# STRUCTURAL DEFICIENCIES OF ENGINEERED BUILDINGS EXPOSED DURING 2001 BHUJ EARTHQUAKE

Prabuddha Dasgupta, Jaswant N. Arlekar, C.V.R. Murty and Sudhir K. Jain
Department of Civil Engineering
Indian Institute of Technology Kanpur

## ABSTRACT

The recent Republic Day earthquake measuring $M_w$ 7.7 (source: USGS) has not only shaken Bhuj, but also shaken the entire engineering community of this country. For the first time in the seismic history of this country, engineered structures were put to test under strong ground shaking. While the devastating 1991 Uttarkashi, 1993 Killari and 1999 Chamoli earthquakes presented examples of seismic effects on non-engineered structures, the 2001 Bhuj earthquake has affected engineered structures as well. Highly damaged columns in the open ground floors of many multistoried buildings emphasized the importance of seismic design of structures. The provision of floating columns on cantilever beam also proved to be structurally distressing. Extensive damages sustained by columns covered partially with infill walls have shown the ills of short column effect.

## INTRODUCTION

The recent Bhuj 2001 Bhuj earthquake ($M_w$ 7.7) has many lessons to be learnt. The widespread destruction of property and human life, when an earthquake of this size hits an area are not new, especially in a country where a large part of the building stock is constructed without application of any approved engineering techniques, whatsoever. So, it was not surprising when, in this earthquake as well as those in Uttarkashi (1991), Killari (1993) and more recent one in Chamoli (1999), these buildings collapsed very easily and claimed their share of human lives. But, a new story unfolded in the cities near Bhuj on that fateful day that shook the confidence of the engineering community of this country and set the Bhuj earthquake apart from all other earlier earthquakes. For the first time, multistorey buildings, apparently built following the engineering guidelines crumbled down like packs of cards. Other engineered structures like port facilities, bridges, dams, etc., also suffered damages to various extents. This makes the engineering community wonder what went wrong and if the same would happen again if another similar earthquake strikes a similar area. So, important lessons are to be learnt from this earthquake about the kind of damage that threatens the large stock of engineered structures existing all over the country. More importantly, it is the RC buildings that require special attention as collapse of these accounted for most of the deaths during this earthquake. This paper presents details of the structural effects on the RC frame buildings during the 2001 Bhuj earthquake.

## RC BUILDINGS

What sets the Bhuj earthquake apart from the previous earthquakes in India, is the extensive damage and collapse of a large number of engineered (though not seismically) RC frame buildings in well-developed and populated cities like Ahmedabad and Gandhidham. Economic growth of the area has seen a real estate boom and a rapid mushrooming of RC multistorey building. While, design of these buildings may have included the general engineering norms, special considerations for earthquake safety, even the basic ones, often eluded them, out of ignorance or neglect. The result has been catastrophic. Many buildings were reduced to rubble. A large number of them sustained heavy damages to an extent that they had to be abandoned. Buildings that were designed and constructed following the seismic design guidelines performed as expected.

Structural deficiencies that caused the extensive damage to buildings during the recent Bhuj earthquake are not unique to the region affected during this earthquake. Such buildings are existing in large numbers all over India. The January 2001 Bhuj earthquake has reemphasized the importance of recognizing these deficiencies and taking adequate measures to save the huge stock of existing buildings in India, and to have safer and seismically adequate structures .

**Open ground storey**

The most common reason that caused the failure and collapse of a large number of buildings was the practice of having soft ground storey. This is a cause of major concern as this is the most common practice throughout the country. Due to the functional requirement of parking, the ground storeys of the multistorey buildings are invariably left open (Fig. 1 shows cars crushed under the building due to the open ground storey collapse). The upper storeys, however have infill walls. While the absence of infill walls does not affect the transfer of gravity loads, it significantly influences the performance of buildings during earthquake shaking. The absence of infill walls in the ground storey results in an open ground storey configuration. Further, the ground storey columns are not designed to resist the lateral force and displacements resulting during the strong earthquake shaking. The presence of infill walls in the upper storeys causes a drastic reduction in the lateral stiffness of the ground storey resulting in a soft ground storey, which by definition is a storey whose lateral stiffness is less than 70% of the adjacent storeys [FEMA 223A, 1995]. The absence of infills in the ground storey gives the building a configuration of an inverted pendulum, with a large mass sitting on top of relatively flexible columns. During earthquake shaking, as the upper storeys are very stiff, the total drift of the structure is concentrated in the ground storey columns. This has been demonstrated in an earlier study [Arlekar, 1997], where deflection profile under lateral loading was drawn to show this variation.

