Performance of buildings during the 2001 Bhuj earthquake

Jag Mohan Humar, David Lau, and Jean-Robert Pierre

Abstract: The performance of buildings during the January 26, 2001, earthquake in the Kachchh region of the province of Gujarat in India is discussed. A majority of the buildings in the earthquake region were either of load-bearing masonry or reinforced concrete framed structure. Most of the masonry buildings were built with random or coursed stone walls without any reinforcement and heavy clay tile roofing supported on wooden logs. A large number of such buildings collapsed leading to widespread destruction and loss of life. Many reinforced concrete frame buildings had infill masonry walls except in the first storey, which was reserved for parking. As would be expected, the open first storey suffered severe damage or collapsed. Observations of failures confirmed the vulnerability of some structural details that are known to lead to distress. However, an important observation to come out of the earthquake was that masonry infills, even when not tied to the surrounding frame, could save the building from collapse, provided such infills are uniformly distributed throughout the height so that abrupt changes in stiffness and strength did not occur.

Key words: Bhuj earthquake, 2001; seismology of Kachchh; earthquake damage survey; performance of buildings; load bearing masonry; reinforced concrete frames; structural details vulnerable to earthquakes.

Résumé : La performance des bâtiments durant le séisme qui a touché la région de Kachchh dans la province de Gujurat en Inde le 26 janvier 2001 est examinée. Une grande part des bâtiments présents dans la région du séisme étaient, soit des structures de maçonnerie portante soit des cadres en béton armé. La majorité des bâtiments de maçonnerie étaient faits de murs en pierre disposée de façon aléatoire ou en rangée, sans armature ainsi que d'une lourde toiture en tuiles d'argile supportée par des rondins de bois. Un grand nombre de ces bâtiments se sont effondrés menant à d'importantes destructions et pertes de vie. De nombreux cadres en béton armé avaient des murs de remplissage de maçonnerie à l'exception du premier étage, réservé au stationnement. Comme il fallait s'y attendre, le premier étage à aire ouverte a souffert de sévères dommages ou s'est effondré. L'observation des ruptures a confirmé la vulnérabilité de certains détails structuraux connus pour mener à l'échec. Cependant, une observation importante émergeant du séisme était que les murs de maçonnerie de remplissage, même non ancrés au cadre, pouvaient empêcher le bâtiment de s'effondrer, à condition que de tels murs soient uniformément répartis à travers le bâtiment afin d'éviter des changements abrupts de rigidité et de force.

Mots clés : séisme de Bhuj (2001), sismologie de Kachchh, expertise des dégâts suite à un séisme, performance des bâtiments, maçonnerie portante, cadres en béton armé, détails structuraux vulnérables aux tremblements de terre.

[Traduit par la Rédaction]

Introduction

The province of Gujarat is located on the west coast of India. It is a comparatively prosperous part of the country with a strong base of steel, power, chemical, and petroleum industry. A powerful earthquake struck the Kachchh region of the province of Gujarat at 8:46 a.m. on the 26th of January 2001. The United States Geological Survey placed the moment magnitude of the earthquake at M_w 7.7. The epicenter of the earthquake was located at 50 km northeast of the town of Bhuj (Fig. 1). The earthquake was felt over a large part of the country, and as far away as Nepal, Delhi, Calcutta (1900 km to the east), Bombay (590 km), and Chennai (1500 km).

The greatest damage due to the earthquake occurred in the region of Kachchh, which is spread over an area of 45 930 km^2 and covers about 22% of the area of Gujarat State. Of the total of 884 villages located in this region, 518 suffered significant damage, 178 were completely destroyed, and another 165 damaged to the extent of 70% or more (Principal Secretary 2001). Several cities and towns in Kachchh, including Bhuj, Bhachau, Rapar, Anjar, and Gandhidham, experienced extensive destruction. The earthquake caused serious damage in other parts of the state as well, including in the cities of Ahmedabad (a straight line

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J. Humar[1] and D. Lau. Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada.
J.-R. Pierre. Direction Expertise et support technique de transport, TransÉnergie, Hydro-Québec, 800, boulevard de Maisonneuve est, 19th floor, Montreal, QC H2L 4M8, Canada.

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[1]Corresponding author (e-mail: jhumar@ccs.carleton.ca).

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Fig. 1. Area near the epicenter of the Bhuj earthquake.

distance of approximately 300 km east of Bhuj), Jamnagar (~100 km south-southeast of Bhuj), Rajkot ~160 km south-east), Surendranagar (~200 km east-southeast), Surat (~390 km southeast), and Patan (~260 km east-northeast).

