Shelter, Retrofit, and Reconstruction of Housing

A Summary of Previously Used Strategies in Developing Regions Applicable for the 2015 Lamjung, Nepal Earthquake

A Report Prepared for the World Bank by

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1. Executive Summary

The April 25, 2015 earthquake in Nepal caused significant damage to structures in many parts of the country. Rural areas were especially affected because of the location of the fault rupture, the relatively large rural population, and poor access to aid and relief. Since residents are particularly vulnerable to the lasting effects of earthquakes, it is crucial to mitigate the damage to houses through temporary shelters, semi-permanent housing, and permanent housing.

This report intends to compile information on shelter, retrofit, and reconstruction strategies following previous natural disasters, particularly earthquakes. The purpose is not to recommend a specific strategy for shelters or reconstruction, but to provide a brief overview of potential options. Choice of one or more strategies would require a detailed ground assessment, and evaluation of the provided options based on cultural, logistical, and engineering considerations.

The geography and current housing stock of Nepal are studied to inform in the availability of resources for reconstruction. When assessing shelter and reconstruction methods, the locally prevalent materials need to considered. An overview of common construction materials in Nepal, namely concrete, stone, brick, and wood, is provided. While all damage reports are still preliminary, common types of damage to the housing stock are presented for the purposes of evaluating retrofit and reconstruction strategies. Finally, potential temporary shelters whose materials can be reused for permanent housing, simple retrofit strategies, and reconstruction methods cognisant of the local culture are presented.

The information in this report comes from technical resources from the Red Cross, Earthquake Engineering Research Institute, and others. It has been compiled by PhD Candidates at Stanford University studying structural engineering and earthquake engineering. Ezra Jampole's research focuses on developing inexpensive seismic isolation systems for light frame structures. Reagan Chandramohan's research focuses on investigating the effects of duration of earthquake ground shaking on the collapse response of structures. Matthew Bandelt and Timothy Frank are investigating the use of high performance fiber reinforced cement-based composites for enhanced structural and life-cycle performance.

2. Introduction

2.1. Geography and Climate

Although the geography and climate of Nepal are highly diverse, the country can be broadly divided into three distinct regions: the Mountains in the north, the Terai plain in the south, and the Hills in between, shown in Figure 2.1. Nepal rises from 65 m above sea level to more than 8,000 m over an average distance of about 200 km as indicated in Figure 2.2. Most of the early settlements in Nepal were scattered in the hills and the valleys in the central portion of the country because of the steep mountainous topography in the north and the hot, humid climate.

Figure 2.1. Map of Nepal

The Terai region today consists of a fertile plain, rich in soil and forests. The southern border with India is open and many business transactions take place including construction material imports. The Terai is well connected by roads and a main east-west highway. Gradually, the Terai has become densely populated and urbanized. In the late 1980s, it provided 65% of Nepal's cultivated area, 34% of its road mileage, and having 62% of its industries. Except for Kathmandu, Pokhara and Tansen, most of the fast growing towns are in the Terai.

The central hills are home to the two largest cities in Nepal: Kathmandu and Pokhara. Urban growth rate is 6.4% per year (as of 2005), but the level of urbanization is only 14%[1], suggesting that much of the population still lives in villages and rural areas. Kathmandu, the capital city, is

[1] Bonapace, Caterina, and Valerio Sestini. *Traditional materials and construction technologies used in the Kathmandu valley*. United Nations Educational, Scientific and Cultural Organization, 2003.

built on top of a dry lakebed, so the soil there is soft and fertile, yet susceptible to dramatic seismic ground motion amplification effects. The hills contain several highways, through which commerce and logistics flow with relative ease.

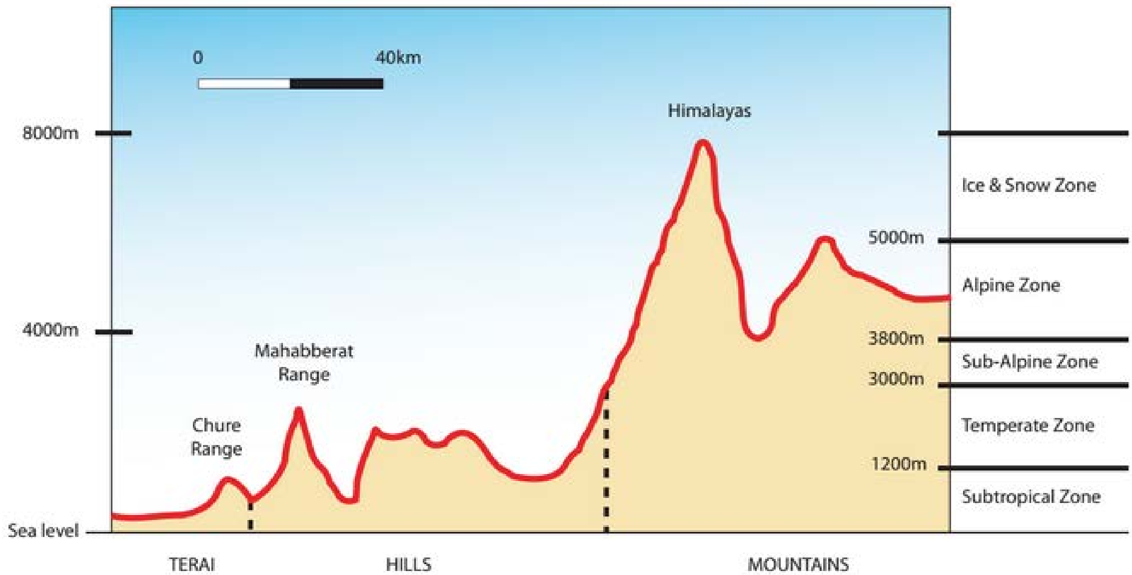

Figure 2.2. Nepal's topography

The mountainous northern region is home to only about 10% of Nepal's population. Travel is difficult due to the elevation change and harsh, cold climate. Villages are sometimes several days away from the nearest road on foot.

Temperature and precipitation vary widely throughout Nepal. An average temperature drop of 6°C occurs for every 1,000 m gain in altitude[1]. In the Terai, summer temperatures exceed 37°C and remain above freezing around the year. In the mountains, summers are pleasant, while winter temperatures drop below freezing. The monsoon season occurs from early June through September, during which moist winds blow from the southeast. The Pokhara Valley receives the most rain, while in general, precipitation diminishes heading north. Deforestation, forest fires, steep terrain, and heavy rains all contribute to a high risk of landslides on hillsides throughout the country.

2.2. Cultural Considerations

Nepal has more than 150 different ethnic groups[1]. These groups often specialize in different kinds of skilled labor, and build their houses following a distinct architecture, employing a unique set of building materials, e.g. bricks, wood, and construction techniques. The Kathmandu Valley joined the World Heritage List in 1979. Throughout the reconstruction phase, it will be important to maintain the cultural heritage with respect to architectural style. Tourism, in part, relies on the traditional style of architecture as part of Nepal's cultural heritage.

