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Soft-Storey Damages in Multi-Storied Buildings: A Critical Review

Abstract: *While the provisions of earthquake resistance are accomplished through structural means, the architectural design and decisions that create it play a major role in determining the seismic performances of buildings. An important aspect considered in architectural design is the seismic structural configuration of buildings. In this paper a critical review of one of the vertical configuration problems namely the soft and/or weak storey is addressed with regards to specific causes, some case studies, remedial measures and the lessons learnt. Soft storey can occur at any floor but is more critical in the first storey as earthquake effects are generally greatest at this level. This paper identifies some major international soft storey failures around the world.*

Keywords: *Structural configuration, soft storey, earthquake effects.*

1. INTRODUCTION

While the provisions of earthquake resistance are accomplished through structural means, the architectural design and decisions that create it play a major role in determining the seismic performances of buildings. An important aspect considered in architectural design is the seismic structural configuration of buildings. Building configuration is influenced by three factors namely (a) Urban design, business and real estate issues, (b) Planning and functional concerns, and (c) usage and style. [1]

Often, building usage and planning a demand specific demarcation and location of spaces which are connected by a circulation pattern for the movement of people, supplies and equipment. These demands ultimately lead to certain building arrangements, dimensions and determinants of structural configuration. Urban design and planning affect the exterior form of buildings while city planning and architectural aesthetics pose additional requirements or restraints on the choice of structural configuration.

Up until the early 20th century, building structural configurations were largely dictated by historical or medieval styles of architecture. Symmetry, massive bases, smaller openings and mass decreasing with upper floors, were some common features in buildings that were highly desirable for good seismic behaviour. Around 1920's, a new wave of architectural aesthetics began, which was called the *International Style*. Frame structures with no frills, rejection of symmetry, unbelievably slender forms, and open first storeys for that floating effect.... Thus, the seeds of problems in seismic configuration were sown. Before World War II, examples of *International Style* buildings were restricted to a few Avant-garde buildings. After World War II, in the rich economic years that began in 50's, The United States of America, Western Europe, Latin America, Soviet Union and Japan saw extensive construction in their regional versions of *International Style*. These were also the years in which seismic design as related to these forms was inadequately addressed.

It took earthquakes in Latin America, Mexico and USA (in Alaska in 1964 and San Fernando 1971) to make engineers realize that earthquakes were unforgiving and intolerant of the very irregularities in building configuration that the architects had embraced with such enthusiasm. Worth mentioning is, that this new style originated from Western Europe and was widely promoted particularly in France and Germany, which were essentially non-seismic zones!! The world just followed suit ignorant of its seismic hazard and the havoc it could cause.

In this paper, one of the vertical configuration problems namely the soft and/or weak Storey (supposedly the largest killer) is addressed with regards to specifiç causes, some case studies, remedial measures and the lessons learnt.

2. DEFINITION OF PROBLEM

Many buildings constructed in recent times have a special feature – the ground storey is left *open* for the purpose of parking, *i.e., columns* in the ground storey do not have any partition walls (of either masonry or RC) between them. Such buildings are often called *open ground storey buildings* or *buildings on stilts*. An open ground storey building, having *only columns* in the ground storey and *both partition walls and columns* in the upper storey, have two distinct characteristics, namely, (a) it is relatively *flexible* in the ground storey, *i.e.*, the relative horizontal displacement it undergoes in the ground storey is much larger than what each of the storey above it does. This flexible ground storey is also called *soft storey*, (b) It is relatively *weak* in ground storey, *i.e.*, the total horizontal earthquake force it can carry in the ground storey is significantly smaller than what each of the storey above it can carry. Thus, the open ground storey may also be a *weak storey*. Hence a soft storey is one that shows a significant decrease in lateral stiffness from that immediately above, while a weak storey has a significant decrease in strength. Literature often refers to this inadequate strength and inadequate stiffness as a soft storey problem. Often, open ground storey buildings are called *soft storey buildings*, even though their ground storey may be *soft and weak*. Generally, the soft or weak storey usually exists at the ground storey level, but it could be at any other storey level too. The presence of walls in upper storey makes them much stiffer than the open ground storey. Thus, the upper storey move almost together as a single block and most of the horizontal displacement of the building occurs in the soft ground storey itself. In common language, this type of buildings can be explained as a building on chopsticks. Thus, such buildings swing *back and-forth* like *inverted pendulums* during earthquake shaking, and the columns in the open ground storey are severely stressed .If the columns are weak (do not have the required strength to resist these high stresses) or if they do not have adequate ductility they may be severely damaged which may even lead to collapse of the building.Generally soft storey failure results from four basic conditions, namely;(a) The first storey significantly taller than other floors; lesser stiffness means more flexibility and thus more deflection, (b) There is an abrupt change of stiffness at any floor due to infill, setbacks and load-path discontinuity, (c) It is caused primarily by material choice – for instance use of very stiff and heavy precast elements above the first storey, and (d) use of a discontinuous shear wall also causes soft-storey problems. [21] This paper identifies some major international failures around the world according to these causes.

3. CASE STUDIES

In 1925 Santa Barbara earthquake Dewell and Willis identified masonry building failures as the first "soft first storey failures". The 1927 UBC was the first comprehensive earthquake code for buildings in general. The April 30, 1933 Long Beach earthquake led to the enactment of the Field Act for School Buildings. This Act gave the California State Division of Architecture authority and responsibility of approving design and supervising construction of public schools. Building codes were upgraded. The 1967 Caracas earthquake clearly identified the soft storey failure risk to tall buildings.