The large drift demands on the ground storey columns due to strong earthquake shaking, results in their heavy damage that distresses the whole building and may even cause collapse. In Bhuj, all this theory turned into a harsh reality. Buildings were reduced by one storey at the ground floor level (Fig. 2). At lest one case with intermediate soft storey collapsed was also observed, even though the drift and force demand on the columns of intermediate floors are much lesser than those on ground floor columns (Fig. 3). The reason for such poor performance can be attributed to lack of adequate transverse reinforcements provided in the columns. It is well established now that providing confinement to concrete with the help of hoops and stirrups can enhance the strength and ductility of the concrete to a large extent [Pauley and Priestley, 1992]. The confinement also helps the RC columns to undergo large deflections without failure. But, unfortunately, building in India are generally designed and constructed by considering the transverse reinforcements as carriers of member shear and something that helps holding the longitudinal bars in place. As a result of this the amount of transverse reinforcement in columns is often too low to enable the columns to undergo the large deformations without being severely damaged.

Some buildings with open ground storeys and RC elevator cores withstood the shaking without collapse. Due to their large size, the RC elevator cores offer much larger stiffness compared to other columns and as a result draw larger seismic. They are also very effective in limiting the drift of the ground storey. In many buildings, the RC elevator cores were severely damaged. Interestingly, these RC cores were not designed as lateral load resisting elements. It has been shown in the earlier study [Arlekar, 1997] that the RC cores can be effectively used as lateral load resisting element in the ground storey in the absence of the infill walls. Due to their large lateral dimension, they were rendered very stiff in the lateral direction as compared to the other lateral load resisting elements (columns) in the ground storey. Further, these were not designed to resist the forces and deformations resulting from the earthquake shaking; they were designed for the loads due to the operation of the elevator. Thus, the RC core walls, being very stiff without adequate deformation and strength capacity, were heavily damaged. However, the columns were not severely damaged as the deformations in the ground storey were limited by the presence of the RC core walls. The columns were primarily designed as gravity columns and all the lateral load resulting from the earthquake was absorbed by the RC core walls, leaving the columns in a state that they could still function as gravity columns and save the buildings from collapse. The connection between the RC elevator core and the rest of the building plays an important role in the effective use of the RC elevator cores. Building with a good connection between the slabs and the walls of the RC elevator core transfer the seismic loads to the RC core and utilize its strength and stiffness. However, there are instances, where lack of good connection between the building and the RC elevator core resulted in the core not sharing the lateral load with the building; the building collapsed while the core stood strong (Fig. 5).

Inadequate detailing of column reinforcement also took its toll. Spacing of stirrups along the member was often too large to effectively confine the column core concrete (Fig. 6 and 7). Indian code for ductile design of RC buildings recommends the use of *135°* hooks for effective embedment of hooks into the core concrete [IS:13920-1993]. However, *90°* hooks were used in columns (Fig. 8). In some cases, failed columns are suspected to have been weakened by insufficient lap lengths of the longitudinal bars.

**Floating columns**

The building bylaws in Ahmedabad and Gandhidham (and rest of the country) require spaces to be left open on all sides of the building. The pre-specified offsets are measured from the edge of the building footprint in the ground storey. Designers often take advantage of this aspect of measuring the offset from the building footprint in the ground storey and have covered balconies on cantilever overhangs in the upper storeys. This configuration invariably results in floating columns located at the end of the overhangs. This is a popular practice in order to have larger floor area in the upper storeys while compiling with the requirement of the offset in the ground storey. This results in cantilever beams that are projected out from the columns at the floor levels, giving the buildings a mushroom like spread on top of the ground floor columns. The exterior columns in the upper storeys are terminated at the first floor level, which results in a sudden change in the flow-path of the seismic forces. Although, no collapse or large scale damage was observed due to this feature, most of the buildings having this feature sustained minor shear cracks in the cantilever (Fig. 9).

