13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1723

HOUSING RECONSTRUCTION AND RETROFITTING AFTER THE 2001 KACHCHH, GUJARAT EARTHQUAKE

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SUMMARY

The January 26, 2001 Bhuj earthquake in the Kachchh district of Gujarat, India caused over 13,000 deaths and resulted in widespread destruction of housing stock throughout the epicentral region and the state. Over 1 million houses were either destroyed or required significant repair. Comprehensive, unprecedented and well-funded reconstruction and retrofitting programs soon followed.

Earthquake-resistant features were required in the superstructure of new, permanent housing by the government and funding agencies. This paper describes those features and their implementation in both traditional (e.g., stone in mud or cement mortar) and appropriate (e.g., cement stabilized rammed earth) building technologies. Component-specific and overall costs are given. Relatively less attention has been paid to foundation design, however, typical foundation types will be described. Retrofitting recommendations and approaches are documented.

Construction could be driven by homeowners themselves, by nongovernmental or donor organizations, or by the government or industry on a contractor basis. The approaches are contrasted in terms of inclusion and quality of requisite earthquake-resistant design elements, quality of construction and materials, and satisfaction of the homeowner.

The rebuilding and retrofitting efforts required a massive mobilization of engineers, architects and masons from local areas as well as other parts of India. Cement companies, academics, engineering consulting firms, and nongovernmental organizations developed and held training programs reaching over 27,000 masons and nearly 8,000 engineers and architects. The achievements of these programs are described.

Technical data and observations presented in this paper were obtained through site visits and interviews with implementing personnel that took place over a seven-month period.

THE EARTHQUAKE AND ITS IMPACTS

The January 26, 2001 Bhuj Earthquake

The January 26, 2001 earthquake (known internationally as the Bhuj earthquake) originated below a rural area north of Bhachau, one of the four urban centers in the Kachchh district of Gujarat state, India (Fig. 1). A Richter magnitude of 6.9 was reported by the Indian Meteorological Agency and a moment magnitude of 7.7 by the U.S. Geological Survey. No ground motion recordings are available from the epicentral region. The PGA in Anjar, a city in Kachchh located 44 km from the epicenter, was estimated

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at 0.55g by EERI [1]. According to the Gujarat State Disaster Management Authority (GSDMA), ground shaking lasted for 2 minutes with strong motion for approximately 25 seconds. Most of Kachchh was thought to have experienced Modified Mercalli Intensity of IX or greater (IIT and EDM [2]).

The official death toll reported by GSDMA was 13,805, with 167,000 injured. 89% of the deaths took place in the Kachchh district, India’s second largest district geographically. Kachchh is relatively sparsely populated (27 people per sq km) due to the lack of water; there are no perennial streams, a diminishing groundwater supply, and an average of only 345mm of precipitation per year. Prior to the 2003 monsoon, the district had experienced three consecutive years of drought. Temperatures in the summer months range from 33-45^{o}C (91-113^{o}F).

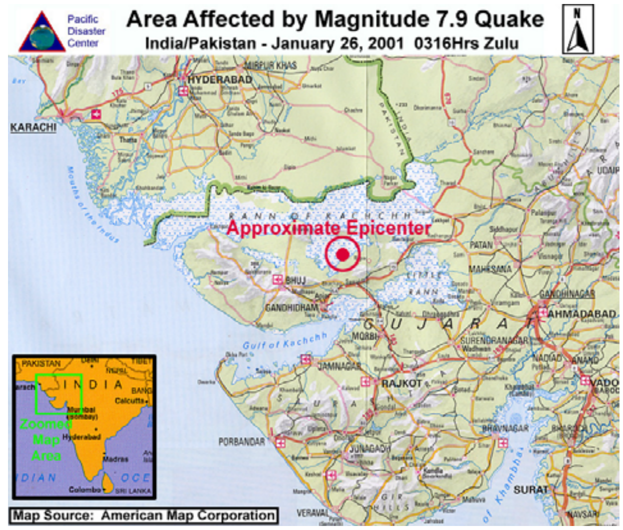

Fig. 1. Location Map

In all of Gujarat, a total of 215,255 houses were documented by the authorities as completely destroyed, 928,369 slightly to severely damaged. 70% of buildings in Kachchh were damaged or destroyed (including 2,000 medical facilities and 12,000 schools). Of the four urban centers in Kachchh, 2 had damage to nearly *every* structure. Losses in housing stock alone were estimated at US$922 million (World Bank [3]).

Seismic Hazard and Historic Earthquakes

India is divided into four seismic zones, of increasing hazard. Kachchh is located in Zone V, the severest zone. Strong earthquakes are common in Kachchh, as are cyclones. The Bhuj earthquake was near in location and magnitude to the Kutch earthquake of June 19, 1819. Also, a moment magnitude 6.0 event leveled much of the old city of Anjar in 1956.

Causes of Collapse and Damage to Single Family Houses

Over 90% of houses in Kachchh are not engineered and do not comply with the Indian Seismic Standards. Two-thirds of the population of Kachchh live in “Kachchha” houses, which are houses made of less durable materials including mud, dung, adobe, and field stone. The other third lives in “pucca” houses, which are made of more durable materials including cement mortar, brick, block, and cut stone.