3.1 The Skopje, Yugoslavia Earthquake (July 26, 1963)[2]

Major cause of soft storey failures identified was non-adherence to already existing codes, which were based on fundamental guiding principles of seismic design. Some columns of the building were shorter hence stiffer than the others which caused them to draw more seismic forces that they could resist.

This kind of failure is termed as short column failure. Fig.1 and Fig. 2 demonstrate this type of failure in a Feminine Secondary School. The two damaged column were shorter than the other columns hence stiffer suffered more severe damage.

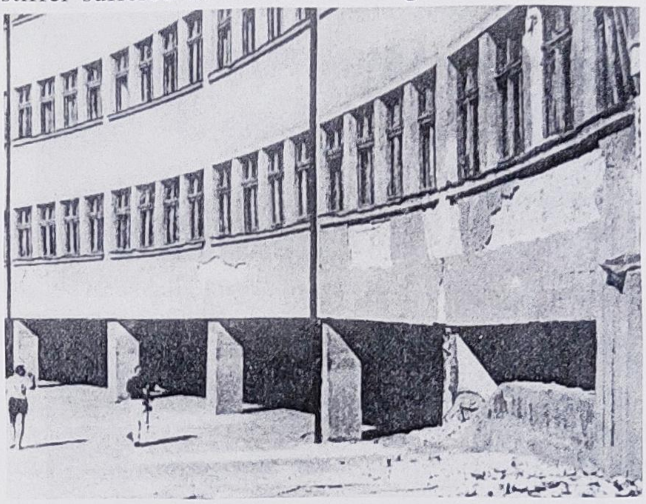


Fig. 1: Open first storey failure

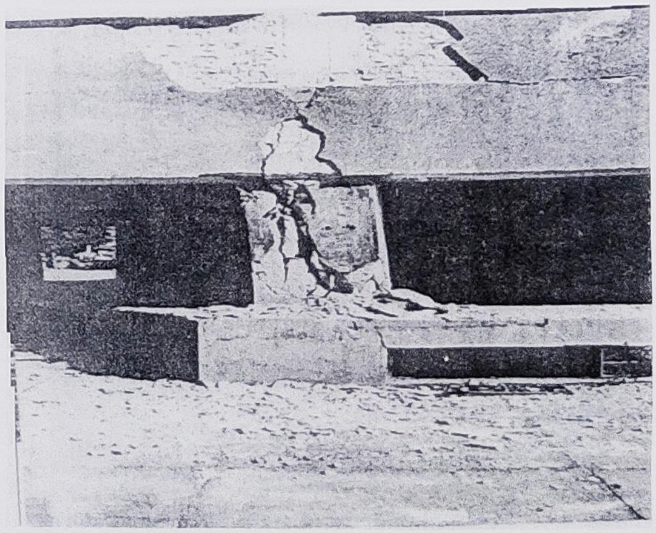


Fig. 2: Column failure due to short Column effect

3.2 San Fernando Earthquake (February 9, 1971)[3,4,5]

Olive View Hospital in the San Fernando Valley (Greater Los Angeles, USA), a new structure which was badly damaged due to a discontinuous shear wall is a classic case of failure occurring due to stiffness disparities. Vertical configuration of the main building was a two storey layer of rigid frames on which was supported a four-storey shear wall frame structure. Severe damage occurred in soft storey portion. Upper floors moved so much as a rigid unit that the huge displacement could not be accommodated by the lower columns. The largest amount by which a column was left permanently out of plumb was $2^1/_2$ feet as seen in Fig.3.

The lower storey columns were crushed and Fig.4 also shows the absence of transverse ties indicating bad ductile detailing.

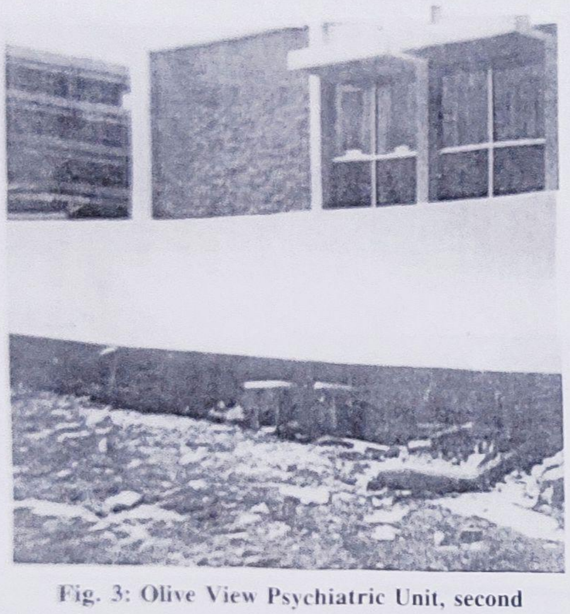


Fig. 3: Olive View Psychiatric Unit, second

Fig. 4: Shear failure of RC Column in ground storey floor rests on tables and chairs

