7. Building Damage

7.1 Damage of Reinforced Concrete Structures

S. Kono and H. Tanaka

Many recently built multi-story reinforced concrete buildings collapsed in major cities like Ahmedabad and Gandhidham. Those buildings had ground floors left open for parking with few or no filler walls, which resulted in a top-heavy and soft ground-floor system. Since buildings with sound construction did not experience any major damage for the level of ground motion experienced, the damage is considered to be due to inherent weakness in the structural system, design, detailing, poor material quality and unsound construction practice. This section overviews damage of RC structures and considers the causes of that damage.

(1) Introduction

The most commonly observed damage to RC structures was in the form of cracking and falling of infill walls. The infill walls were very vulnerable and damage to these walls resulted in significant economic loss and human casualties. However, the most striking failures were the structural failures of modern multi-story buildings. Since buildings with sound construction should not have experienced any major damage for the level of ground motion experienced, the damage was due to inherent weakness in the structural system, design, detailing, poor material quality and unsound construction practice. The damage spread not only to cities close to the epicenter but also to major cities far from the epicenter. Some of those cities are Morbi (125 km from the epicenter), Rajkot (150 km), Ahmedabad (300 km).

Among the multi-story buildings that collapsed, most had the ground story left open for parking with few or no infill walls between the columns. This created a top-heavy structure with insufficient strength and stiffness in the open ground story. Most buildings with complete infill walls in the ground story withstood the earthquake without collapse.

Typical structural systems and major reasons of damage of RC structures are explained in this section based on the field investigation.

(2) RC structures in Ahmedabad

In Ahmedabad 300 km away from the epicenter, sixty-nine reinforced concrete buildings of five stories (ground floor plus four stories) and eleven stories (ground floor plus ten stories), such as shown in Photo 7.1 and Photo 7. 2, collapsed resulting in 746 causalities (Dept. of Earthquake Engineering, University of Rookie, 2001). About 80 percent of these buildings were built after the introduction of earthquake design codes. Although local geotechnical conditions and site amplification seemed to have influenced the damage patterns in Ahmedabad which is located on thick alluvial deposits along the Sabarmati River, the maximum recorded peak ground acceleration was as less as 0.11g at the basement of passport building as shown in Figure 7.1. Most of the properly designed buildings survived with minor damage but many five- and eleven-story buildings having "soft story" at the ground floor sustained heavy damage. These buildings were not designed for lateral loads as required by Indian Standard 1893 and no concept of ductile detailing recommended in Indian Standard 13920 was seen.

The typical construction in Ahmedabad consists of reinforced concrete moment-resisting frame structures with un-reinforced brick or stone infill walls. Ahmedabad Municipal Corporation has the floor surface index rule that limits the total covered area on a construction site. If the area is not surrounded by walls at the ground floor, balconies at the higher floors can be surrounded by walls and it is not counted. Therefore on the ground floor, no walls are provided and only columns are present as shown in the plan drawings in Figure 7. 2 and Figure 7. 3. This makes a 'soft story' at the ground floor, which is highly vulnerable to earthquakes. Additionally, rigid continuous beams and relatively less stiff columns created an undesirable strong-beam and weak-column system.

Photo 7.1. Typical five-story RC building.

Photo 7. 2. Typical eleven-story RC building.

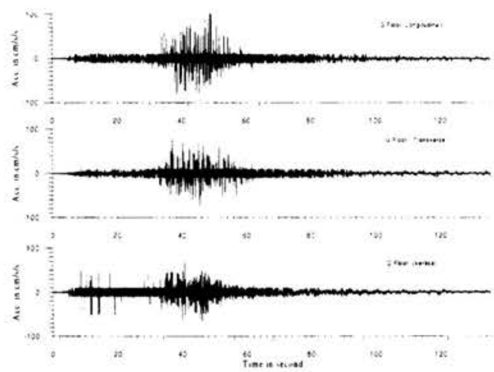

Figure 7.1. Ground acceleration at the Ahmedabad Passport Building.

Most of the buildings that collapsed or suffered structural damage rested on shallow footings. Foundation depths are usually 1.5m for a five-story building and 2.0 - 2.7m for an eleven-story building as shown in Photo 7.3. Soil is alluvial and ponds have been filled to construct buildings at many places. Geotechnical investigations are not carried out as a basic engineering requirement. Tie beams are absent as the foundations were shallow. Buildings are designed only for gravity loads using 15MPa concrete for five-story buildings and 20MPa concrete for eleven story buildings (Goyal et al. 2001). The provisions of Indian Standard 1893 to calculate equivalent lateral loads for seismic conditions are not considered, and structural engineers are not even aware of the ductile detailing requirements of Indian Standard 13920. For example, the shear reinforcing hoops are arranged as shown in Figure 7.4. . For a ground floor column of 230 mm x 450 mm, common practice is to provide 6mm mild steel stirrups at a spacing of 200 mm in five-story buildings and in a 230 mm x 600 mm column, 8mm steel stirrups for eleven story buildings at a spacing of 200 mm (Goyal et al. 2001).

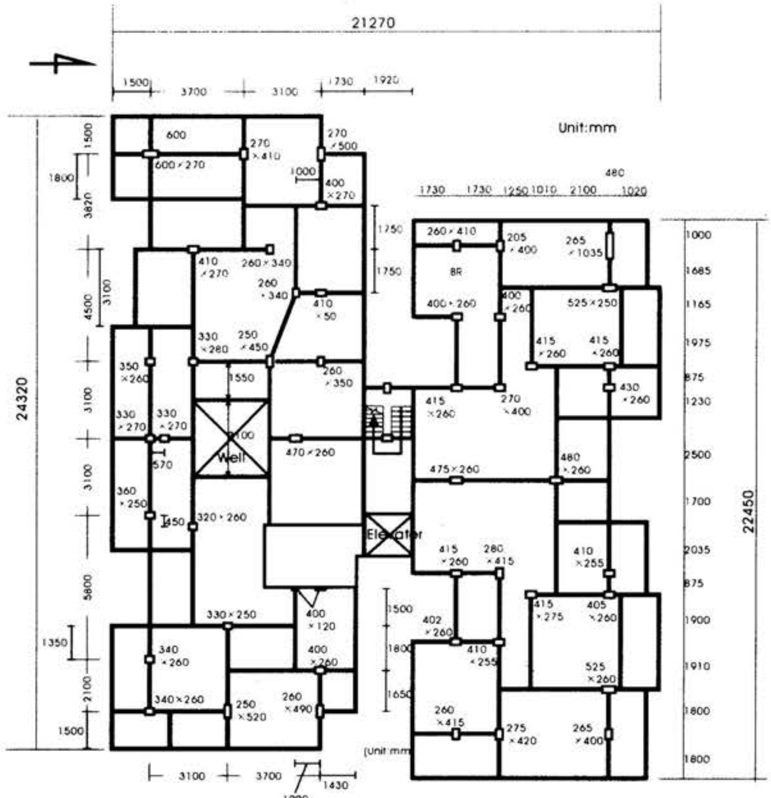

Figure 7. 2. Plan drawing of Block C in Akshar Deep Flat show irregular column arrangement.

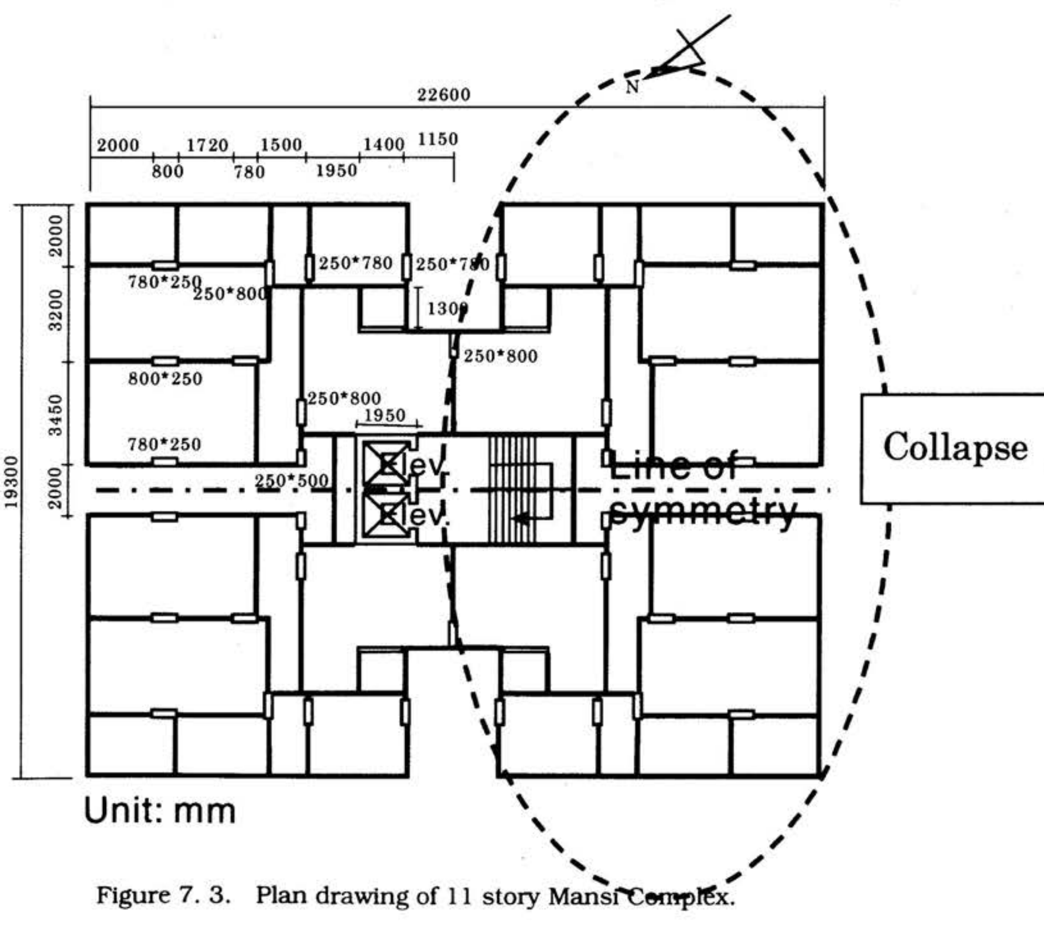

Figure 7. 3. Plan drawing of 11 story Mansi Complex.

Photo 7.3. Foundation of collapsed five-story RC building.

Photo 7.4. Honeycomb concrete can be seen above the construction joint.

