

Structural Behavior of Buildings

Introduction

This Annex describes a variety of building types in the zone of earthquake impact, analyzes their performance in the earthquake, and suggests methods for prudent construction practices in the recovery phase. The process of building permits (sanctions), and construction quality control (supervision and code enforcement) are also part of this annex. In terms of ownership, the building stock reviewed includes both private and public (government) buildings, and in terms of use it comprises all types of rural and urban housing (single- and multi-story units), school, hospital and industrial buildings, as well as other public buildings. All reference to damages have been excluded from this Annex, as they are incorporated in other annexes.

Overall, the building stock in the zone of impact (and in the state in general) is typified by the use of a wide range of disparate construction materials, frequently combined in the same structure. Phased construction, consisting of the addition of new parts of buildings at different times (without structural consolidation) is very common, and includes both single- and multi-story structures.

According to the *Vulnerability Atlas of India 1997 for Gujarat State*, there were a total of about 10 million housing units in the State (1991 housing census). Sixty-six percent of these were in Rural and 34 percent in urban areas. The following level of exposure to major earthquake damage risk, indicates that the predominant types of building construction in the State, as nonengineered structures, offer almost no resistance to ground shaking. The component materials have low strength, and the structures do not have further resilience once the materials have cracked.

	Category 'A' (Mud, Unburned Brick or Stone walls)	Category 'B' (Burnt Brick walls)
Level of earthquake Damage Risk in Zone V (> MM IX)	Very High	High
Rural housing units (%)	52	32
Urban housing units (%)	23	73

There is little quantitative information available about the details of the ground motion or the intensity of shaking in the earthquake-affected region.

Damage Assessment According to Building Use and Structural Type

Urban/towns. There is a predominance of single, two (and some) three story units. More recent trends in the larger towns (Bhuj, Gandhidham, etc.) has been towards construction of multi-storied apartment units (typically 1+4 or higher). The construction of additional floors ("penthouses" in multistory housing buildings) with heavy additional loads (e.g., roof gardens, swimming pools) became a trend among the affluent in larger cities in recent years. The fast construction process, that accompanied increased financial capacity of the middle- and higher-income strata, contributed to the structural vulnerability.

Ahmedabad a city of about 4 million, has about 12,000 low-rise and 450 high-rise apartment blocks, in addition to the usual one- to three-story single family units.

Traditional housing units, very common in old city areas made of sloping red clay tile or AC/GI sheet roofing on timber framing, reinforced concrete floor slabs, unreinforced load bearing masonry walls—typically stone (cut or rubble), concrete solid block or clay set in cement or lime mortar; and mostly stone rubble masonry wall foundations. Widespread mix of traditional and modern building material/construction within the same unit was most visible in the “walled towns” of Bhuj and Anjar, respectively.

Modern single family units. Up to three floors high (ground floor plus two floors) typically comprised of reinforced concrete roof and floor slabs, supported partly on load bearing masonry walls and partly on reinforced concrete beam/column frame structures. In the epicentral region (*e.g.*, Bhachau, Ratnal, and adjoining villages) virtually all traditional housing units and nonengineered structures collapsed and turned into rubble; all two story and most single story RCC slab load bearing structures have also partially collapsed. Also, in the “walled towns” of Bhuj and Anjar, virtually all traditional houses collapsed.

Modern multistoried multifamily low-rise housing. Usually five floors high (Ground-floor plus four floors) these are by and large reinforced concrete framed structures with non-structural masonry in-fill walls (cut stone, concrete block or burnt clay brick). Several such structures collapsed or have undergone major distress, while most others have experienced varying degrees of cracking and damage. In Bhuj, approx. 100 buildings collapsed or were damaged beyond repair—out of a total stock of about 280. About 75 such buildings (including several hotels) collapsed in Gandhidham. In Ahmedabad, 68 such buildings collapsed out of a stock of about 12,000. About 54 of these had been constructed during the last ten years.