Following the earthquake, GSDMA (and several other organizations) surveyed the damage and categorized the buildings according to the IAEE Guidelines [4] listed in Table 1. The data collected by GSDMA did not include construction type and likely cause of damage. However, IITB and EDM [2] estimate that 187,000 pucca houses collapsed and 500,000 were severely damaged, while 183,000 kachchha houses collapsed and 420,000 experienced moderate to severe damage. Given that there were twice as many kachchha houses as pucca houses, as a group, the pucca houses were more deadly.

Several researchers did post-earthquake reconnaissance studies, tabulating the major causes for failure and the design and construction deficiencies of certain housing types (EERI [1], IITB and EDM [2], and GREAT [5]). Damaged rural low-rise buildings can be generally divided into four categories: (1) random rubble or stone masonry, (2) burnt brick or concrete block masonry, (3) adobe or mud, and (4) precast concrete panels. Poor soil conditions and weak foundations also contributed to damage.

Table 1. IAEE Damage Classification and Number of Houses in Each Class

Damage Category	No. Houses*	Walls	Roofs/Floors
G1 - Slight nonstructural	414,903	Thin cracks in plaster, falling of plaster bits in limited parts	Thin cracks in small areas, roofing tiles only slightly disturbed
G2 - Slight structural	260,337	Small cracks; falling of plaster in large areas, damage to non-structural parts (e.g., parapets)	Small cracks in slabs, AC sheets; ~10% tiles disturbed, minor damage understructure of sloped roofs
G3 - Moderate structural	146,483	Large and deep cracks; widespread cracking of walls, columns and piers, or collapse of one wall; load carrying capacity of structure partially reduced	Large cracks in slabs; some AC sheets broken; up to 25% tiles disturbed/fallen; moderate damage to understructure of sloping roof
G4 - Severe structural	106,646	Gaps occur in walls; two or more inner or outer walls collapse; ~50% of main structural elements fail; building in dangerous state	Floors badly cracked, part may fail; understructure of sloping roof heavily damaged, part may fall; tiles badly affected, fallen.
G5 - Collapse	215,255	Large part or whole building collapsed	Large part or whole floor and roof collapse or hang precariously

*Numbers presented in September 2003 Progress Report, GSDMA [6]

Random Rubble Masonry

Stone or random rubble masonry in mud mortar was very common and very deadly, and is prevalent throughout India. Uneven stones are laid in weak mortar, often in wide walls consisting of two wythes. The major deficiency of this type of construction is the low tensile strength of the mortar, which was easily exceeded in the strong earthquake, causing walls to separate at corners and T-junctions. The absence of through stones or shear connections between parallel wythes contributed to separation and collapse. Also, the walls are often built one at a time, which produces a weak connection at the corner.

Brick and Concrete Block Masonry

Concrete block and burnt brick masonry load bearing structures also failed catastrophically, for similar reasons, such as weak mortar and poor connections. For masonry structures, the type and connection of the roof influenced the severity of damage. Poor quality or unprotected timber, heavy stone slab, or concrete roofs were not properly connected to the walls, reducing the transfer of roof inertial forces to the walls, and making the roofs susceptible to collapse. Generally, buildings with lightweight roofs suffered relatively less damage than buildings with heavier roofs. In the case of ceramic tile roofs, tiles that were not connected to the wooden battens became dislodged and cracked.

Mud or Adobe (Bhungas)

A bhunga is a traditional, typically circular plan structure made of mud bricks or an interior matrix of tree branches packed with mud. The roof is supported by a vertical post resting on a single wooden beam that sits on the walls. Bhungas performed comparatively well during the earthquake. Shell action of the wide, low circular walls distributes the shear forces. Some bhungas have ring beams or some kind of connection between the roof and the walls. According to IIT and EDM [2], the primary cause of damage was collapse of the vertical post and roof. The walls usually collapsed outward.

Precast Concrete Panels

Precast concrete panels were used by the Government of Gujarat to build 6000 primary schools throughout the state (IIT and EDM [2]). These buildings performed very poorly because the panels, in both the walls and roofs, were connected using a tongue-in-groove system without dowels, allowing the connections to simply open up and the panels to separate during the earthquake.

Soils and Foundations
Black cotton soil, a highly expansive clay, is present throughout Kachchh and may have contributed to pre-earthquake damage of brittle masonry structures. Also, loose alluvial soils in the coastal areas and flood plains caused loss of bearing support and excessive settlement (GREAT [5]). Generally, rural buildings in Kachchh are poorly founded on shallow loose stone strip footings. Damage to precast panel buildings was accelerated due to differential movement of isolated spread footings.

Seismic Bands
Masonry buildings with reinforced concrete seismic bands at the lintel and sill levels performed well during the earthquake. Damage was limited to minor cracks near the corners and along the lintel bands.

TECHNOLOGIES FOR HOUSING RECONSTRUCTION

Prescriptive Guidelines for New Masonry Construction
Within 6 months of the earthquake, GSDMA released guidelines for earthquake-resistant construction using traditional wall materials (fired brick, stone, concrete blocks) and roofing options (reinforced concrete slab, pitched roofs with ceramic tiles on a wood understructure) (GSDMA [7]). In December 2001, GSDMA released similar guidelines for stabilized earthen wall buildings (GSDMA [8]). Quality control procedures were also published (GSDMA [9]). The minimum requirements for the most commonly observed rural and peri-urban construction types are briefly summarized in Table 2.