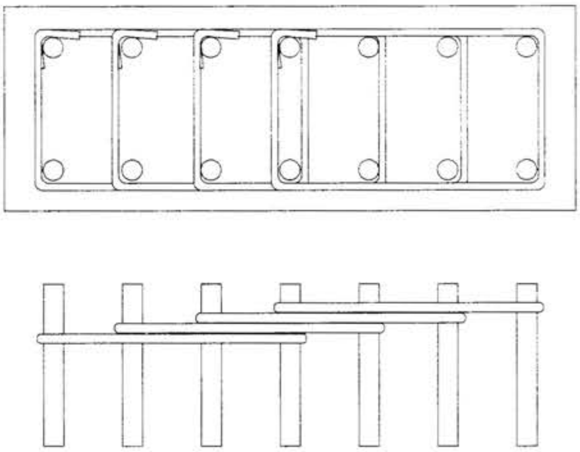

Figure 7.4. Spliced shear reinforcing hoops.

Photo 7.5. Mansi Complex collapsed because of the too much load from the pool at the top.

At the ground floor, columns are not cast up to the bottom face of the beam and a gap of 200 - 250 mm is left. For a 2.7m story height, casting is done up to 2.4m for the column, and the remaining 0.3 - 0.4 m is cast with beams. Because of heavy longitudinal reinforcement in the continuous beam, a part of the column just below the beam has poor quality of concrete as shown in Photo 7.4. . This part of the concrete is very brittle as it is difficult to compact due to heavy reinforcement of cantilever beam. Therefore plastic hinge zone below the beams is the most vulnerable part and top of the column was severely damaged by crushing and spalling of concrete.

Extra floors and water tanks, added at the top of the building without strengthening the columns, further increased damage. For example, one of the most devastating failures of buildings was that of Mansi Complex constructed in 1994 in Photo 7.5. whose plan view is shown in Figure 7. **3**. This eleven-story building had a soft ground floor with strong beams and weak columns. The half of the buildings split from the lift core and collapsed resulting in 46 casualties while the other half part in Photo 7.5. is still standing. Poor design practice, shallow foundations, and improper detailing caused the shear failure of columns at the ground floor. Additional loads of swimming pool and water tank without strengthening the columns worsen the vulnerability. The half of the building did not collapse as the connecting beams and slabs failed due to improper embedment of reinforcement.

In some of the buildings, part of the building collapsed while stiff lift core block remained standing as there was no lateral load transfer mechanism to the core as shown in Photo 7.5. The slab reinforcement was not properly anchored to the beams or walls of the core. Failure of columns at the ground floor resulted in pulling out of the improperly placed slab reinforcement.

Akshar Deep Flat had three five-story RC buildings with penthouse on the top and parking on ground floor. The penthouse was used as the part of the residence of fifth story. Two buildings collapsed in a pancake manner and the only one building withstood with heavy damage. As seen from Figure 7. 2 and Photo 7.6. , the floor plan and column arrangement is irregular and some beams are eccentrically connected to columns. The floors of second and upper had 2 m cantilever floor hanging out from the outermost column resulting in a top heavy structure.

Photo 7.6. Columns are arranged in an irregular manner and the aspect ratio is large.

Siddhi Apartment is a five-story RC frame with infill walls. The ground floor was open for parking. Four residents in each floor are symmetrically arranged and the floor plan and column locations are quite regular. The ground floor columns under the east half part collapsed first and the upper part followed resulting in a pancake failure while the other half part and the lift core is still standing. The columns of the remaining part will be retrofitted by fiber reinforced plastic sheet and the structure will be reused.

(3) Damage outside Ahmedabad

Outside Ahmedabad, damage to RC building structures can be also seen in major cities like Bhuj, Gandhidham, Anjar, Rajkot and the failure modes are quite similar to those observed in Ahmedabad. Typical failures are briefly introduced below.

Photo 7.7. shows a commercial two-story RC building in Bhachau. All columns have large aspect ratio so that the inside can be fully utilized as a commercial space. In this type of columns, the anchoring of the beam reinforcement cannot be secured in a short distance of the weak axis direction and consequently ends of some beams completely pulled out from beam-column joints. The stiffness and strength in weak axis direction were not enough and the ground floor and the second floor swayed in the opposite direction. The complete pancake failure was avoided since some infill walls sustained the vertical load.

Photo 7.7. RC building in Bhachau collapsed in a side sway mechanism.

Photo 7.8. shows a brand-new six-story

RC building named Pooja Flat in the city of Anjar. The ground and second floors were to be used for a commercial area and had large openings. As shown in Photo 7.9. , damage concentrated on the lower floors with shear failure at the most ground floor columns which had shear reinforcement of ϕ 8 at 200 mm pitch. The part of the structure beside the one in picture failed in a pancake manner and the other part behind lost the ground and second floors completely. These collapsed parts detached from the part in the picture because beams and slabs were not properly anchored to the standing block.

Sayaji hotel in Gandhidham shown in Photos 7.10, 7.11 lost its ground floor. The columns of the ground story had a section of large aspect ratio of 250x700 mm. The upper floor had 600 mm thick wall for an architectural reason. Those thick walls were made of solid brick and created an overload condition. The overload and the soft lower story lead to the failure.

Photo 7.8. Front & side view of Pooja Flat in Anjar

Photo 7.9. Shear failure of columns in Pooja Flat

Photo 7.10. Sayaji Hotel in Gandhidham failed at the soft ground story.

Photo 7.11. Columns with large aspect ratio failed at the ground floor at Sayaji Hotel in Gandhidham.

Table 7.1 Investigated RC buildings

No.	Building name	Location	No. of Stories	Height (m)	Fundamental Period (s)		Damage Level
					Longitudinal	Transverse	
B1	Akshar Deep Flat	Ahmedabad	5	14.2	0.66	0.67	4
B2	Siddhi Flat	Ahmedabad	5	15.6	0.56	0.61	3
B3	Mansi Complex	Ahmedabad	11	30.7	0.72	0.98	3
B4	Hotel Mahesh	Morbi	4	12.2	0.20	0.22	1
B5	Prince Hotel	Bhuj	4	10.0	0.17	0.17	2
B6	Limdiwaca Terrace	Bhuj	5	15.4	0.29	0.41	2
B7	NK Tower	Bhuj	6	21.6	0.54	0.53	2
B8	Pooja Flat	Anjar	6	18.0	0.59	0.44	4
B9	Classic Complex	Gandhidham	5	14.7	0.38	0.36	3

(4) Detailed investigation of nine reinforced concrete buildings

Nine RC buildings were investigated in detail in order to study causes of the damage and measure the fundamental period. The fundamental period was obtained from the micro-tremor measurement and it is compared to a simple predictive equation.

Table 7.1 shows the number of stories, building height, fundamental period in longitudinal and transverse directions, damage level based on EMS98 (European Seismological Commission, 1998). B1~B3 are located in Ahmedabad 300km east of the epicenter and B4~B9 are in cities closer to the epicenter.

Fundamental period for each building was obtained from the micro-tremor measurement. Measurement was carried out three times at the top of the buildings using an accelerogram for the period of 20.48 seconds. Recorded acceleration history was Fourier-transformed and smoothened with Parzen window of 0.5Hz bandwidth. Three spectra were averaged and fundamental period was read from the average spectra. The procedure was carried out in both longitudinal and transverse directions independently. These values are listed in Table 7.1. Figure 7.5 shows the relation between the fundamental period and the building height. The equation to predict the fundamental period ($T=0.02H$, where T is a fundamental period in second, H is a building height in m) is also shown. A solid circle ● and a square ⊞ show the fundamental periods in longitudinal and transverse directions, respectively. The measured period is longer than the prediction partly because of the damage. However, Abe et al. (1979) reported that the damage increases the fundamental period by 1.5 times at most. Hence, the period of investigated structures was originally longer because the contribution of the non-structural components was very small.

(Note : Section (4) was originally written in Japanese by Takumi Toshinawa.)

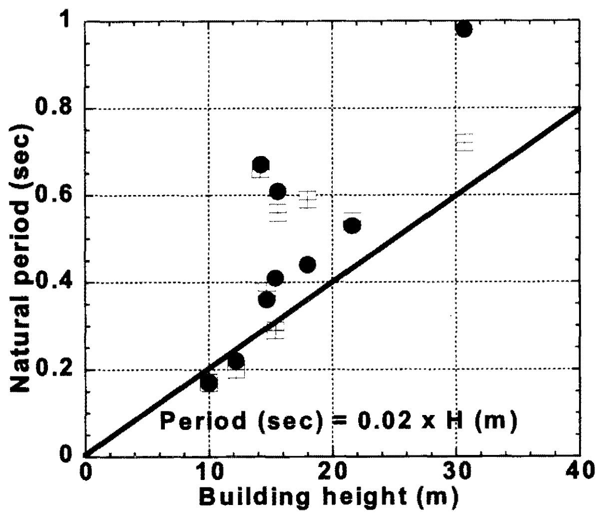

Figure 7.5. Fundamental periods of structures.

(5) Conclusions

In this earthquake, many reinforced concrete structures suffered minor to catastrophic damage. The most commonly observed damage to RC structures was in the form of cracking and falling of infill walls but the most striking failure was the structural failures of modern multi-story buildings. Damage to RC buildings especially concentrated on the five-story or eleven-story buildings, which had soft ground floors used for parking. Since buildings with sound construction should not have experienced any major damage for the level of ground motion experienced, those damage was due to inherent weakness in the structural system, design, detailing, poor material quality and unsound construction practice. This explains the widespread structural damage to RC buildings in cities very far from the epicenter like Rajkot and Ahmedabad. Damage to RC building structures can be attributed to the combination of the following reasons.

1. Soft story effects
2. Poor detailing of structural joints
3. Inadequate reinforcing steel tie spacing and 90 degree hook
4. Insufficient reinforcing steel development length in columns with large aspect ratio
5. Honeycomb concrete at the top of ground floor columns
6. Lateral force is not considered in design
7. Inappropriate anchoring of beam and slab reinforcement

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(6) Acknowledgment

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Note:

This study is based on the reconnaissance survey by the TKM survey team. TKM survey team consists of four field members (Leader: Prof. Hitoshi Tanaka, Toyohashi University of Technoloty at the time of investigation, Kyoto University as of this writing) and three backup members (Leader: Prof. Fumio Watanabe, Kyoto University).

7.2 Damage in Gandhidham

Yasuhiro Hayashi, Sumio Sawada, Sanjay.Pareek and Yoshiaki Hisada

Since concentration of building damage was found in a town district of Gandhidham city, we investigated the relation of the damage to the soil conditions and the characteristics of buildings, mainly in that area.

