Gujarat Relief Engineering Advice Team (GREAT)

GREAT Publication: June 2001

Repair and strengthening guide for earthquake damaged low-rise domestic buildings in Gujarat, India

A guide for:

- Self-build Owners
- Builders
- Local Engineers and Architects
- Local Authorities
- Relief Agencies

and other interested parties

by

UK Engineers with local knowledge:

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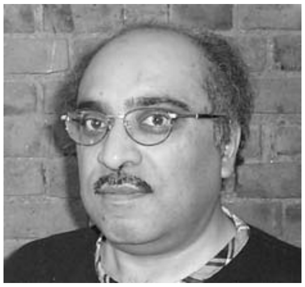

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Devraj is an Associate at Maslen Brennan Hanshaw Partnership and is a practising structural engineer. He has extensive experience in the design and construction of structures and is based in London. He has worked on a number of projects in both the UK and in Europe. He was in India when the Bhuj Earthquake occurred and observed first hand the extent of the damage in Kutch.

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"GREAT" COMMITTEE MEMBERS

A group of UK qualified Professional Engineers from the Shree Kutch Leva Patel Community (SKLPC) in the UK have formed a working party, called the Gujarat Relief Engineering Advice Team (GREAT) to produce this Guide to Repair and Strengthen buildings damaged in this earthquake.

This Team comprises the following members:

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Without the support of these members, whose background and experience have been invaluable, this guide would not have been possible to produce.

Should anyone wish to contact the above people please direct all enquiries to web site: http://www.sklpconline.co.uk.

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DEDICATION

This Guide is dedicated to the memory of those who lost their lives and those that have been injured as a result of the Bhuj Earthquake of 26 January 2001.

Repair and strengthening guide for earthquake damaged low-rise domestic buildings in Gujarat, India

FOREWORD

The 26 January 2001 earthquake in Kutch, Gujarat has had a devastating affect on the area with many buildings damaged and large loss of life occurring. To date 20,000 people are known to have died and 167,000 people injured. This toll will increase as towns are cleared, an operation that will take many years.

We, a small group of professional engineers in the UK, have decided to help in some small way by bringing our expertise to help rebuild the local communities by producing this Guide. We visited the Kutch area following the earthquake. We are also familiar with local building practice as many of our families and relatives living abroad have close ties to the region.

The aim of this publication is to make the self-build owners, builders and local engineers aware of the effects of earthquakes on low-rise domestic buildings. These are identified as buildings of up to 2 storey plus attic, which are constructed of rubble masonry, cut-stone masonry and reinforced concrete frame structures. They are referred to as non-engineered buildings because often little or no engineering has gone into their design and they almost certainly have not been designed to resist earthquakes.

This Guide must also help local government bodies, relief agencies and other interested parties in Gujarat.

There is little published guidance on how to carry out proper repairs and strengthening of earthquake damaged buildings. Indian standards exist but are not used by local engineers or builders in urban or rural areas, mainly due to lack of knowledge and training. As a result, many of the owner-occupiers have unknowingly been carrying out bad repairs in Gujarat.

Many buildings have been severely weakened, and the authors are concerned that there could be another disaster in waiting from a future earthquake. Good repairs, using well-recognised seismic standards may reduce this vulnerability.

This Guide aims in simple terms to explain to the user why earthquakes happen in India, which regions are seismically active, how buildings respond in an earthquake; and how to safely carry out good repair and strengthening techniques to earthquake damaged buildings.

In order for this Guide to be produced acknowledgement is paid to Professor AS Arya's book "Guidelines for earthquake resistant non-engineered construction", produced in conjunction with the International Association For Earthquake Engineering, October 1986. Extracts from this publication have been used in this Guide. As highlighted in that book, we too are of the same opinion that the material given in this Guide should be readily available to people at various levels concerned with earthquake disaster through safe construction. For this purpose no royalty is to be paid and only due acknowledgement is to be given to this Guide. Hence, this Guide is intended for issue free of any charges, by sponsors who wish to print and distribute.

RESPONSIBILITY

The building owner is responsible for determining the need for the repair and its extent, whether it is practical and safe to carry out the repair and whether it is within his budget. It is advised that the building owner should in all cases seek professional advice from a qualified structural engineer before carrying out any repairs. It is also equally important to retain the services of a qualified builder when carrying out repairs. This Guide is intended to provide general assistance **OR** provide general guidance in the repair process but where there is difficulty in interpretation the relevant Indian standards related to earthquake design and construction should always be used.

Since the writers of this Guide do not have any control over the inspection of and diagnosis of damage and the design/control of the repair, they cannot accept responsibility for any loss or damage arising from any reliance on this Guide.

This Guide does not replace any rules, regulations and codes of practice in force.

Some of the illustrations used in this Guide have been reproduced from a variety of sources. Efforts have been made to contact any copyright sources where this is possible.