**Short column effect**

At some locations it was observed that brick walls of partial storey height were constructed along the perimeter of the building frame to serve as an enclosure. The partial heights of these walls allow adequate lighting and ventilation while maintaining privacy. Such configuration reduces the effective length of the columns giving rise to short columns, which are very stiff as compared to the other columns that are not embedded in the walls. During lateral shaking, these columns attract large forces for which they are not designed. Due to their short height, the shear behavior is dominant, which brings about a shear failure in these short columns (Fig. 10). Failure of such short columns can result in the collapse of the building if alternate path for the transfer of gravity loads is not available.

## SUMMARY

The damages to buildings observed during the 2001 Bhuj earthquake are not new; they have already been observed in past earthquakes and their causes have also been identified. However, during this earthquake, Indian RC buildings were put to test for the first time, exposing their deficiencies. The issues and illustrations discussed in this paper may not be exhaustive; these, however highlight the major causes of building damages and collapse during this earthquake. India has a huge stock of buildings similar to those collapsed during the 2001 Bhuj earthquake. The repair and retrofit of the existing buildings is a mammoth task and it will take a substantial time. It is now essential to ensure that the new buildings be built avoiding the deficiencies identified. While the engineering community in India does not seem to have learnt much from the past earthquakes around the world, it is high time that they do from the devastations of the 2001 Bhuj earthquake.

## REFERENCES

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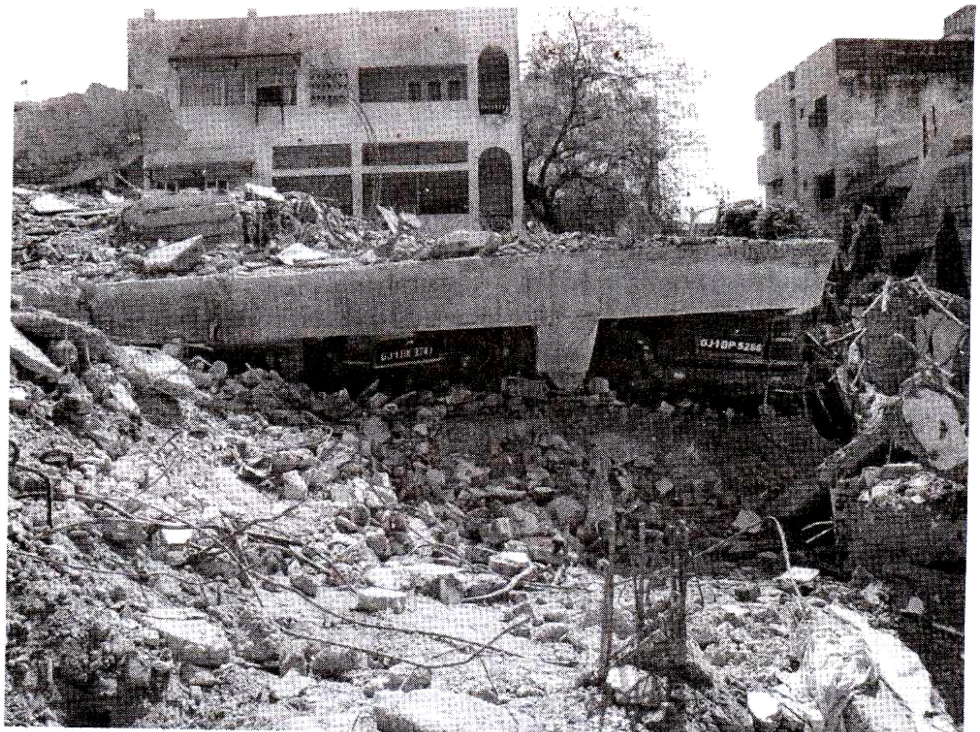

Fig. 1 Cars crushed under a building due to the collapse of open ground storey in Ahmedabad.