Housing construction can be an important and symbolic event in Nepal. Building your own house is something every Nepali aspires to be able to do; it is an honor and a symbol of success. Stone plates are laid underneath the foundations that symbolically represent the base of the universe. A ceremony is usually held in which the foundations are laid and the house-owner puts a small vase with coins and rice grains under the stone plates[1], an offering to the house and soil gods. Further ceremonies can take place at later stages of the house construction.

3. State of Housing Prior to the April 2015 Earthquake

3.1. Types of Houses and Living Conditions

Most of the houses in urban and semi-urban Nepal fall into two broad categories: reinforced concrete framed buildings with masonry infill walls (locally known as pillar-wala ghar) and unreinforced brick masonry buildings with wooden frames (traditional Newari house)[2]. In urban areas, about 70% of houses are made of concrete and brick masonry; about 25% are made of stone masonry; and the remaining 5% are temporary in nature, made of wood or bamboo with mud plaster and thatch or plastic sheet roofs[1]. Rural housing consists predominantly of, usually oval-shaped, unreinforced rubble stone masonry houses with timber roofs.

The practice of constructing traditional Newari houses goes back more than 200 years. These houses are concentrated in the Kathmandu valley, and are typically between two and four stories tall. Several are often built connected to each other in a large complex surrounding an interior courtyard, called Chuka in Newari. Often, families who live in the interior of the housing group may have to walk through one or more other homes to get out to the public street. The first floor is commonly reserved for a storefront, workshop, or store-room, as dampness makes it unfit for habitation. The top story is used as a kitchen and eating room. The middle stories are used for living and sleeping. There is usually no interior latrine or running water. In plan view, traditional houses are rectangular, with a length to width ratio of less than 2, often divided by a central interior partition. The size is between 4 and 8 m long by approximately 6 m deep. The ratio of height to width is typically less than 2 as well. Ceilings are low, around 1.8 m, and consistent across all floors of the home and uniform across entire town[3]. Most houses have steep (40-50 degree) pitched roofs topped with clay tiles[1]. A cut-away of a typical Newari house is shown in Figure 3.1.

[2] "World Housing Encyclopedia — an EERI and IAEE project." 2002. 22 May. 2015 <http://www.world-housing.net/>

[3] Pradhan, R. 2000. Seismicity and traditional buildings of Kathmandu valley, Nepal. In *Proceedings of the ICOMOS international wood committee (IIWC), Earthquake-safe: lessons to be learned from traditional construction, international conference on the seismic performance of traditional buildings.*

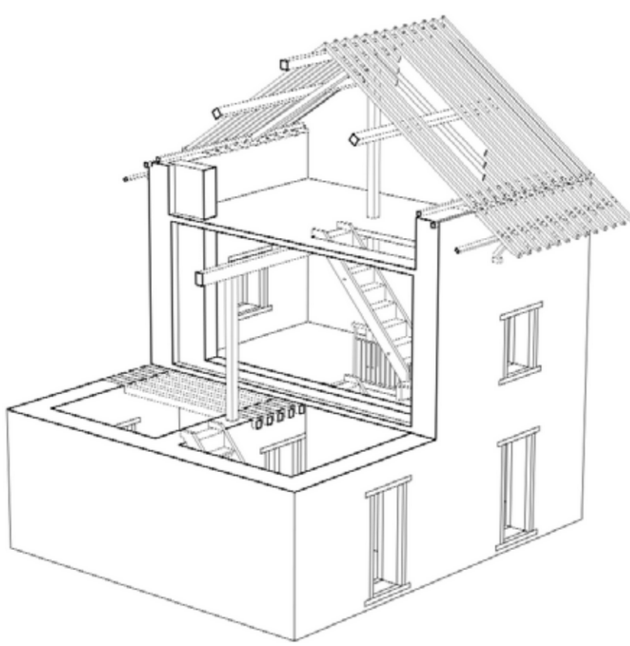

Figure 3.1. Traditional Newari house[1]

Of the traditional Newari houses, the period in which they were built can affect style and finishes. The Malla style is the oldest and characterized by a horizontal window style with square latticed openings. Around the year 1800, the Shah style appeared, which is characterized by a more vertical window orientation. By the end of the 19th century, the Rana style brought forth larger windows almost one story high, and the lattice work disappeared. The Malla style dominates the landscape in most urban areas.

Since the early 2000s, high rates of rural-urban migration have put immense burdens on the city's infrastructure. Still, only 440 thousand homes are located in urban areas of Nepal, while 3.6 million remain in rural areas per the 2001 census. Urban populations have been subjected to rising prices of land, and thus squatters have grown to 10 percent of the urban dwellers. Average households across the country contain 5.4 persons (4.9 in urban areas). The number of households per house is 1.2 (1.5 in urban areas), suggesting families are much smaller in urban areas than in rural[1].

Densification of urban areas has led to the construction of taller buildings through incremental construction (see Figure 3.2), and houses that are four to five stories are no longer uncommon. Additionally, apartment complexes of a dozen stories or more have appeared on the Kathmandu skyline. Building codes exist, but are rarely enforced due to economical considerations.

Figure 3.2. Incremental construction of an RC framed building with masonry infill walls[3]

3.2. Structural and Construction Details

Traditional Newari houses are constructed of usually unreinforced brick masonry walls, supported by wooden frames. The original Newari building techniques have remained relatively unchanged over the centuries. This is mainly due to a fairly unchanged way of life. Reports are mixed as to the quality of construction materials such as clay bricks, workmanship, and even whether or not bricks are standardized in geometry and size. Some are hundreds of years old, and are likely to have survived previous earthquakes due to their extremely thick walls (approximately 18 inches thick). Wooden beams run across the ceilings and rest on top of the load-bearing walls[1].

Modern houses are usually reinforced concrete framed structures with brick masonry infill walls (Figure 3.2), and are known locally as "pillar-wala ghar", which literally translates to "house with columns". Gravity and lateral loads are resisted by both the RC frames and the masonry walls. The RC frame may or may not be connected to the masonry walls by means of horizontal or vertical reinforcement. These RC frames are usually non-engineered structures, and commonly have seismically-deficient non-ductile detailing. Nonetheless, this is currently the most prevalent form of urban construction. Nepal has not suffered a major earthquake since the introduction of this form of construction, so there is a general misconception among the public that this is the safest type of house than can be constructed. This is the preferred form of construction for any family that can afford it[2].

House foundations are made from square brick footers arranged above a stone base course. Typically, wall thickness is 9 inches (the length of one brick), but interior partition walls may be only 4 inches thick (the width of one brick). The floors of pillar system houses are usually reinforced concrete slabs tied into the frame with reinforcing bars. Reinforced concrete plinth rings are understood as a way to increase seismic resistance, and can be found sporadically.