At the end of March the official estimate of casualties was 20 000. The number of injured is reported to be 166 000, of which 20 700 suffered serious injury. It is estimated that about 370 000 houses and huts were completely destroyed, while another 931 000 were partially destroyed. The total financial loss is estimated at Rs. 21 300 crores (approximately Can$7.1 billion) (Department of Agriculture 2001).

The authors of this paper visited the area affected by the earthquake from 11 March 2001 to 18 March 2001. Because of limitation on time and the size of the team, it was not possible to survey all aspects of the earthquake event and the damage caused by it. The team therefore concentrated its efforts on a survey of the damage caused to buildings and lifeline structures, and to some extent of the ground movement. The results of the survey on the performance of buildings are presented in this paper. For the sake of completeness, and to provide a background to the observations made by the authors, brief references are made to the survey data available from other sources.

Seismological aspects and tectonic setting

The region of Kachchh is a seismically active region lying in the western continental margin of the Indian subcontinent. It can be viewed as a transition zone between the stable continental region of peninsular India on the south and active plate margins on the north and east. Along the northern plate boundary the Indo-Australian plate is pushing against the Eurasian plate (Fig. 2). The boundary between the Arabian plate and the Indo-Australian plate lies to the east. The epicenter of the January 26 earthquake is located at a distance of about 400 km from the junction of the three plates.

The Kachchh region is traversed by a number of east–west tending faults, including the Katrol Hill fault, Kachchh Mainland fault, Banni fault, Island Belt fault, and the Allah Bund fault (Fig. 3). Historically, a number of earthquakes of varying magnitudes have occurred along or in the vicinity of these faults (Malik et al. 2000). The largest of these was the earthquake of June 16, 1819, having a moment magnitude M_w 7.8. That earthquake caused the formation of an east–west alluvial scarp, about 90 km long and 9 m high. It dipped quite steeply on its south face, but more gently along the north face. The scarp blocked the southeast flowing tributary of Indus known as Nara and was given the name Allah Bund, or the Dam of the God, by the local people. The Allah Bund earthquake took place in a sparsely populated region and caused the death of between 1500 and 2000 people. The other large earthquake in the Kachchh region occurred in 1956. This earthquake, known as the Anjar earthquake, had a moment magnitude M_w 6.1, and its epicenter was located along the Katrol Hill fault.

Several teams of geologists and seismologists from U.S.A., India, and Japan have visited the epicentral region after the January 26 earthquake and have carried out both aerial and field reconnaissance surveys. There is some difference of opinion about whether or not the earthquake caused surface fault rupture. A team from U.S. Earthquake Engineering Research Institute (EERI) first noticed the presence of a 16 km long and about 0.5 km wide zone of ground deformation tending east-northeast immediately north of the Kachchh Mainland fault (EERI 2001). It was accompanied by extensive sand boils. Other teams, including one from U.S. National Science Foundation and another from Japan, reported evidence of a possible fault rupture or a slump east of the zone of ground deformation observed by the EERI team. It is now believed that the ground deformations observed by the different teams were all caused by lateral spreading and liquefaction rather than by surface faulting.

On the basis of evidence collected so far, the geologists believe that the Bhuj earthquake originated from an east–west tending blind thrust fault at a focal depth of about 20 km. The fault strike was in the direction N60°E and the fault plane dipped about 60° to 70°S (EERI 2001). The fault rupture did not propagate to the surface.

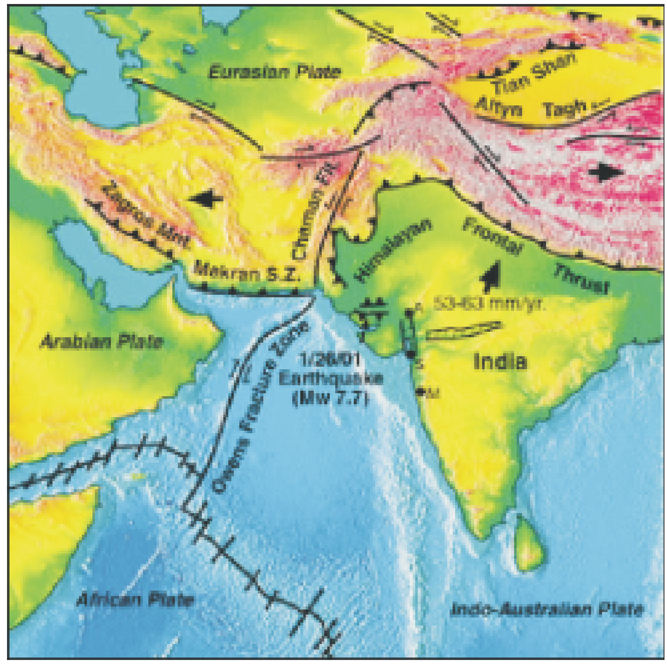
Unfortunately, no strong ground motion instruments were located in the region affected by the earthquake. A broad-band station located in Bhuj was evidently functioning. We were, however, unable to obtain a record. Acceleration measurements were recorded by instruments located at the ground and several upper floors of the Passport building in Ahmedabad and maintained by the University of Roorkee, Roorkee, India. The maximum acceleration recorded at the ground level was 0.11*g*.