Table 2. Guidelines for Reconstruction of Low-Rise Dwellings in Kachchh, GSDMA [7] and [8]

Feature	Requirements
Layout	Max 2 stories, internal wall length < 6m, wall height < 3m, distance between opening and inside corner > 450 mm, distance between consecutive openings > 560 mm
Foundation	Minimum depth 750 mm (deeper for black cotton soil), width 600 mm. Options for base layer: (1) 150 mm thick layer of unreinforced cement concrete (1:3:6) (Figs. 2 and 3), or (2) < 600 mm cobble-size stones with sand filling (Figs. 4 and 5) overlain by unreinforced concrete layer. Vertical bar anchored in unreinforced concrete layer. Followed by a 380-450mm thick wall of masonry in 1:6 cement mortar up to plinth.
Stone Masonry Walls	Wall thickness < 380 mm. Interlocking of inner and outer wythes using through stones or bonding elements, min spacing 600m V, 1.2m H. Long stones (500-600 mm) at corners, T-junctions, min spacing 600mm V.
Masonry Walls	1:4 cement mortar in superstructure
Rammed Earth Walls	Min wall thickness 230 mm (9”), min crushing strength 5.0 MPa (50 kq/cm^2), compacted in forms to required density and strength, seismic bands required.
Compressed Stabilized Earth Block Walls	Interlocking blocks typ 230 mm (9”)wide, min crushing strength 5.0 MPa (50 kq/cm^2) laid in 1:4 soil-cement glue, seismic bands required.
Horizontal Seismic Bands	Reinforced concrete (1:1.5:3) bands at plinth, lintel, top of gable walls. Reinforced with two longitudinal (10mm dia) high strength deformed (HSD) steel bars tied together with 6mm dia stirrups at 150 mm (6”) increments (Fig. 6).
Vertical Steel Bars	Single 12mm dia (HSD) bar at the corners, door jambs and adjacent to large openings (> 600m x 600 m). Bar embedded in the foundation concrete and roof band or RC slab roof. Pocket (within masonry) surrounding the bar backfilled with 1:1.5:3 concrete.
Roofs	(1) Cast-in-situ reinforced concrete slab of 1:1.5:3 concrete, attached to walls, or (2) Mangalore pattern tiles on wood understructure, tiles fixed to battens with hooks.

Comments on Design Guidelines and Lessons from Practice
Foundation Construction
Both foundation approaches allowed by the guidelines were commonly used (see Figs 2-5). In the latter option, the cobbles are laid out, covered with loose sand (Fig. 4), and flooded with water so as to slurry

the sand into the voids between the cobbles. In practice, this procedure rarely fills the voids completely. The support matrix consists simply of the cobbles themselves, which are often rounded and in poor contact with each other and the base of the excavation. Thus a competent support matrix is not formed, leaving the foundation vulnerable to differential settlement under the static load of the walls, which is especially problematic for brittle masonry and earth construction. A tenet of foundation construction in seismic regions is that the foundation should be able to span soft spots so that settlement occurs uniformly; yet this approach *creates* soft spots. Plus, foundations should be connected horizontally to reduce shear forces induced in the structural elements resting upon the foundation. Further, differential settlement due to static and seismic loads is unlikely to be restricted by the unreinforced concrete layer.

The practice of placing cobbles in loose sand was defended as a form of base isolation. Some engineers and architects maintained that a frictional interface existed between the cobble/sand layer and the unreinforced concrete such that sliding would occur, reducing the energy transmitted to the walls. However, it is physically very unlikely that sliding of the unreinforced concrete layer could take place relative to cobble/sand foundation because the concrete is confined on all sides by the ground, and the masonry wall up to the plinth band is confined in its interior by backfill for the floor. Thus the structure from the unreinforced concrete layer on up is not free to slide relative to the cobble/sand layer.

Fig. 2. Unreinforced concrete base layer for strip footing, with vertical steel bars

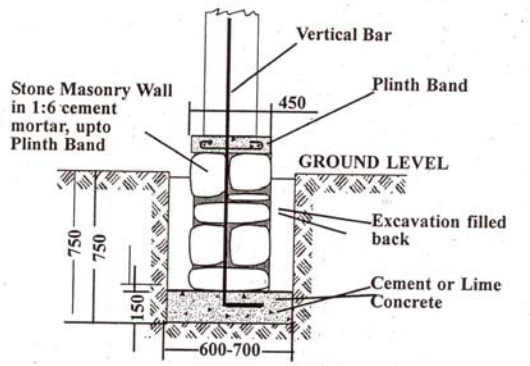

Fig. 3. Section view of strip footing with unreinforced concrete as base layer (after GSDMA [8])

Fig. 4. Random cobble foundation covered with loose sand

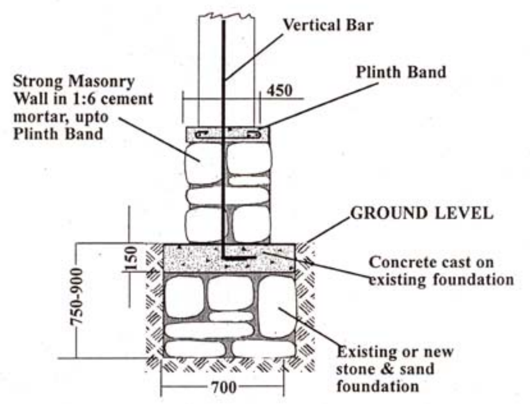

Fig. 5. Section view of random cobble foundation covered with loose sand (after GSDMA [8])

Masonry Walls

The type of masonry unit used varies across Kachchh and is driven primarily by cost and availability. In Rapar area, stone is most common. In Bhuj area, microconcrete blocks and fired bricks are common. In Bhachau area, fired bricks dominate the construction practice. The stone masonry units observed during construction ranged from soft sandstone to slightly harder granite. Most bricks are country-fired, that is, made in coal-fired outdoor kilns as shown in Fig. 7. This process does not burn the brick uniformly. Crushing strength of country-fired bricks varies from 0.3-6 MPa (3-60 kg/cm^2).