Rural construction consists predominantly of, owner-built, usually oval-shaped, uncoursed rubble stone masonry houses with timber floors and roofs. The stone masonry walls are laid on strip foundations, also made of uncoursed rubble stone. Since the walls are mostly unreinforced, they have very poor seismic performance, and are extremely susceptible to in-plane and out-of-plane failure[2].

In rural areas, such as the Pyangaon village, an entire community is usually involved in building a house[3]. Construction is carried out in the winter months when field work is not as demanding. One or more construction experts would be called in from neighboring villages to supervise the work. In general, skilled labor in the plumbing, masonry, and carpentry sectors is lacking, as many capable men migrate to the Arabian Peninsula or East Asia for work and send remittance back to their families in Nepal[4].

In the urban reality of Nepal, housing is more a personal responsibility of the household than a government responsibility. Owner-built housing is still by far the most common approach in housing construction in Nepal (85%); typically an individual fulfils the roles of financer, planner, manager, and sometimes designer and builder too[1]. About 73% of urban homes are either completely self-built or with contracted labor, but there is a growing trend of owners outsourcing part of the planning and construction job to third parties[1]. In rural areas, the owner-built format is still the predominant form of housing construction. Private developers have only recently been introduced into Nepal's urban areas.

3.3. Materials

Principal building materials in Nepal are concrete, brick, stone, and wood. Most basic building constituents are produced in Nepal, with stone quarrying, sand mining, and brick making being a major source of employment in the Kathmandu Valley and the Terai. Other industrial products like cement, steel reinforcement, and Corrugated Galvanized Iron (CGI) sheets are also produced in the country, although the raw materials for these products are mostly imported[1]. Items such as nails, hinges, glass, and aluminum are imported mainly from India or China.

3.3.1. Bricks

The types of clay used, the way bricks are fired, and the way they are used in construction comes from knowledge passed down over many generations. Bricks are fired in traditional kilns, and can take several weeks to gain proper strength. The brick quality is, on average, low, as manufacturers often cut corners to increase profits. The general principle when buying bricks is that larger kilns produce cheaper products while smaller kilns produce better products[1].

[4] "Nepal's Young Men, Lost to Migration, Then a Quake" 2015. 22 May. 2015 <http://www.nytimes.com/2015/05/05/world/asia/nepal-already-stripped-of-young-men-faces-a-darker-problem.html>

Grey and black clays are most commonly used to manufacture bricks and tiles. The strength of bricks produced in the Terai are considered superior to those produced in the Kathmandu Valley. Furthermore, Chinese bricks generally have a higher compressive strength compared to the local bricks. Due to environmental regulations, many Chinese brick factories have closed, and only one remains in the Kathmandu Valley[1].

While bricks are roughly 9 in by 4 in in plan, there is no standardized brick dimension used in Nepal, which often results in uneven wall thicknesses. Walls are traditionally built by constructing two brick wythes, with the space in between filled with a mix of clay soil and pieces of broken brick. Through-bricks and wall-ties are not common. Mud mortar is commonly used in between brick layers of older houses, whereas newer houses use cement mortar.

Roof tiles are made from the same clay as masonry bricks. They are flat and have two longitudinal grooves where one tile can be fitted to the next, as shown in Figure 3.3.

Figure 3.3. Clay roof tiles[1]

3.3.2. Wood

Kathmandu means "city of wood," and timber is one of the oldest and most extensively used building materials in Nepal. It is used in house construction for doors, windows, staircases, flooring, roofing, and wall panels, as well as for structural members such as columns, beams, and trusses. Timber flooring, bands, and corner knee-braces are sometimes used in home construction. A typical timber flooring system is shown in Figure 3.4.

Figure 3.4. Timber floor[5]

Sal, a type of tree found in the Terai, is a high quality wood that is very strong and durable. The trees are big and grow as high as 30 meters, with a large diameter trunk that provides for as large a structural element as is required. Apart from the Sal, the most common species used for construction are Gwaisasi (Schima Wallichi), Salla (Pinus Roxburghii) and Utis (Alnus Nepalensis)[3]. All are found growing on the slopes and hills around the Kathmandu Valley, but large-scale harvesting of trees is primarily done in the Terai region today since deforestation of the hills around the nearby valleys has left the region with inadequate trees to meet market requirements.

3.3.3. Stone

Stone is perhaps the oldest and most abundant building material found in Nepal. It is also the largest visible mineral resource in the country. The major varieties in Nepal are limestone, sandstone, dolomite, granite, quartzite, and marble[1]. Stone is quarried in the surrounding hills and mountains of the Kathmandu Valley, particularly in the south near Parping village, Kirtipur city in Macche Narayan Gaon, and near Chobar gorge. Marble stone can be found near Godavari[3]. Other stones are found along the river beds and are neither cut or squared. The two main types of stone are black stone and white stone; both are metamorphic rock with finely packed grains. The white stone is more easily quarried than the black stone, while the black stone is stronger and more resistant to weathering elements.

Houses may be made completely out of stone, or stone may be used for portions of the house. The brick walls of Newar houses, for example, stand on stone foundations. Stone masonry walls are supported by continuous stone masonry strip footings. In some rural adobe houses, the first floor walls are also made of stone. In urban areas, entranceways around doors may be made of stone. Stone may be stacked without the use of mortar, or mud or cement mortar may be used. Like bricks, stone may be used to construct double-wythe walls. Examples of stone walls are shown in Figure 3.5.

[5] Bothara J. and Brzev S. 2011. *A Tutorial: Improving the Seismic Performance of Stone Masonry Buildings.*

Figure 3.5. a) Cross section of a double-wythe wall and b) gable wall made of stone[4]

3.3.4. Iron and Steel

Despite the presence of iron ore mines in the country, iron is not used in Nepalese house construction. Nearly all joints and hinges are made using only wood. There are five CGI sheet manufacturing plants in Nepal[1]. All are privately owned and are located in the Terai. Due to its light weight and ease of transportation, CGI sheets are commonly used as roofing material in houses in the hill and mountain regions. There are thirty-five plants that manufacture reinforcement steel rods and structural steel sections in Nepal[1]. Again, all are privately owned, and most are located in the Terai. The demand for iron and steel is met within the country.

Steel reinforcement is used in the frames and floor slabs of concrete frame structures (pillar-system houses). Reinforcement bars are used horizontally to tie the corners of the columns into the brick masonry walls, but no vertical steel is used in the walls. Recognized as a benefit against seismic loading, plinth layers of steel reinforced concrete are constructed about 3 feet above ground level in some houses.