Indian loading codes and design standards

In India the responsibility for developing national standards for loading and design lies with the Bureau of Indian Standards, formerly known as the Indian Standards Institution. The provisions related to earthquake loads are contained in Indian Standard IS: 1893–1984 “Criteria for earthquake resistant design of structures.” This standard defines the general principles of design and the design criteria, the seismic zones, and the methods to be used for the design of buildings. Two different methods are specified: the seismic coefficient method, which is similar to the equivalent static load method of the National Building Code of Canada (NBCC), and the response spectrum method. The standard also specifies the seismic coefficients and the response spectra applicable for the different seismic zones. As in NBCC, the design base shear obtained from the seismic coefficients or the response spectra is modified by an importance factor, a foundation factor, and a factor related to the ductility of the structural system. Empirical expressions are provided for determining the approximate period and for the distribution of base shear across the height for use with the seismic coefficient method. The standard contains special provisions for the design of elevated tanks, stacks, bridges, dams and embankments, and retaining walls.

In accordance with IS: 1893–1984, India is divided into five seismic zones: Zone I to Zone V, the last one being the most severe (Fig. 4). Recently, zones I and II have been merged into one for the purpose of design. The area around Bhuj is recognized as being an active seismic zone and is placed in Zone V. Ahmedabad, the major urban center of Gujarat, lies in Zone III. A ten-storey residential or office building with a structural system consisting of ductile moment-resisting frame and located in Zone V would be designed for a base shear equal to 4.25% of the total dead load and 25% of the live load when working stress method of design is used. For limit states design, the load factor to be applied to the earthquake loads when combined with dead load and live load ranges from 1.2 to 1.3. It may be noted that in this combination the live load is the same as that used for determining the earthquake forces. The design base shear for Zone III is half of that for Zone V.

Fig. 2. Plate boundaries in the vicinity of the epicenter of the Bhuj earthquake (from EERI Web site).



The loading standard is supplemented by a special code designated Indian Standard IS 4326: 1993 “Earthquake resistant design and construction of buildings — code of practice.” This code contains recommendations on building configuration, separation of adjoining structures, foundation ties, reinforcing bands for otherwise unreinforced masonry buildings, restrictions on the openings in bearing walls in masonry buildings, and good practice for timber construction. The design of reinforced concrete structures is governed by IS 456: 2000 “Plain and reinforced concrete — code of practice.” However, a separate code exists for ductile detailing of reinforced concrete structures, namely IS 13920: 1993 “Ductile detailing of reinforced concrete structures subjected to seismic forces — code of practice.”

Evidently, India has a comprehensive set of codes and standards governing earthquake resistant design of structures, and these codes are based on the most recent knowledge of behaviour under seismic loads. The practice specified in these codes is comparable to that followed in Canada and United States. Indian codes are, however, not mandatory, just advisory. As will be shown later, design of most structures in Gujarat does not comply with the seismic design requirements specified in the Indian standards.

Construction practice related to building structures

A majority of building structures in Gujarat can be divided into the following two broad categories: (*i*) load bearing masonry and (*ii*) reinforced concrete frames with unreinforced masonry infill walls.

Load bearing masonry

A majority of buildings in the Kachchh region are built in unreinforced load bearing masonry. A large number of such buildings also exist in areas outside Kachchh, including in

Fig. 3. Fault lines running across the Kachchh region (Malik et al. 2000).