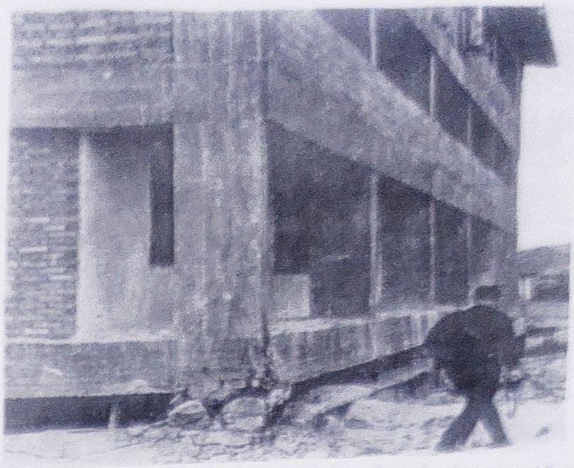


Fig.5: A close-up showing shattered columns, and some cracking of brick interior columns in the basement were free to deflect over their entire height whereas the exterior columns were greatly restrained by the heavy basement wall.

3.3 Burdur and Bingol, Turkey Earthquake (May 12, 1971) [15]

Poor quality construction materials, unskilled poor workmanship and lack of adequate knowledge of capacity design concept where the failure of vertical members namely the columns is to be preceded by the beam failure caused numerous failures in this eartquake. Stiffness disparities, no ductility provision and weak columns were the causes as shown in the (Figs. 5 and 6). Columns of the building in Fig.5 were the basement

Fig.6: Under construction, across the street from Burdur's hospital, is this 3-storey school, of rather common design in Turkey. Every exterior column, between the top of the foundation wall and the bottom of the first floor, was shattered, causing the building to settle slightly. There was also minor damage to brickwork at roof level and in the first storey.

columns which were free to deflect over their entire height whereas the exterior columns were greatly restrained by the heavy basement wall. This great difference in stiffness resulted in the entire lateral load being resist by the exterior columns, and consequently suffering all the damage. Note that columns are weaker in the longitudinal direction of the building, but column damage appears to be caused chiefly by motions in the transverse direction.

3.4 Managua, Nicaragua Earthquake (Dec 23, 1972)[6]

A 3 storey classroom building at Teressiano School had a column failure in 1968 Managua Earthquake. Repair was accomplished by building RC piers along the damaged columns upto the level of second storey windowsills. The remaining column height was unchanged. In the 1972 earthquake, damage occurred in the second and third storeys as seen in Fig.7. Repair altered the dynamic behaviour of entire structure.

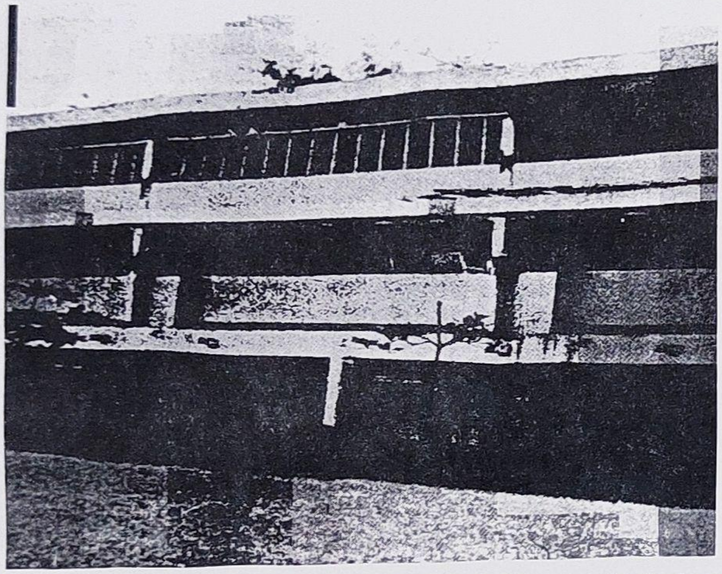


Fig.7: Damage to Teresiano School building repaired after 1968 earthquake.

3.5 Friuli, Italy Earthquake (May 6 and Sept 15, 1976) and Campania – Basilicata, Italy Earthquake (November 23, 1980) [11,13]

The 5-storey hospital building in Gemona (Fig.8) had partition walls of hollow clay tile. The second floor had far less clay tile in filled walls them other stories, creating an abrupt decrease in stiffness in trait storey. Fig.9 shows damage of partially constructed building due to randomly distributed masonry infill walls in the 1980 Earthquake.

Fig. 8: Five storey eastern wing of Gemona Hospital. The second story had a discontinuity of partition walls, creating a more flexible story

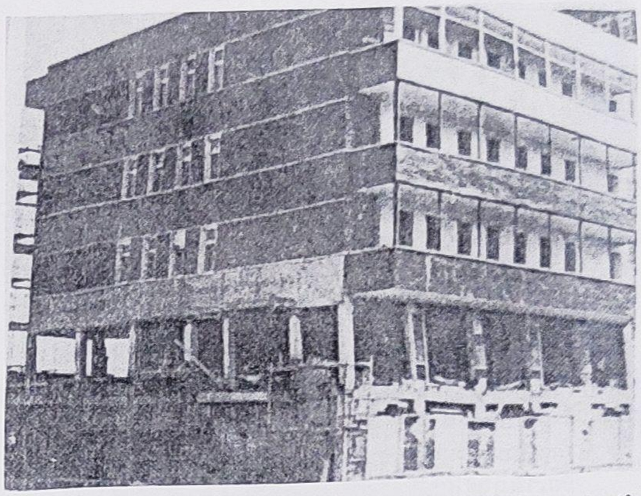


Fig. 9: Randomly distributed Masonry infill in a partially constructed building

3.6 Romania Earthquake (March 4, 1977) [10]

The building in Figs.10 and 11 was constructed prior to the 1940 Romanian earthquake. Cumulative

Fig.10: Apartment building with soft ground story designed and constructed prior to the 1940 Romanian earthquake.