In some cases owners have indicated that buildings with relatively light structural damage, are to be demolished and rebuilt. Informed decision making is in order, since it may be practical to return some of these buildings to acceptable levels of safety, naturally with appropriate repairs and strengthening, under the guidance of competent structural engineers.

Modern multistoried multifamily high-rise housing. Up to 10 storeys high, these are usually reinforced concrete framed structures with non-structural masonry in-fill walls (concrete block or burnt brick). Three such 10 storied structures collapsed in Ahmedabad—all three were constructed during the last five years.

Generally, the reinforced concrete framed structures that collapsed during the January 26, 2001, earthquake, were poorly designed, detailed and constructed, apparently without considering earthquake risk and related lateral loads or, in most cases, local soil conditions. Most of the collapsed buildings had an open lower level (so called soft story—created for parking. In such cases, masonry wall elements were not available to restrict lateral frame drift and provide reserve vertical load carrying capacity, when columns failed under the earthquake loads. Building collapse was largely restricted to certain specific types of structures, particularly in Ahmedabad, indicating that resonance between the frequency of ground motion and the fundamental building period may have contributed to failure. However, this can only be confirmed after an analysis of detailed ground motion data and records. In Ahmedabad, Bhuj, and Gandhidham, collapsed reinforced concrete frame buildings are concentrated in specific parts of town, highlighting the need for microzoning, and careful consideration of local geotechnical conditions while designing for seismic loads.

The collapse of some buildings appears to have been precipitated in part, by their irregular (L or T) plan shapes and lack of separation joints between individual “legs.” In general, the building materials and overall construction quality observed in the earthquake affected areas was rather low. Quality of *in situ* poured reinforced concrete, and on the ground pre-cast concrete slabs for pre-fabricated construction deserves special attention. In some cases it appears to be common practice to use saline water for concrete mixing and curing—which eventually leads to severe corrosion in the reinforcing steel. *If drought conditions continue, and if damage to dams prevents adequate water storage, lack of sufficient watering/curing of concrete could remain a significant problem for quality assurance in the reconstruction and rehabilitation phase.*

Residential quarters for government employees. These buildings are typically Ground-floor + 1 story high, or Ground-floor + 2 story-high multi unit buildings. They typically have reinforced concrete roof and floor slabs, supported on masonry load bearing walls following standard Public Works Department (PWD) layouts and construction practices. The G+2 structures in particular, have experienced serious wall cracking in some high damage earthquake affected areas, and may need replacement.

Rural housing. Rural housing construction, almost 100 percent nonengineered, is characterized by use of low quality materials, phased construction and mixing of different materials over a long time span. Rural nonengineered building stock (including large span buildings for storage of agricultural products and machinery) are by and large masonry-constructed single story units that can broadly be classified as follows:

Pucca Housing. Clay tile or galvanized iron (GI)/asbestos cement (AC) sheet sloping roof on timber framing. Unreinforced load bearing masonry walls (burnt brick or cut stone, set in cement, mud-cement or lime mortar). Burnt brick or stone masonry strip foundation.

Kutchra housing consists of unburned brick, bamboo, thatch or mud roofing. Mud, unburned brick or rubble stone masonry load bearing wall structures and strip foundations (in mud mortar).

Building techniques recommended by the advanced and user-friendly guidelines for building nonengineered structures in the rural, seismically-prone regions of India (See relevant Indian Standards, and *Manual for Earthquake Resistant Construction and Seismic Strengthening for Nonengineered Buildings in Rural Areas of Maharashtra, 1998*) were not being followed. Traditional (unreinforced) masonry construction was unable to withstand large seismic loads or ground shaking in the epicentral region. Large portions of the heavy masonry walls collapsed, crushing or trapping people and leading to widespread destruction of entire villages.

There is very little use of construction wood. Where wood is used, its profiles are almost universally undersized, especially for sloped roofs, where rafters and secondary bearing elements for heavy burnt clay tiles were made either of split bamboo poles or very thin wood, which generally caved in during the earthquake. Roof tiles, which by and large are freely set on the understructure, slid from the roofs, adding to damage and personal injury. Exceptions have been observed on some houses, where rafters were made of steel profiles, with roof tiles set in cement mortar. These generally performed better.