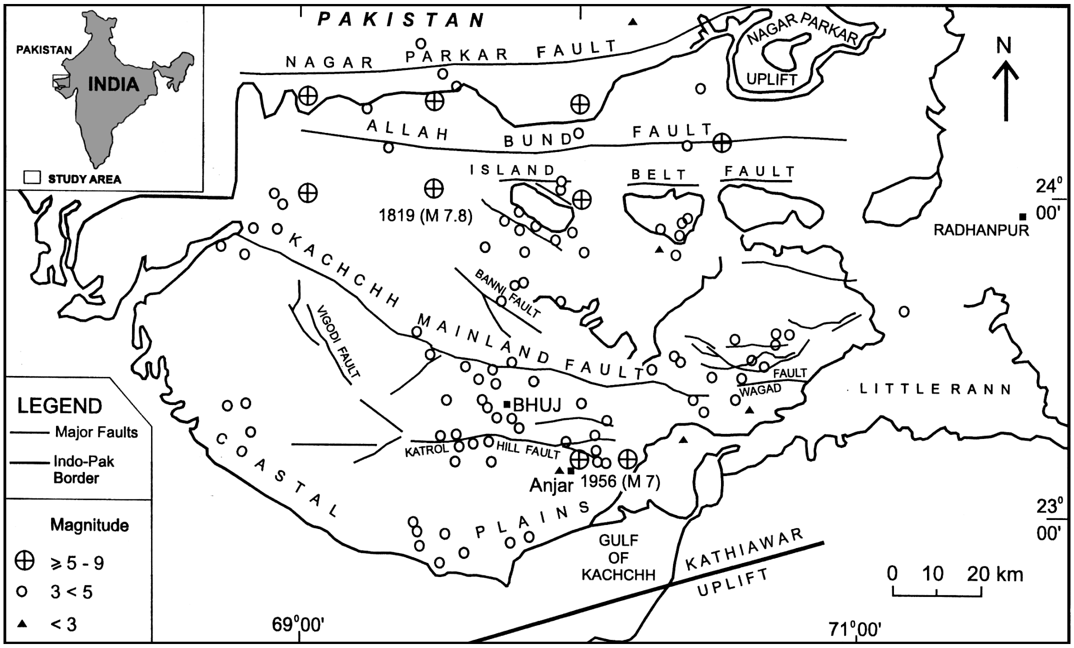
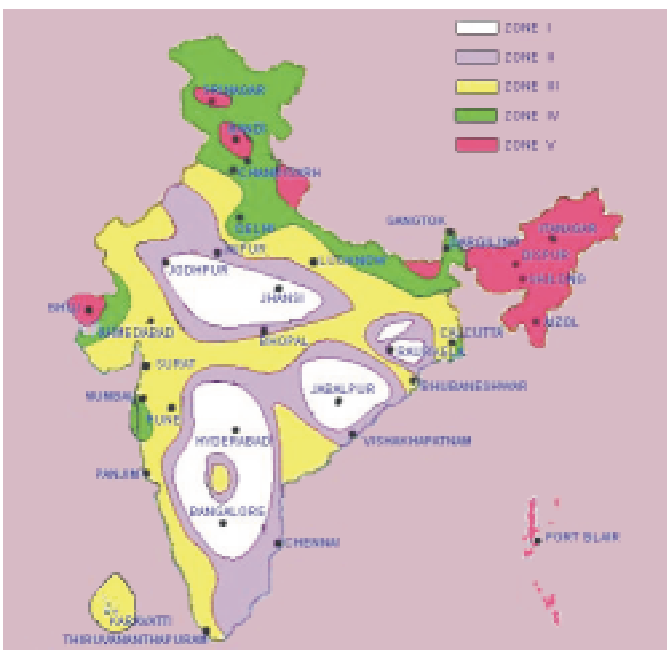


Fig. 4. Seismic zoning map of India (source: Indian Meteorological Department).



urban centers such as Ahmedabad. The types of masonry units used include (*i*) random rubble stones, (*ii*) rough dressed stones, (*iii*) clay bricks, and (*iv*) solid or hollow concrete blocks. The units are assembled with mud mortar, lime mortar, or cement mortar. The stone blocks used in load bearing masonry are generally quite large, the commonly used dimensions being 400 mm by 600 mm by 225 mm thick. The roof structure consists of either Manglore clay tiles laid on timber planks supported by purlins and rafters made from wooden logs or a reinforced concrete slab. When the building has more than one storey, the floors and roofs are generally reinforced concrete slabs.

Reinforced concrete frames

In most cases buildings taller than three storeys have a structure that consists of reinforced concrete frames with unreinforced masonry infill. The masonry infill may consist of stone blocks, clay brick, or solid or hollow concrete blocks, generally set in cement mortar. The concrete used for the construction of frames is site mixed using mechanical mixers. The batching is usually by volume. The commonly used mix volumes are 1 part Portland cement, 2 parts fine aggregate, and 4 parts coarse aggregate. Richer concrete will have a volume proportion of 1:1½:3. The specified 28-day cube strength is either 15 or 20 MPa. Concrete is vibrated by means of needle vibrators, although in many cases manual tamping may be used. The main reinforcing steel consists of twisted steel bars, known as Torsteel, having a yield strength of 415 MPa. Some older buildings may have plain reinforcing bars. The stirrups and hoops are generally either 6 or 8 mm plain steel bars.