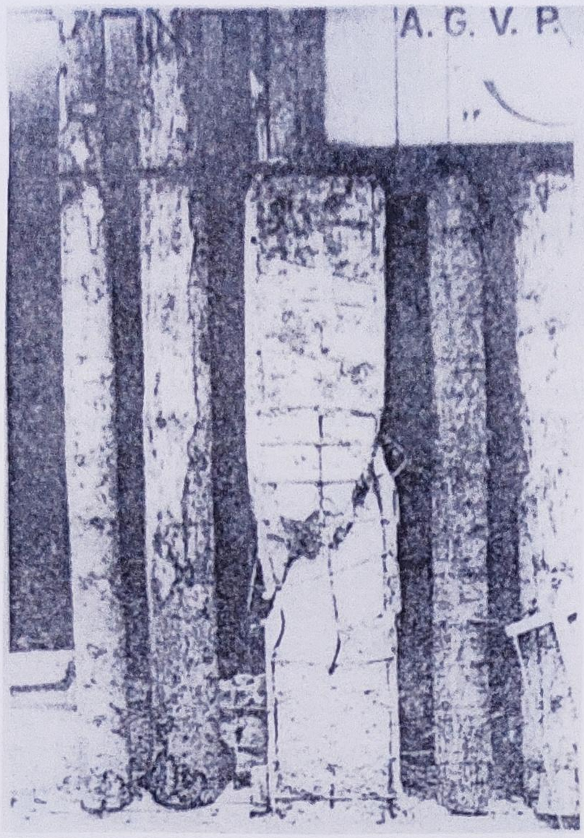


Fig.11: Column in the open ground story of tall building designed and constructed before the 1940 Romanian earthquake.

damage due to both the earthquakes caused collapse. Lateral code provisions were implemented only after 1940 earthquake. Quality of concrete was poor, though the most fatal cause was the open first storey.

3.7 MIYAGI-KEN-OKI, Japan Earthquake (June 12, 1978) [12]

The Obisan Building (Figs.12 and 13) was a 3 storied structure. Due to combined effect of a soft storey and eccentric stairwell, torsional stresses were induced due to the earthquake causing the stiffer upper stories to rotate as a rigid body when the first floor columns collapsed.

3.8 Imperial County, California Earthquake (October 15, 1979) [7]

The performance of Imperial County Services Building, El Centro (Figs.14 and 15) provides another example of architectural characteristics on seismic resistance. Origin of this failure lies in the discontinuous shear wall at end of the building. The west end had shear wall upto the foundation. While the east end had

Fig.12: Obisan Building Oroshicho area, Sendal: view from the northwest. This is a 3-storey reinforced concrete frame building with a soft first story, one span in each direction. The columns were inadequate to resist the torsional force caused by a heavy eccentric stairwell that cantilevered over the column line at the right end of the building.

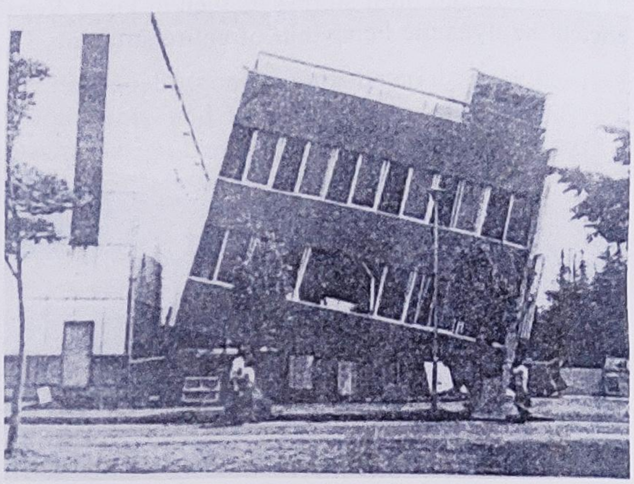


Fig.13: Obisan Building Oroshicho area, Sendal: view from the south. The upper stories rotated as a rigid body when the first-floor column support was lost.