3.3.5. Adobe

Adobe refers to sun dried bricks made from clay earth. Adobe is common in the agrarian and rural areas surrounding the Kathmandu Valley, particularly along the Bagmati River[3]. An example of an adobe house is shown in Figure 3.6. Bricks are usually made with earth found near the building site to minimize transportation costs. They are molded and left to dry outside. The same earth is used for making the mortar. Using adobe lessens energy and environmental impacts when compared to traditional bricks. Additionally, little skill is required to make adobe. Adobe blocks can be compacted by using a machine to increase compression strength; it is unknown how widespread the practice of compacting blocks is.

Figure 3.6. An adobe house[1]

3.3.6. Bamboo

In 2005, a local NGO called RES-Nepal, with support from the Global Environmental Fund of UN and International Network of Bamboo and Rattan (INBAR), introduced a bamboo eco-housing in the Terai[1]. The houses are examples of earthquake resistant, low cost housing solutions with a proposed durability of over 30 years. The houses are made of prefabricated bamboo panels supported by a wooden frame. Stone and concrete make the foundation upon which the bamboo house is erected. Finally, cement mortar seals the walls. This technique was promoted for the rural poor, but are also considered suitable for low income urban communities. It is unknown how prevalent these bamboo houses are, and how they have been received in various communities, but bamboo is locally grown throughout most of lowland Nepal.

3.3.7. Cementitious Materials

Lime mortar is a hard, quick-drying material often spread across the brick facades of houses for additional strength and aesthetic reasons. In villages, women commonly assume the role of plastering their houses.

The use of cement has recently become more prevalent in Nepal. It is now widely used for both walls and plasters, as well as for reinforced concrete construction[3]. A large-scale cement production plant is located along the Bagmati river near the Jalbinayak temple complex, where limestone is quarried nearby[3]. The annual demand for cement in Nepal is about 2.5 million tons; the 54 domestic cement factories meet only about 20% of this demand and remaining 80% comes from

India[1]. It is believed that the environmental legislation and lack of a reliable energy source (as opposed to lack of raw materials or the ability to extract them) limits cement production in Nepal.

4. The April 25, 2015 Earthquake

4.1. Background Information

On April 25, 2015 at 6:11:26 local time (UTC), a magnitude 7.8 earthquake struck Nepal eighty kilometers northwest of the capital, Kathmandu, as shown in Figure 4.1. Seismic energy was directed eastward with approximate fault area dimensions of 120x80 kilometers[6]. The hypocenter is estimated to be at 28.15N 84.71E, at a depth of 15 km[7].

Figure 4.1. Location of the epicenter of the April 25, 2015 Nepal Earthquake

The Kanti Path (KATNP) station in Kathmandu, Nepal was the sole instrument to capture shaking near to the earthquake at 27.7120N, 85.3160E. The epicentral distance to the station is 60 km, and the nearest distance of the station to the fault is 14 kilometers. The measured peak ground acceleration was 0.16 g, with a peak ground velocity of 107 cm/s. The ground motion acceleration time history, velocity time history, displacement time history, and 5% damped response spectra, as reported by the Center for Earthquake Strong Motion Data (CESMD), are shown in Figure 4.2.

The combination of relatively low peak ground acceleration with very high peak ground velocity warrants further investigation into the local site conditions at the recording station, the response of the structure on which the sensor was mounted, and the accelerogram processing parameters.

[6] National Earthquake Information Center (NEIC) and United States Geological Survey (USGS)
[7] Center for Earthquake Strong Motion Data (CESMD)

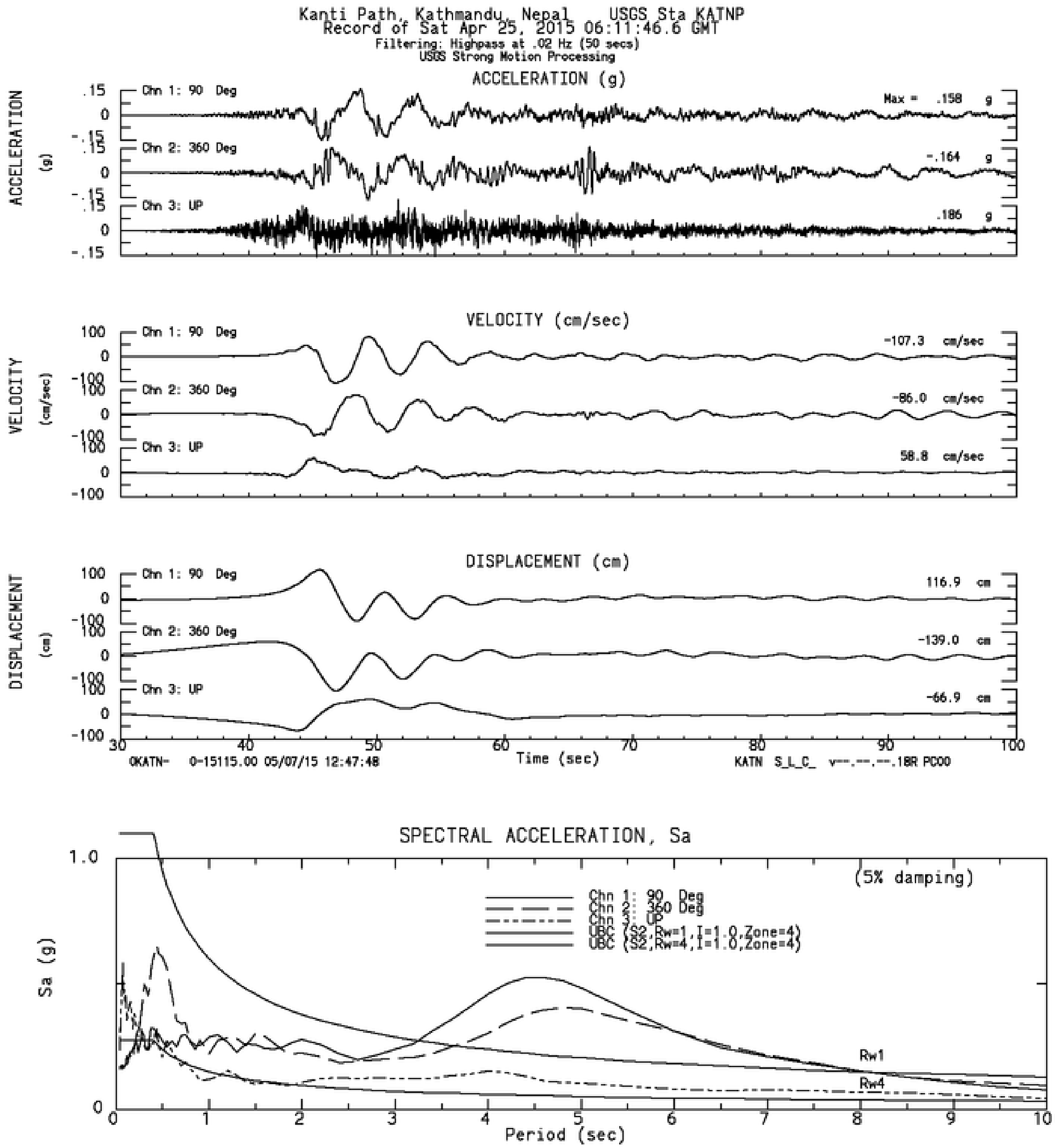

Figure 4.2. Acceleration, velocity, and displacement recordings, and 5% damped response spectra at the KATNP station

Following the main shock on April 25, 2015, there have been numerous aftershocks in Nepal, including a magnitude 7.3 earthquake on May 12, 2015, eighty kilometers east-northeast of

Kathmandu[8]. A map of the region and location of the epicenters of the aftershocks is shown in Figure 4.3.