The reinforced concrete columns in framed buildings are generally rectangular in shape with the smaller dimension being 225 mm. This is useful in accommodating a 225 mm masonry infill. The larger dimension may be 300, 375, 525, or 600 mm, depending on the number of storeys supported. A large number of framed buildings provide an open first storey for parking or retail shops. In upper storeys the perimeter frames have unreinforced masonry infills, built tight with the frame members, but not positively attached to them.

The local building regulations require that in every multistorey apartment building, parking should be provided at the ground floor. To comply with this regulation the builders provide an open storey at the ground, supported by the same set of columns as used in the upper storeys, but without the infill walls. As will be observed later, the soft storey created by such a framing proved to be highly vulnerable during the earthquake.

In a majority of buildings, including buildings up to 10 and 12 storeys high, the reinforced concrete columns are

Fig. 5. A village house in Kachchh; stone masonry with Manglore tile roof.

Fig. 6. Destruction of heavy stone masonry walls that had no reinforcement and were not tied to each other.

supported on isolated spread footings. The footings are located at some depth below the ground level to go past the fill material on the top. In general, no geotechnical investigation is carried out, and the quality of foundation soil is judged on the basis of visual inspection. Foundation ties are not provided.

Performance of load bearing masonry buildings

Load bearing masonry buildings in Ahmedabad performed quite well, but for minor damage in some cases. As noted earlier, Ahmedabad is about 300 km away from the epicenter and the ground shaking in the area was not very intense.

The performance of masonry buildings in the Kachchh region was very poor. No reinforcement had been provided in any of the buildings. The walls were not tied to each other or to the floors and roofs. Most buildings used large-size, heavy stone blocks, either undressed or rough dressed. The roof construction of wooden logs and Manglore tiles was very heavy. All of these factors made the buildings very vulnerable to damage during earthquake, leading to widespread destruction. As would be expected, the worst performance was that of random rubble construction in mud mortar. In

Fig. 7. Virtually complete destruction of masonry buildings in a village in Kachchh.

Fig. 8. A scene of destroyed load bearing masonry buildings in the town of Anjar.

many villages and towns not a single building was left standing. The worst-affected towns were Anjar, Bhachau, and Rapar. Figures 5–9 show examples of the destruction caused to load bearing masonry buildings. Figure 9 shows a masonry control building located at the Samkhiali electric substation. The damage to this building disrupted the functioning of control panels and batteries housed inside, leading to tripping of the power. A number of similar buildings in electric substations throughout Kachchh were either completely destroyed or severely damaged leading to a complete power blackout in the region.

The Indian Standard IS 4326: 1993 carefully defines the requirements for load bearing masonry construction for the various seismic zones of India. This code was first formulated in 1967 and subsequently revised in 1976. The requirements in the code relate to configurations of the building, reinforcement required to tie the walls and the roof, restrictions on the size and spacing of openings, etc. Few buildings in Gujarat satisfy the recommendations of the code. A vast majority of private housing in the rural areas and small

Fig. 9. Damaged control room building at the Samkhiali substation.

Fig. 10. A block of damaged reinforced concrete frame buildings in Ahmedabad with open first storey and brick masonry infills.

towns are built without any engineering input. Construction follows antiquated traditional practice, which while satisfactory for sustaining the loads imposed by gravity or wind, is inadequate for an area that is seismically active. To a large extent, a similar problem exists in relation to nonengineered load bearing masonry construction in the larger urban centers. There is a large inventory of structures built according to traditional practice. It would be unrealistic to expect that people will have the will or the resources necessary to strengthen the existing buildings.

Performance of reinforced concrete frame buildings

A large number of reinforced concrete frame buildings located in Ahmedabad suffered serious damage or collapsed. As stated earlier, Ahmedabad is about 300 km from the epicenter. At such a distance the intensity of ground motion would not be expected to be large. The fact that a number of buildings in Ahmedabad suffered damage could be attributed to several factors. Many buildings were founded on deep sediments deposited by the Sabarmati river. This may have amplified the ground motion experienced by such buildings. Another important factor contributing to the damage was the use of open first storey combined with poor detailing and indifferent quality of construction.

