

DAMAGE MECHANISMS AND DESIGN LESSONS  
FROM CARACAS

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1.0 INTRODUCTION

At 8'clock on Saturday evening on 29th of July, 1967 a moderately severe earthquake caused about 277 deaths, 2,000 injuries and damage estimated at 100 million U.S. dollars in and near the city of Caracas, Venezuela. Estimates give the Richter Magnitude as 6.5, the epicentre as 70 kilometers NNW of Caracas, and the depth as 10 kilometers.

Many factors combine to give great importance to an engineering study of the damage at Caracas. The City contains over a thousand large modern buildings, nearly all being variations on the same theme, vis. a slender reinforced-concrete frame with non-structural panels of hollow ceramic brick.

Dramatic microzoning effects were observed. The tall buildings in one city area were severely damaged while there was no damage to very similar building in nearby areas. Those buildings which were only a few storeys high were attacked more severely than taller buildings in areas where the alluvium was of moderate depth. Within the area of deep alluvium in Caracas City only tall buildings were damaged, however at Macuto Beach, where the alluvium was deep, buildings and other structures were damaged irrespective of height. Buildings located on rock foundations suffered little or no damage whatever their height.

Damage mechanisms were clearly demonstrated since similar buildings suffered all degrees of damage up to total collapse. Some buildings suffered structural damage to beams and slabs while other buildings had most of the structural damage confined to the columns. Buildings with column damage appeared to have an unexpectedly low resistance to the transient overloads imposed by the earthquake. Final failure of four ten-storey to twelve-storey buildings appeared to result from collapse of the first-storey columns under excessive vertical loads. Added to gravity loads on the columns were cyclic vertical loads due to over-turning forces on the buildings and also cyclic end moments. The fragility of these collapsed buildings resulted from a failure mechanism with a low plastic reserve.

Accepted design practice was given a searching test by this moderate earthquake since Caracas buildings were designed to withstand such earthquakes. The code requirements for building in this area are approximately equivalent to those for Zone 2 of the Californian Uniform Building Code.

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Hollow ceramic brick panels, although not taken into account during the design of the reinforced concrete frames, exerted a dramatic and usually detrimental effect on the performance of the buildings. Panels shattered in the most heavily loaded regions near the base of the building. Higher in the buildings the panels withstood the earthquake loads and in many cases these remaining panels greatly changed the load distribution among the first storey columns. This must have increased column damage and contributed to the collapse of some buildings. The panel damage was expensive and hazardous. While most of the deaths occurred in collapsed buildings some of the deaths and most of the injuries were doubtless caused by falling masonry.

Special theoretical and experimental studies should be directed towards increasing the plastic reserve of this form of construction. Increase in the ratio of column strength to beam strength should tend to concentrate damage in the beam system with its greater plastic reserve. Increased column ties and beam stirrups should increase plasticity at little additional cost. The modified columns and beams should be tested under a realistic set of combined cyclic and static loads to establish their strength and plastic reserve.

The interaction of the hollow brick panels with the reinforced concrete frames should be checked experimentally by cyclically loading test frames. Particular attention should be paid to frame damage by the panel and to preventing parts of the panel from falling out, with consequent casualties during an earthquake.

## 2. Caracas Area

### 2.1 Ground Condition

The central spine of the city extends about 12 miles along an alluvial valley with some extensive alluvial fans from the mountains within the northern part of the city. These fans contain gravels, sands, and boulders, together with moderate amounts of clay. The large modern apartment buildings extend from the alluvial valley onto a number of gently sloping rocky ridges. The older parts of the city including shanty-town areas, extend onto steeper rocky ridges. The coastal towns and beach resorts to the north are either on gently sloping rocky ridges or on alluvial fans.

### 2.2 Caracas Buildings

The Caracas area contains over 1,000 buildings with heights ranging from 10 to 22 storeys. These buildings are sometimes long and narrow, and they are frequently built in pairs with a connecting tower containing all the lifts and stairs for both buildings. Almost every tall building is a variation on a single method of construction. They contain a slender reinforced concrete frame which is designed to take all the vertical and horizontal loads. The floors are of waffle construction with a 4" slab of mesh-reinforced concrete below which are reinforced ribs 4" wide and 6" deep.