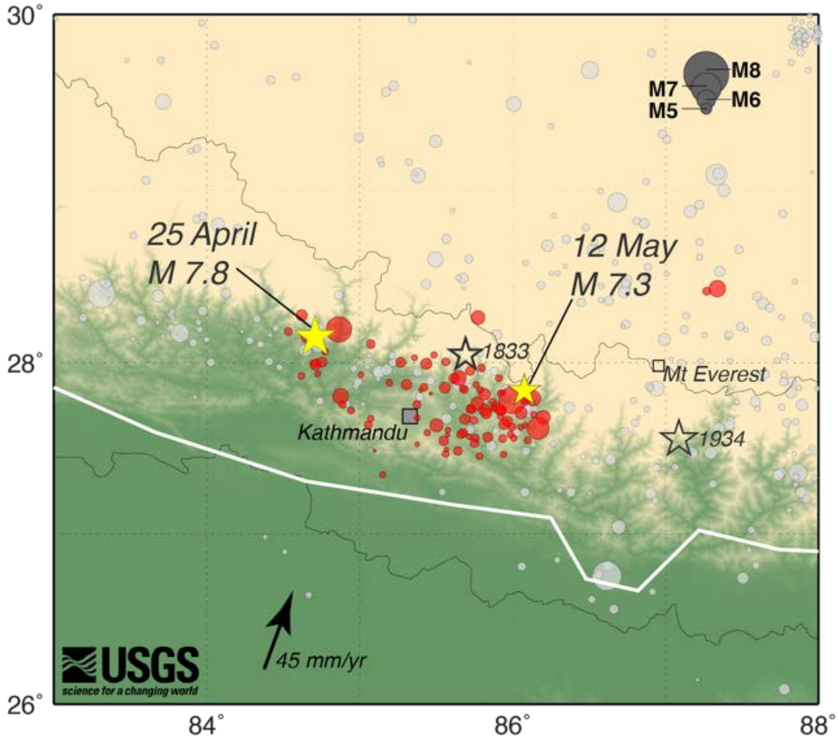

Figure 4.3. April 25–May 12 Nepal aftershocks

4.2. Affected Housing and Population

As more information from aid workers, government officials, and reconnaissance missions comes in, the location and distribution of affected persons will evolve, however, several government organizations and news organizations have provided intermediate reports on damage. Topical information related to housing in Nepal is selectively chronologically shown below:

- April 25 – Earthquake occurs in the Gorkha District of Nepal.
- April 27 – CTV news reports that up to 70% of the homes in many villages in the Gorkha District have been destroyed.[9]
- April 27, The New York Times reports that all of around 1,300 homes in the town of Surpani have been destroyed.[10]

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[8] USGS
[9] http://www.ctvnews.ca/world/shattered-villages-near-epicentre-of-nepal-quake-plead-for-aid-1.2346174
[10] http://www.nytimes.com/2015/04/28/world/asia/nepal-earthquake.html?_r=0

- April 28 – FT World quotes an engineer with the International Nepal Fellowship as saying nearly all homes within fifty kilometers of the epicenter will need to be rebuilt.[11]

- April 28 – BBC reports that most towns near the epicenter in Gorkha have been completely destroyed.[12]

- April 28, CNN reports that 90% of the homes in the town of Ravi Opi are destroyed or uninhabitable.[13]

- April 30 - CNN reports 1 in 36 homes in Arkul Bazar, Nepal as habitable, approximately 20 kilometers from the epicenter.[14]

- May 3 – The Guardian reports more than 75% of buildings in Kathmandu as uninhabitable or unsafe.[15]

These selected topical reports highlight the plight in many regions of Nepal, though they are not comprehensive. More comprehensive estimates of the destruction of houses have been made by the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA). A situation report by OCHA on May 6 indicates 284,455 houses destroyed, and an additional 234,102 houses damaged[16]. Additionally, OCHA released a map estimating the population directly affected by destroyed houses by district in Nepal, and the proportion of the overall population in that district affected, shown in Figure 4.4. The most heavily affected populations are seen to be outside of Kathmandu, in rural Nepal, where a large proportion of the population of the country resides.

In addition to destroyed houses, many roads have been blocked by landslides, thus rendering the remote villages accessible only by helicopter and by foot. This has made, and will continue to make, the distribution of aid to these districts a challenge. The Shelter Cluster has distributed nearly 51,000 tarpaulins as temporary shelters to affected districts, but has experienced difficulties in distributing them to remote areas.[17]

As of May 15, 8,460 fatalities have been reported but early in the recovery process, the Prime Minister of Nepal was widely reported as saying that the fatalities could rise to 10,000[18]. As a result of the causalities, many Nepalese fear returning to structures and are hesitant to sleep indoors.

[11] http://www.ft.com/intl/cms/s/0/70c2badc-ed8e-11e4-987e-00144feab7de.html#axzz3YqYSstb2
[12] http://www.bbc.com/news/world-asia-32503353
[13] http://www.cnn.com/2015/04/28/asia/arwa-damon-rural-nepal-earthquake/
[14] http://www.cnn.com/2015/04/30/asia/nepal-earthquake-epicenter-region/
[15] http://www.theguardian.com/world/2015/may/03/most-buildings-in-kathmandu-deemed-uninhabitable-following-quake
[16]/reliefweb.int/sites/reliefweb.int/files/resources/OCHANepalEarthquakeSituationReportNo.11%286May2015%29.pdf
[17] http://un.org.np/sites/default/files/OCHANepalEarthquakeSituationReportNo%209(2May2015).pdf
[18] http://www.cnn.com/2015/05/15/asia/nepal-earthquake/