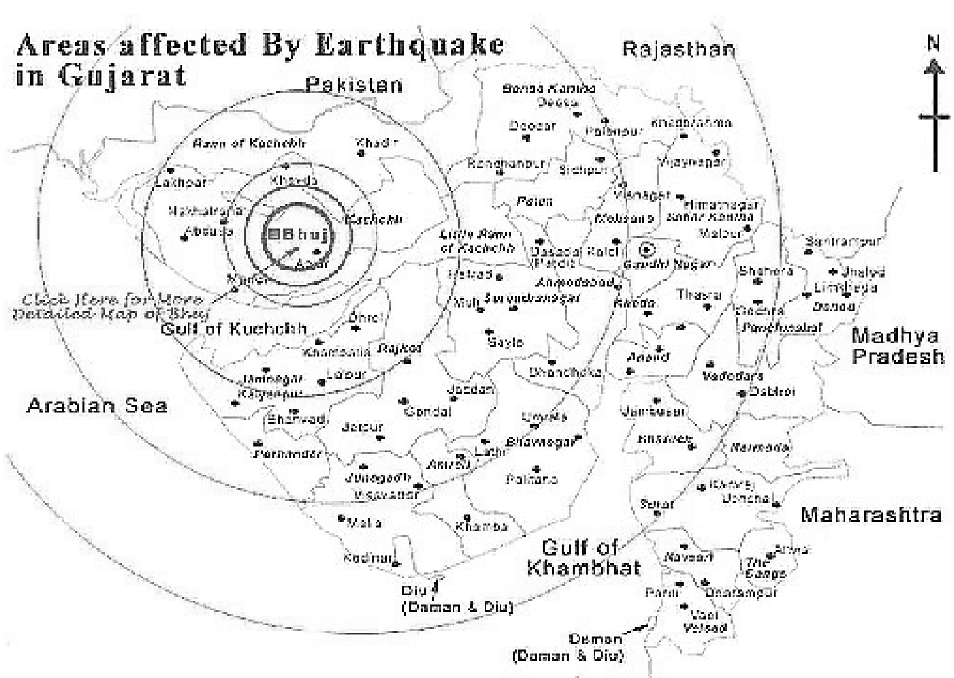
THE BHUJ EARTHQUAKE –26 JANUARY 2001

The Bhuj earthquake in Gujarat, India occurred on the 26 January 2001 and caused massive destruction to property and loss of life. This earthquake had a moment magnitude Mw = 7.9 USGS and struck the Kutch region of India at 8.46am local time, with the shaking lasting for a few minutes. Kutch has a population of about 1.3 million people. Other major cities in Gujarat eg Ahmedabad and Jamnagar, which are hundreds of kilometres away, were also effected by the earthquake.

In Kutch, major towns such as Bhuj (pop 150,000), Anjar (pop 50,000), Bhachau (pop 40,000), and Rapar (pop 25,000) were almost totally destroyed and many villages surrounding these towns were badly damaged. To date over 20,000 persons are reported dead and over 167,000 injured, predominantly from the Kutch region. The reported deaths will increase as towns are cleared, an operation which will take many years.

Most people were killed or badly injured because of:

a) poorly constructed buildings either totally or partially collapsing
b) walls collapsing within narrow streets, burying people escaping into them
c) untied roofs and cantilevers falling onto people
d) free standing high boundary walls, parapets and balconies falling due to the severe shaking
e) gable walls falling over
f) the failure of modern reinforced structures with large open spaces at ground to first floor level, for example garage or shop spaces, collapsing and burying occupants (soft storey collapses)
g) inhabitants not knowing how to respond to the shaking and collapse of walls around them.



1 INTRODUCTION

This Guide is written by UK based Gujariti engineers who are professionally concerned that repairs and strengthening works on low rise domestic buildings damaged by the Bhuj earthquake are not being carried out properly, nor employing some of the Indian and other international standards that describe how non-engineered buildings can be made more earthquake resistant. This Guide is produced to help owners and builders, as well as other interested parties. The Guide is specific to Kutch but may also be relevant to other parts of Gujarat or India where similar forms of materials and construction technology are used.

The authors of this Guide are UK practising structural and geotechnical engineers who wish to help the local community because many Gujartees in the UK originate from the earthquake area and still have close family ties to the region. Other members of the team have international experience in earthquakes that have occurred during the last two decades.

Damage to buildings were caused by a combination of affects:

- Old decaying buildings predating modern construction practices
- New Buildings not being designed to Indian earthquake codes
- Lack of knowledge, understanding or training in the use of these codes by local engineers
- Unawareness that Gujarat is a highly seismic region
- Buildings erected without owners seeking proper engineering advice
- Improper detailing of masonry and reinforced structures
- Poor materials, construction and workmanship used, particularly in commercial buildings
- Alterations and extensions being carried out without proper regard for effects on structure during an earthquake
- Buildings having poor quality foundations or foundations built on poor soils
- Little or no regularity authority administering or policing the codes

Generally, commercial buildings were worst affected by the earthquake because of poor workmanship, use of materials and inadequate attention to detailing.

Low-rise rubble masonry buildings were totally destroyed near to the epicentre, but some survived (though badly damaged) when further away. These were also older forms of construction. Cut-stone masonry and more modern reinforced concrete framed buildings faired much better, although damaged to varying extents. These later building types are largely built by owner-occupiers and hence better care was taken in the materials used and their workmanship. Many lessons can be learnt from those non-engineered low rise buildings which survived.

The vast majority of owner-builders are also the ones who have spent their life savings in constructing their homes, and who wish to ensure their homes are properly repaired to resist a possible future earthquake, but who are unable to always obtain proper advice. This Guide is intended to help those people. These are also the most in need of this advice, as they carry no home insurance.

Even though this Guide provides lots of advice on how to repair and strengthen buildings, each building will respond uniquely in an earthquake, and therefore it is difficult to generalise in a Guide such as this. Therefore, it is important for the property owner to seek professional advice from an experienced structural engineer and builder to check whether repairs can be carried out. Also, any repairs must always consider the safety of the people involved.

Large earthquakes can still cause damage to buildings even if designed to the relevant Indian codes and this Guide. However, the seismic measures taken are intended to absorb damage in a controllable way and save lives. They are not intended to ensure that a building always survives intact. If seismic measures had been taken into account in the design of buildings the loss to life would have been significantly reduced as many buildings would have not collapsed.