The waffle pattern is poured around hollow bricks. This allows simple supporting formwork to be used and results in plain ceilings.

Both the longitudinal and the transverse beams of most buildings frames are wide and shallow so that they can be contained within the 10 inch depth of the waffle floors. Columns usually have one face which is much wider than the other. The wide column faces match the wide beams which abutt them. Beams in the other direction which abutt the narrow column face, are usually 10 inches deep also but are sometimes 18 inches or more in depth. Exterior columns are of reduced cross section and corner columns are further reduced in section. The column areas appear to be proportional to the dead loads which they carry.

Exterior walls and interior partitions are of ceramic bricks containing about 80% voids. No reinforcing or grouting is used. Panels are of brick, usually 12" by 10" by 5", and are often plastered on both sides to give a finished thickness of 6". The strength and flexibility of the brick panels depends upon the size and shape of openings and upon the way in which the edges of the panels are framed by the columns and beams. Floors are often cantilevered beyond the outer columns so that the exterior panels have no associated columns. Identical layout is employed for all storeys above the first. Most first storeys contain few panels, leaving room for car parking, for shelter and for reception areas.

### 3. Earthquake Character

#### 3.1 Ground Movements

When compared with damage and measured or estimated accelerations during earlier earthquakes the damage was consistent with maximum accelerations of 5%g on rock, in Caracas, 10%g on deep alluvium in Caracas, and 25%g in the Macuto Beach area, 8 miles north of Caracas.

The pattern of damage in buildings at Macuto Beach was quite different from the pattern of damage in similar buildings on the deepest City alluvium. The severe jolt was said to have occurred some time after the onset of the earthquake.

Damage at Macuto Beach suggests a single large acceleration pulse towards the North together with sharp irregular shaking of short total duration. The acceleration Response Spectra would be similar to that of the earthquake on 30 December 1934 at El Centro, California.

Damage to structures on the deepest City alluvium, Los Palos Grande in NE Caracas, was consistent with an acceleration having a substantial sinusoidal component at about one cycle per second, of moderate amplitude, and of long total duration. The acceleration response spectra would have a maximum near 1 sec period and this maximum would be 0.3g or more for low damping. Severe damage was associated with both north-south and east-west shaking.

The acceleration on rock in the Caracas area and irregular. The acceleration response spectra would peak up at a period of less than 0.15 secs.

### 3.2 Damage Areas

The Caracas earthquake caused very severe damage in one small area in NE Caracas, Los Palos Grande, and on the coast at Macuto Beach 8 miles to the NNW. An area of less severe damage occurred in NW Caracas. Moderate to slight damage occurred in many areas, but many other areas had no trace of earthquake damage. Some damage occurred along the coast east of Macuto Beach. No significant damage occurred on the rocky ridges in the city area and in particular the shantytown dwellings on the steeper rocky ridges were not damaged. There was also no damage to buildings on the slopes of weathered rock near the airport and seaport.

The Los Palos Grande area in the NE has the deepest alluvium in the city, over 300 feet. This consists of an alluvial fan over a deep basin-shaped depression in the rock surface, thought to be a recent graben. The water table is from 3 to 15 ft. below the surface in this area. The area of less severe damage in the NW is over a similar but shallower graben filled with alluvium.

The Macuto Beach area consists of a deep alluvial fan deposited around the central lagoon. Part of the lagoon is reclaimed by tipped "non-engineered" fill, two of the large buildings are probably on this fill.

Both high-rise and lesser-height buildings were situated on each main ground type.

### 4. Building Design Code

Damage to buildings must be related to the severity of earthquake which they were designed to resist. In 1955 the earlier design code for earthquake resistance in the Caracas area was superseded by a code based upon the Zone 2 provisions of the Uniform Building Code of California. The Code provides for comparatively small horizontal design loads.