Figure 7.6 shows the town map of Gandhidham city. Damage concentration was observed in an enclosed area in Fig. 7.6. The sites of heavily damaged buildings are shown in Fig. 7.7. Photo 7.12 shows a bird's view of the district and the main street of Gandhidham, which runs from west to east. The heavily damaged district is in the vicinity of the old town. However, we had hardly seen severely damaged buildings in the old town as shown in Photos 7.13 and 7.14. The buildings of this area are mainly two storied row houses and their structures are reinforced concrete framed masonry. This block of the town was established in 1950s, and therefore, is the oldest in Gandhidham city but far newer than towns like Bhuj or Bhachau.

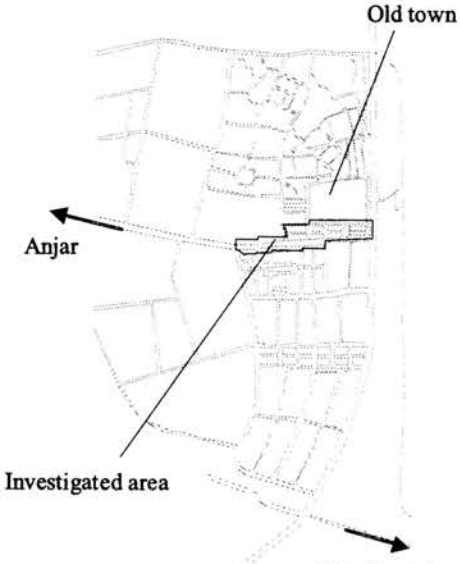


Figure 7.6 Town map of Gandhidham

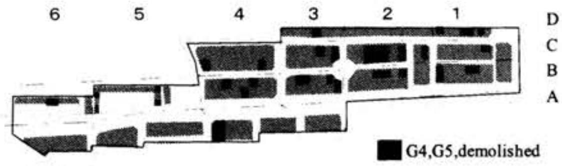


Figure 7.7. Distribution of heavily damaged buildings

Photo 7.12. Bird's view of the newly developed town district of Gandhidham

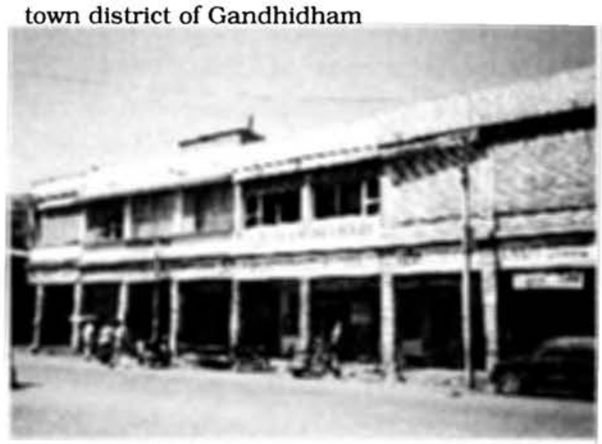


Photo 7.13. Buildings along the center street in the old town of Gandhidham

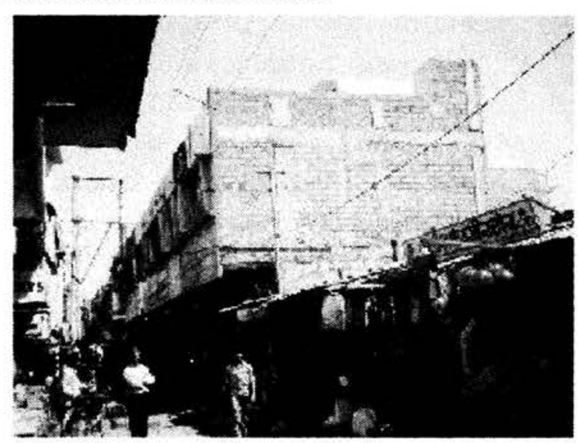


Photo 7.14. Buildings along the center street in the old town of Gandhidham (side view)

In order to clarify the cause of the damage concentration, we first investigated the correlation between building damage and the soil condition.

To investigate the soil conditions, we conducted microtremor measurements on the soil surface at seventeen sites as shown in Fig. 7.8. Based on the measurements, we evaluated a H/V spectrum at each site to identify the predominant frequency of the soil. Simultaneously, we recorded average damage condition of surrounding masonry buildings and reinforced concrete buildings. The definition of damage rank is based on the EMS-98 [1]. The index of G1, G2, G3, G4 to G5 in Fig. 7.8 is corresponding to the Grade 1 (negligible to slight damage), Grade 2 (moderate damage), Grade 3 (substantial to heavy damage), Grade 4 (very heavy damage) to Grade 5 (destruction) of classification by EMS-98. In addition, the index G0 means that we cannot find any damage around the site. Vulnerability class of both masonry buildings and reinforced concrete buildings are considered to be C judging from the quality of construction, material, and structure.

It is clear from Fig. 7.8 that RC buildings have generally higher grade of damage compared with masonry buildings. Moreover, damage grade along the main street is the highest in the whole Gandhidham. On the other hand, there are some sites whose H/V spectra have peaks corresponding to predominant frequency of the surface soil layer. However, we cannot recognize any clear tendency in H/V spectra that explains the difference between damage degree of damage concentrated area and that of the others. Judging from H/V spectrum obtained from microtremor measurement, the soil conditions at most of the places in Gandhidham city are very good and the soil condition could not account for the damage concentration of buildings along the main street.

Next, damage survey of all buildings in the block, where concentration of building damage was observed, was conducted. A total of 147 buildings were investigated. Investigated parameters are the grade of building damage, the number of stories, the type of use of buildings, and structural type. However, when a building has RC frame, we also filled infill material in the investigation sheet. The definition of damage grade also follows EMS-98.

First, the relationship between structural type (masonry or RC frame) and damage ratio is shown in Fig. 7.9. This figure shows that damage of RC frame buildings was clearly severe than that of masonry buildings.

Next, the material currently used for the infill wall of RC framed masonry was classified according to sand stone (SS), solid brick (SB), and the concrete block (CB). Variation in the quality of a concrete block is very large. The quality of concrete block is dependent on the mix proportion of cement in the concrete blocks and the mortar used for bonding paste. Figure 7.10 shows the relationship between infill material and damage ratio. From this figure, it seems that the ratio of serious damage increases in the order of sand stone, concrete block, and solid brick.

For reference, natural periods of RC framed buildings and masonry buildings in India obtained from microtremor measurement are shown in Figs. 7.11(a) and (b), respectively. First, the natural periods T of buildings, whose damage grade are less than G2, are almost same as those of Japanese buildings [T=0.07 N, where N is the number of stories]. However, the buildings suffered more serious damage when the natural period becomes longer than T=0.1N in many cases. Therefore, it seems that the buildings with longer natural periods show considerable damage in structural members and infill walls.

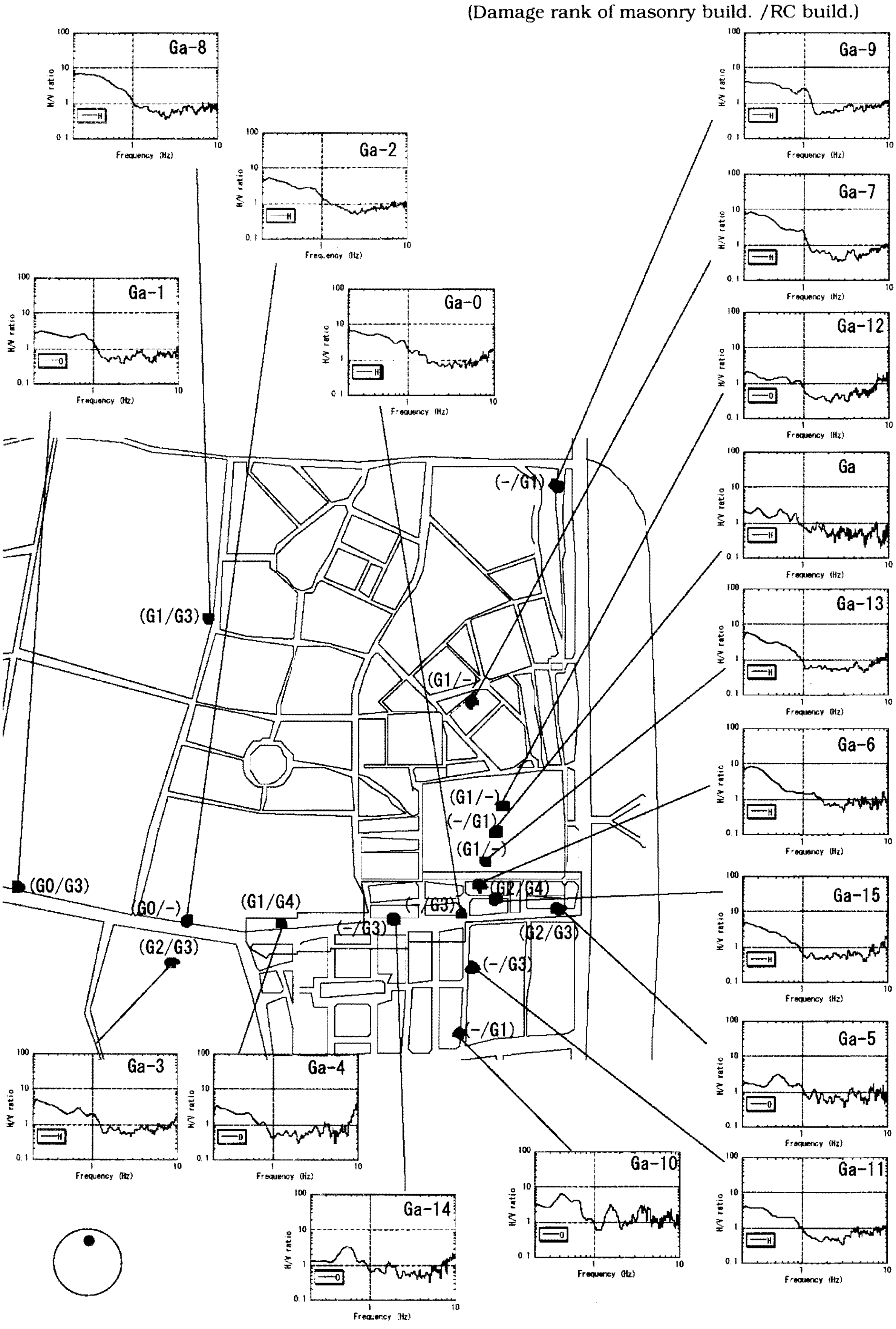


Figure 7.8. Building damage and predominant frequencies of the soil.