2 PURPOSE OF GUIDE

2.1 The Potential End User

This Guide is primarily aimed at the owner-occupier or builder who wishes to carry out proper repairs to his damaged building to improve its safety. At the same time he may wish to carry out strengthening works to make the structure more seismically resistant, in which case this Guide will also assist him. It will also serve as a useful reference document for the local engineer and other interested parties for new low-rise buildings, defined as up to 2 storey structures plus roof.

The illustrations for the repairs and strengthening works to random and cut stone masonry walls and reinforced concrete damaged buildings given in this Guide, have taken information from mainly Indian Standards on design and construction for seismic resistance structures and from many other published papers and textbooks. These structural building types are very common in Kutch, Gujarat. Since there are about six different seismic Indian standards this Guide introduces into one document some of the main repair and strengthening methods. However, a technical reader is recommended that he should also consult these standards. The owner or builder may not have ready access to these standards hence, why this Guide may be a useful source of reference. It does not replace the Indian standards or codes or other regulations in place.

The references used in producing this Guide are given at the end of this booklet.

2.2 What the Guide is not

This Guide does not address repair and strengthening works to:

a) earthen and adobe type buildings
b) wooden structures
c) very weakly bonded or poorly constructed rubble masonry construction which have been severely damaged beyond repair
d) precast concrete and brick buildings.

For these building types, the user is recommended to consult the Indian standards and the IAEE (1986), "Guidance for earthquake resistant non-engineered construction", and to obtain the opinion of a qualified structural engineer.

2.2 History of Earthquakes, Seismology and Geology

Those who are interested in understanding why Kutch and parts of Gujarat are in the worst effected earthquake zones in India, can read Annex 1 of this Guide.

2.3 Structural Performance of buildings during an earthquake

Similarly, a section of the population (eg local engineers) may be interested in the structural response of buildings during an earthquake and this is described in Annex 2 of this Guide.

2.4 Good Practice notes on new build

Some advice is also given to those wishing to build up to 2-3 storey homes to resistance future earthquakes, see Appendix D.

3 TYPES OF OBSERVED DAMAGE IN KUTCH

3.1 Non-Engineered rubble masonry buildings

Many buildings in Kutch of up to 2 storeys in height are made of random rubble masonry construction. The 26 January 2001 earthquake caused massive damage to these buildings. A great many partially or completely collapsed, especially close to the epicentre in Bhuj, Anjar, Bachau and Sukhpur, where the destruction was almost total. Towns and villages that are further from the epicentre of the earthquake were less affected but only in the sense that total collapse was not as widespread. For example, near the villages of Kera or Naranpur buildings of this nature were still standing with sometimes only partial collapse.

During the earthquake, many buildings easily separated at corners and T-junctions resulting in walls overturning and roofs collapsing, which killed thousands of people. This was because the random rubble walls were made of uneven stone and the stones were laid on either weak soil or mortar bedding. Under the heavy seismic shaking, the tensile strength of the mortar (and rubble) was easily exceeded, and walls bulged or totally collapsed.

In addition many of these buildings had timber or heavy stone slab roofs that were not properly tied to the top of the walls and the walls then came apart causing the roof to cave in. The buildings are also poorly founded with stone footings nominally below the ground surface on weak loose soils. This is particularly so across the Bhuj plain as the surface is often covered by an alluvial fan from the surrounding mountains where streams flow during the rainy periods. It is likely that many failed by loss of support from the ground as a result of bearing failure on the loose sands or by excessive settlement.

Even single storey buildings suffered severe damage and/or partial or complete collapse. Figure 3.1 and 3.2 shows some of the failure of these buildings.

As Kutch is in the highest seismic zones, new buildings should not be made from random masonry walls, if affordable, as they are incapable of resisting the severe shaking.

Figure 3.1- Collapse of random masonry building in Manukawa

Figure 3.2 – Partial collapse of gable wall for a single storey random masonry wall in Kera

Figure 3.3 – Heavily damaged single storey rubble masonry wall with concrete roof in Manukawa & Sukhpur.
Note:
Walls survived due to diaphragm action from roof. Cantilever beams embedded in walls also helped this. Note window openings are also not close to corners.

3.2 NON-ENGINEERED CUT-STONE MASONARY WALL BUILDINGS

3.2.1 General

Generally, cut-stone and concrete blockwork buildings are built with more care and attention than rubble masonry structures but again were not seismically designed. Older buildings had timber floors and roof, while newer construction have concrete floors with a flat concrete roof or a clay tiled timber roof. Many were damaged but did not collapse. Damage varied from slight to heavy damage.

The masonry buildings which performed the best, have the following features in common:

- Cut-stones were bedded in cement mortar
- Roofs were properly fixed to the top of the walls.
- Window openings were sensibly sized in relation to the total wall length;
- Buildings were symmetrical with no concentrated masses;
- Many had cross walls at sensible spacing, although it was unclear whether they were adequately tied at T and L junctions;
- Foundations were typically founded at 0.5 to 1.0m depth, probably on firm to medium dense soils or rock.

3.2.2 Old masonry building built with thick cut-stones

An old government building (predating 1900's) made with solid cut stone masonry walls is shown in Figure 3.4. This building received slight to moderate damage although it is in the centre of Bhuj and all around, rubble buildings have totally collapsed. The floors and roof are of timber and an adjacent similar building had cut-stone walls which were at least 0.5m thick. The upper storey wall is seen to be damaged at the edges by bending cracks caused by out-of-plane shear forces. Untied architectural stonework has also fallen off at roof level, as might be expected from severe shaking. The heavy wall units and regular stone blocks prevented collapse of these old buildings.