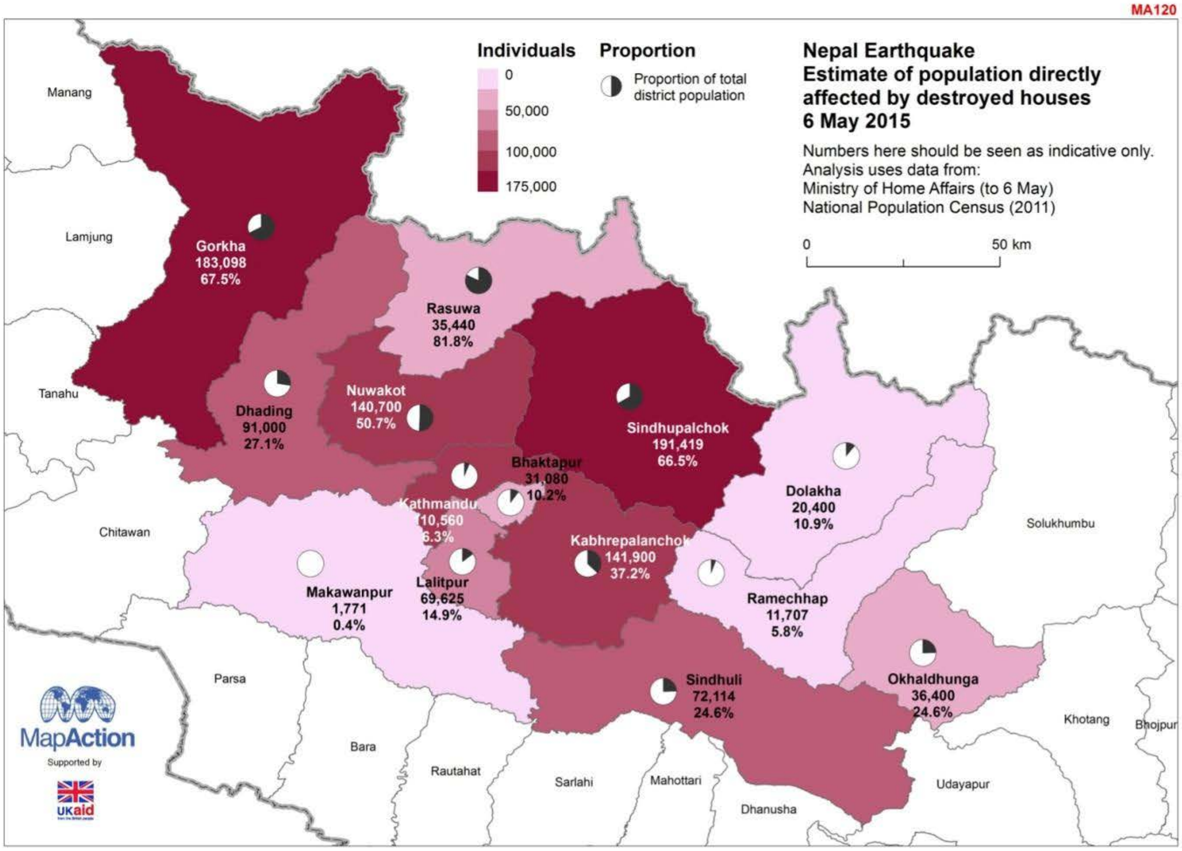


Figure 4.4. OCHA map of affected populations in Nepal.

5. Damage from the Earthquake

A preliminary assessment by ARUP has resulted in several failure observations. The failures stem from the following general categories: architectural layouts, construction and structural design inadequacies, and material weaknesses. The architectural layout problems include:

- Poor layout
- Irregularities on plan and elevation
- Mass irregularities
- Soft Stories
- Weak Stories
- Short columns
- Seismic joints missing
- Openings too close to corners
- Strong beams – weak columns due to disregard of slab strength
- Inadequate site selection

The construction and structural design inadequacies include:

- Inadequate anchorage
- Incomplete timber bands
- Roof trusses without bottom tension chords
- Inadequate retaining walls
- No through stones
- Limited corner details
- Incomplete diaphragms
- No lintels
- No band beams
- Lack of connectivity of increment construction
- Lack of band between cross walls
- Links don't start close enough to the joints
- No joint reinforcement in RC
- Workmanship issues

The material weaknesses include:

- Very poor quality concrete
- Weak bricks
- Deterioration of the building fabric (timber and bricks)
- Material quality issues

Many of the structural, construction, architectural, and material deficiencies are seen through representative photos from topical articles and social media posts. In many cases, stone walls have collapsed in their out-of-plane direction. This was seen in Ravi Opi (Figure 5.1) with several foot thick walls. It does not appear that anything tied the stone walls to each other. The roof was made of sloped timber with metal sheathing, however, no diaphragm existed connecting walls at the top of the second story of the structure.

Figure 5.1. Location: Ravi Opi, Nepal (Source: CNN)

A similar situation was observed in the Paslang village, pictured in Figure 5.2. A thick stone/brick wall with limited mud mortar collapsed out-of-plane, with a galvanized iron roof sheathing supports by a timber gable roof still standing.

Figure 5.2. Location: Paslang village, Nepal (Source: CTV)

Another rural Nepal example in Figure 5.3 shows that the timber roof with galvanized iron sheathing may not be adequately connected to all walls. In this case, a stone wall has collapsed while the roof remains, cantilevered from walls that have not collapsed.

Figure 5.3. Rural Nepal. (Source: Tom Newby)

Urban areas with brick and mud mortar construction experienced similar out-of-plane wall collapses, without full structure collapse. Lalitpur is pictured in Figure 5.4. Multiple brick facades have collapsed outwards. The many loose bricks in the street indicate a lack of mortar, or effective mortar in construction.

Figure 5.4. Location: Lalitpur, Nepal (Source:NPR)

A similar failure is seen from Kathmandu in Figure 5.5.

Figure 5.5. Location: Kathmandu, Nepal (Source: New York Times)

In many locations in rural Nepal, stone structures with galvanized iron roofs have collapsed as shown in Figure 5.6. In the Gorkha district, shown below, little or no ties are used around the walls, and mortar is often not used either, so the only lateral resistance is provided by friction between the pieces of stone.

Figure 5.6. Location: Gorkha, Nepal (Source: New York Times)

In some cases, such as in Chautara, damage is binary. Taller stone structures are seen to have collapsed while a one-story stone structure with a light galvanized iron sheet roof has not. Another light structure with wood posts and a galvanized iron sheet roof does not appear to have sustained damage.

Figure 5.7. Chautara. (Source: Sitanshu Kar)

Material weaknesses were a significant problem during the earthquake. A photo of a house in Sindhupalchok (Figure 5.8) shows that many of the bricks crumbled. This is likely due to a lack of cementitious material in making the bricks. They are often made through compression only in Nepal[19].

[19] https://www.facebook.com/bill.ashwell.1/videos/10153438459778974/

Figure 5.8. Location: Sindhupalchok, Nepal (Source: Reuters)

In rural Nepal, stone construction without any mortar is common due to material unavailability. Through-stones are also seldom placed between wythes of stone courses. The effects of this are seen in Figure 5.9, where the stone wall has delaminated (shed a stone course).