Buildings generally appeared to comply with the letter if not the spirit of the Californian Code. The inadequate ties and stirrups led to building components with a relatively low plastic reserve of strength. Also the low earthquake design loads frequently resulted in buildings which concentrated the earthquake overloads in a few members and hence made inefficient use of the plastic reserve of the individual building components. These two points are taken up again after the damage is described.

### 5. Damage and Collapse Mechanisms

The significance of damage to particular buildings can be seen more clearly after a general examination of probable mechanisms of damage.

The damage mechanisms in the Los Palos Grande area in north

east Caracas differed considerably from the damage mechanisms in the Macuto Beach area and they will therefore be discussed separately.

### 5.1 Step by Step Progress of Damage

In the Los Palos Grande area severe damage and collapse were confined to the many tall buildings in the area. The severe shaking probably lasted for 30 to 40 seconds with most of the energy concentrated in the period range of  $\frac{3}{4}$  to 1 second.

The following picture of progressive damage is formed by examining similar buildings which have suffered various degrees of damage up to total collapse. Moderate horizontal earthquake loads are taken by the panels of hollow brick. The pattern of panels is identical and the strength of each is the same for all storeys except the first which usually has few panels. As the horizontal loads are increased the first storey panels are destroyed and the loads are transferred to the first storey columns. As the earthquake loads are increased panel damage occurs in the second and then higher storeys.

With a further load increase some buildings suffer first storey column damage while other buildings suffer beam damage up to almost the sixth floor. Severe panel damage typically extends up to the third floor of buildings with damaged columns and higher than the sixth floor of buildings where beams and slabs are damaged. Around stairways the panels and auxiliary frame members are damaged to a considerably greater height than elsewhere in the building. Four buildings collapsed with the lowest few floors falling almost exactly in their plan position. It is inferred that these buildings collapsed due to complete failure of the first storey columns.

Moderate structural damage often occurred in both beams and columns. However, severe damage was usually confined to either the columns only or to the beams and slabs only. These two damage mechanisms differ in many important respects.

The building period must have been increased more by the damage to beam ends, which was extensive, than by the more localized column damage.

### 5.2 Column Damage

The earthquake horizontal loads apply cyclic shears and end moments to the columns while the overturning forces apply cyclic vertical forces, particularly to outside columns. These cyclic forces are additional to the dead-weight vertical loads of the building. Severe column damage was confined to the first storey. Panel damage occurred up to the second or third storey but was only partial and the panels continued to give some support to almost all frame members except the first storey columns. The corner columns were most severely damaged and the remaining outside columns also suffered considerable damage. Hence the severity of damage is directly related to the attack by overturning forces. This

pattern of damage is encouraged by the column areas which are less for external columns than for interior columns and are least for corner columns.

Three buildings which suffered typical column damage were the San Bosco, the Petunia II, and the Coromay. In each of these buildings one or more light corner columns of the first storey were completely shattered.

### 5.3 Beam and Slab Damage

The columns of some buildings remained intact while the beam ends were severely damaged. The slabs between the damaged beam-ends were cracked. The beam damage extended up for six storeys or more. This is to be expected since failure of beams at one level throws additional moments onto the ends of the beams above. In these buildings severe panel damage extends upwards for a greater height than the beam damaged. This damage mechanism requires that the columns are sufficiently strong to damage the beams and panels of several storeys which are giving each other some mutual support. Hence this type of damage is more likely in the direction parallel to the wide faces of the columns. Panels with considerable openings and without column support will increase the likelihood of damage by this mechanism. Two buildings which suffered this beam and slab damage were the Residencia Union and the Blue Palace.

## 6. Damaged Buildings in North East Caracas.

### 6.1 Buildings with Damaged Columns

Tall buildings, with severe damage to columns but not to beams, are concentrated in the Los Palos Grande area of north east Caracas. With this damage mechanism very severe lateral deformation of the building frame was confined to the first storey or completely absent.

#### 6.1.1 San Basco - 13 storeys, 7 bays by 3 bays

The long axis of the San Bosco is north-south. The beams along both axes are shallow and the corner columns are slender.