Next, the relation between type of use of the building and damage is shown in Fig. 7.12. Three among five hotels and nine among twenty-three office buildings suffered G3 damage or more. That is, the hotels and the office buildings had much serious damage. On the contrary, there is little damage with respect to a residential houses and stores.

The relation between building use and the number of stories is shown in Fig. 7.13. Most of the residential houses and stores have one or two stories. However, all the hotels with severe damage had three or more stories. The office buildings had much severe damage next to hotels, and there were many office buildings with three stories or more.

Finally, the relation between the number of stories and damage is shown in Fig. 7.14. The ratio of buildings with a damage of Grade 3 or more is about 60 percent for 4 or 5 storied buildings, while it is 35 percent or less for 2 or 3 storied buildings. These results are consistent with the fact that hotels and office buildings suffered much severe damage compared with residential houses and stores.

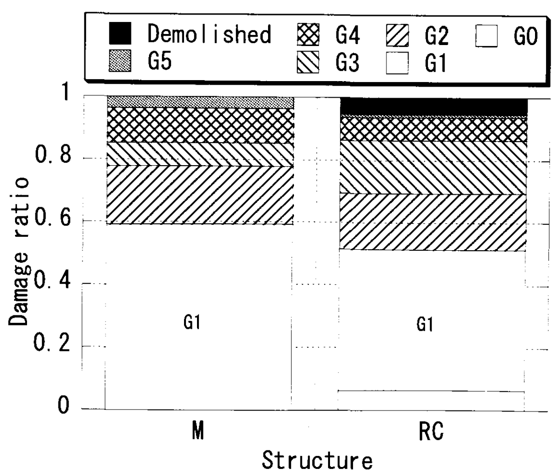


Figure 7.9. Relationship between damage ratios and structure type.

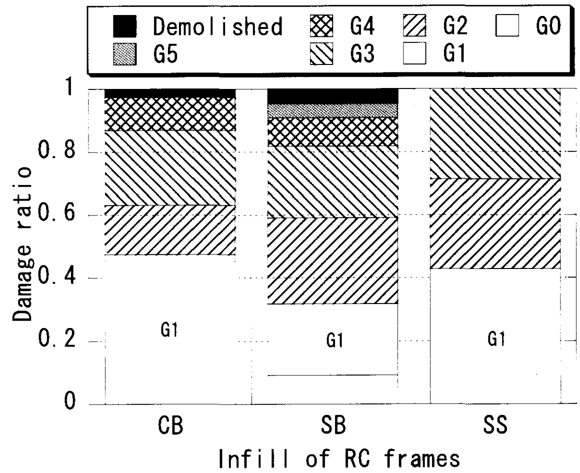
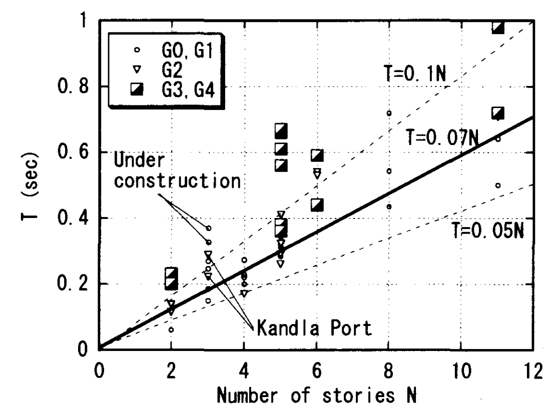
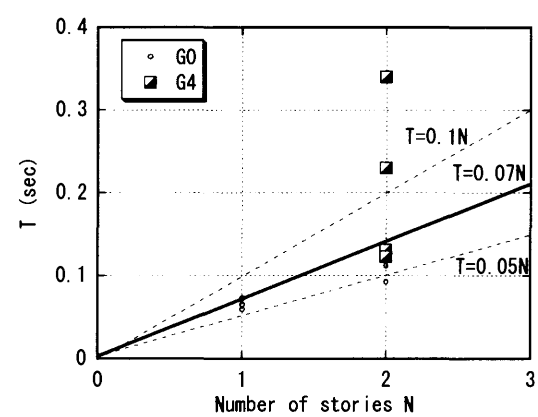


Figure 7.10. Relationship between damage ratios of RC and infill material.



(a) RC buildings



(b) Masonry buildings

Figure 7.11. Natural periods evaluated by microtremor measurements.

In addition, most masonry buildings have two or less stories. There was almost no difference in damage ratio between RC and masonry buildings if the number of stories is limited at two or less. After all, it can be said that the damage ratio increases with the number of stories, which is the main cause of damage concentration in Gandhidham. This tendency is not peculiar to the Gujarat earthquake. The same tendency was seen also in the Turkey earthquake and Taiwan earthquake of 1999, and the 1995 Hyogo Nanbu earthquake. When a high building collapses, casualties and losses increase drastically. Therefore, it is very important to improve the seismic performance of high-rise buildings.

On the other hand, in the investigated area, the average damage grade of one or two storied buildings was G2 to G3. It is obviously large, compared with the damage grade G1 of buildings in the old town. The causes of the damage can be explained as follows.

The town of Gandhidham is built from 1950s. Anjar earthquake in 1956 affected the town planning, and it was supposed that houses in Gandhidham were made to be strong against earthquakes. Actually, the residences in the old town had many walls, and the quality of infill material was also very good. Therefore, the houses were healthy structurally after the earthquake, although very slight cracks can be found. Therefore, from damage investigation of Gandhidham city, we see the importance of the strengthening of buildings in a fresh light in order to mitigate earthquake disaster.

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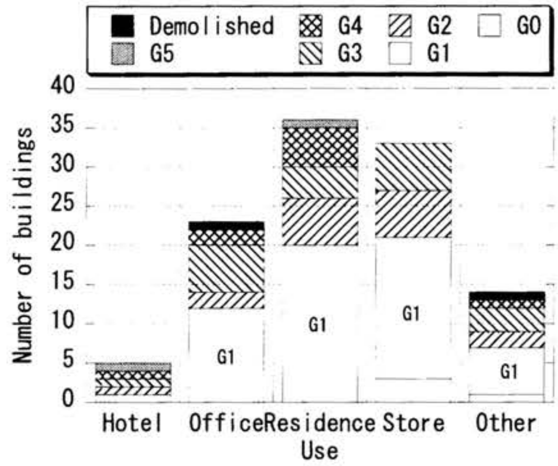


Figure 7.12. Relationship between building damage and type of use.

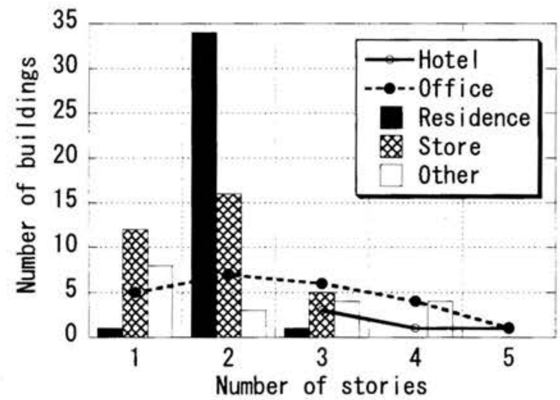


Figure 7.13. Relationship between building use and the number of stories.

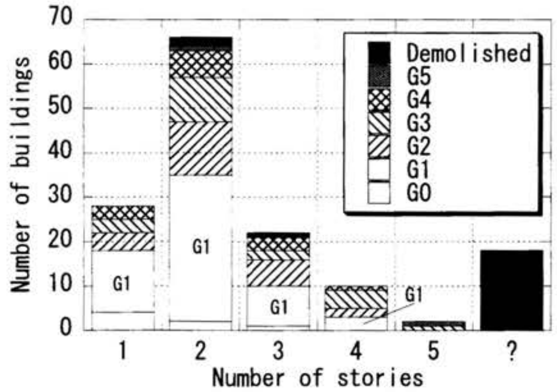


Figure 7.14. Relationship between building damage and the number of stories.

7.3 Damage to Masonry Structures

Kimiro MEGURO, Fumiaki UEHAN and Pradeep Kumar RAMANCHARLA

1. Introduction

Past earthquakes have revealed that the collapse of masonry structures is responsible for more than 80% of the casualties during these events. During the ground shake, masonry bricks or blocks fall and strike the people inside the structure. Due to the small size of the bricks, the space left free after the collapse is very small and even in case the resident survives, the generated dust makes breathing difficult. There have been cases of people surviving the structure collapse that have died of asphyxiation.

In some of the countries where masonry is widely used for construction, there is still not enough concern about the seismic performance and strength of this type of structures. This situation is aggravated by the fact that masonry, especially adobe, is commonly constructed by the user himself without any engineering knowledge.

Even in countries where earthquake engineering development is high, most of the research is focused on the study of complex structures such as high-rise buildings or long span bridges while little attention is given to masonry buildings. A similar situation is observed in Japan where there is an urgent need for the study of strengthening and retrofitting techniques for timber structures, a material widely used for housing. In spite of its vulnerability, which has been exposed in the recent earthquakes, very few researchers are focused on this type of structures.

In this chapter, a summary of the type of masonry structures commonly used in India as well as their earthquake related damage is presented.

2. Characteristics of masonry structures in the affected area

This section provides the characteristics of masonry construction as well as a description of the conditions prior to the event.

Masonry structures in the affected area are classified in seven types, A1 to A4 and B1 to

Photo 7.15 Traditional masonry house called Bhonga

Photo 7.16 Single-story brick masonry house constructed in 1956

Photo 7.17 Overview of the typical town constituted by low rise masonry structures

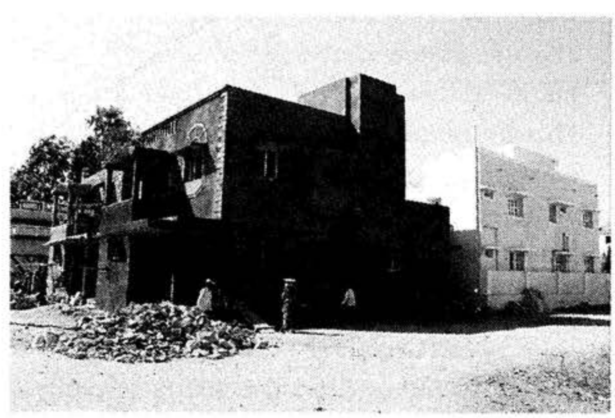
B3. A1 and A2 are formed by natural shape stones whereas A3 and A4 are formed by cut stones. As for the mortar, A1 and A3 have clayey mud whereas A2 and A4 have poor quality sand/cement mortar. Masonry types A3 and A4 are sometimes combined with RC column or slab.