Fig. 6. Reinforcement for plinth band

In all types of masonry, a 1:4 mortar mix was required in the superstructure. If mixed properly, this mortar will be much stronger than many of the masonry units used, such as country-fired bricks. Ideally, mortar should match the physical properties of masonry unit, satisfy structural requirements (i.e., number of stories (gravity load), flexural tensile strength (lateral load)), and be appropriate to weather conditions and the mason's preferences in workability. A large difference in strength between mortar and masonry unit usually means a large difference in thermal expansion and contraction properties. In other words, if the mortar is too hard, the walls will not expand and contract uniformly, which can lead to cracking.

Excessively strong mortars also have quick set times, which is especially problematic in hot, dry climates such as Kachchh. The mortar dries out quickly and becomes unworkable for the masons, who tend to add more water, which changes the water to cement ratio, reducing the ultimate compressive strength and the strength of the bond. Country-fired bricks in particular are soft and absorptive and have a tendency to draw the water out of mortar before the cement can completely hydrate. The guidelines recommend that bricks are soaked prior to construction, but this practice was not always followed. Also, it was very common practice for the mason to lay the bricks without completely filling the head joints, as shown in Fig. 8. After the entire course was laid, the mason would fill the head joints while spreading the next course of mortar. This is a time consuming process, in which the bed mortar would remain exposed to the sun and heat for prolonged period of time before the next course of bricks is laid.

The potential lack of compatibility between the mortar and masonry units may be offset by the quality of the mortar as put in the wall. Mechanical mixers are non-existent in rural Kachchh for low-rise housing construction; instead, mortar is mixed on the ground by hand (Fig. 9). Dry materials are mixed together in a pile that is formed into a circular berm with a hollowed out center portion where water is added. Mixing takes place by gradually pulling in material from the sides. In this process, some of the material on the sides is hydrated for a longer time, producing variations in strengths and consistency.


Fig. 7. Kiln for country-fired brick production


Fig. 8. Brick masonry using rat-trap bond


Fig. 9. Typical mortar mixing

Earthen Walls

At least nine non-profits used earth-based technologies to build over 5700 houses, representing roughly 12% of the houses built or facilitated by non-profits. Earth-based houses took the form of interlocking compressed stabilized earth blocks (CSEB) (Fig. 10) or stabilized rammed earth (Fig. 11). The stabilizing agent was 7-10% cement by weight. The most commonly used interlocking block was made with a manually operated block press produced by the Auroville Building Centre in Tamil Nadu, India. The block measures 248mm (10”) by 24.8mm (10”) by 98mm (4”) thick and has two circular protrusions on one side, and like indentations on the other side. The interlock is approximately 4mm deep. A 2mm-thick stabilized soil glue is used as mortar between the blocks. There are holes at the center and edges for vertical reinforcement.

Rammed earth walls are constructed by tamping the mixture of moist soil and cement between two forms. In the Bhuj reconstruction, each 8” layer of rammed earth is followed by a thin cement slurry.

Both techniques are very promising ways of building improved earth-based houses with locally available materials. However, the shortcoming with the state of practice for the earth-based housing technologies is that very little is understood about their performance during strong seismic shaking. The only parameters that are fairly well understood are the compressive strength and modulus of rupture of a single earth block. Little information is available on the degree of block interlocking required, the effect of the amount and strength of mortar, the stability of a tall interlocking block or rammed earth wall, the effect of the roof weight and connection, and the performance of a structure as a whole.


Fig. 10. Interlocking compressed stabilized earth wall


Fig. 11. Stabilized rammed earth house with RC slab roof

Seismic Bands

Reinforced concrete horizontal bands connected with vertical steel at the corners were considered pivotal components for changing a traditional building method to an earthquake-resistant one. The Bhuj earthquake and experimental research have demonstrated that structures built with seismic bands as specified in the guidelines are unlikely to collapse and kill or injure their occupants, though they may develop cracks (Arya, [10], UNCRD [11]). The primary issue in terms of practice is whether or not the seismic bands will continue to be used after the reconstruction program, which includes a subsidy on cement and steel. This issue is addressed later in this paper.

Reinforced concrete seismic bands were required for the structures built out of stabilized earth blocks and rammed earth. In some CSEB houses, the reinforced band was surrounded by a course of U-shaped earth blocks. One of the strengths of a rammed earth structure is its monolithic form and continuous properties; however, that form is interrupted by reinforced concrete bands with different strengths, curing rates, and expansive properties. The performance of such a structure in static and seismic conditions is not well understood.