The north-east corner column was shattered just above ground level, with a loss of height of about three quarters of an inch. All the other first storey columns showed some sign of damage and compression near the lower end.

#### 6.1.2 Petunia II - 21 Storeys, 3 bays by 3 bays

The probable sequence of serious damage is as follows. A lurch towards the east caused overturning forces which resulted in tension cracks in the NW corner column and probably the SW corner column. Small tension cracks also appeared on at least one of the intermediate western columns. Later there was a lurch towards the west which crushed the SW and NW columns and caused

small tension cracks in the NE column. Finally there was a lurch towards the south which crushed an intermediate column situated in the southern wall and near the SW corner. In addition to these sudden lurches the building must have swayed from side to side for about three quarters of a minute, causing a progressive increase in the existing damage, Fig. 1. Most of the exterior panel damage was directly associated with crushing failure of the building frame.

#### 6.1.3 Caromay - 18 storeys, 8 bays by 2 bays

The most severe frame damage is crushing of first storey columns. The crush zones were near the mid-height of the columns or a little above. The crushing forces were generated by swaying of the building in an approximately east-west direction. The most severe column crushing was near the SW and NW corners of the first storey and near the centre of the eastern row of columns. If the building had deformed as a flexible frame, as normally assumed during design, then the curvature of the longitudinal axis would not have increased the vertical loads on the severely crushed columns. However, the building above the first storey swayed as a relatively rigid box so that the curvature increased vertical forces in these severely damaged areas.

#### 6.1.4 Discussion of Buildings with Damaged Columns

Each of these three buildings swayed as a relatively rigid box above the first storey columns. The interior columns and panels of the first storey acted as a fulcrum so that the swaying caused vertical crushing forces in the outer columns and particularly in the slender corner columns. The San Bosco and the Petunia II were damaged by swaying in both the north-south direction and the east-west direction. There were probably rotational movements as well. The structural damage to the Coromay was caused by east-west swaying.

### 6.2 Buildings with Damaged Beams and Slabs

#### 6.2.1 Blue Palace - 18 storeys, 3 bays by 3 bays

The Blue Palace was constructed in a similar manner to the Residencia Union, Fig. 2, and suffered similar damage. The east-west beams are wide and shallow. The north-south beams are deep and extend about four feet beyond the outer rows of columns to support cantilevered floors. There is very little effective framing of the panels in either direction. The first storey contained a full set of panels. The panels were constructed of high void bricks.

Sidesway in a north-south direction caused beam and slab damage to about the fifth storey and panel damage to the twelfth storey. East-west panels were severely damaged to the fifth storey. There appears to have been some rotational movement since the panels in the southern wall were more severely damaged than the panels in the northern wall.

## 6.2.2 Discussion of Buildings with Damaged Beams

Since frame distortion and consequent beam damage is opposed by the stiffness of the panels this damage mechanism is more likely in the very tall buildings in which the heavier frames are stronger in relation to the panels. Moreover the gravity loads of very tall buildings will dictate an increase in the ratio of column strength to beam strength. Panels which are effectively framed and panels of special low void bricks will also oppose this mechanism of damage.

The large number of plastic hinges formed at the ends of the beams absorb a large amount of energy.

While the column failures led to total collapses and many deaths (as discussed below) the beam failures led to extensive shedding of masonry and almost certainly to many injuries and some deaths.

## 6.3 Damage Due to Panel Position

### 6.3.1 Mene Grande - 14 storeys and 2 Basements

#### 2 Blocks of 5 Bays by 2 Bays

The distribution of frame loads in the Mene Grande was completely dominated by a few wall panels. This is a large office building which has two identical parallel blocks running east-west and a central link block running north-south. The building has a flexible reinforced concrete frame but no internal load-resisting panels. Throughout the interior there are moveable light-weight partitions. The longitudinal outer walls have half-height panels so that the building is very flexible in the east-west direction. However the sides of the link block contain complete panels framed by beams and columns. The ends of the building, except at the first storey level which is open, are filled with complete fully framed panels. The end panels, transmitted the overturning forces to the corner columns, which suffered tension damage near the top of all four first storey columns. The end panels, while sustaining some edge cracks, were relatively little deformed.