Masonry type B1 corresponds to adobe with clayey mud. B2 and B3 are constituted by bricks with clayey mud and sand/cement mortar, respectively. The latter structures sometimes present RC columns, lintels, or slabs. This chapter does not discuss the masonry infill walls because these structures are considered as a special type of RC structure.

Photo 7.15 shows a traditional structure called *Bhonga* or *Kuchchli*. The lower part is made of adobe or brick masonry whereas the roof is usually made of straw. Generally, the *Bhonga* have one singly room, i.e. there are not interior partitions. The main feature of this structure is its cylindrical shape, which provides it with a better seismic performance when compared with the commonly used rectangular shaped structures. Due to its axisymmetry, the *Bhonga* exhibit good seismic performance no matter which is the earthquake direction. On contrast, the rectangular shaped structures tend to concentrate stresses at the corners causing damage at these regions and eventually the separation of adjacent walls.

Photo 7.16 shows a house that did not suffer any major damage. It was constructed in 1956 just after the Anjar earthquake. While in other cities, the newer the house, the stron-

(a) Left side: Before finishing the outside wall, Right side: After finishing the wall



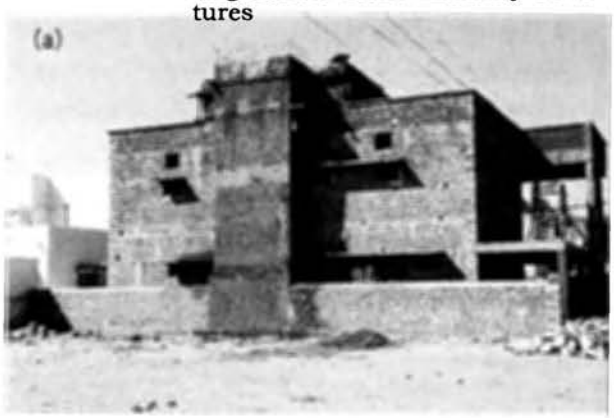
(b) Left side: After finishing the wall, Right side: After finishing and painting the wall

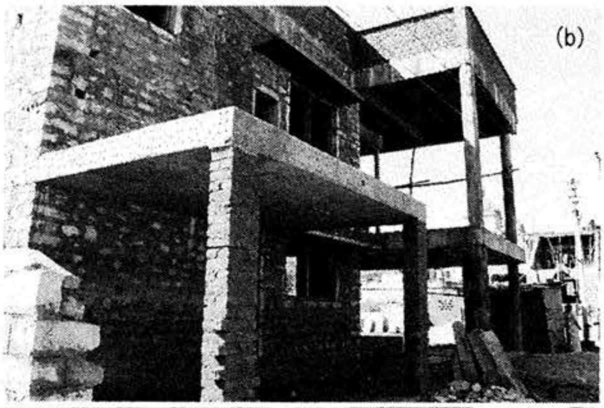
(c) Overview of the structure in the right side of Photo 7.18 (b) from a different viewpoint

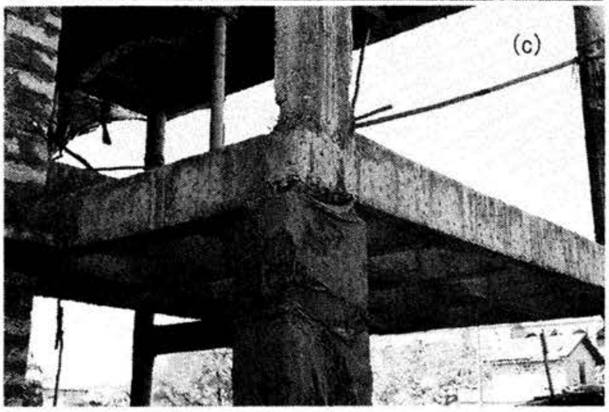
Photo 7.18 Different construction stages of stone masonry houses

Photo 7.19 Different construction stages of largerubble stone masonry structures

Photo 7.20 This partially damaged structure seemed to look very nice before the earthquake.







(a) Overview of the house

(b) The column supporting RC slab is made by just piling the bricks (Column in back side is RC)

(c) Close up of the RC column (It is very slender and joint connection is poorly constructed.)

Photo 7.21 Two-story stone and brick masonry house with RC slab and lintel band

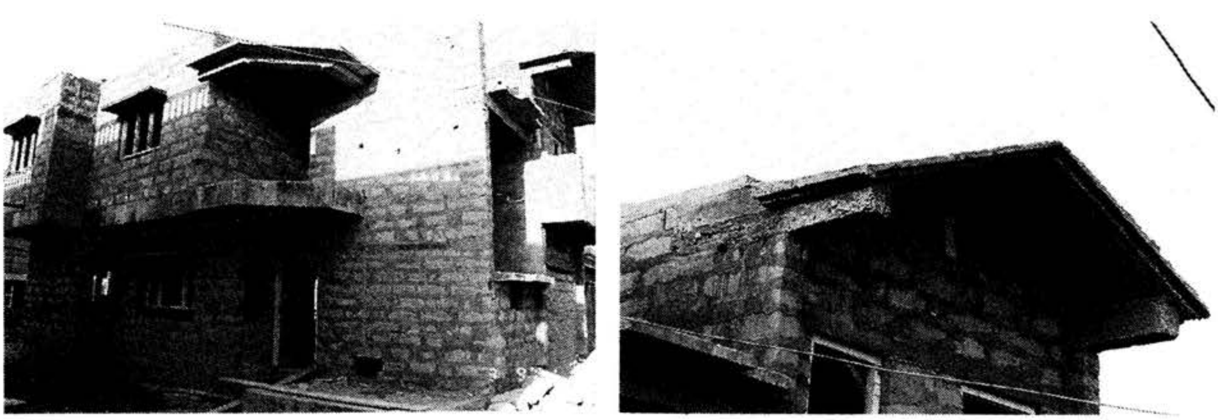


Photo 7.22 Huge stone masonry structure. Detail of a poor connection between RC beam and masonry wall, which might induce tension stresses on the wall

ger it was, in Anjar, older houses tend to be stronger than new ones. The reason for this is that after the Anjar earthquake, the entire city was relocated and house construction quality was given proper attention. Only one-story buildings were built in the newly developed town. Unfortunately, the awareness of earthquake related problems and attention to seismic strength of structures did not endure and decreased as time passed.

Photo 7.17 shows an overview of low masonry structures in the affected area. This photo depicts the typical town prior to the earthquake.

Photos 7.18 and 7.19 show the construction stages of a couple of typical two story residential buildings. Photo 7.18 series show masonry structures conformed by huge and heavy stone blocks in combination with RC lintel and slabs. At the last stage of construction, the structures look like sound RC buildings. It is impossible to assess the real structural system unless earlier stages of construction are observed. Photo 7.19 shows a similar situation. The structures at the back are at the last stage of construction whereas the front ones are not provided with finishing yet.

Photo 7.20 shows another case of a partially damaged structure. The back of the building, which collapsed, reveals the poor quality of the construction practice. This building seemed sound before the earthquake struck it.

Photo 7.21 series show a masonry building with RC elements such as columns and

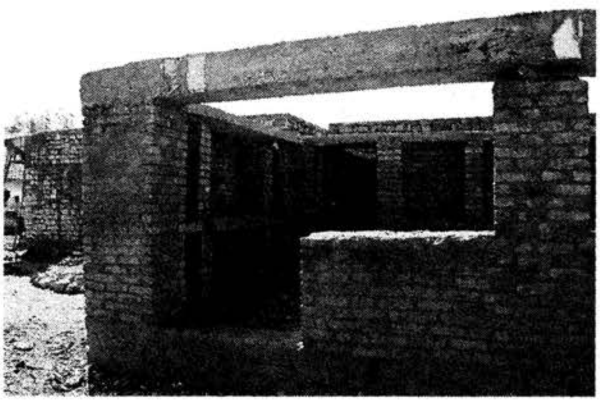
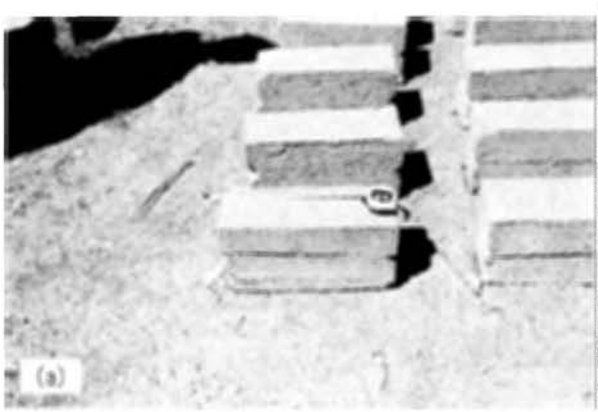


Photo 7.23 Masonry structure with lintel band



(a) Blocks left under the sun heat for drying.

(b) Cement/sand mortar mixing for the block preparation.

(c) Compression, compaction and vibration of the mortar for forming the blocks

Photo 7.24 Block fabrication process

slabs. Photo 7.21(b) is a close up of one of the columns. After this column is finished it will look like a RC element. However, it is just a very weak unreinforced masonry element. Photo 7.21(c) depicts a slab-column detail. The upper column is obviously too slender whereas the lower column is very poorly connected with the slab.

Photo 7.22 series show a masonry structure composed of huge stones. The photo on the right presents the detail of the slab support on a RC cantilever beam. This beam is directly supported on the masonry wall without any special anchoring detail. In case of an earthquake, the cantilever vibrates vertically causing tension stresses in the masonry. Since the masonry tension strength is very low, this type of connection is likely to fail.

Photo 7.23 shows a masonry structure with a RC lintel. This element usually provides integrity to the structure, increasing the strength and improving the seismic performance. However, in this case, the connection between the lintel and the masonry wall is poor and therefore no benefit is obtained.