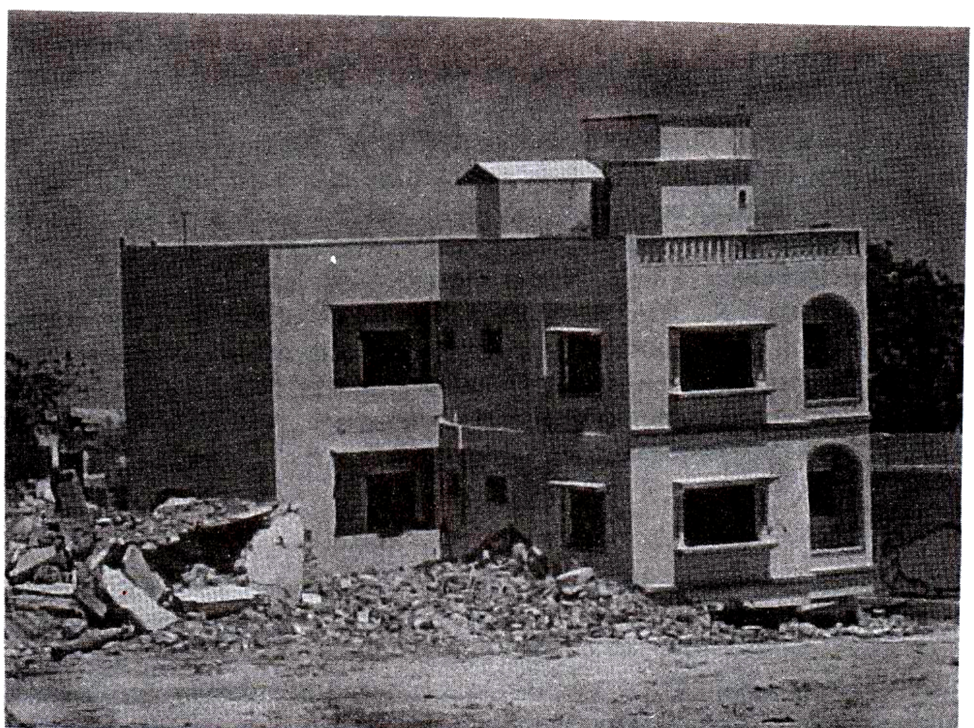

Fig. 2 Building having infill walls in the upper storeys with the open ground storey collapsed.

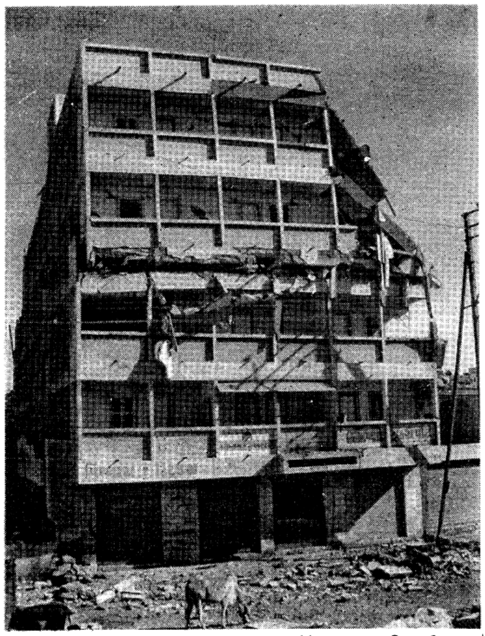

Fig. 3 Intermediate storey collapse of a 6-storey building in Bhuj.