Roofing

Although several alternatives for roof construction were available in the guidelines, two methods were most common. The first consists of a reinforced concrete slab and the second was Mangalore pattern tile roofing on wooden battens with hooks for cyclone resistance. The purlins were fixed into the gable bands by simply setting them in the concrete as it was curing. The design guidelines do not specify the degree of reinforcement required for an RC slab roof, nor do they specify the attachment for roof and walls.

THE HOUSING RECONSTRUCTION PROGRAM

GSDMA was established as the executing agency for what has become a comprehensive rehabilitation program, including not only housing and public infrastructure reconstruction, but also other programs directed toward employment, emergency preparedness and response for future disasters, training for permanent skill upgradation among engineers and masons, and others. The program components, as they pertain to new housing construction in rural and peri-urban areas, are addressed in the following sections.

Program Funding

According to a September 2003 progress report by GSDMA [6], US$300 million had been released for the reconstruction of 183,461 houses. The World Bank is the primary external source of funding for the housing component. Indian and international non-profits, state governments, and private construction companies are roughly estimated to have spent at least US$58 million of their own donor funds for the construction of new houses. Cement and steel were provided at subsidized prices and the sales tax waived. Funding from the Government of India under the Indira Awaas Yojana program, which provides small grants for housing construction to below poverty line families, was also used.

Housing Reconstruction Costs

Up to 90,000 Indian Rupees (US$2000) in cash assistance was available for reconstruction of a category G5 single-family rural house. The assistance was not intended to cover electrical pointing and wiring, toilets, piped drinking water, or water storage. With a subsidy on cement and labor, the financial assistance was sufficient to build a typical 300-400 sq ft house. Table 3 contains cost estimates for a 300 sq ft house built of brick masonry with a pitched roof of Mangalore pattern tiles on a wooden understructure. The table contains cost estimates for (1) a house built during the reconstruction (cement subsidized), (2) an equivalent house built in Gujarat without any subsidy, and (3) a house built without subsidy and lacking the prescribed earthquake-resistant elements. In comparing the latter two figures, it is clear that including the earthquake-resistant elements as prescribed can increase the cost by up to 45%.

Table 3. Component and Overall Reconstruction Costs (Materials and Labor)

Component	Subsidized Materials, Guideline-Compliant	Unsubsidized Materials, Guideline-Compliant	Unsubsidized Materials, Traditional
Excavation and Layout	11	11	11
Foundation	196	196	182
Wall Masonry	243 (1:4 cement mortar)	294 (1:4 cement mortar)	194 (mud mortar)
Seismic Bands	105	246	--
Mangalore Tile Roof	139	139	139
Flooring	64	64	64
Plastering	93	93	93
Windows, Doors, Shelves	124	124	124
Total Cost	$ 974	$1,166	$ 806

Training Programs

The rebuilding and retrofitting efforts required a massive mobilization of engineers, architects and masons from local areas as well as other parts of India. Cement companies, university faculty, engineering consulting firms, and nongovernmental organizations developed and held training programs reaching over 27,000 masons and nearly 8,000 engineers and architects. Local language flyers were distributed in villages. Brochures for training masons and engineering and technical manuals were developed by several organizations.

Masons Training

Engineers, architects, and social scientists working in the field should be credited with some very creative ways of communicating the construction process and utility of certain features to homeowners, masons and unskilled labor. The level of understanding of the importance of earthquake-resistant design has increased across the board, from villagers to masons to engineers. Many masons trainees saw a significant increase in their wages as a result of the training programs. The courses ranged in scope and duration from two-day seminars to two-month long classroom and practical exercises. The basic trainings covered tool identification and usage, site excavation, material usage and preparation, mixing concrete and mortar, foundation and wall masonry construction, reinforced concrete seismic bands, roof construction, flooring, pointing, plastering. There was a much greater focus on covering the basic elements of construction (i.e., topics appropriate for participants who had no or little previous experience in the housing construction sector) than advanced topics such as reinforced concrete and earthquake-resistant design. In one example, only 4 of 40 demonstration hours (14/200 total hours) was spent on earthquake-resistant construction practices, such as opening size, shear connectors, mortar strength, and reinforced concrete (TISS [12]).

Even though the number of persons trained in masonry construction is staggering, not all the trainees sought and found work as masons after being trained. In one post-training follow-up study, only 33 out of 88 respondents were masons doing masons work (TISS [12]). Job opportunities are limited in Kachchh especially during times of drought, and some trainees attended the training for the daily stipend and free toolkit, without intending to work in the housing sector. In other cases, the attendees were not willing to travel from their village to find work.

Compliance with Construction Guidelines

To ensure the guidelines were followed, cash assistance was doled out in installments. The first installment was given prior to construction. At two subsequent points (plinth level and lintel level), third party inspectors from the National Council for Cement and Building Materials (NCCBM) were dispatched to check the overall quality of construction and inclusion of the required elements. Once the inspections were completed, the additional disbursements were released. As of August 2003, inspectors had made 233,866 visits to houses. An overall conformance rate of 84% was reported in July 2003 by GSDMA [13], which was based on weighting the presence of required elements with overall construction quality.

Approach

Owners with G5 category houses had three different options for obtaining a reconstructed house. They could rebuild themselves with cash assistance (owner-driven approach), partner with a non-profit to rebuild the house with partial cash assistance (donor-facilitated approach), or move into a house built by an non-profit or government organization (donor-driven approach).