In the affected area, very weak construction materials were observed. Blocks and bricks could be holed just with the finger. Photo 7.24 series show the typical process of block preparation. Blocks (400 x 200 x 200mm) are made of sand/cement mortar. This mix is poured into molds and compressed while the preparation table shakes to help the compaction (Photo 7.24(c)). The prepared blocks are left on a yard to dry under the sun heat. Although the sand has high concentration of salt and organic materials, it is not washed prior to the block fabrication. As a result, the bricks exhibit very poor quality and low strength. The Schmidt hammer was used

Photo 7.25 Separation of adjacent walls of a rectangular shaped dwelling

Photo 7.26 Roof damage caused by tile slipping

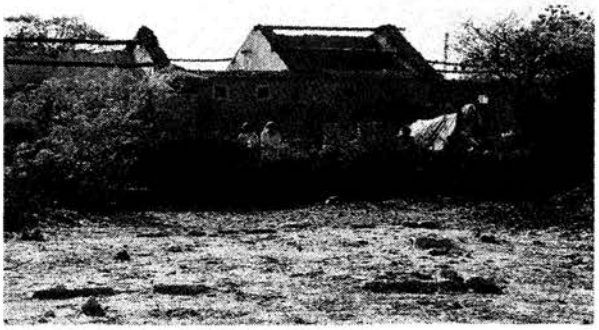
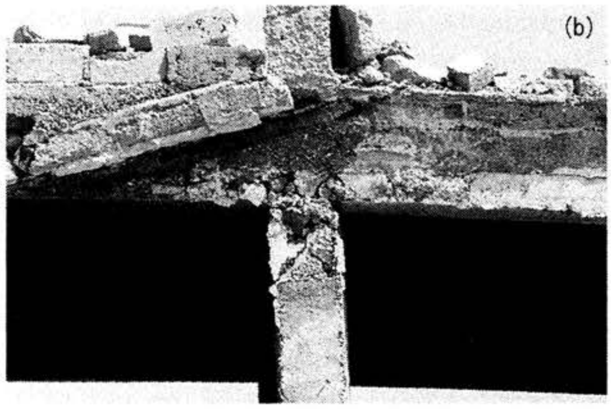


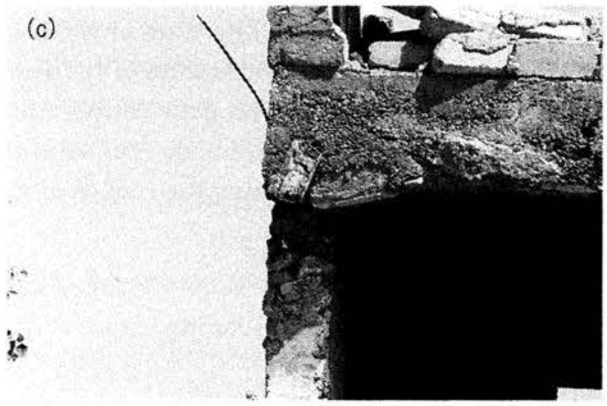
Photo 7.27 The roof collapsed and left the house unprotected

Photo 7.28 Separation of the adjacent walls of a single story masonry dwelling

Photo 7.29 Topography induced local site effects caused extensive damage at this area located on top of a hill

Photo 7.30 Towns where a large number of masonry houses collapsed





(a) Overview of the damage.
(b) Column-beam joint.
(c) ditto.

Photo 7.31 Damaged two-story RC frame houses with infill bricks (poor connection joints between column and beam, beam and wall, and column and wall)

(a) Overview of the damage.
(b) No RC column can be seen at the corner of the structure
(c) View of the structure interior, RC beams can be seen

Photo 7.32 Damaged single-story masonry substation building to check the strength of the blocks ready for sale. Unfortunately, the material strength felt below the limits that could be measured through this device.

3. Damage report

(1) Residential masonry structures

These section reports damages to single and two story residential buildings.

Photos 7.25 and 7.26 show separation of adjacent walls due to concentration of stresses at the building corners and poor connection between walls. After the cracking, the lateral walls (which are not resisting the roof weight) are likely to fall.

Photos 7.27 and 7.28 show roof damage consisting of slipping and falling tiles.

Photo 7.29 shows a typical case of local site effect caused by topographical configuration. The damage at this site is extensive compared to the surrounding areas because it is located on top of a hill.

Photo 7.30 series shows typical masonry structure collapse configuration. At some areas, almost 100% of the structures collapsed. As mentioned before, adobe and masonry structures with small units present two main inconveniences. First, in case of collapse, these structures leave very small free space underneath the debris and thus the probability of survival is low if somebody is trapped under the fallen structure. Second, due to dust generated by the collapse, even if a person can survive the collapse, he or she might asphyxiate.

Photo 7.31 shows the overview and details of a damaged structure. The connection between columns, walls, and slab is very poor.

Photo 7.32 presents a damaged substation facility whose main structure is masonry. An external roof and its supporting columns, both RC elements, are appended to it. Due to the lack of an appropriate connection between the slab and the masonry wall, the supporting wall was seriously damaged (Photo 7.32(c)). This

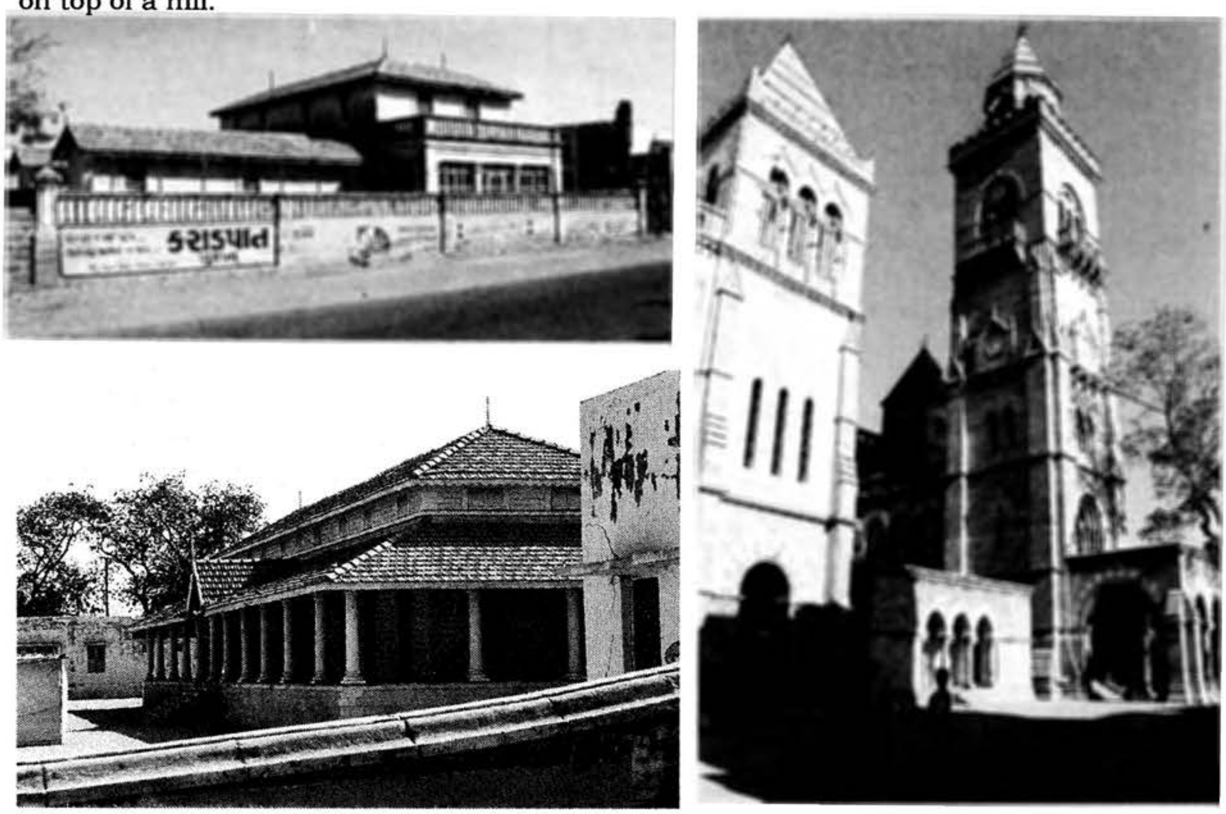


Photo 7.33 Public buildings that did not suffer severe damage during the earthquake. Public structures are enforced by law to follow the seismic design code.

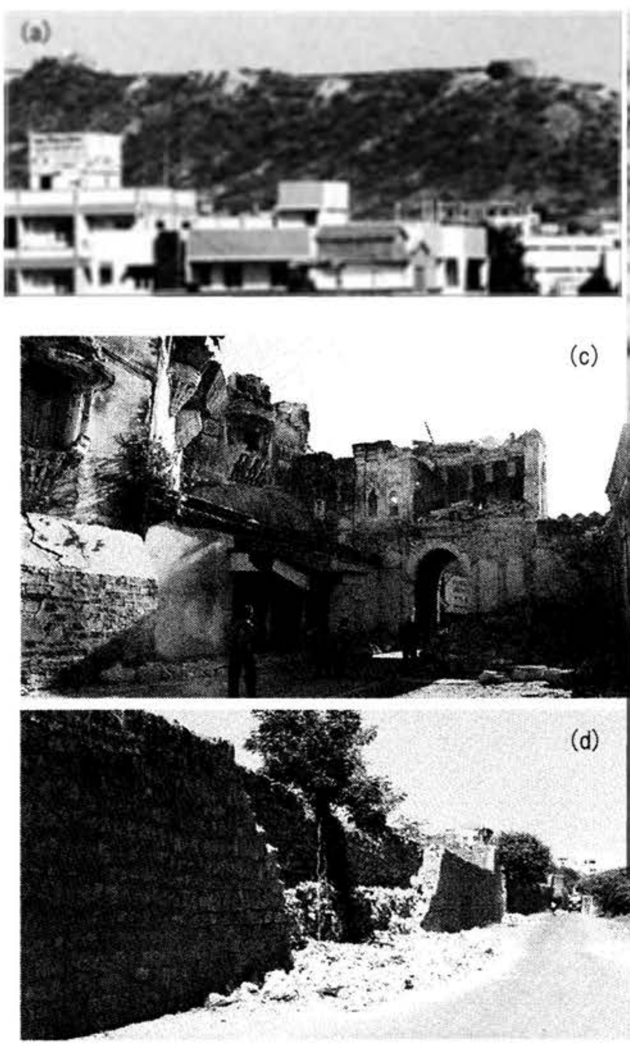
building damage level requires immediate reconstruction. However, due to the necessity of keeping the equipment stored in it operative, provisional steel struts have been provided to support the roof. Reconstruction is delayed for a while.

So far, damaged structures have been presented. However, at the same locations, another group of structures performed well. Photo 7.33 shows public buildings made of masonry with very low damage level. From this, it can be concluded that masonry structures built with appropriate care, sound materials, i.e. well shaped brick/stone, and good foundations can perform well in case of earthquakes. The key issue is to study these structures and extract as much experience as possible from them.