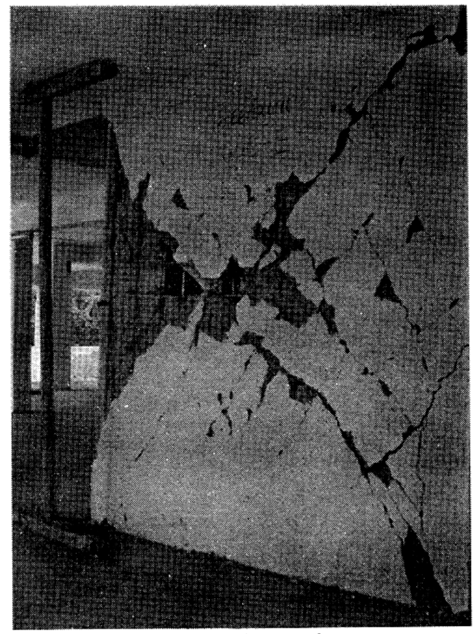

Fig. 4 Severely damaged RC elevator core of a 5-storey building in Ahmedabad

Fig. 5 Collapse of a 4-storey RC building in Ahmedabad due to inadequate connection between the RC elevator core and the building.

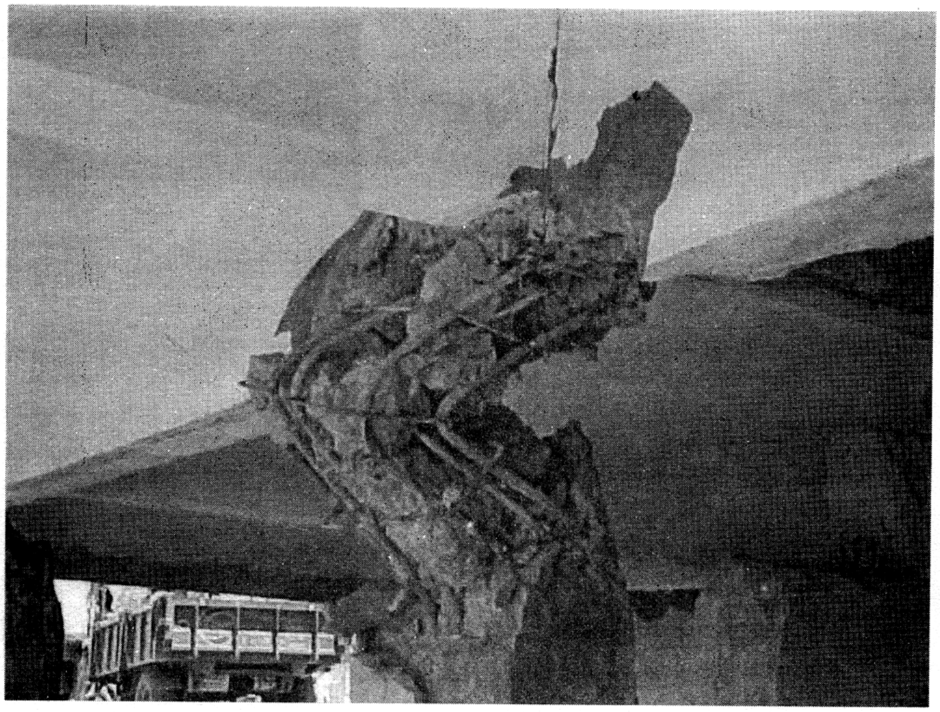

Fig. 6 Crushing of core concrete due to inadequate confinement.