Almost all buildings with open first storey suffered some damage. In some cases the buildings collapsed, while in some others the damage was so severe that the buildings had to be written off. At the time of our visit, which is about 7 weeks after the earthquake, the rubble from the collapsed building had been cleared but the severely damaged buildings had not been pulled down. Repair work was in progress in some of the private buildings that had suffered repairable damage. A typical example of a framed building with open first storey is shown in Fig. 10, which shows what was once a complex of four identical five-storey blocks. Each block had a reinforced concrete frame construction with an open first storey and brick infill walls in upper storeys. Two of the four blocks, which were located in the foreground of the picture, completely collapsed killing several residents. The other two blocks that are seen standing in the picture suffered severe damage. The owners have decided to pull them down. Temporary supports have been provided to the buildings in their lowest storey so that the useful contents of the buildings could be salvaged.

Figures 11 and 12 show details of the damage suffered by the first-storey columns. The columns are 225 mm by 375 mm in size. The longitudinal reinforcement consists of six 15 mm diameter torsteel bars. The hoops are of 6 mm plane bars spaced at 200 mm with 90° hooks. Given the local practice, it is unlikely that the confining reinforcement extends into the beam–column joint. The open first storey combined with the rather slender column size has caused hinging of most columns at their junction with the beams in the first floor above ground. The columns have a low ductility capacity because of inadequate confining reinforcement and absence of proper hooks. The situation is aggravated by the fact that according to the local practice concreting of the columns is stopped at about 200–250 mm below the soffit of the beam and a construction joint is provided at that level. The concrete in this region of 200–250 mm is poured along with the beam and usually has a poor bond with the rest of the column. This makes the hinge region even more vulnerable. The construction joint can be clearly seen in Figs. 11 and 12.

Any number of examples can be cited of the damage suffered by the open first storeys in multistory reinforced concrete buildings in Ahmedabad. A particularly tragic case was of a ten-storey building known as Shikhara. The building was in the shape of an H. It had been completed only recently and was not fully occupied. One of the open arms of the H collapsed during the earthquake causing the death of 89 persons. Details of the building are shown in Figs. 13 and 14. The collapse was evidently caused by the failure of the columns in the open first storey. The first-storey columns in parts of the building that remain standing are severely damaged. Attempts have been made to repair these columns, as shown in Fig. 14, but the residents are unwilling to return to the building.

The technique used for repairs to the columns of the first storey can be observed from Fig. 14. The columns are being prepared for concrete jacketing. In the present case they have been encased in four vertical angle sections, one at each corner. The angles are tied together by welding hori-

Fig. 11. Damage suffered by the open first storey columns in concrete frame building.

Fig. 12. The hinge in a first storey column showing the steel reinforcement.

Fig. 13. One wing of the Shikhara building detached itself from the building and collapsed.

Fig. 14. Repairs to damaged columns in the first storey of the Shikhara building.

zontal steel bars. Forms will be erected around this assembly and concrete will be poured from an open space at the top of the forms to complete the concrete jacket. We observed a similar technique being used for the repair of many damaged columns. For low-rise buildings and smaller columns, a reinforcing cage of longitudinal bars and hoops is placed around the column before concreting. However, in all cases the concrete jacket is not tied to the column foundation or to the beams above. It is evident that while the jacketing may restore the vertical load carrying capacity of the columns it does not improve the resistance to earthquake loads.

Another large reinforced concrete frame building whose failure attracted much publicity was the Mansi building located in downtown Ahmedabad. The building is 12 stories tall and consists of two identical but separate blocks. A part of one of the two blocks completely collapsed killing 22 people. The open first-storey columns of the parts that remain standing are heavily damaged. The building has been abandoned and its fate remains to be decided.

Figures 15 and 16 show some details of the damaged building. An observation of the remaining parts of this building indicates that the most likely cause of the collapse was the soft first storey. The masonry infills in the upper stories of the building make the building stiff, attracting significantly higher earthquake forces. The high shears imposed on the first-storey columns have caused damage to the visible hinge regions at the top of the columns, as well as shear failure in some of the columns, as seen in Fig. 16.

A number of buildings having open first storeys located in the Maninagar area of Ahmedabad suffered significant damage or collapsed. Most of these buildings were four or five storeys in height and had slender columns in the open first

Fig. 15. The portion of the Mansi building that collapsed detached itself from the block seen in the foreground; the other block in the background is still standing, but its first-storey columns are heavily damaged.

Fig. 16. Shear failure of a first-storey column in the Mansi building.

storey. The number of frame buildings that collapsed in Ahmedabad was reported to be 60, and the estimated death toll is placed at 750.

Concrete frame buildings with open first storeys and masonry infill walls in the upper levels located in the epicentral region of Bhuj, Anjar, and Gandhidham suffered a worst fate. First, the ground motion was more intense in these areas; second, the infills were in most cases made with heavier stone blocks rather than in clay bricks. Some examples of damaged or collapsed buildings are shown in Figs. 17–19.