The damage to this building was completely dominated by the stiffening action of the panels, particularly the end panels. If all wall panels had been separated, so that they exerted no forces as was assumed during design, there may well have been no damage to this building.

## 6.4 Collapsed Buildings - Probably by Column Failure

Four buildings collapsed in the Los Palos Grande area; the San Mijagual, 11 storeys with 4 bays x 2 bays, the Palace Corvin, 10 storeys with 7 bays x 2 bays, the Neveri, 10-12 storeys with 4 bays x 2 bays, and the San Jose, 11 storeys with two sections of 5 bays x 3 bays with a substantial link block. Each of these buildings collapsed with very little lateral displacement of the first few floors. Consider the two mechanisms of serious damage

to buildings in this area. It is almost certain that the crushing of the first storey columns would lead to a vertical collapse while failure of the beams and slabs over the first few storeys would lead to a large lateral spread of the first few floors. Hence all four collapsed buildings almost certainly failed by crushing the first storey columns. This form of collapse could well drive the second storey columns into the ground, as occurred in the case of the San Mijagual and the Palace Corvin.

Additional support for a column failure mechanism for the Palace Corvin is given by the pattern of panel damage in the surviving block. The first storey panels are very severely damaged while the second storey panels are only moderately damaged, a pattern typical of first storey column damage. Indeed this block may have survived because it had more longitudinal panels in the first storey than the failed block.

## 7. DAMAGE AND COLLAPSE MECHANISMS AT MACUTO BEACH

The earthquake forces at Macuto Beach, 10 miles north of Los Palos Grande, attacked tall buildings throughout their full height and also shorter buildings and other structures. This is in contrast to the earthquake attack in Los Palos Grande area where severe attack was restricted to the lower levels of tall buildings.

Of the five tall buildings at Macuto Beach, four were very severely damaged. A four storey building collapsed and a three storey building was so severely damaged that it was later demolished. A set of concrete canopies were supported by steel columns which remained deformed by several inches towards the south. There was clear evidence that structures lurched towards the south much more violently than towards any other direction.

The character of the damage shows that there was a very large pulse of acceleration towards the north. A considerable part of the energy of the attack must have been at short periods, probably less than 0.3 seconds. There is some lesser damage associated with swaying towards the north and also in an east-west direction. There is little evidence of progressive damage so the severe shaking was probably of shorter duration than at Los Palos Grande.

### 8.1 Macuto Sheraton - 10 storeys, 11 bays

The Macuto Sheraton runs east-west, parallel to the beach. It is a large building of unusual construction, Fig. 3. The cross-section shows two pairs of large columns for the first three storeys with a narrow shear wall rising from each pair of columns for the remaining seven storeys.

The shear walls were spaced at 27 feet intervals along the 300 foot building.

When the building lurched to the south, the top and bottom of each triple-storey column suffered very severe end moments since the beams were insufficiently stiff and suffered cracking. Most of the overturning forces at the foot of each shear wall were transferred as vertical forces to the pair of columns below since the shear

resistance of the beam systems connecting each pair of shear walls was inadequate. The second and fourth rows of columns were therefore subjected to very severe moments and compressions as shown in Fig. 3. The northern row of columns shows moment - tension damage and the second shows very severe moment - compression damage. The third and fourth rows from the north show relatively little damage. The lesser damage to the southern rows of columns would be accounted for if the outer rows of piles, particularly the southern row, settled under earthquake shaking and building loads, relieving the overturning forces under the southern shear walls. This settlement is highly probable as the ground settled up to several inches within a few feet of the building, and it is thought that the whole building may have settled about two inches. Hence the component rigidities and the foundation settlement can account for the type of damage suffered by almost every column.

The few exceptional cases of column crushing are probably due to underlying piles with an exceptional resistance to being driven deeper.