Figure 3.4 Cut-stone building in Bhuj

3.2.3 Window openings

Figure 3.5 shows a two-storey modern cut-stone wall building near Bhuj, in town called Mirzapur. The building has cut-stone walls about 0.225 to 0.3m thick and has a 1st level concrete floor and a pitched timber roof. The window openings are not close to the edge and are also sensibly spaced. This is probably one of the main reasons why it survived with so little damage. Even so some vertical bending cracking has happened near to the corners, again due to out of plane shear forces.

Many buildings which did not collapse suffered from severe diagonal cracking at their corners, some with partial collapse at corners, primarily because of window openings being too close to the corner and because of lack of toothing between returns.

Figure 3.5 Modern cut-stone masonry building in Mirzapur

3.2.4 Peripheral seismic bands or ties

Seismic bands or ties greatly increase the strength of buildings in earthquakes. The railway lookout building in Figure 3.6 is made with random masonry, is well-constructed and is bonded with cement mortar and suffered very little damage. What sets this building apart from others that collapsed nearby, is that it has been designed with strong reinforced concrete seismic bands at lintel and cill level, which completely tie the four walls. There is also a flat concrete roof. The seismic shear force is resisted by the lintel and cill bands, and has clearly strengthened the building against repeated shaking from an earthquake which would make lesser buildings collapse.

Figure 3.6: Strengthening of buildings by use of seismic bands

3.2.5 Typical foundations of masonry buildings

In villages radiating to the southwest and southeast of Bhuj, Kutch, many masonry cut-stone buildings have the following foundation details:

(1) Stepped walls which rise from a weakly cemented broken rock filled trench strip; or
(2) Walls that are cast off a concrete strip footing, lightly reinforced.

The foundations of newer type buildings are typically about 0.5 to 1.0m depths below ground.

Where the inland soils are sedimentary sands and rock little or no damage to these foundations were observed as the ground conditions were good. However, towards Anjar and to the coastal regions of Kutch or the lower areas of the Rann, for instance, many buildings failed because they were founded on soft clay or loose sand which was saturated by groundwater. Many buildings failed when the ground liquefied, the loose water-filled sands turning to a quicksand during the earthquake.

3.3 NON-ENGINEERED REINFORCED CONCRETE BUILDINGS

3.3.1 General

In the last 10 to 15 years reinforced concrete frame structures have become a common construction feature of domestic buildings in Kutch. These are usually frames of concrete column and slab construction with either a flat concrete roof or a pitched timber roof to keep the interior of the building cool in the summer. They are usually up to 2 to 3 storeys in height. These buildings were designed to support the vertical weight of the structure. The majority were damaged in the earthquake because they were not designed to resist horizontal forces caused by seismic loading.

Often, the owner retained an local architect and sometimes a local structural engineer's practice to design the building. Even so, no buildings were designed for seismic shaking. If it were not for buildings having "non-structural" infill wall panels many more buildings might have experienced total collapse. Seismic shear force and deformations would have been concentrated at the column heads, causing soft storey failures as occurred in many multi-storey structures with large openings at ground level.

3.3.2 Building Configuration and Soft Storey Collapse

Some domestic reinforced concrete buildings had large internal openings or unsymmetrical masses at first or ground floor level. This caused severe structural damage and even collapse. Figure 3.7a shows a building, which collapsed because part of the floor area was converted to an opening for car parking. The building was subjected to torsion about its centre of rigidity and failed because of soft storey behaviour with large deformations and rotations concentrated at the top of the columns (Fig 3.7b).

Fig 3.7b The inset shows large deformations were concentrated at column heads, which caused many soft storey failures, as per picture. Buildings if designed with uniform deflections as per left diagram of insert would have survived without collapse.

Figure 3.7a – Typical soft storey and torsion collapse in Bhuj

Figure 3.8 shows a building where the owner had a middle floor supported on columns with large internal open spaces, and hardly any masonry infill walls. Under seismic loading, large deformations occurred at the top and bottom of the columns and a soft storey collapse occurred, the upper floor storey falling onto the first storey. This shows that soft storey collapses do not always occur at ground floor.

Figure 3.8 – Soft storey second floor collapse in Sukhpur

3.3.3 Non-Engineered infill walls acting as shear walls

Many buildings were prevented from collapse by the presence of "non-structural" infill wall panels which acted as **shear walls** despite not being designed for this purpose. No buildings were designed as moment resisting concrete frames to resist cyclic shear and bending moments at column and beam connections.

The infill walls were mainly made of cut-stone masonry or concrete block. Reinforced concrete walls were not used. Buildings survived collapse because these infill walls took the brunt of the lateral shaking. They were most effective when the construction procedure involved a high degree of bonding between the wall and column. This was often achieved during the construction, by building the walls up to first floor level leaving a gap at column positions, then casting the columns using the walls as shutters. Minimum wall sizes were about 220mm thick for blockwork.

Figure 3.9 shows the effectiveness of shear walls in preventing an RC framed building from collapse. This building experienced severe shaking causing moderate to heavy damage to the infill panels, but this prevented column failure. Many infill panels in these types of buildings will need to be restored following the earthquake. It should be noted that this wall was effective despite being compromised by the presence of a door opening.

Figure 3.9 Infill panels to an reinforced concrete frame building acting as non-structural shear walls, provided stability to the overall frame – Bharasar

Figure 3.10 Infill panels again prevented collapse of this structure although all the roof tiles fell off - Mirzapur.

3.3.4 Window openings in infill panels

Large window and door openings severely undermined the ability of infill panels to act as non-structural shear walls. These openings were placed too close to the corner columns of the building. Lintels were placed over the openings but did not extend over the length of the wall as is recommended for seismic design. Consequently, wall panels experienced diagonal shear cracking which extended from the openings to the top and bottom of the solid walls, sometimes causing diagonal cracking of columns when no resistance was afforded by the wall, see Annex 2.