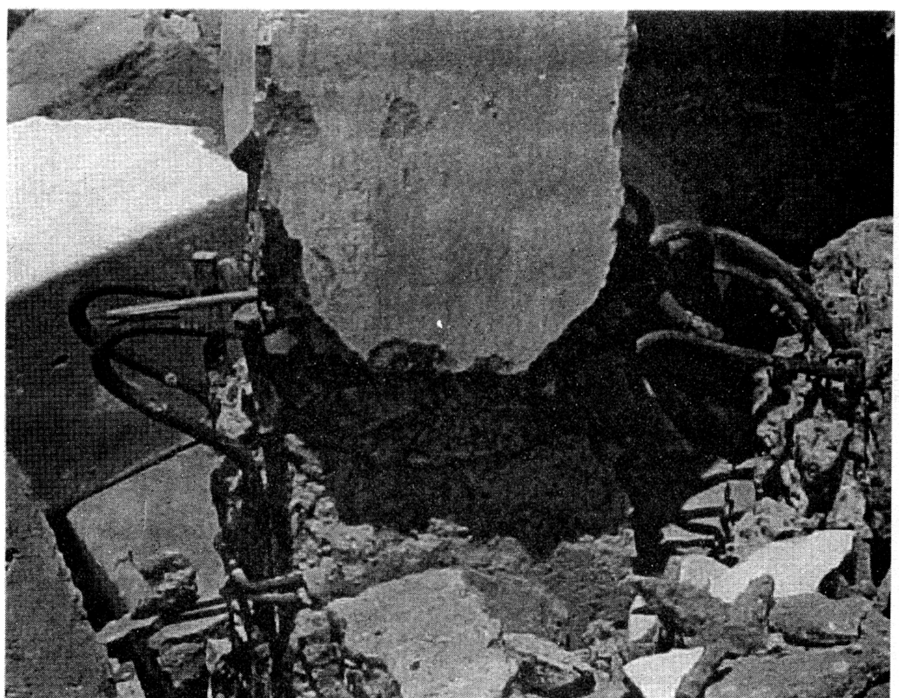

Fig. 7 Buckling of longitudinal reinforcement due to large spacing of lateral ties.

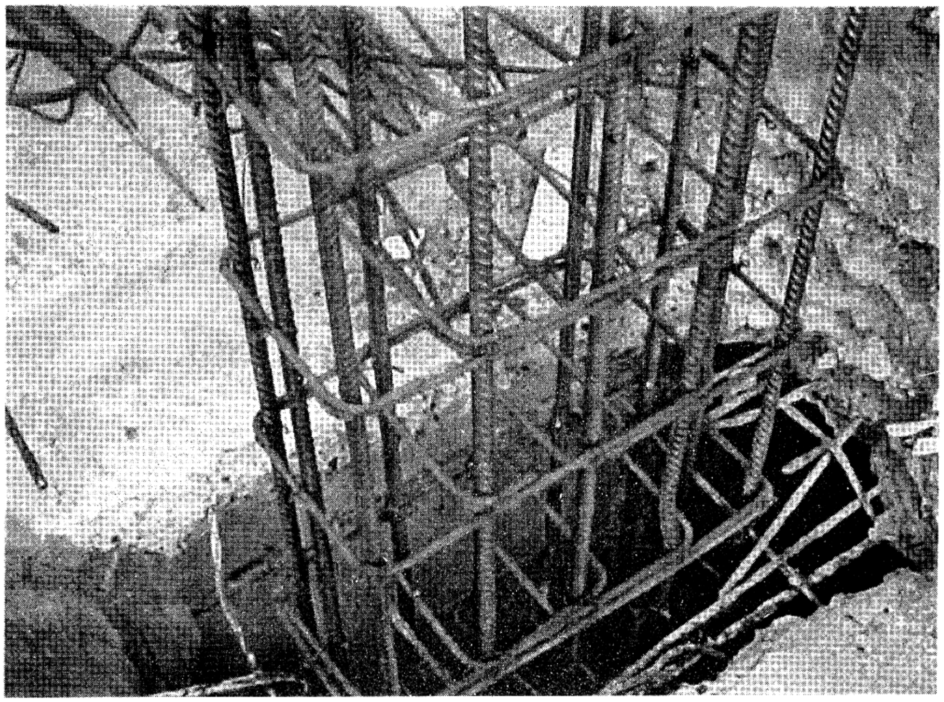

Fig. 8 Use of *90°* hooks for the transverse reinforcement.