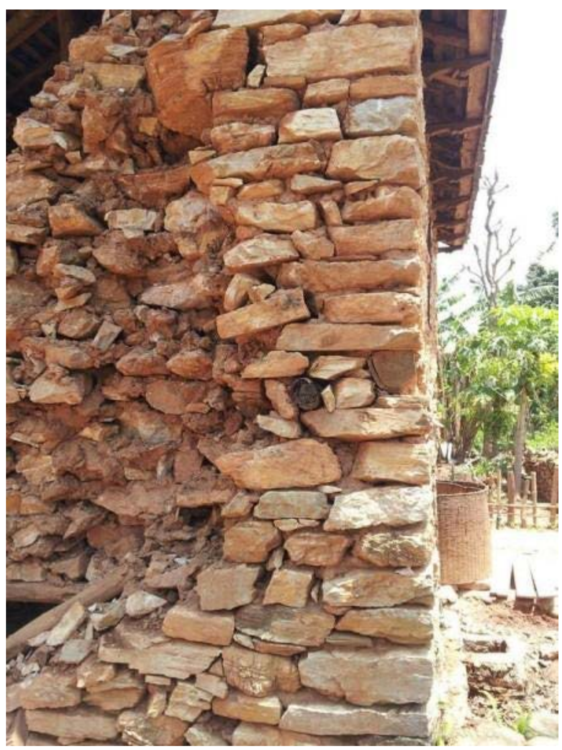


Figure 5.9. Rural Nepal. (Source: Tom Newby)

A structure in rural Nepal that uses concrete masonry unit (CMU) blocks with cementitious paste between the blocks has survived the shaking. Shown in Figure 5.10, the walls have acted as one unit, rather than independent blocks, which likely prevented the structure from collapsing. Still, nothing is seen to have tied the perpendicular walls to each other.

Figure 5.10. Rural Nepal. (Source: Tom Newby)

6. Rebuilding Strategies from Past Earthquakes

Rebuilding a country after a devastating earthquake is a challenge that must be met. Examining proven solutions from past disasters within the context of the given disaster will help gain insight into the temporary shelter and permanent reconstruction and retrofit strategies that will be most effective in Nepal. Ideally, temporary shelters can be provided where the materials can be transitioned to more permanent, earthquake-resisting structures.

6.1. Transitional Shelters

This section provides background information on shelters that can be used for the people of Nepal on a transitional and temporary basis. The transitional shelters discussed here have been used either in Nepal, or in countries that have economic means and labor capabilities that are similar to Nepal.

The expected structural life of the transitional shelters discussed here may range from several weeks and months, to several years. The temporary shelter options presented in this section were selected based on materials that are either readily available to the Nepal, or may be easily deployable throughout Nepal.

6.1.1. CGI Semi-circular shelters with brick infill (Nepal 2015)

Shortly following the 2015 earthquake in Nepal, a group from Tribhuvan University in Nepal began constructing some sample temporary shelters using corrugated iron sheets[20]. Rebar is bent into semi-circles and anchored into the ground. Galvanized iron sheets are then placed over the rebar, as is shown in Figure 6.1. Brick or stone infill walls with mortar are then constructed at either end of the tube-like structure. Straw or hay can be placed on the roof to provide thermal insulation and maintain the character of current design practices.

[20] http://abstengineering.com/corrugated-sheet-vault-transitional-shelter-for-earthquake-victims-in-nepal/

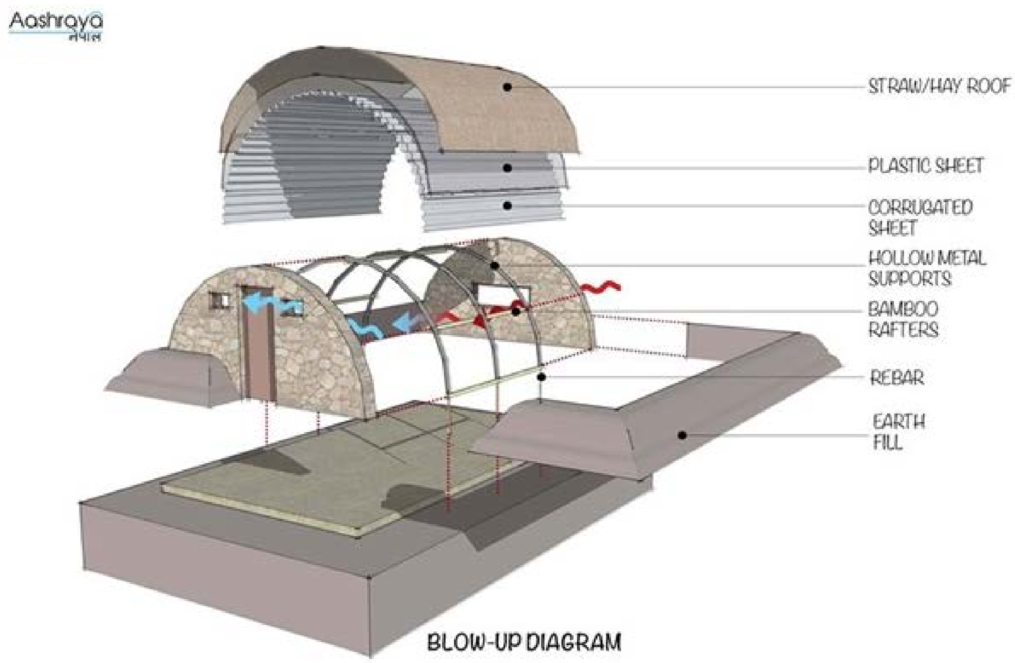


Figure 6.1. Schematic diagram of semi-circular CGI design

Material availability is a large concern for building shelters in Nepal. Galvanized iron sheets may be readily available in both urban and rural locations because it has commonly been used in the past for residential construction. Similarly, stone or brick can be salvaged from collapsed structures. An important additional aspect of reconstruction is involvement of the community. In Figure 6.2, community members can be seen assisting in the construction efforts.

Figure 6.2. Community members assisting with reconstruction

The final product is shown in Figure 6.3.

Figure 6.3. Final CGI semi-circular shelter

The major benefits of this design are:

- required material can largely be salvaged from earthquake rubble
- materials can be re-used for future construction because they are already common to construction in Nepal
- light roof will likely not cause death if the structure collapses
- corners are completely eliminated from the design by employing a semi-circular layout
- design is simple so that locals can participate in reconstruction efforts
- character of the existing housing stock is maintained

The major disadvantages of this design are:

- little out-of-plane stability of brick or stone walls, however, they are not high or numerous
- there may be difficulties anchoring the shelters into the ground
- many bricks crumbled during the earthquake, so this building material is not preferred
- additional structural analysis is required to assess the stability of the shelter during an earthquake since it is a new design

6.1.2. CGI shelters with plastic sheathing (Pakistan 2010)

Following flooding in 2010 in Pakistan, 10,000 galvanized iron sheet based shelters were constructed[21]. A timber frame built on low brick or stone walls supports galvanized iron sheet gable roofing, as pictured in Figure 6.4. A plan and cross-section are shown in Figure 6.5.

