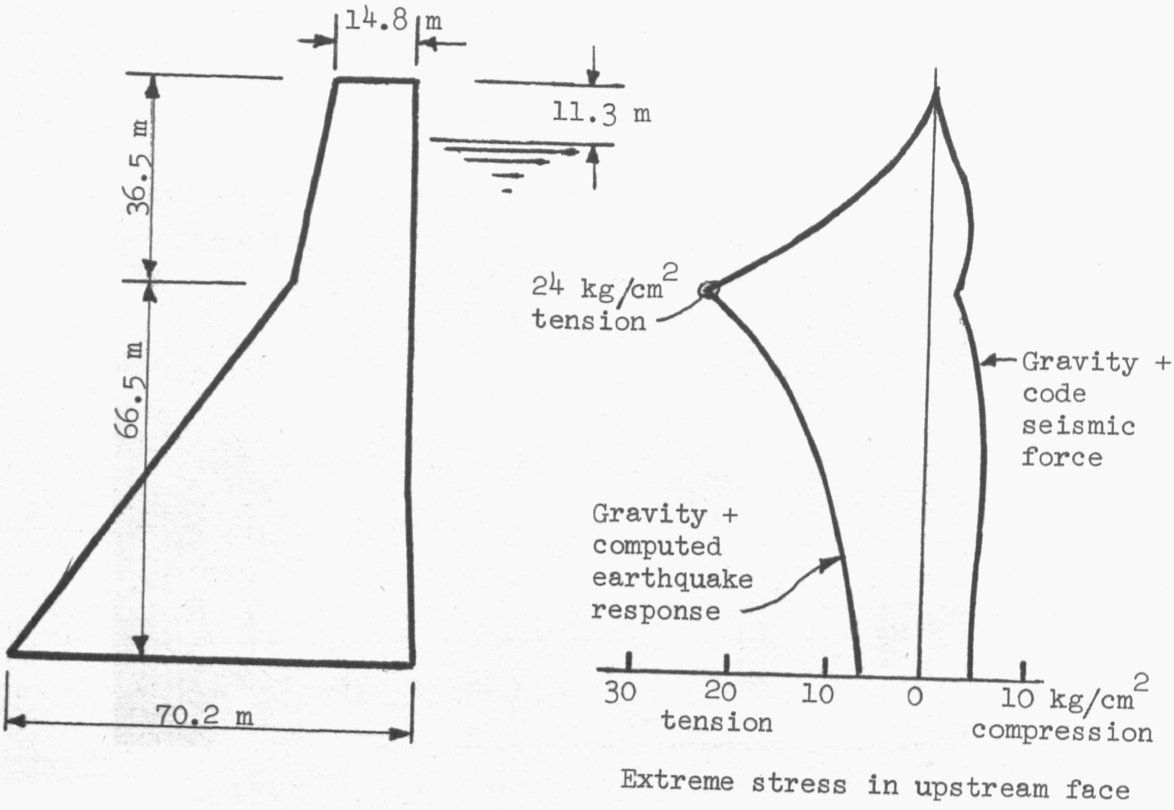


Fig. 7. Precast concrete structure, Anchorage



Extreme stress in upstream face

Fig. 8. Koyna dam section and stresses

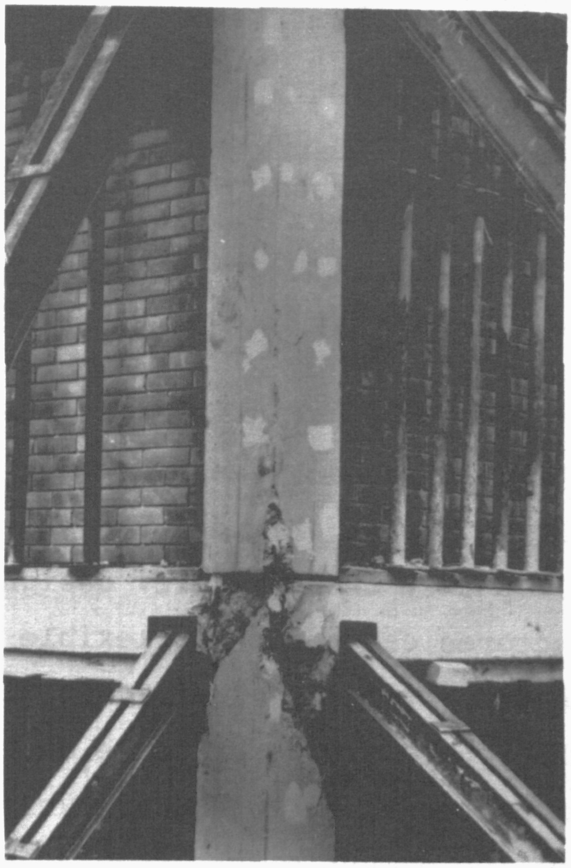


Fig. 9. Tension effects in column, Caracas

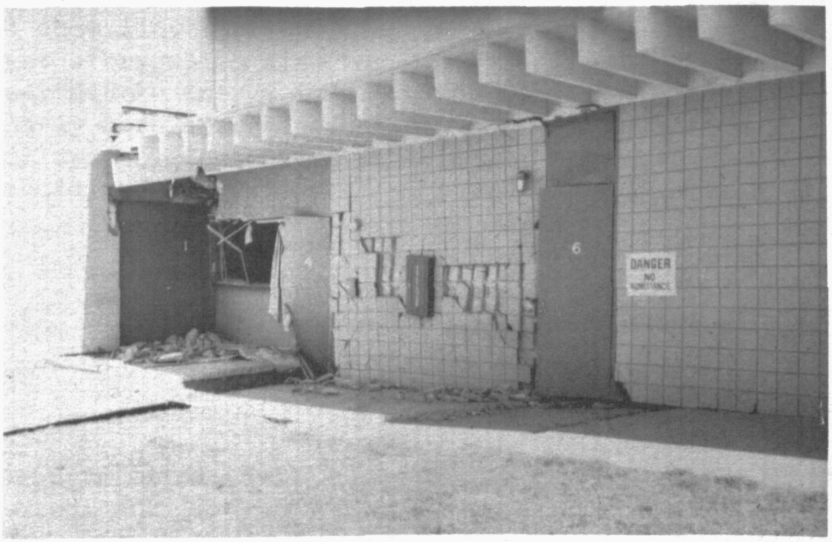


Fig. 10. Grouted block walls, San Fernando