Owner-Driven Approach

Approximately 77% of the homeowners chose to build the house themselves. In most cases, reconstruction took place at the original location. The owner could choose the floor plan, layout, and building materials, hire masons and artisans, and seek advice from government-trained engineers.

Compliance with earthquake-resistant design guidelines among the owner-built houses varies. NCCBM audit reports indicate that at least 30% of the houses audited were missing at least one earthquake-resistant design element. The author’s own observations of a small number of owner-built houses revealed an absence of roof bands and gable bands and violations of the opening size restrictions.

Donor-Facilitated Approach

In the donor-facilitated approach, owners were given up to half the government cash assistance package, and the non-profit facilitated the construction of the house using its own donor funds. The homeowner was usually expected to contribute something to the process, such as labor and materials. Most of the reconstruction took place in the original location. The level of involvement of the non-profit in the construction process varied, with some deciding on floor plans, hiring masons, procuring materials, and others simply helping owners build their own houses with technical advice. Some non-profits employed or contracted with engineers or architects to design the house.

Non-profits played a critical role in housing reconstruction and many other programs. According to KNNA [14], 102 non-profits were working in the permanent shelter sector alone. Many of them had not been involved in a housing construction project prior to the Bhuj earthquake, and a wide range of skills existed among the field staff of the non-profits interviewed by the author, from very detailed understanding of the elements of earthquake-resistant construction, to difficulty in explaining why a window could not be moved closer to a corner. Generally, those houses built by non-profits with partial cash assistance from GSDMA had a higher conformance rate than owner-built houses, although omission of gable bands and vertical steel reinforcing bars occurred. NCCBM audit reports indicate that only 10% of the non-profit built houses were missing one or more earthquake-resistant design element.

Donor-Driven Approach

There is clearly some overlap between the donor-driven and the donor-facilitated approach; however, two distinctions set them apart. In the donor-driven approach, the homeowners had little, if any, role in the design and construction. And, the houses were built primarily with donor funds. In the donor-driven approach, houses were built en masse by government or non-profit organizations, usually at relocation sites. The houses were typically constructed by contractors and the homeowners were relatively uninvolved in the construction and decisionmaking process. The houses built by non-profits were usually entirely funded by their own donor sources, and thus not subject to the inspections as the other houses. Regardless, many of the non-profits followed or exceeded the reconstruction guidelines in order to preserve their reputation and gain the homeowners' trust. According to NCCBM reports, houses built by the Government of Gujarat complied with all earthquake-resistant building norms.

It should be noted that several relocation villages built by donors remained uninhabited during the author's visit in 2003. Reasons cited for the delay were (1) awaiting water and power (2) awaiting formal ceremony (3) beneficiaries had not yet been chosen (4) beneficiaries had refused to occupy the houses until they had endured 1 year of aftershocks without damage.

ARCHITECTURE PREFERENCES AND SUSTAINABLE CONSTRUCTION PRACTICES

Architectural Preferences

During all post-disaster reconstruction or large-scale housing projects in developing countries, some general rules regarding architecture and appropriateness of design and construction materials should be followed. The following is a non-exhaustive list of characteristics each house should possess, based on observations in the Bhuj earthquake reconstruction.

Fig. 12. Circular CSEB house with pitched roof

Climatically Suitable

The materials and form of the structure should be suitable to the climate. For hot climates, thick (earth, masonry) walls are preferable to thin (prefab panels, asbestos or GI sheets). Pitched roof houses (Fig. 12) are better than flat roofed houses for air circulation; however, a surprising number of houses were built with flat, heavy RC slab roofs (Fig. 13).

Fig. 13. Flat roofed house with preparations for second story

Expandable

Houses should be structurally capable of supporting extensions, additions, and modifications with inexpensive and locally available skills and materials. If a structure is built with a flat roof, it is likely that a second story will be added as the family expands (Fig. 13). Many foundations for one-story structures with flat roofs were not designed with the possibility of a second story in mind.

Easy to Maintain

It should be easy for the homeowner to maintain the structure using inexpensive materials and traditional methods. The integrity of the structure should not rely on removable parts, such as nuts and bolts, which can be misplaced or used for other purposes. If a prefabricated element is damaged or needs to be replaced, it is very difficult for a rural, remote homeowner to procure the needed element and install it once the builder or contractor has left the village.

Architecturally and Spatially Appropriate
The architecture and space should be appropriate to the lifestyle of the homeowners. Covered verandahs and enclosed (private) areas for cooking are essential components for a comfortable life in Kachchh, yet many organizations omitted these items from their design. It is also preferential to have doors and windows open to a courtyard, as opposed to a busy street. Some homeowners have blocked in openings and created others in a more preferable locations. Also, provisions for shelves, storage spaces, fan fixtures, and traditional or religions features were absent in some of the donor-built houses.

Long-Term Change in Construction Practice
Clearly there has been an increased understanding of the prescribed earthquake-resistant design elements among the mason/artisan community, homeowners, and the rural population at large. Whether or not the masons training programs were effective at building capacity and creating a long-term change in construction practices remains to be seen. A follow-up study by a cement company with one of the most ambitious and comprehensive post-earthquake masons training programs showed that less than 40% of the structures built by trained masons during the height of reconstruction had *any* earthquake-resistant features (TISS [12]). Evidence indicates that, in the absence of funding, inspection, and engineer/non-proft oversight/facilitation, implementation of GSDMA-prescribed earthquake-resistant design elements will likely cease, even when trained masons are doing the building.