Generally, the greatest damage occurred at ground floor level. Upper storeys survived with surprising little damage (slight).

Sometimes older RC buildings, modernised by adding an extra floor, suffered greater damage as columns were not properly connected to the original concrete frame and the structural mass was altered by adding this floor.

3.3.5 Crushing of column head and bases

When masonry infill walls were ineffective because of large openings, column heads were subjected to large vertical and lateral seismic forces. The heavy eccentric compressive stresses crushed column heads and large shear deformations caused concrete to spall away from the main bars because of links being to far apart. The extent of damage to the column heads often depended on how well the infill wall panels were bonded to the columns. Figures 3.11 and 3.12 give examples of this.

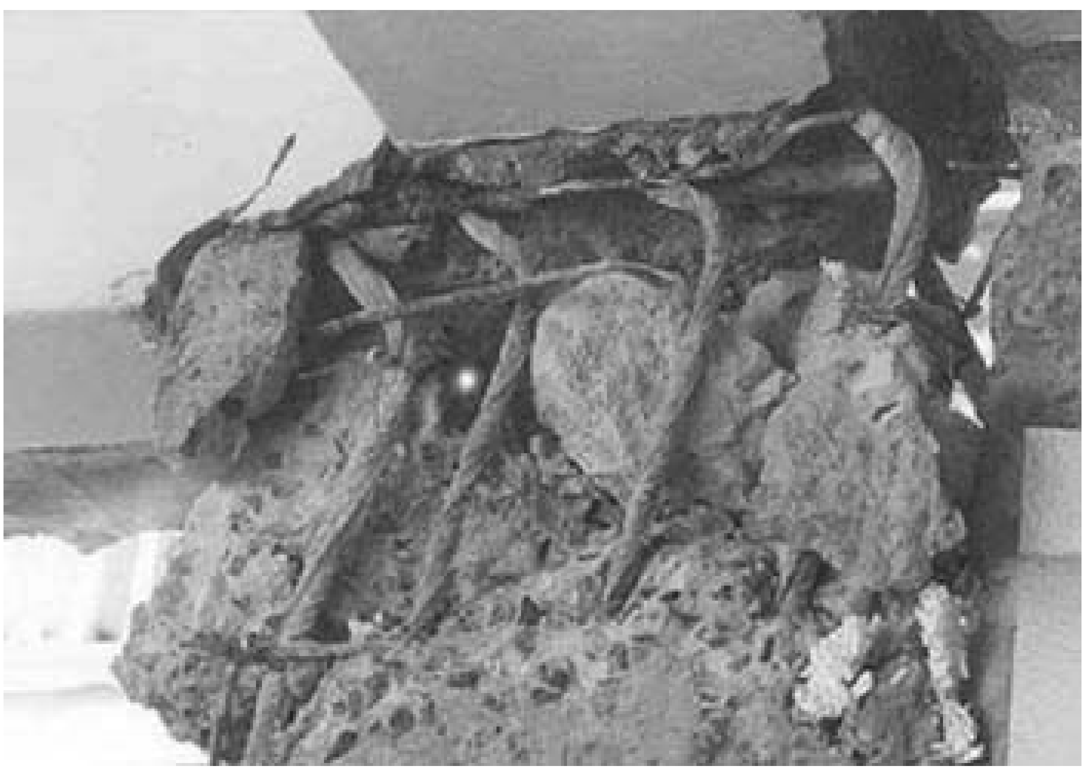


Figure 3.11: Heavy compressive stresses with large deformations causing total destruction of column head with heavily bent main bars. Concrete not contained by links because they were to far apart.

Figure 3.12 A column that survived with minimal distortion as infill walls performed well and repairs being carried out to damaged column head showing minimal distortion to main bars (right)

Some common problems, which resulted in severe damage to the column heads or bases, were from poor detailing as follows:

(1) Drain pipes and other services placed inside columns, caused severe weakening of the columns making it less resistant to lateral loading;

(2) Shear link spacing was too large (typically 200-300mm), thus not providing adequate confinement to the main bars, causing concrete to fall out;

(3) Links were not bent backwards into the columns so they easily separated, again letting concrete out of the main bars;

(4) Very small links (6mm diameter) were used;

(5) Main bars were not bent back into the floor or ground beams so that reversal of shear loads could not be resisted by the beam and column connections. Many failures occurred at beam/column junctions, see Figure 3.13.