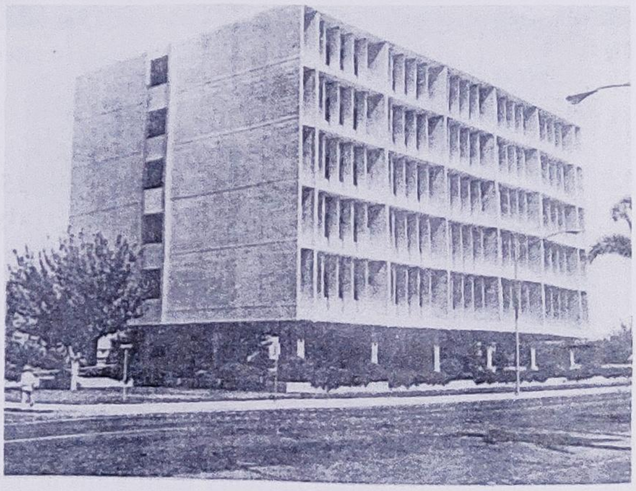


Fig.14: Imperial County Services Building, El Centro (Photo by John Robb, LA Department Building and Safety)

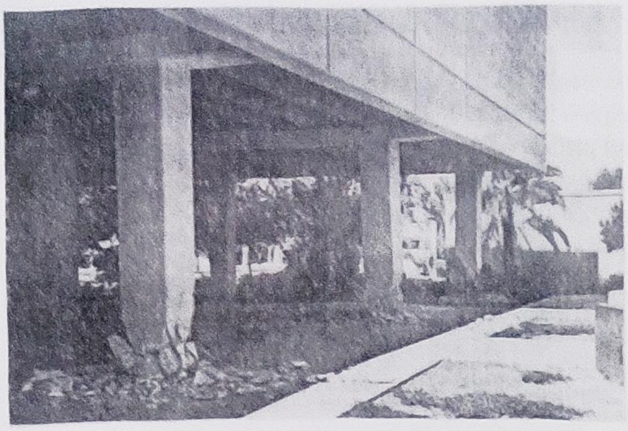


Fig.15: Column line G (2G, 3G, 4G), east end of building. (Photo supplied by J. Robb)

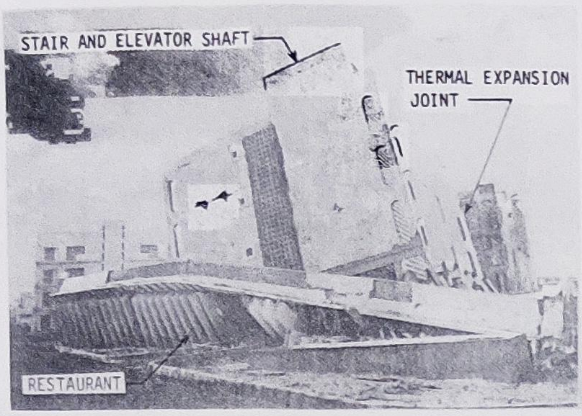


Fig.16: Collapsed first-story restaurant

it discontinued at the second floor, this small variation caused a major failure.

3.9 El Asnam, Algeria Earthquake (October 10, 1980)[8]

The cause of soft storey damages was attributed to a prevalent construction practice in El Asnam. A use of *vide sanitare,* a crawl space about 3 feet above ground level. Only structural elements in this space were 3 feet tall columns without any interior partition or walls. Perimeter masonry walls were used to enclose this space. Structure above this was in filled with stiff masonry walls. These vide *sanitare* constituted a soft storey with very short columns lethal combination. Building inclined as much as 20^{o} and dropped 1 m causing damage of first storey while other stories were undamaged (Figs.16 and 17).

3.10 Central Greece Earthquake (February 24, 1981)[9]

A typical construction in Greece is "Sur pilotis' - rigid superstructure supported on weak and flexible first

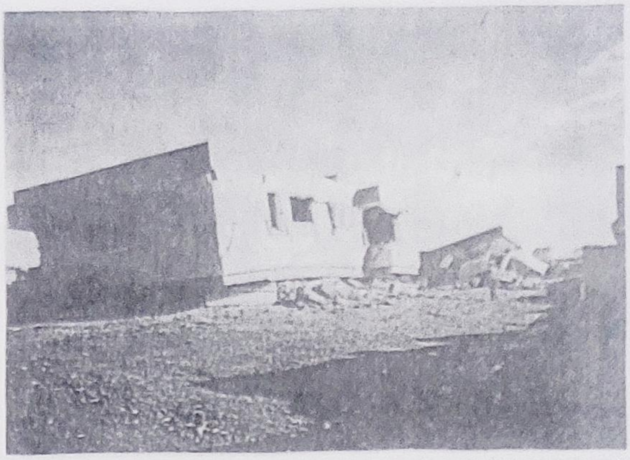


Fig.17: Collapsed two-story houses under construction in Boucaa Sahnoun that had soft first story

storey. Rigidity in upper stories was due to large partition, relatively low storey height and presence of many deep beams (Fig.18). Performance of those types of structures was very poor owing to large disparity in stiffness values.

Fig.18: Modern resort apartment building in Alepohori with open first story. The damage was limited to the lower story. The heavy scaffolding (placed after the earthquake) consists of H-shaped steel beams.

3.11 Loma Prieta Earthquake (Oct 17, 1989)[14]

Researchers determined that soft first stories were a major contributor's upto 8% of serious failures. Actual percentage may be more because many failures precipitated by this condition. Fig.19 shows a building with a open first storey which was situated on soft soil deposits which aggravated the situation further.