## 8.2 Discussion of Damage at Macuto Beach

The primary attack on buildings was the ground vibrations. In at least one instance, the Macuto Sheraton, ground settlement modified the pattern of damage. However, settlement appears to have contributed little towards the damage of the other buildings. There were cracks and settlements of several inches close to the shore and close to the lagoon, and a swimming pool close to each was seriously damaged.

## 9. STEPS TO REDUCE CASUALTIES AND DAMAGE

### 9.1 Avoid column crushing

The frame should be designed to avoid failure by column crushing. A high ratio of column strength to beam strength should be used, particularly for outer columns. This high ratio may be achieved by designing for large overturning forces. Adequate ties should be provided to develop compression concrete and to resist the buckling of reinforcing rods. The ties should be detailed so that they will not unwrap when the outer concrete cover is spalled off. They may be closed by welding, they may form a spiral, or their ends may be carried around a rod and terminated towards the centre of the column.

### 9.2 Beam ends with large plastic reserve

The beam ends should have rods and stirrups detailed in a way which ensures that there is a low rate of damage increase when the beam ends are rotated far beyond their elastic limit for many cycles. The beams should be capable of supporting the floor loads when hinges are introduced at the beam ends.

The building should be proportioned so that beam end hinges form over as many beams as possible. This will tend to occur when the same plastic reserve is required by all beams.

### 9.3 Reduce Hazards of Panel Damage

Ideally the panels should be separated from the columns and from the beams and slabs above them. However, this would introduce difficult and expensive sealing problems on external walls. Also, it may be difficult to provide for face loading on the panels.

Most of the casualties caused by shattered panels are due to masonry falling from the external walls and from the walls around stairways. Hence steps should be taken to prevent falling masonry. A wire mesh may be placed outside the panels and attached to the building frame. This would then be covered by plaster. A similar wire mesh should be used to prevent masonry falling down stairways.

The next severe damage to Caracas City may be caused by a closer earthquake with ground vibrations similar to those which occurred at Macuto Beach during this earthquake. Under these conditions panels may be shattered to much greater heights in city buildings. Buildings of lesser height would also be attacked severely.

## 10. CONCLUSION

This earthquake drew attention to a number of important aspects of earthquake resistant design.

Particularly dramatic microzone effects were evident. The severity and character of the shaking varied greatly with the depth of the alluvium. The movement of the alluvium was much more impulsive at Macuto Beach than in Caracas. These effects emphasised the urgency of microzone studies.

The value of all the engineering studies of this earthquake would have been greatly increased if one or more strong-motion accelerograph records had been obtained in the Caracas area. In particular a three-component record from Macuto Beach would have helped in assessing the importance of T-wave propagation to the earthquake attack in this area.

Various mechanisms of building failure occurred, particularly first storey column failure and beam failure over several lower storeys. Defects of steel detailing, particularly inadequate ties and stirrups, were evident. There was dramatic interaction between the light weight non-structural panels and the flexible frames. Special studies and experimental work are required on the interaction of building frames and infill brick or masonry panels under severe cyclic overloads.

The seven-day visit to the earthquake damage at Caracas was a most valuable experience for the author. Although the visit was delayed until eight weeks after the earthquake, this resulted in little loss of information since the local investigating Presidential Commission set the seriously damaged buildings aside for special studies. Moreover considerable work had been done

in removing plaster and some non-structural components to reveal details of damage to structures. Some information was removed in the cleaning up and in the removal of hazards but much of this information was available from the systematic records kept by the investigation Commissions and from overseas experts who visited Caracas during the first few weeks following the earthquake.

A two-man Emergency Study Mission was dispatched to Caracas by Unesco.

The author has not yet seen a copy of their report but he is unaware of any proposal for a follow up study Mission. Many small groups of international experts visited Caracas during the few weeks immediately following the earthquake. Also local Commissions are engaged in extensive and systematic studies of the earthquake damage. While the reports of both the international experts and the local Commissions will doubtless make a major contribution to engineering seismology, the studies of the former were brief while those of the latter are necessarily related to local conditions. The author is convinced that this earthquake would have justified a special engineering study for three or four months by a small group of world experts.