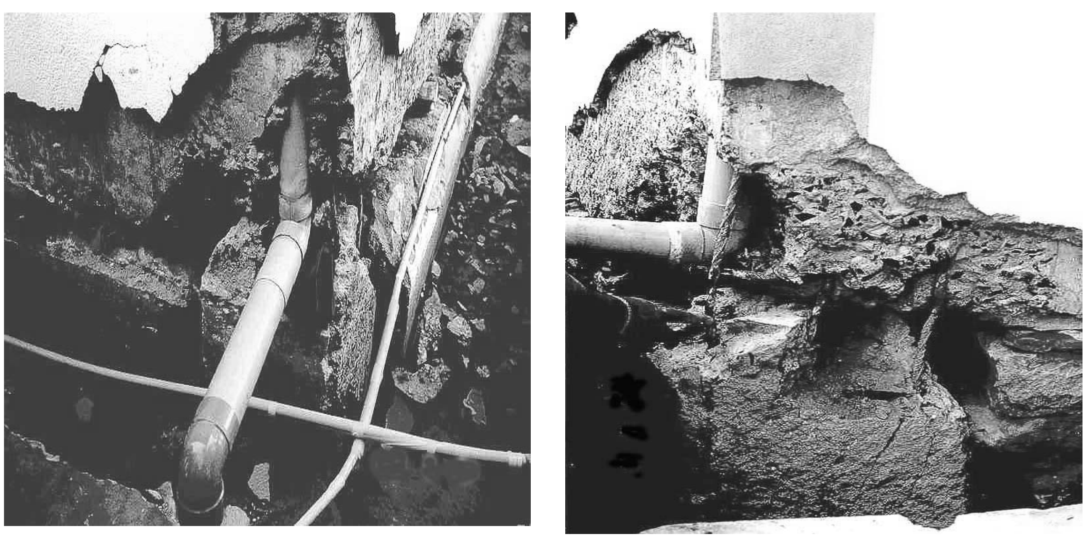


Figure 3.13: Separation of ground beam and column junctions caused by concrete crushing in Sukhpur. Damage made worse by the weakening presence of a plastic pipe within the column.

3.3.6 Roof failures

Damage to flat roofs was rare. However, pitched roofs often experienced non-structural damage by tiles falling through open space between the timber battens as no tiles were nailed into the timbers. Many tiles were manufactured with no holes to allow them to be nailed to the roof.

3.3.7 Canopy structures

Several modern buildings had a single storey canopy with a flat roof supported by columns at one end and beams running into the main structural frame at the other end. These suffered varying degrees of damage depending on how slim the columns were, see Fig 3.14.

Beam Fracture Snapped Column

Fig 3.14 Collapse of a canopy structure due to column failure

3.3.8 Underground water tanks and storage containers at roof level

Many modern buildings have large concrete water tanks with bases about 2 to 3m depth below ground. This stores the water, which is regularly pumped to much smaller header tanks at roof level. The tanks appeared to survive the earthquake with little or no damage. However, tanks lined with masonry walls are said to be damaged.

Smaller storage containers built on top of the roofs were either located directly on flat roofs or on short columns. These either slid along the roof breaking water pipes or sometimes toppled over when the short columns fractured. There was no evidence that the smaller header tanks were responsible for structural failure of 2 storey domestic houses.

Figure 3.15 Flat roofs with small water storage containers - Madhapur

3.3.9 Typical foundations of reinforced concrete frame buildings

Typically foundations for these structures are pad footings founded at 1 to 2m below ground. The footings are not usually tied but often have a ground beam located just below plinth level. In the area around Bhuj the footings are founded on weakly cemented sandstone layers, medium dense sand or rock. The infill masonry walls below ground are generally built off a shallower depth coming up to the underside of a ground beam. Walls are then continued above the ground beam.

Few failures of foundations were observed outside areas of liquefiable soils. When failure occurred at column and ground beam junctions, infill walls also failed. Structures with this mode of failure will need temporary foundations to support the main structure before carrying out permanent repairs.

There were however many examples of poor detailing to columns, ground beams and foundations. Figure 3.16 show one example of poor detailing of column to base, with typical link spacings over 250mm to a very slender column.

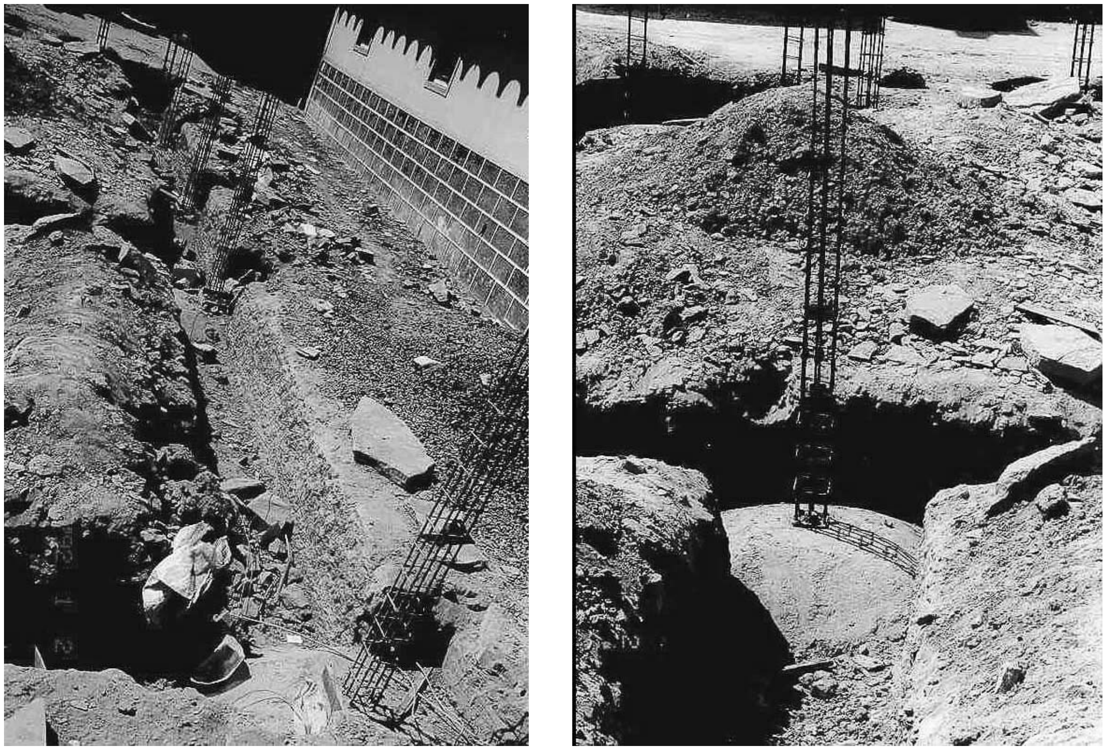


Figure 3.16 Poor reinforcement detailing for an Reinforced Concrete frame building about to be constructed in Sukhpur