3.12 Philippines Earthquake (1990)

Soft storey is created in the middle stories of a building causing crushing of that storey. The building

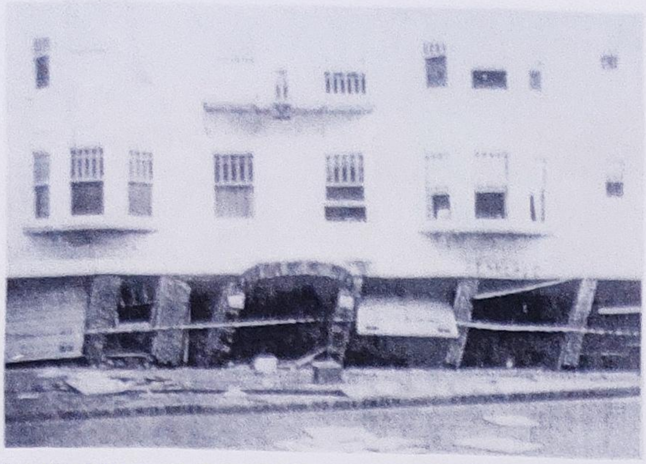


Fig.19: Many of the buildings that failed in the Marina District of San Francisco were particularly vulnerable because of the lateral weakness of the first story caused by many openings, such as for garages. Many of the most severely damaged buildings in this area were outside the original shoreline on filled areas. These soft soils experienced more severe shaking than adjacent firm soil sites and in some cases liquefied.

in Fig.20 had block work in fills. Being brittle, the panels disintegrated as soon as their strength was reached. Falling masonry was a considerable hazard to passer by. Behaviour of structure became unpredictable during the earthquake due to an abrupt change in stiffness following panel failure causing the soft storey collapse to occur.

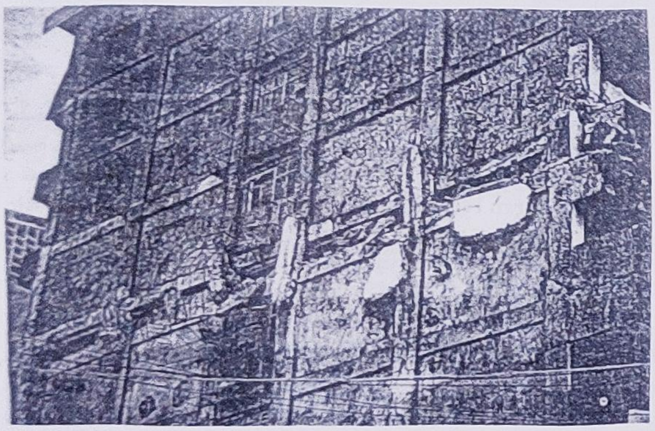


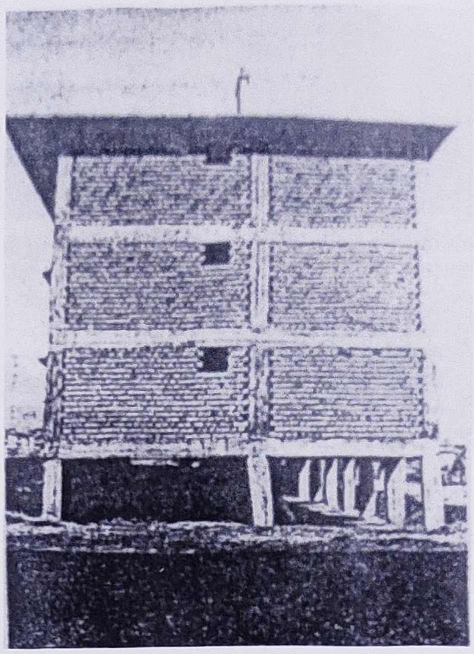
Fig.20: Soft-storey failure in frame building with infill blocks work, Philippines earthquake 1990. (Photo: Ove Arup & Partners)

3.13 Costa Rica Earthquake (April 22, 1991)

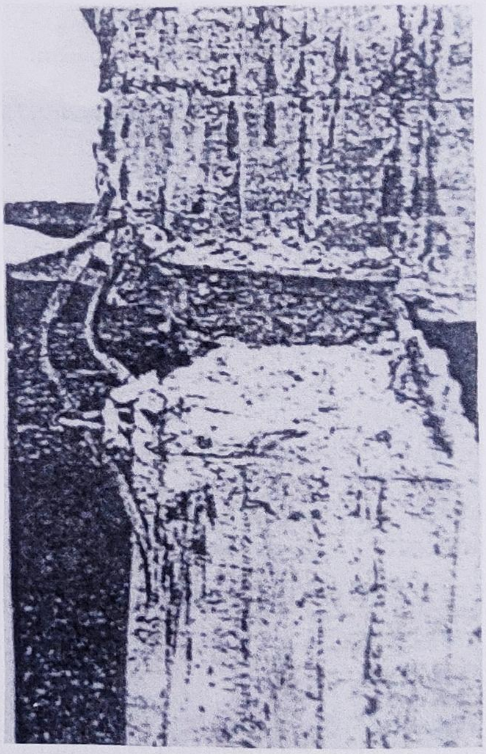
Only one structural catatastrophic collapse of 4-storey concrete frame was reported. It apparently had soft first storey.

3.14 Erzincan Turkey Earthquake (1992)

In Fig.21, the building has block work infill and open first storey. This cause large increase in strength and stiffness at upper floor in relation to first storey.



(a)



(b)

Fig.21: (a) Soft storey created by block work infill, Erzincan, Turkey, 1992; and (b) Detail at top of ground-floor column on the left in (a). (Photo: Ove Arup & Partners).