(2) Non-residential masonry structures

Photo 7.34 series shows damages to walls and fences. Photo 7.34(a) shows a wall that was built on top of a hill to protect the city against the enemy. The topography favored the amplification of the ground shake and therefore, the wall felt at several locations (white spots on top of the hill). Photo 7.34(c) shows an arch type structure. This shape is very convenient for materials with poor performance in tension, like masonry, because the induced stresses are all compression. If the support is sufficiently strong, these structures are very resistant.

Photo 7.34(d) shows the effect of a tree on the performance of a masonry wall. The roots of the tree growing on top of the wall pen-



(a) Defense fence on top of the hill (white spots show fallen wall)
(b) Typical collapse of a defense wall
(c) Arch structure that performed well during the earthquake
(d) A tree weakened the wall causing its collapse

Photo 7.34 Walls and fences

(a)

(b)

(c)

(a) Damaged masonry monumental structures
(b) Completely collapsed monumental structures
(c) Undamaged monumental structure in spite of its heavy roof. The surrounding structures suffered different levels of damage.

Photo 7.35 Monumental structures at Bhuj (18th century)

etrated it and generated a weak plane in the structure. During the strong shake, both wall sides lost connection and one of them felt.

Photo 7.35 series shows damage and undamaged monumental structures. Photo 7.35(c) presents a structure, which in spite of having a heavy roof, performed well during the earthquake. The large and sound foundation together with the quality of the materials, evidenced by the uniform shape of the masonry units, contributed to its good performance.

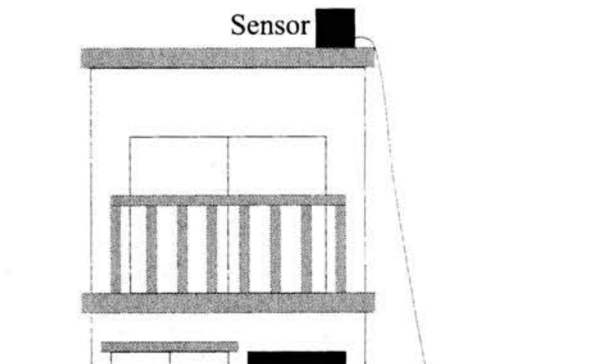


Figure 7.15 Microtremor measurement system

4. Characteristics of the structures

Microtremors were measured on both damaged and undamaged structures as shown in Figure 7.15 . These measurements were used to obtain the natural period of the structures in the affected area. Figures 7.16 and 7.17 show the natural periods of the single and two story brick masonry structures shown in Photos 7.36 and 7.37, respectively. Figure 7.18 shows the relation between the natural period and the number of floors. The brick masonry structure G4 shown in Photo 7.38 has a larger natural period than other structures with similar height due to the damage inflicted by the earthquake.

Dynamic properties of elevated water tanks were also surveyed. These structures exhibit natural periods around 1sec, much larger than the corresponding to residential buildings. Residential buildings with such large periods are over 13 stories high and were not surveyed in this occasion.

The concrete strength of various structures was evaluated by means of the Schmidt hammer. For residential structures, strength felt between 100 to 200 kg/cm^2 whereas for water tanks it was between 400 to 500 kg/cm^2. The reason for such a big gap is that for public structures, such as elevated water tanks, the seismic resistant code is mandatory, whereas for residential buildings it is not. Although owners are required by the local government to submit the plans of their residences for revision prior to the construction, only comments regarding the layout are given by the appointed office. No structural comments or remarks are given.

The surveyed revealed that the elevated water tanks performed better than residential buildings during the present earthquake. Two reasons could explain this situation: quality of construction and difference in dynamic properties. The first one is clear from the survey. However, due to the lack of seismic records no discussion can be done on the frequency contents of the strong ground motion and its effect on the different type of structures.

Photo 7.36 Microtemor measurements at a single-story masonry building

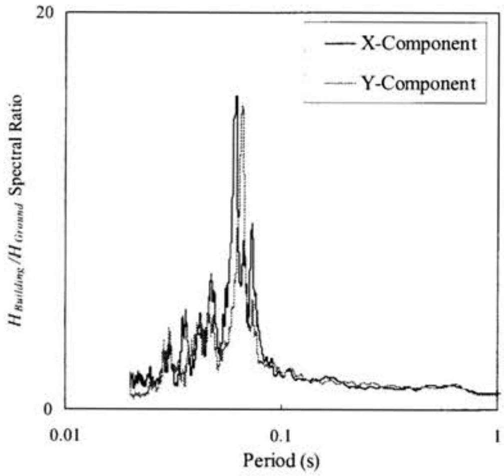


Figure 7.16 Microtremor spectral ratio for building in Photo 7.36

Photo 7.37 Microtemor measurements at a two-story masonry building with RC frame

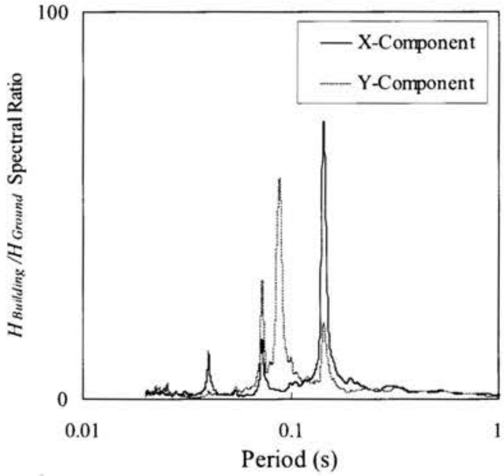


Figure 7.17 Microtremor spectral ratio for building in Photo 7.37

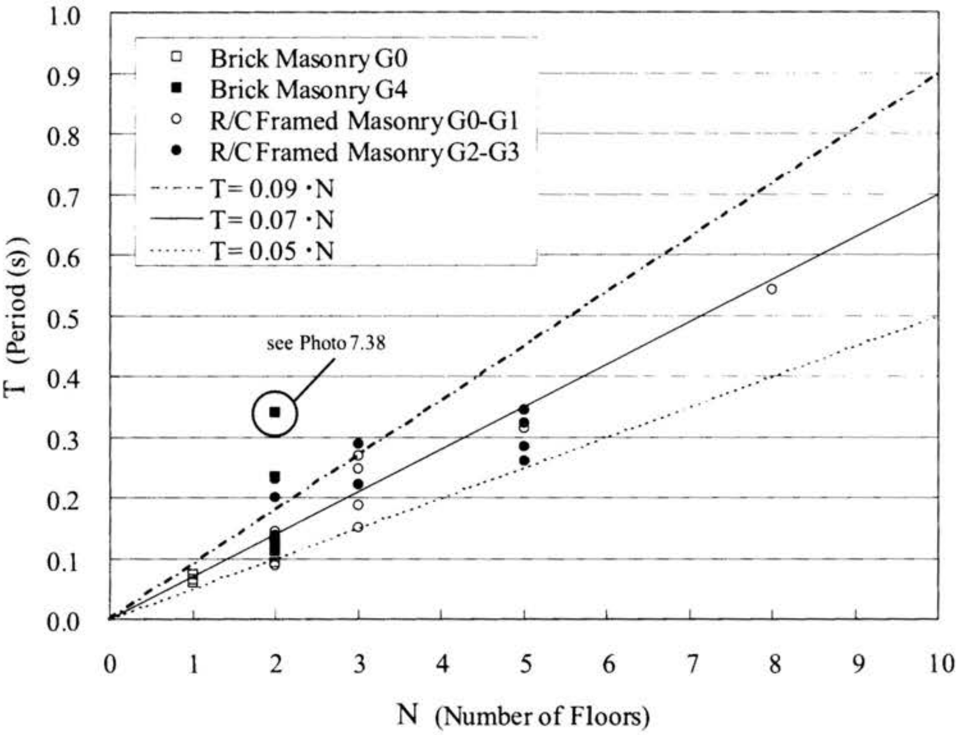


Figure 7.18 Relation between natural period and the number of floors of the structures in the affected area

5. Conclusions

A powerful earthquake struck the state of Gujarat, India on 26th Jan, 2001. This quake was responsible for the immense casualty and property loss. Casualty loss was mainly due to the collapse of poorly constructed structures. This chapter mainly discusses the mechanisms of the damage to the masonry structures in the earthquake-affected areas. There are several types of the masonry constructions that can be classified according to the construction materials and construction type. The major reasons for the poor performance are weak bond of the masonry wall, weak beam-column joints, etc. However, there were some structures that performed well in the affected areas. This was mainly due to the proper care and good workmanship during the construction.

Photo 7.38 Microtemor measurements at a two-story brick masonry house damage level G4

7.4 Building Materials and Repair and Strengthening Methods of Earthquake Damaged RC Structures

S. Pareek, Y. Hayashi and S. Sawada

(1) Strength tests of building materials

The most prominent reason for the damage of building structures pointed out by the mass media and the engineers was the poor quality of materials used. In order to clarify the quality of building materials, samples were collected from various sites of damaged buildings in Gandhidham city and their strength tests were conducted. The types of materials tested were concrete from RC building, solid concrete block, 2 types of bricks and bricks with mortar joints and sandstone. The strength test results of sandstone samples taken from an apartment building (4F) are shown in Fig.7.19. Although the sandstone itself possesses moderate strength, the bonding mortar between the stones was of poor quality, which yields at relatively low shear loads. The concrete used for the RC building (Hotel 5F) had a compressive strength of 232 kgf/cm² and was not of poor quality. Thus the collapse of the building due to the number of stories (5F) and the structural design could be accounted for the collapse of the building. The samples of solid concrete blocks used as the infill material for RC frame structured building (3F) were of extremely poor quality and the compressive strength was merely 22 kgf/cm². The bricks obtained from a shopping complex building (3F) with RC frame and brick infill structure were of two types. The low strength bricks are the sun-dried bricks and the ones with higher strength are baked at low temperatures.