3.3.10 Example of a 3-Storey reinforced concrete frame structure, which is severely damaged in Kundanpur (near Kera) Kutch

An example of a recently completed reinforced concrete frame building with blockwork masonry infill walls which was severely damage, caused by a catalogue of poor design practices is described below (see also Figures 3.17 to 3.21). The owner of this property had retained the service of a local engineer to design his building.

a) **Poor building configuration (resulting in torsion during earthquakes).** The ground floor plan was asymmetrical (L-shaped internally) relative to the floors above. As a result, the whole building at ground floor level has twisted clockwise under the heavy mass from the floors above. Severe damage has occurred to the walls and columns at ground floor level, see Figure 3.17. The reason for the L shape plan at ground level was because the owner wanted a large open plan living room area.

b) **Discontinuous columns.** Figure 3.18 shows that the external columns along the wall are not continuous with the columns at first floor level and above. Only the corner columns are continuous through all the floors. This was a building where the owner decided during construction that the engineer had not allowed enough columns and he decided to place a few more between the walls. Unfortunately, they were placed randomly along the walls as shown.

c) **Large window openings.** Figure 3.18 also shows that the window openings between columns are large, exceeding the limit of 33% of total wall length as advised by the Indian codes for a three storey plus roof structure. The ability of the masonry blockwork walls to resist shear is thus diminished due to lack of continuity. Diagonal cracking has occurred through the masonry wall and columns. Other photos show that the bond between the columns and walls was very good because the walls were erected first and then columns cast afterwards, the walls being used as shutters. This probably prevented collapse of the building even though the columns were damaged.

d) **Short column failures.** Short column failure (diagonal cracking) can be seen to have occurred over the mid height of all the external concrete columns (these were 225mm square) and through the masonry columns. This is because when infill walls with wide openings are attached to columns, the portion of column that will deform under lateral seismic loading becomes very short compared to its normal height. Such short columns become much stiffer and attract much larger shear forces resulting in severe diagonal tension and cracking failure in the columns. This failure is plainly seen in Figs 3.19 and 3.20. The problem was magnified because plastic service conduits ran inside some of the corner columns and walls, reducing the column stiffness.

Under the action of the seismic shear and torsional effects, the damage to this building was largely concentrated at ground floor level with upper floors remaining intact and undamaged. The first floor concrete slab and beams were undamaged by the earthquake.

The foundation plans show walls were on concrete strip foundations, 0.75m wide, founded at a depth of 0.9m below ground. The external canopy columns were on 1.2m square pad foundations located at the same depth. The building was founded on a mixture of weak weathered sandstone rock at one end and medium dense to dense sand at the other end. The owner stated that the foundations had not failed. Photos and videos examined by the authors confirmed this was correct. There was no evidence of the structure experiencing significant total and differential settlement.

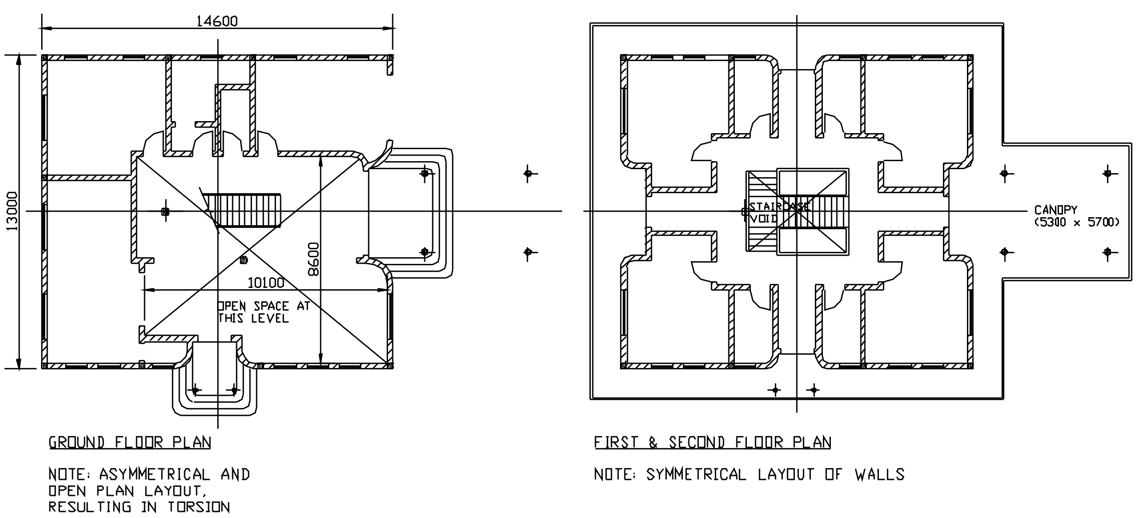


Figure 3. 17 Floor plans

Figure 3.18 Building under construction one year prior to earthquake

Figure 3.19 Damage to completed building after earthquake

Figure 3.20 Large window openings close to corners and short column failures

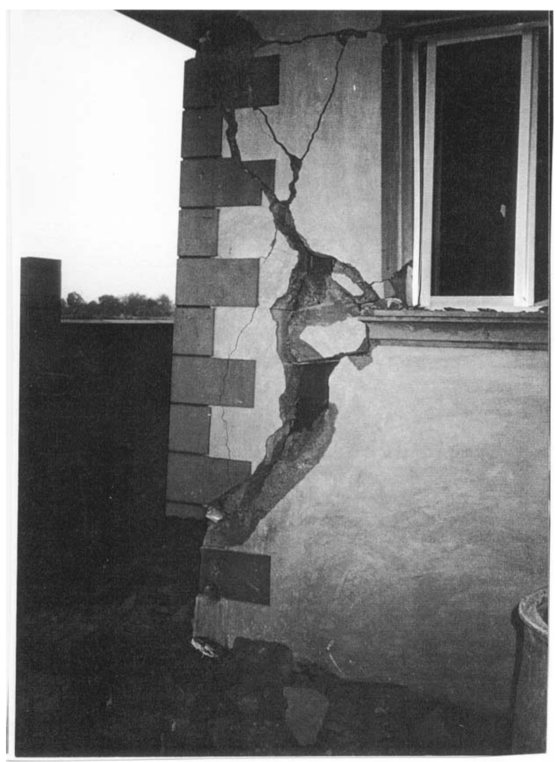


Figure 3.21 Diagonal cracking at corner column caused by twisting of frame and short column failure.