3.15 Northridge Earthquake (January 17, 1994)[20]

Fig.22 shows a medical office building which suffered damage in the 1994 Northridge earthquake due to discontinuous shear wall at each end. These proved inadequate to deal with the forces with consequent severe torsional damage at each end of the building. Fig.23 shows another first storey collapse of Northridge Meadows Apartment Complex killing 16 people.

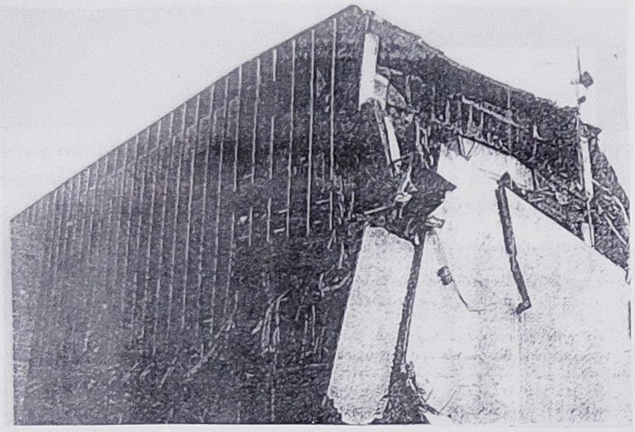


Fig.22: Discontinuous shear wall failure, office building, Northridge

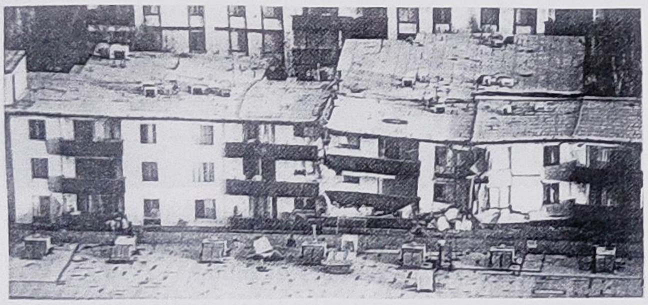


Fig.23: Northridge Meadows Apartment Complex where 16 people died in the partial collapse of the first story. (LA Times Photos).

3.16 Hyogo-ken Nanbu Earthquake (January 17, 1995)[16]

Figs. 24, and 25 speak for themselves. The 5 storey apartment is resting over the vehicles parked in the open first story.

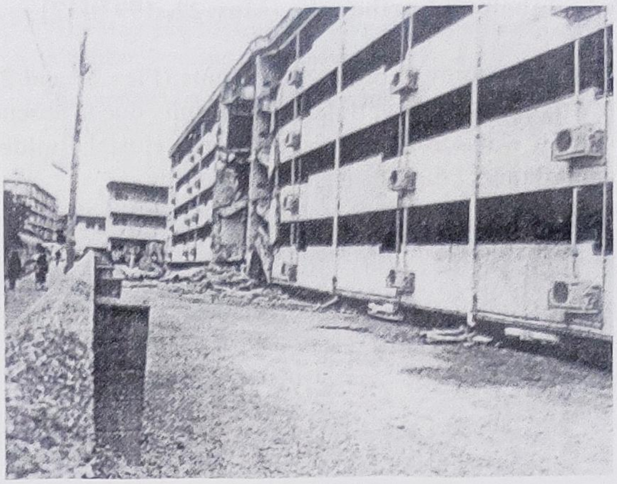


Fig. 24: Collapse of the first story

Fig.25: 2 story apartment house building: collapse of the first piloti floor.

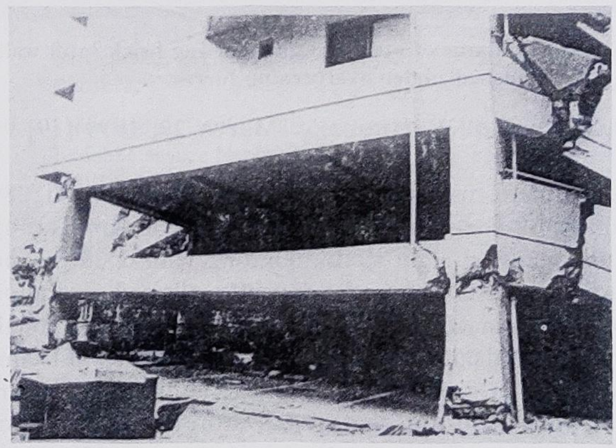


Fig.26: Fracture of the top and base of columns

4. THE INDIAN SCENARIO

As mentioned in the beginning, soft storey provisions in design codes are to accommodate urban design, planning and functional requirements. Till date with an exception of 1997 Jabalpur and 2001 Bhuj earthquakes, all significant earthquakes in India have had their epicentre in rural India. This type of construction was not prevalent in rural parts. It was only when Jabalpur (1997) and Bhuj (2001) earthquakes occurred that Indian engineers took note of the faulty design practices that are being adopted and practiced by the engineering community.

4.1 Jabalpur Earthquake (May 22, 1997)[17]

Five-storey Himgiri Apartments (Figs.27 and 28) in Wright Town has vertical discontinuity due to absence of infill walls in first storey. A Youth Hostel Building had columns crushed in the open storey.