Figure 17 shows the collapsed open first storey of a four-storey concrete frame building in Bhuj in which the upper

Fig. 17. The open first storey of this building in Bhuj was crushed bringing the upper three storeys down.

Fig. 18. The columns on one edge of the open first storey of this building in Bhuj collapsed bringing the building down on its side.

storeys have come down as a rigid body. Figure 18 shows a similar building also in Bhuj. In this case the columns on one side of the building failed and the building came down to rest on its side. Figure 19 shows some columns in the first storey of a building in Anjar. The loss of concrete cover and the lack of sufficient hoop reinforcement have caused the columns in the open storey to be severely damaged in the hinge region.

Role of infill panels in the behaviour of concrete frame buildings

Observation of the behaviour of reinforced concrete buildings indicates that in many instances the presence of masonry infill panels saved the buildings from collapse or serious damage, particularly when such panels extended throughout the height of the building. Even the presence of a few infill panels in an otherwise open first storey saved the building. In almost all cases the panels had no reinforce-

Fig 19. Failure of column through plastic hinging and buckling of longitudinal reinforcement due to loss of concrete cover and insufficient hoop reinforcement.

ment, nor were they tied to the reinforced concrete elements on their boundary. In spite of this, the panels seldom collapsed out-of-plane, and even when severely cracked held the building together. This behaviour has been observed in a large number of similar buildings throughout the area affected by the earthquake. Clearly, infill masonry panels can have a beneficial effect in resisting earthquake forces, and for the type of building construction commonly used in India, they are not much susceptible to out-of-plane failure. Other observers have noted a similar behaviour and have pointed out the beneficial effect of masonry infills (Zarnic 1990; Murty and Jain 2000). Obviously there is a need for further study in this area.

Figure 20 shows an interesting example of two buildings located in the Maninagar district of Ahmedabad. The buildings stood side-by-side and were connected by a staircase. The three-storey building on the left was of concrete frame with infill panels extending throughout the height in most of the column bays. It sustained the earthquake with minor damage. The four-storey building on the right had an open first storey, which suffered severe damage in the earthquake as seen in Fig. 21. Evidently the right-hand building leaned against the building on the left, which supported it and prevented it from collapse. The support was provided through the interconnecting staircase, which was damaged in the process as seen in Fig. 22.

Figure 23 shows the first storey of a building in Anjar. The columns of this soft storey were heavily damaged in the hinge regions as seen from the figure. However, it appears that a few infill walls at this level protected the building against total collapse. Interaction between the columns and the walls damaged the latter quite severely as evidenced by

Fig. 20. Two adjoining buildings in Maninagar; the interconnecting staircase allowed the building on the left to support the building on the right.

Fig. 21. The damaged first storey of the building on the right-hand side of Fig. 20.

the large shear cracks in the wall panels. However, the panels did not fall out of their plane. It may be noted that the infill panels had no reinforcement, nor were they tied to the boundary elements.

Examples of vulnerable structural details

As observed during previous earthquakes, certain structural details and components are especially vulnerable during an earthquake. One such component is a short column. Short columns attract comparatively large shear forces and are therefore likely to suffer damage. Numerous examples of

Fig. 22. The staircase interconnecting the two buildings in Fig. 20 allowed the building on the right to be supported by the building on the left.

Fig. 23. The hinge regions of the columns in the open first storey of this building in Anjar are heavily damaged; complete collapse of the building was prevented by the presence of a few infill walls, which although heavily damaged remained in their place.

short column failures were evident following the Bhuj earthquake. Figures 24 and 25 show the failure of short columns in a school in Bhachau for sight-impaired children. The columns are restrained in one direction by partition walls built in stone blocks, but were unrestrained in the other direction. As will be noted from Fig. 25 the columns are quite slender and are reinforced by just four longitudinal Torsteel bars 15 mm in diameter and have widely spaced hoops of 6 mm plain steel bars.

Fig. 24. Failure of reinforced concrete short columns in a school in Bhachau.

Fig. 25. Details of the short columns in the building shown in Fig. 24.

Figure 26 shows one of a row of newly built semi-detached houses in the town of Samkhiali near Bhachau. The developers had just finished constructing the bungalows, which were not yet occupied. As will be seen from Fig. 26, the fronts of the houses are open for a large portion of the first storey to provide space for parking. A very slender circular column (Fig. 27) supports the staircase leading to the floor above ground. A masonry perimeter wall at the back of the first storey provides considerable stiffness in its plane, creating a large torsional eccentricity. This eccentricity combined with an open floor and very slender supporting col-

Fig. 26. Row of semi-detached houses in Samkhiali; note the open spaces in the first storey, the masonry infill wall at the back, and the slender columns supporting the front of the building.