4 REPAIRS AND STRENGTHENING GUIDE

The authors suggest that Government and other local relief organisations provide grants as an incentive for the public to adopt earthquake resistant repairs and strengthening of damaged buildings and properly constructed new build. There is a genuine lack of awareness and necessary skills for improved construction. This Guide is intended to help in this process. It should also be noted that there are also excellent Indian codes/standards and the IAEE (1986): Guidelines for earthquake resistant non-engineered construction, should also be consulted. These should be on the reference shelves of all libraries and consulting practices in Gujarat.

We have tried to take the best from these codes and guidelines and to tune the repair and strengthening works to the more common types of 2 storey buildings, which apply to Kutch.

4.1 Definitions

Repairs – *actions taken to damaged buildings, which are intended to restore the structural strength lost in an earthquake, to the original level.* Such structural repairs involve actions such as rebuilding of cracked wall elements, stitching of walls across cracks by using steel reinforcement on wall faces and covered by cement mortar, or grouting of cracks using cement or epoxy like adhesive materials which are stronger than mortar and have tensile capacity. Non-structural repairs would also be included in this category.

Seismic Strengthening (retrofitting) – *actions taken to upgrade the seismic resistance of an existing building so that it becomes safer under future earthquakes.* This can be in the form of providing seismic bands, eliminating sources of weakness or concentrations of large mass and openings in walls, adding shear walls or strong column points in walls, bracing roofs and floors to be able to act as horizontal diaphragms, adequately connecting roofs to walls and columns and also connecting between walls and foundations.

4.2 Cost of seismic protection

It is much cheaper to design a building for earthquake resistance in the first place than to carry out repairs and strengthening works. Studies have shown that a building designed for seismic resistance is about 10% more expensive than one without. However, repairs to a non-engineered building may involve as much as 2 to 3 times the initial cost of introducing seismic features into a building. If repairs and strengthening has to be carried out, this could even be 4 to 8 times as expensive (Arya, 2000).

4.3 Assessment of building damage before carrying out repairs or strengthening

Before commencing any repairs it is important to

- Determine the materials which have been used in the damaged building
- Carry out a detailed foundation check;
- Carry out a detailed structural assessment of the damaged building with particular attention to vulnerable elements of the structure.

This should be assessed by a qualified structural engineer. It should be noted that both non-structural and structural repairs might be required to a building. The priority repairs should be to the structural components before embarking on any non- structural repairs (cracked slabs, falling plaster from walls and ceilings, rebuilding of parapets etc).

There is absolutely no point carrying out repairs to a building if the foundations have failed or the ground can no longer support the damaged building. Repairs to damaged foundations can be costly and difficult to instigate and hence a fine line may exist between demolishing the building or continuing with the repair.

Earthquakes may also cause failure of soft or loose ground whilst hillsides or sloping ground may become unstable. Whole towns and villages may be affected and although a building may appear safe for repair, near the foot of the slope or on it, further slope failures could be triggered by relatively small aftershocks or another future earthquake. Buildings in such terrain will require specialist advice of the stability of the whole area. No repairs to buildings should take place until this advice has been obtained. Elsewhere in the World, it should be noted that whole towns have had to be relocated to a stable area after an earthquake before a rebuilding programme can start.

The Building Damage Assessment Form and classification of damage (to recognised standards) is given in Appendix E. This is intended to provide more details in assessing damage to buildings.

4.4 Building types requiring repairs and strengthening

Illustrations showing how repairs and strengthening works should be carried out is given in various appendices listed below:

1) Appendix A - Repairs to random (rubble) masonry buildings
2) Appendix B - Repairs to masonry cut stone buildings
3) Appendix C - Repairs to reinforced concrete framed buildings

In some of the appendices a number of options are presented. Choice of repair method will depend on ease of repair, physical constraints and degree of damage.

The figures enclosed in the appendices are intended for use as follows:

- The owner-builder can identify a particular repair type and use the figure to suit his repair.
- In certain cases the repair types are accompanied with good practice notes for use with the figure(s).

Where the required repair is difficult to decide, the relevant Indian standards on design and construction practice should always be used with professional advice being sought from a structural engineer.

4.5 Guidance notes for new buildings

Although this Guide concentrates on providing good repairs and strengthening works to non-engineered structures, it was considered that some guidance may be useful on new buildings. For this purpose, Appendix E: Table E1 provides some useful tips for the design and construction of cut-stone or blockwork masonry stone buildings no higher than 2 storey plus roof. Similarly, Table E2 provides a note for reinforced concrete buildings of the same height.

However, all new buildings must be designed by a structural engineer, with knowledge of earthquake resistance design to the relevant Indian and/or American UBC: 1988 codes.

4.6 Some guidance on allowable bearing pressures for shallow foundations

Guidance on this is given in Annex 3 attached.

5 ACKNOWLEDGEMENTS

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