Commercial buildings/shops. These buildings were typically constructed of reinforced concrete as (single or two storied) framed structures, not designed or detailed for seismic loading. In the epicentral region (*e.g.*, Bhachau) most such RCC frame shopping blocks partially collapsed or swayed laterally leading to structural damage beyond repair.

School buildings. These structures were built following the traditional PWD designs (single or G+1) and standards. Some are up to 50 years old. They consist of concrete roof and floor slabs supported on load bearing un-reinforced stone masonry walls. A number of school buildings suffered collapse or serious damage (*e.g.*, extensive wall cracking) all over Kutch.

Some prefabricated single storied concrete primary school buildings have recently been constructed in some parts of Kutch, but *no measures have been taken to ensure integrity of these structures during an earthquake through appropriate joint and connection detailing.* Such structures collapsed at Kukma and Sapeda in the epicentral region.

Other public buildings. Colleges, training centers, hospitals, court buildings, are comprised in this category. They also normally follow PWD designs, and are typically up to G+1 structures –consisting of concrete roof and floor slabs supported by a mix of load bearing un-reinforced stone masonry walls and partial RCC frame structures. The load bearing portion of several two and most three storied structures in Bhuj and Anjar suffered major damage or collapse.

Elevated Water Tanks. These stand-alone structures consist of both the traditional RCC supporting frame type of tanks, as well as the more modern inverted pendulum type structures. In most cases these appear to have been designed for lateral forces and have survived without significant distress, even near the epicentral region.

Industrial buildings/ structures. These buildings typically consisted of a mix of reinforced concrete and structural steel framing, GI or AC sheet roofing and masonry load bearing walls. Several industrial buildings, storage sheds and compound walls suffered significant damage/partial collapse in the Bhuj industrial area and along the Gandhidham to Bhachau road - on account of lack of lateral bracing of roof framing members/masonry walls, the lack of reinforced concrete columns/bracing beams to support the high masonry walls.

Current building codes. India introduced its first Earthquake Code in 1967. The Bureau of Indian Standards currently has a set of standards, guidelines, and codes of practice for earthquake resistant design and construction of buildings. The coverage includes design criteria, loading standards, plain and reinforced concrete, unreinforced masonry, guidelines for repair and seismic strengthening, and so forth. The Design Criteria (IS: 1893 to 1984) and the subsequently issued *Vulnerability Atlas of India, 1997*, include an earthquake zoning map for India which puts Kutch in zone V (highest earthquake risk–MM: IX and above) and Ahmedabad in Zone III (moderateearthquakerisk–Modified Mercalli scale VII). *The Design Criteria and Code endeavor to ensure that structures are able to respond, without structural damage, to shocks of moderate intensity, and without total collapse to shocks of heavy intensity.*

Normally, codes of practice only have a recommendatory status, unless they are incorporated into relevant building by-laws and regulation through an appropriate legal framework. Compliance with *the Indian Standard Code of Practice for Earthquake Resistant Design and Construction of buildings (IS 4326-1993)* has been very weak across Gujarat. In the case of private multistoried housing and one to three storied public buildings, code compliance seems to have been the exception rather than the rule. A limited inspection of some of the collapsed and heavily damaged structures confirms that structural damage/distress and adverse impact of the January 2001 earthquake could have been significantly reduced, through better compliance with applicable earthquake codes.

Review of Current Building Permit and Construction Procedures

The building permit process, as well as enforcement of the Indian building Codes and Standards appear to have been flawed in many respects. Observations and discussion in the field, indicate that the developers'/contractors' rush to cash in on the disposable income of the affluent, particularly during the development boom years of the last decade, led to a series of violations of building regulation, prudent structural and architectural design practices, and shoddy construction practices, frequently using poor quality building materials. In most smaller towns building regulation and permit procedures have been almost nonexistent. In all urban areas enforcement has been lax.