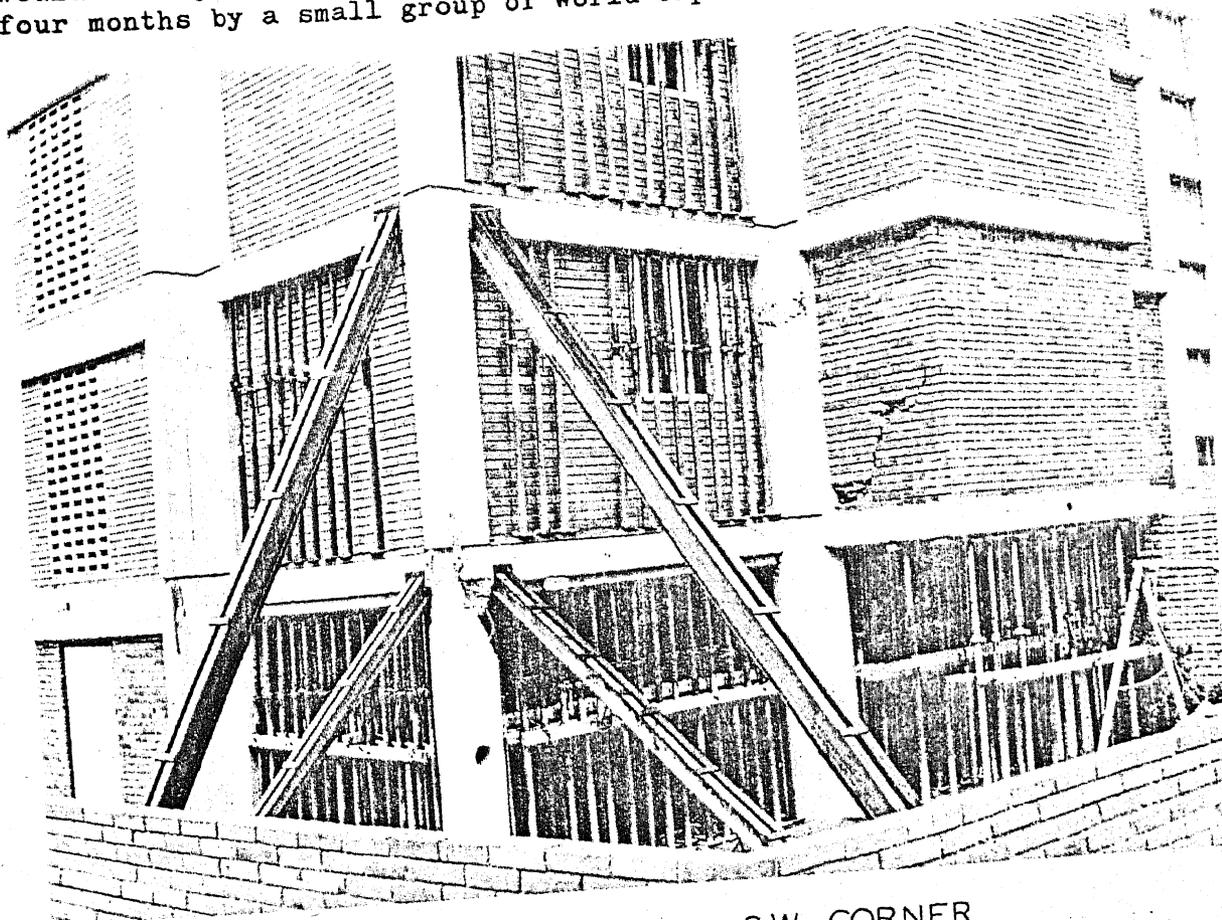


FIG.1. PETUNIA II, S.W. CORNER

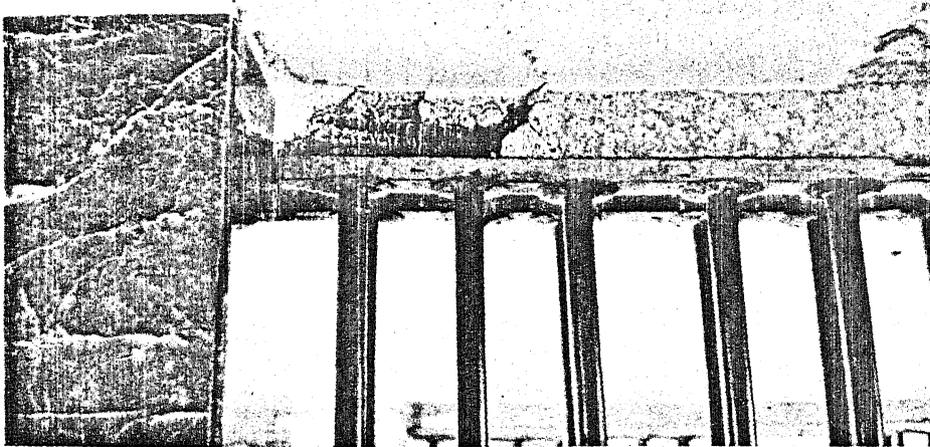


FIG.2 RESIDENCIA UNION, FIRST STOREY

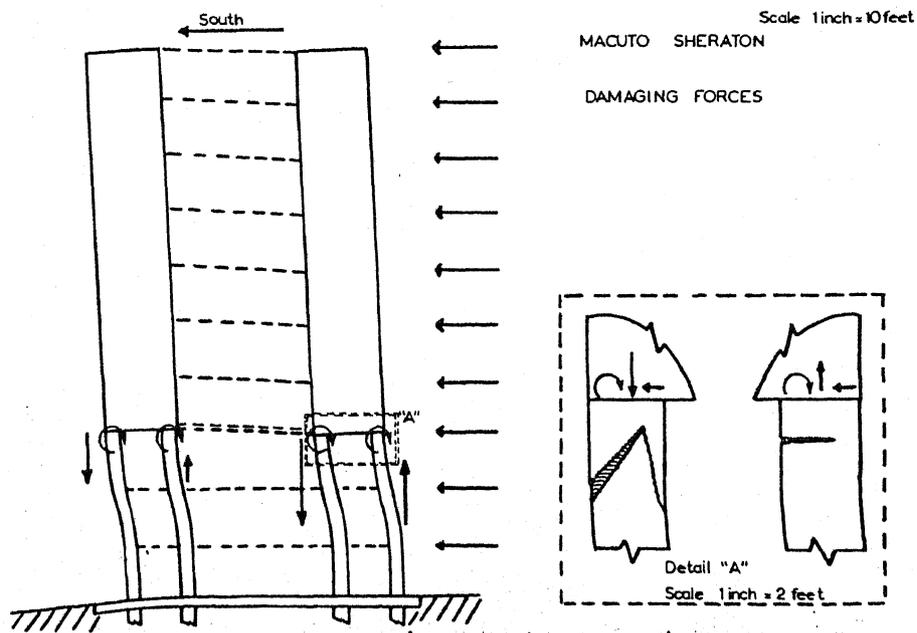


FIG.3 MACUTO SHERATON, DAMAGE MECHANISM

ABSTRACT  
of the paper

IMPLICATIONS ON SEISMIC STRUCTURAL DESIGN  
OF THE EVALUATION OF DAMAGE TO THE SHERATON-MACUTO

by

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The main building of the Sheraton- Macuto Hotel is an eleven-story reinforced concrete structure. A significant feature of the structural system is that, in one direction the lateral forces are carried in the top seven stories by a pair of parallel slender shear walls which are supported by heavy columns in the lower four stories. During the earthquake of 29 July 1967, severe damage was sustained by the columns supporting the shear walls.

Analyses of possible causes for the column failures suggest that the columns failed primarily because of the lack of ductility, a shortcoming aggravated by the increase of axial load and the failure of some of the connecting girders in shear.

The damage to the building emphasizes the importance of considering in design the deformations of the entire structure under the influence of earthquake forces to make certain that all structural elements have compatible ductility and of insuring that enough web reinforcement is provided to develop the flexural capacity of beams and columns.