(2) Repair and strengthening methods of earthquake damaged RC structures

In addition to the testing of materials, a survey on the repair and strengthening methods of RC structures in Ahemadabad city. The survey team visited the sites almost 45 days after the earthquake hit the region and the repair works of damaged RC buildings was under process. Photo 7.39 shows one of the most common repair practices adopted. As described in the previous chapters the columns of the "soft-first-story" were badly damaged and as a most immediate remedy to vertical loads, I-section steel columns were installed under the floor beams of second story and temporary brick columns were erected and finally the original damaged columns were repaired by

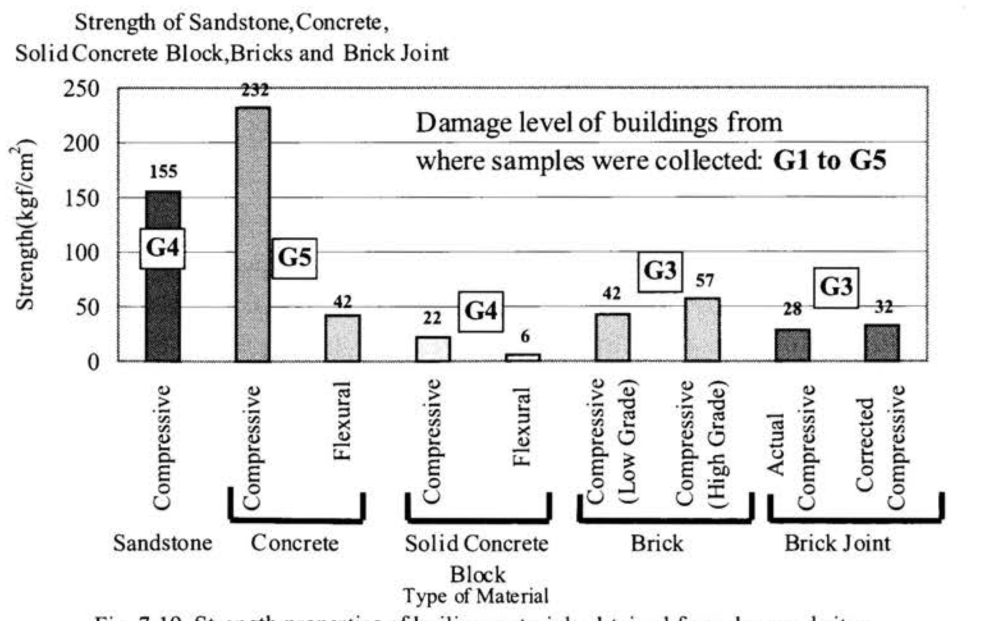


Fig. 7.19 Strength properties of builing materials obtained from damaged sites.

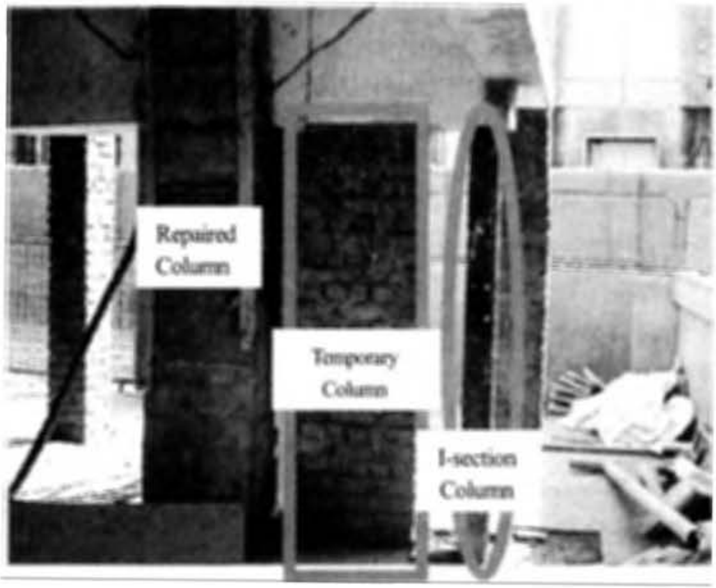


Photo 7.39 Typical repair process of damaged column of RC building.

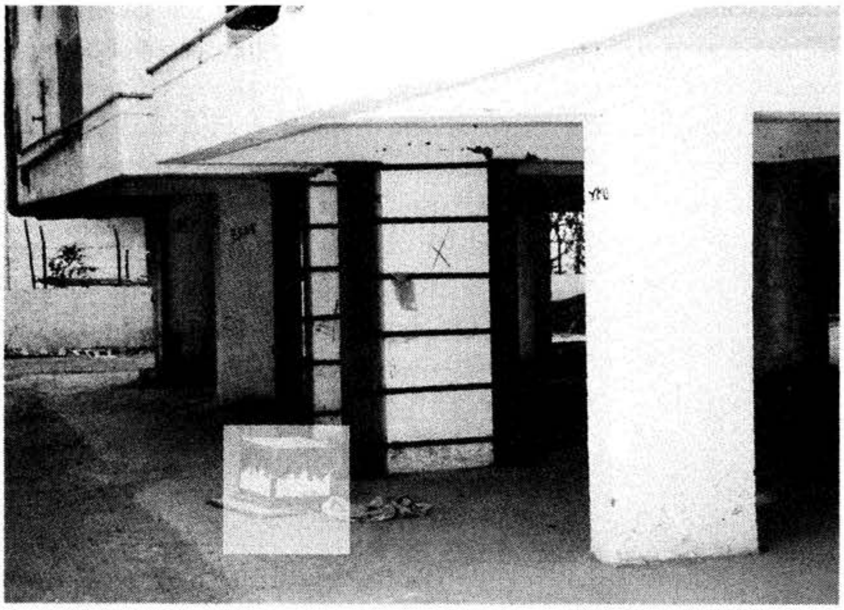


Photo 7.40 I-section columns that were placed on the sides of the damaged columns of a 11 storied apartment building (Mansi Complex) in Ahemadabad.

additional reinforcement and concrete jacketing.

Photo 7.40 shows the steel frames of I-section columns that were placed on the sides of the damaged columns of a 11 storied apartment building (Mansi Complex) in Ahemadabad. The steel frames of I-section columns support the vertical loads and without any criteria to the lateral loads. Furthermore, as the minor gaps existed between the I-section columns and the floor beams of the second story, that would hardly provide any effectiveness of the steel frames to the structure. In some instances the repair work had already been completed by merely shotcreteing mortar on the damaged columns of the "soft-first-story" (Photo 7.41).

Photo 7.42 shows the repair work under progress, which is a relatively good example of structural repair of the damaged columns of the open-first-story of a 4-story apartment building in Ahemadabad. In this case, the old

Photo 7.41 Repair work was done by shotcreteing mortar on the damaged columns of the first-story.

Photo 7.42 Repair work under progress of the damaged columns of the open-first-story of a 4-story apartment building in Ahemadabad. Old concrete from the columns had been chipped-off with additional reinforcement before concrete jacketing.

concrete from the columns had been chipped-off and additional reinforcement was placed. Furthermore, the additional reinforcement was extended to the footing that would considerably increase the load bearing capacity of columns (Photo 7.43). However, the connection between the reinforcement of the column of first story and the floor-beam of the second story was inadequate, leading to weak beam-column joint (Photo 7.44).

Photo 7.45 is an example of enhancing the lateral loads by the brick infill walls of the open-first story. The anchorage between the brick infill walls and beams and columns was barely considered.

(3) Conclusions

A. The quality of building materials used varied drastically from site to site and was not always of very poor quality. However, mal concrete practices led to the poor quality materials. In some instances, the quality of materials used was satisfactory but the damages of building structures occurred due to poor detailing and structural design.

B. From the observations made by the undergoing repair works, it is clear that the "soft-first-story" problem has to be eradicated for most of the RC building structures. For this, it is recommended that a "Repair-manual" should be prepared and distributed to the local contractors for practice to attain an effective structural repair of damaged buildings.

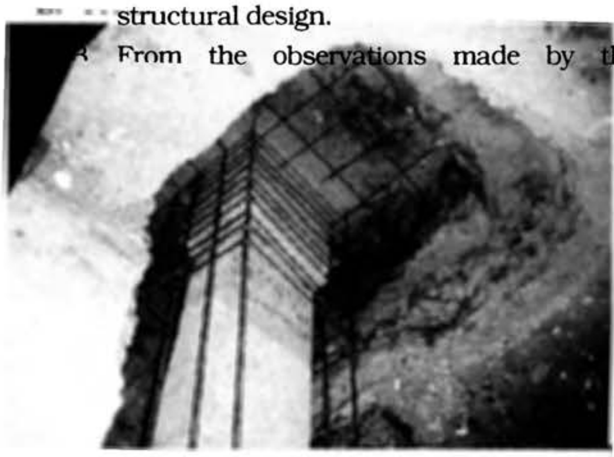


Photo 7.43 Reinforcement was extended to the footing that would considerably increase the load bearing capacity of columns.

Photo 7.44 The connection between the reinforcement of the column of first story and the floor-beam of the second story was inadequate, leading to weak beam-column joint.

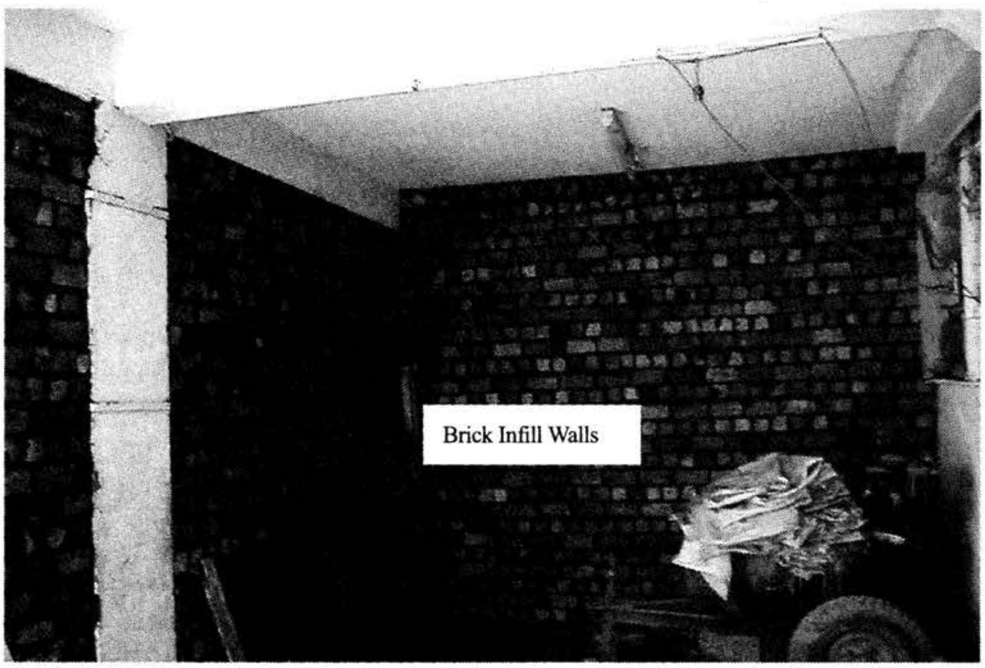


Photo 7.45 Brick infill walls of the open-first story.