Small towns (characterized by Bhuj). The municipality nominally categorizes the 25 odd practicing Architects/Engineers in the city (A, B, or C) on the basis of qualifications and experience. Builders are not registered. Municipality by-laws prescribe an application and review process for grant of building permits. Technical review capacity of staff is very limited (no graduate engineers) and focuses on compliance with planning norms only. Structural engineering drawings, soil investigation or material testing reports are not required to be submitted or reviewed. A Town Planning Committee comprised of seven members four elected and three governmental) is charged with final responsibility of issuing building permits, and frequently overrules any technical objections recorded by municipality staff. There is no site inspection by Municipality staff during the construction phase. After completion, the municipality engineer gives a completion certificate to the owner. Government officials acknowledge that present practices are clearly deficient and do not assure quality.

Buildings of large corporations (characterized by Ahmedabad). In 1999, a common set of regulations (*General Development Control Regulations, Ahmedabad Urban Development Authority*) was introduced for the Ahmedabad Urban Development Area – covering both the Ahmedabad Municipal Corporation (AMC) and the Ahmedabad Urban Development Authority. These require that building plans be signed by registered architects. *Registered Structural Designers* (graduate civil engineers with at least five years structural design experience) *are required to prepare detailed structural designs strictly on the basis of National Building Code or relevant Indian Standards*, to sign off on all major buildings and high rise structures and issue a formal Certificate of Structural Safety on completion of construction. A registered Clerk of Works is required for execution of all major buildings and high rise structures. AMC currently has a surprising 400 'Registered Structural Designers' on its records, and anecdotal evidence suggests lack of rigor in the screening and registration process, as well as in its strict enforcement--core steps under the present arrangement to ensure public safety.

Government buildings. R&B Department is responsible for the design of all reinforced concrete frame structures centrally, at its design circle in Gandhinagar, and has some seismic design capacity. Performance of RCC public buildings designed to meet this code by R&B has generally been satisfactory during the recent earthquake event. However, one to three storied load bearing structures (including primary schools and most hospital buildings) are left to field engineers, many of whom (particularly under Panchayats) have no design capacity or familiarity with earthquake requirements.

Recovery and Reconstruction Needs

Overall recommendations for improving earthquake resistance of buildings are presented in the following section. Generally these are short-term recommendations for the Government of Gujarat, *unless specifically stated for the medium-term and highlighted in italics.*

Legal and Regulatory Framework. *(a) mandate compliance with relevant Indian Earthquake Resistant Design Codes and related Standards for all buildings and works, through necessary amendments to State level legislation, Bye-laws and Regulations applicable to Municipal/Panchayat areas, etc. (b) make earthquake ground motion records/data from the seismological network particularly for major events, routinely available in the public domain for use by the technical community. (c) strengthen development control regulations in place in Ahmedabad, to include enhanced quality assurance through: mandating peer review of structural designs for major buildings, requiring soil investigation and material testing/reporting, screening and registration of builders based on demonstrated qualifications, experience and financial strength, random third party inspections (and, in the medium term use of licensed structural engineers), introduce use of higher grades of concrete in multistoried RCC structures, (d) replicate such regulations/bye-laws, as far as possible, in other municipal corporations as well as in secondary towns of Gujarat - particularly the high earthquake hazard districts. In the medium term: (e) Pursue Licensing of Professional Engineers/Structural Engineers to help safeguard public life and property; and (f) update earthquake codes and standards to reflect lessons from building performance during the 2001 Gujarat EQ, as well as latest global knowledge and research*