This is primarily due to cost, and secondarily, due to lack of skills and materials. In the Bhuj earthquake reconstruction, RC bands were the critical component in changing the traditional construction method of unreinforced masonry to an earthquake-resistant one. However, forming, casting, and curing a reinforced concrete element was considered a specialty skill and not thoroughly taught even in the most comprehensive masons training programs. Also it is presumed that material banks and subsidies will be discontinued at the end of the reconstruction program. And most critically, reinforced bands add over 25% to the cost. It is unlikely that RC bands will continue to be used effectively in the absence of funding, technical oversight, and enforcement.

REPAIR AND RETROFITTING

According to GSDMA [6], 513,466 houses were categorized as G2, G3 or G4. According to the IAEE Guidelines [4], strengthening is necessary for houses in category G3 and G4 and desirable for category G2. A guideline covering repair (patching of cracks and superficial defects), restoration (restoring lost strength of structural elements), and retrofitting (upgrading the seismic strength) was released in March 2002 by GSDMA[15].

Technical Aspects of Retrofitting
The main elements of the strengthening approach are ferrocement horizontal belts and vertical straps, ferrocement patches, vertical reinforcement, cast in situ bond elements (through hooks), shear connectors, and in the case of pitched roofs, guy lines and bracing. Table 4 summarizes the guidelines.

Table 4. Guidelines for Retrofitting of Low-Rise Dwellings in Kachchh, GSDMA [14]

Feature	Requirements
Layout	Add crosswalls or pilasters to reduce unsupported wall length; fill in large openings
Ferrocement horizontal belt (Fig. 14)	150mm wide 12 gauge 25 x 25 mm welded wire mesh embedded in a 35mm thick microconcrete (1:3 cement mortar), min clear cover 15 mm. Anchored to the wall at min 1m horizontal spacing using shear connectors, modified bond elements, or large diameter iron nails with washers; also, two horizontal steel bars can be synched together around building, with mesh attached to bars. Belts typically at lintel and gable levels. Interior and exterior belts should be connected together.
Ferrocement vertical straps	Identical to belts, except vertical, and tied into horizontal belts and shear connectors along vertical length.

Ferrocement patch	Identical to belts, except they do not encompass the entire building perimeter; used to repair wide cracks, strengthen wall-to-wall connections at corners.
Vertical corner reinforcement (Fig. 15)	HSD bar from 450mm below floor level of ground floor to roof level. A 90^{o} bend with 30 cm min length leg anchored in concrete or within foundation wall. Vertical bars inside and outside wall, connected with horizontal hooks at vertical increments <750mm. Tied to the horizontal ferrocement bands.
Cast in situ bond elements	To provide connection between parallel wythes of stone masonry. One hole every 0.7 sq m of wall; cleaned, wetted. 8mm dia HSD bar with hooks at both ends placed in hole, filled with 1:2:4 concrete, cured 7 days.
Shear connectors	8mm dia HSD rod, hook at one end, L-shape at the other; L projection tied to the ferrocement belt. Like bond element, hole is cleaned, wetted, filled with concrete.
Roof reinforcement	Various measures to increase integrity of roof, such as replacing the roof structure entirely, adding guy wires, tile hooks, diagonal bracing for gable walls, tying walls into RC bands.

Fig. 14. Wire mesh and tie-rods for ferrocement belt at lintel level

Fig. 15. Vertical bar with shear connectors

Comments on the Guidelines and Lessons from Practice

Horizontal Belts, Straps and Patches

The ferrocement belts, especially if connected together with each other and the vertical bars at the corners, are the most important aspect of strengthening. Such an approach has been shown to increase both the shear and flexural strength of the wall. EERI [16] reports the results of a study by Zegarra and colleagues (in Spanish), indicating that welded wire mesh in horizontal and vertical straps simulating beams and columns was the best method for retrofitting existing adobe houses. Houses with this retrofit technique were capable of withstanding the Arequipa, Peru earthquake of 2001 while nearby unretrofitted houses collapsed. Tolles et al. [17] tested various retrofitting systems for historic adobe structures, including horizontal and vertical straps, ties, vertical center core rods, and improvements in anchoring the roof to the walls. The researchers found that vertical straps worked well for reducing the risk of out-of-plane wall collapse, although the straps had minimal effect on crack initiation. Meli et al. [18] indicated that an interior and exterior welded wire mesh mortared to the entire wall surface was better than a bond beam alone.

In practice, belts are most easily implemented on a square structure. For an L-shaped plan, it is difficult to get the welded wire mesh and tie rods to lie flat, ensuring a continuous connection to the building and adequate cover of microconcrete.

Cast In Situ Bond Elements

In practice, the holes that were made for the shear hooks were very large. Also, in order for this technique to be effective, the concrete should be placed under pressure, or a non-shrink grout used. Neither technique was observed in the field.