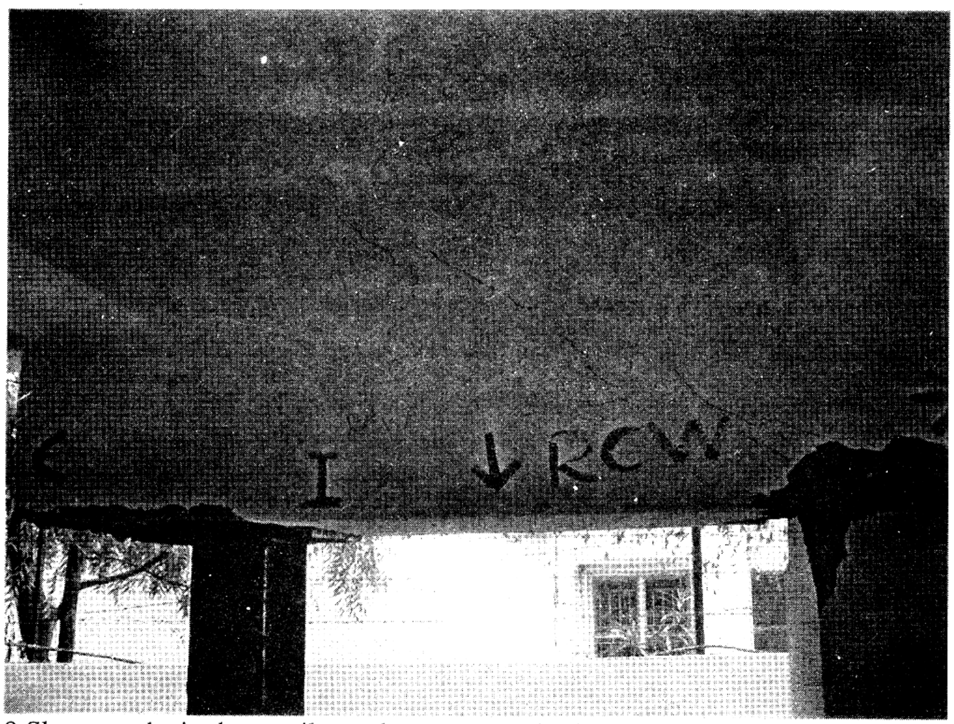

Fig. 9 Shear cracks in the cantilever that supports the floating column of the upper storeys.

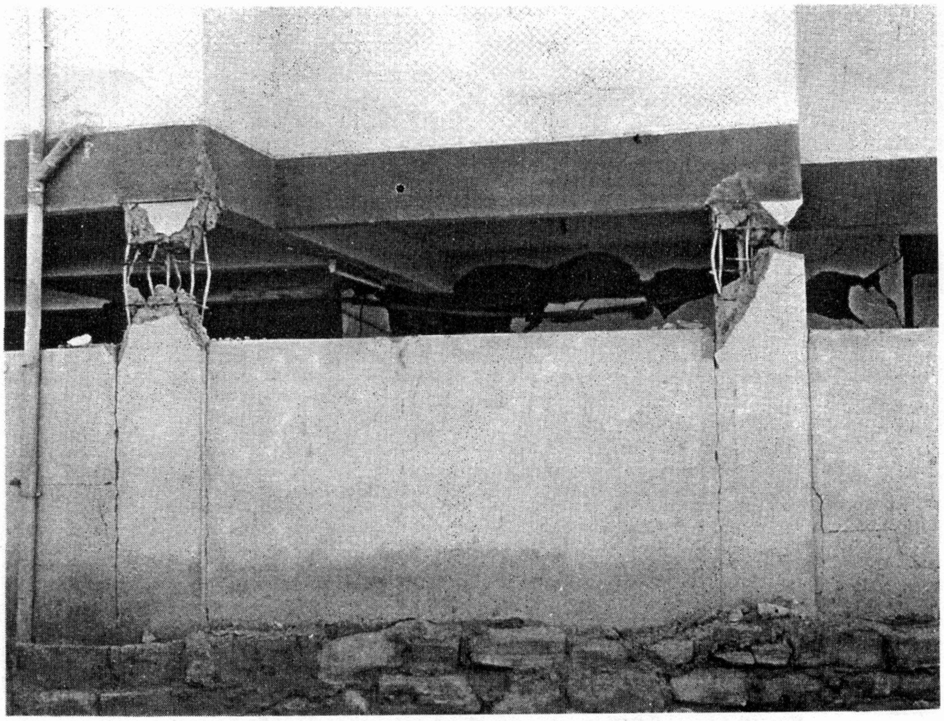

Fig. 10 Severe shear damage to short columns.