Fig. 27. Details of the column supporting the front of the building shown in Fig. 26.

umns made the structure very vulnerable. All of the houses in the complex suffered extensive damage, and some actually crumbled.

As another example refer to the six-storey reinforced concrete frame building shown in Fig. 28. The first three storeys of this building had been built earlier, the remaining three storeys being added subsequently. Evidently the connections between the structural columns of the two parts were not adequate and led to shear failure of columns at the junction.

Previous observations have shown that a change in stiffness across the height of the building constitutes a location of weakness. An example of this is provided by the damage suffered by the building of Hotel Abha in Bhuj. At the time of the earthquake the first three storeys of the building had been completed, including the masonry infill walls. The concrete frame structure for the upper floors had been constructed, but the walls had not been built. During the earthquake the concrete columns at the transition between the completed portion and the bare concrete frame suffered damage as seen from Fig. 29. The columns, however, had

Fig. 28. The fourth storey of this six-storey building in Bhuj collapsed bringing the topmost two storeys down and causing more extensive damage to one corner of the building.

Fig. 29. Damage suffered by the columns in the partially completed upper floor of the Abha building in Bhuj.

sufficient ductility to sustain the displacement imposed by the earthquake.

In the concrete frame residential buildings in Gujarat it is a common practice to place a water storage tanks at the top of the building. The tank is constructed in reinforced concrete and is usually supported by short concrete columns projecting above the roof level. The storage capacity of the tank depends on the size of the building but is of the order of 20 to 25 000 L. Many of these tanks were filled with water at the time of the earthquake. In many instances the sup-

Fig. 30. A water tank supported by four short columns projecting above the roof collapsed during the earthquake.

porting columns were unable to sustain the large seismic shear and failed. An example is presented in Fig. 30.

Summary and conclusions

The moment magnitude M_w 7.7 earthquake that struck the Kachchh region of the province of Gujarat in India at 8:46 a.m. on 26 January 2001 caused tremendous loss of life and property. The epicenter of the earthquake was located at 50 km northeast of the town of Bhuj. The earthquake was felt over a large part of India, and while the greatest damage due to the earthquake occurred in the region of Kachchh, many other parts of Gujarat, including the major urban center of Ahmedabad, were quite severely affected. The official estimate of casualties is 20 000. The number of injured is reported to be 166 000. The earthquake caused extensive ground movement, cracking, liquefaction, and lateral spreading in the region of Kachchh. About 370 000 houses and huts were completely destroyed, while another 931 000 were partially destroyed. The total financial loss is estimated at Can$7.1 billion.

The authors visited the area affected by the earthquake from 11 March 2001 to 18 March 2001 to survey the damage caused to buildings, bridges, lifeline structures, and essential facilities. The results of the survey of damage to buildings are presented in this paper. Observations made during the earthquake confirm what has been learnt during previous events. Important conclusions that can be drawn from the present survey can be summarized as follows:

1. There is a need for a study of the type of earthquake-resistant construction that would be suitable for the rural areas and smaller urban centers of developing countries. Most of the destruction caused by earthquake has taken place in such countries, and in the present age of global interaction and global economy it is incumbent upon developed countries such as Canada to undertake such a study.
2. The beneficial effect of masonry infill walls in reinforced concrete frames in resisting earthquake forces was evident in the performance of various buildings during the Gujarat earthquake. The infills prevented the collapse of many buildings even though such infills were neither reinforced nor positively tied to the boundary elements. A comprehensive study is required to assess the effectiveness of infill panels in providing resistance to earthquake forces.
3. Experience during the Gujarat earthquake has shown that building codes and standards should form the basis of regulations governing building design, so that they have a legal standing. Although India has a comprehensive set of codes and standards governing earthquake-resistant design, they do not have a legal standing and are thus only advisory in nature. A consequence of this was that the designers in Gujarat had little incentive to conform to the codes and standards, and even the engineered buildings did not conform to the recommendations of the relevant codes and standards.
4. The Gujarat earthquake reestablished the need for designing the lifeline structures and essential facilities to ensure their survival during such events, so that the services necessary for rescue and recovery are not adversely affected. Widespread failure of power in the district of Kachchh was caused because a large number of control room buildings in the electric substations collapsed, damaging the control equipment and batteries. A number of hospital buildings, telephone exchange buildings, civil administration buildings, and water service buildings were damaged or destroyed, seriously hampering the rescue and relief operations.

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