Funding and Implementation

Owners with houses in damage categories G2, G3 and G4 were given cash assistance for repair, restoration and retrofitting. According to GSDMA [6], 513,466 houses were categorized as G2, G3 or G4. An additional 414,903 classified as G1, for which no cash assistance was provided. As of September 2003 [6], approximately US$100million in World Bank funds had been disbursed for the repair, restoration, and retrofitting of 413,599 G2-G4 category houses. It has been observed by the author that very little cash assistance has actually been used for strengthening measures. The cash assistance, if used at all on the house, was typically put towards repairs only. In other words, only a small fraction of the total population of G1-G4 houses underwent complete retrofitting. Nearly 1 million houses remain vulnerable to further damage and collapse. The possible reasons are discussed in the following sections.

Lack of Enforcement

Unlike the new constructions, cash assistance for the repair/restore/retrofit program was disbursed in one installment only. In addition, only a fraction of the houses for which assistance was disbursed were actually inspected in the quality control auditing program. Further, the degree of strengthening (from repair to retrofitting) was the decision of the homeowner; the GSDMA did not insist on retrofitting. In a typical month, approximately 400 houses under repair/restoration/retrofit would be inspected. Approximately 40% of the houses had retrofitting done generally as per the GSDMA guideline. Approximately 30 percent had undergone only general crack repair by carving out a V-groove and plastering, and the remainder lie somewhere in the middle.

Lack of Funds

Retrofitting a 300 sq ft single story, rural Kachchh house of random rubble masonry with a pitched, tiled roof would cost approximately US$300 in materials. For estimating purposes, the retrofit includes interior and exterior connected mesh bands at the lintel and gable levels; a vertical interior and exterior strap connecting the apex of each gable to the lintel band, shear connectors for every 0.7sq m of wall area, and diagonal bracing for the roof structure and gable walls using GI wires. GSDMA [6] indicates that homeowners were given on average $120 for a category G2 house, $260 for a G3 house, and $560 for a G4 house.

Regardless of whether the cash assistance provided through GSDMA was sufficient to pay for materials and labor required for a full retrofit, in many cases the owner used the cash assistance provided for repair, restoration and retrofitting to satisfy more urgent needs. A satisfaction survey done by the non-profit KNNA [14] indicated that 54% of the respondents would have rather had livelihood support (e.g., assistance finding work) instead of housing support after the initial relief phase ended. It is very difficult to convince a person with limited financial resources to spend money to strengthen a structure that is cracked but livable. In a follow-up study to a month-long, hands-on masons training program given during the height of the reconstruction efforts, only 10/88 (or 11%) of the respondents actually retrofit their own home TISS [12].

Lack of Timely Expertise

Shortly after the earthquake, GSDMA released a simple Gujarati language flyer illustrating the fundamentals of strengthening techniques. The detailed guidelines for repair, restoration, and retrofitting were not released until March 2002, a full 14 months after the earthquake. A capacity building program began in January 2003 and finished in July 2003, in which one demonstration building in each of 422 buildings was retrofitted by trainees. According to Karani [19], only a "handful" of trainees retrofit their own homes after the demonstration program. Outside the capacity building program, another 7 non-profits have been involved in the retrofitting of 1768 houses in Kutch. In other words, even if the homeowner had in mind to retrofit, s/he was not equipped with the skills and knowledge necessary to do the retrofitting. Retrofitting was a topic not included in most masons training.

Lack of Easily Accessible Materials
The prescribed retrofitting guidelines rely heavily on steel, welded wire mesh, and cement. Material banks were set up in the reconstruction program, but such banks were not included in the capacity building program. In other words, even if a homeowner had in mind to retrofit after the demonstration program, materials were not easily available.

Lack of Need
Some homeowners with category G1-G4 houses were able to build a new house by entering into a partnership with a non-profit organization.

FUTURE RESEARCH

Foundation Design and Construction
Further research is required to illustrate the potential for and impact of differential settlement under static and seismic conditions for the foundation approach using cobbles flooded with loose sand. This foundation practice is prevalent throughout India (INTERTECT [20]), and a low-cost alternative should be identified and tested, such as manually crushed, angular hardcore. The level of energy dissipation provided by the common and proposed approaches should be quantified so that the benefits of a reduction in energy transfer can be weighed against the consequences of settlement.

Improved Masonry Wall Design and Construction
Experimental research has shown that brick and block masonry houses built to the prescribed guidelines are capable of resisting strong shockwave inputs without collapsing. Improved masonry and lower cost masonry and reinforcing methods should be developed using appropriate technology, such as stabilized rammed earth or earth blocks. The effect of including seismic bands in structures made out of stabilized earth is not well understood.

Retrofitting
Despite numerous studies on retrofitting techniques for low-rise, masonry and adobe dwellings in developing country settings, continued research is needed to confirm the effectiveness of existing methods and identify lower cost means of strengthening damaged or vulnerable houses. The research should focus on locally available materials that require minimum skill to implement.

Masonry Training and Awareness
Long-term monitoring of the impacts of masons training and public awareness campaigns on permanent changes in construction practice should be made a central part of any funded post-disaster reconstruction program.

ACKNOWLEDGEMENTS

This research was funded by the J. William Fulbright Foreign Scholarship Board. Prof. Ravi Sinha and his graduate students were very gracious hosts during the time I spent at Indian Institute of Technology, Bombay. Numerous individuals from international and local non-profits, private businesses, and government organizations were very generous in sharing their time and experiences. Members of KNNA were particularly helpful in organizing shared transportation to several villages. The contributions of these individuals are gratefully acknowledged.

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