Technological Enhancement and Capacity Building. It is necessary to: (a) undertake an urgent technical review of current rural housing practices by a high-powered expert committee – to develop innovative (safe, affordable and climatically appropriate) rural housing solutions, particularly for the high risk seismic zones of Gujarat, using earthquake resistant technology based on indigenous materials and community implementation arrangements - as far as possible. Incorporate lighter materials/components to minimize risk to life, in case of collapse. The process must actively discourage the return to existing housing construction practices in rural areas; (b) set up demonstration centers in rural areas: to help widespread dissemination and acceptance of these solutions, and for training of artisans/rural folk in the required construction practices; (c) arrange refresher courses/workshops/seminars for practitioners: covering earthquake engineering analysis, design, code compliance, construction aspects and retrofitting practices, in collaboration with professional bodies/academia; specific training of construction supervisory level staff, etc. *In the medium-term:* (d) facilitate establishment of a network of soil and material testing facilities throughout the state; (e) facilitate introduction of post-graduate earthquake engineering programs in local institutions; and (f) support continuous research aimed at improving the knowledge base in earthquake hazard mitigation.

Code enforcement. As a matter of urgency, the following measures should be implemented: (a) urgently complete structural damage assessment of building structures; (b) facilitate repair of damaged buildings; (c) link state funding of new residential units that are built to replace collapsed structures in rural and urban areas to compliance with appropriate seismic resistance standards/ safe housing types; (d) introduce mandatory building insurance - as an incentive towards code compliance; (e) hold R&B Department accountable for strict compliance with earthquake resistant codes in design and construction of all essential government buildings such as primary schools, hospitals and emergency health facilities (irrespective of the size of the facility), to ensure public safety and continued operation in emergencies. *In the medium term to*

meet minimum safety standards; (f) undertake a program of retrofitting essential government facilities (including primary schools and hospitals); and (g) facilitate a program aimed at retrofitting of the existing private building stock.

Retrofitting. Given the vulnerability of the building stock in Gujarat, painfully confirmed in the past two years in successive devastation first by a cyclone and now by an earthquake, it is necessary for the government, primarily, to undertake a systematic inventory of public buildings. Especially critical facilities, such as hospital and school buildings, police and fire stations, as well as buildings essential for the uninterrupted functioning of the government need to be carefully reviewed and, if necessary, subsequently “retrofitted,” or more accurately – repaired and strengthened. Techniques for retrofitting of most common building types are well known in India and internationally. For example, the Building Materials and Technology Promotion Council (BMTPC), under the Ministry of Urban Affairs, published guidelines for earthquake-resistant construction, and in 1999, issued technical guidelines for retrofitting of existing houses and building of new ones for architects, engineers and construction agencies.

In addition to public buildings, the government in partnership with the private sector – specifically professional associations of structural engineers, institutes of architects, academic institutions, relevant NGOs, and above all, consulting groups of practicing engineers and insurance companies—should reach out to home owners and home-owners’ associations to educate them about the benefits of certain retrofitting measures. This process should be well weighed, as all retrofitting measures do not yield desired results. Innovation with relatively low-cost, but otherwise state-of-the-art retrofitting techniques, such as base isolation (rubber-and-steel bearings that allow a building to “ride” with the seismic waves), should be seriously explored. In the neighboring Maharashtra, following the 1993 earthquake, a school was built in one of the villages using this technique.

NGO capacity for housing reconstruction. The Joint team’s assessment is that NGOs in Gujarat, knowledgeable in house construction are limited in number. There are good institutions in the state for producing plans, layouts, type designs, and technical specifications, but experience of building demonstration centers and providing outreach appears to be inadequate. Private agencies in the building industry may be better suited for these activities. There is also limited capacity among NGOs for working with communities to mobilize, organize and guide them in the housing sector. The state would need to draw on NGOs that have been working in other areas of rural development (such as watershed development, non-formal education, women’s organization) to meet the needs for housing. NGOs with good experience of participatory development could partner with the more technical institutions to achieve the desired participatory planning of and involvement in housing. These partnerships could also be “force multipliers” if they train other village-based groups – such as the proposed village reconstruction committees. The situation in urban areas is somewhat more complex, and institutions, including NGOs, that have experience of working with urban dwellers would need to be brought in to assist the process of owner-driven reconstruction.