Fig. 27: 5 Storey Himgiri apartments, Wrighty Town

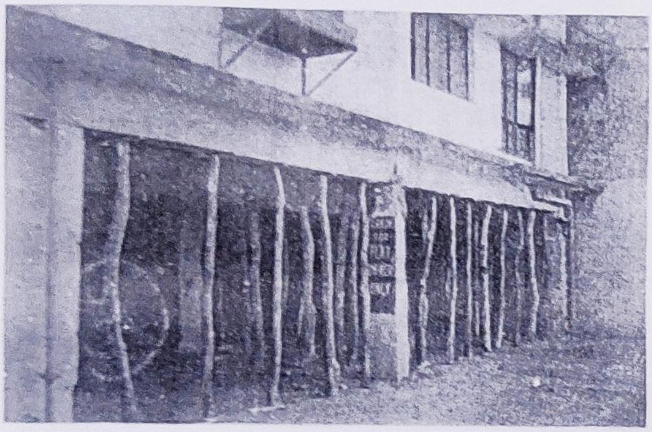


Fig. 28: Columns of open bays supporting brick infill walls crushed under overturning forces.

4.2 Chamoli Earthquake (March 29, 1999)[19]

Interesting aspect was few buildings at Delhi, 280 km from the epicentre sustained damage. Tarang apartments an eight storey building with open ground storey (!) sustained cracks in infill walls and separation of infill from RC frame at the lowest storey. Even though minor, this damage underlines the vulnerability of Delhi, which is in seismic zone IV. The numbers of multi-storeyed buildings with open storeys in Delhi are uncountable. The capital is sitting on a ticking time bomb....

4.3 Bhuj Earthquake (January 26, 2001)[18]

The soft storey failure was the biggest killer in this earthquake. This earthquake is an eye opener and a

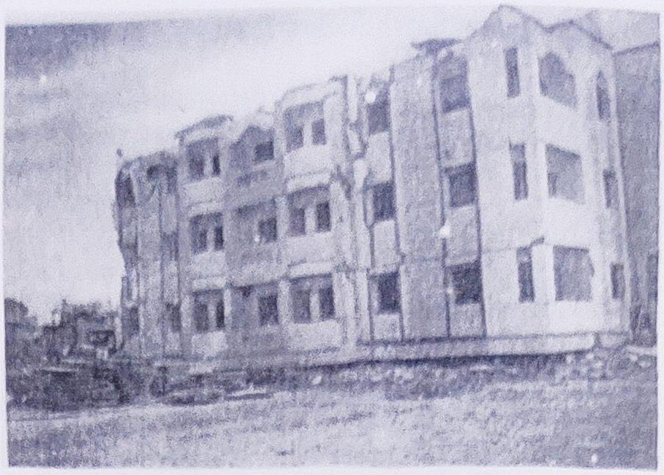


Fig.29: Collapse of apartment building in Ahmedabad owing to open ground story failure. No structural damage is observed in the upper stories.

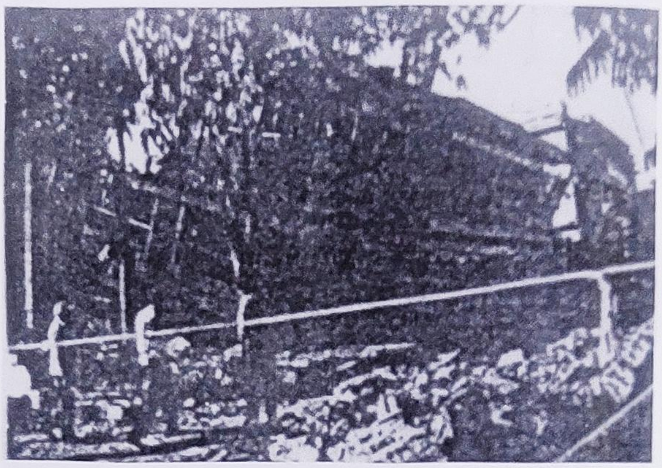


Fig. 30: Complete collapse of apartment building in Ahmedabad, a building with an open ground story and poor reinforcement detailing

warning as to what can be expected in case of another quake. The soft storey failures indicate the man-made catastrophe that the architects and engineers can inflict on the nation in future.

5. REMEDIAL MEASURES

The following measures are suggested:

a) For tall first storey's, introduction of bracings that stiffen columns upto a level comparable to the superstructure.

b) Addition of extra columns at first storey to increase stiffness

c) Design of first storey columns to provide increased stiffness.

d) If large opaque wall required, ensure that it is not a part of lateral load resisting system

e) Reduce mass of wall by use of light material and hollow construction

f) For brick in fills or block in fills, separate from frame so that they do not attract seismic forces and also the frame behaviour under seismic forces is not affected due to in fills.

g) No discontinuous shear walls

h) Provision of strong interior shear walls (Elevators, Lift-wells, etc.)

i) Adoption of Base isolation techniques.

6. LESSONS TO BE LEARNT AND IMPLEMENTED

(a) Earthquake spanning over the whole century indicate that maximum number of damages to urban construction in due to soft storey failures.

(b) Open first storeys are here to stay. Hence, prevention is the bottom line, i.e., adoption of the capacity design philosophy. Ductility provisions are a must.

(c) Stringent codal provisions to prevent abrupt changes in storey stiffness or strength

(d) Building Bye Laws or codes need to seriously penalize designs not confirming to stiffness or strength considerations or codal provisions.

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