Figure 6.4. Shelter following 2010 flooding in Pakistan

The expected lifespan of these shelters in Pakistan was 24 months. The estimated construction time is one day for a team of four relatively low skilled workers.

[21] International Federation of Red Cross and Red Crescent Societies 2011. *Transitional Shelters: Eight Design.* http://www.ifrc.org/PageFiles/95186/900300-Transitional%20Shelters-Eight%20designs-EN-LR.pdf

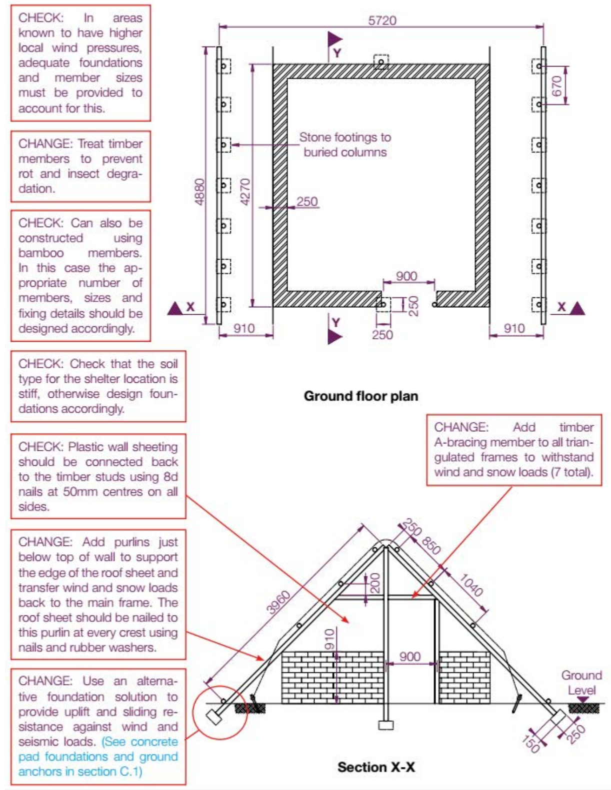


Figure 6.5. Plan and section for CGI based shelter following 2010 flooding in Pakistan

The major benefits of this design are:

- material for the low brick wall and galvanized iron sheets could likely be recovered for reconstruction using this method in Nepal.
- timber is available in many regions
- the shelter frame is lightweight and flexible. If it sustains damage, there is a lower likelihood of injury to occupants than a heavier unconfined stone or brick structure.
- masonry walls are low
- limited labor is required for construction
- materials can be dismantled and used in the future for permanent construction

The major deficiencies of this design are:

- better anchorage may be required to prevent uplift of the CGI sheets and sliding at the base
- additional cross-members should be used to resist wind forces
- provides little to no thermal insulation

6.1.3. Galvanized steel frame with CGI sheet roofing (Indonesia 2004)

Following a 2004 tsunami in Indonesia, 20,000 galvanized steel frame shelters with galvanized iron sheet roofing were built as semi-permanent shelters with an expected life of at least five years[22].

[22] International Federation of Red Cross and Red Crescent Societies 2011. *Transitional Shelters: Eight Design.* http://www.ifrc.org/PageFiles/95186/900300-Transitional%20Shelters-Eight%20designs-EN-LR.pdf

Timber planks were used for sheathing and flooring. The shelter is shown in Figure 6.6 with a plan and cross-section shown in Figure 6.7.

Figure 6.6. Timber frame with CGI sheet roofing from Indonesia

Proper nailing of wood to cold form steel is required for there to be any lateral stability in the structure. The major benefits of this design option for implementation in Nepal include:

- timber and galvanized iron sheet materials may be available.
- light frame provides good resistance to collapse during earthquakes
- material can be recycled and reused for more permanent housing solutions
- this shelter can be classified as semi-permanent because it is expected to last at least five years by the original proponents

Major disadvantages include:

- several days construction is required for four builders
- more advanced construction expertise may be required when compared to other designs that use conventional material like stone and brick in Nepal
- the shelter is not in character with existing structures in Nepal
- multiple materials may need to be provided, depending on the location

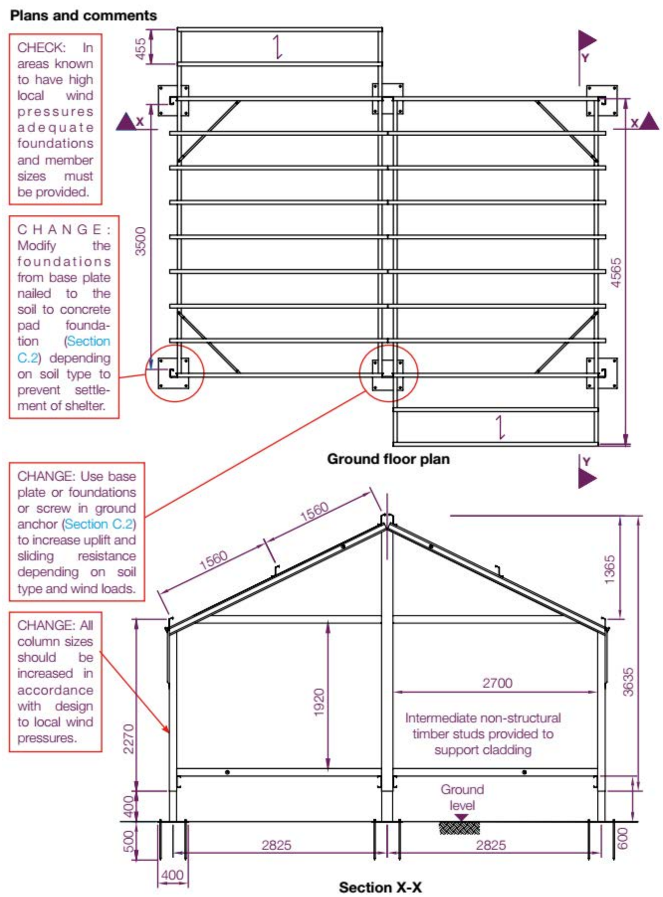


Figure 6.7. Plan and cross-section for timber frame with CGI sheet roofing from Indonesia

6.1.4. Refugee Shelters developed by the United Nations and IKEA Foundation (2013)

In 2013, The United Nations Commissioner for Refugees and IKEA worked together to build flat-packed, build-it-yourself homes complete with solar power[23]. In 2013, the units cost approximately $10,000, but IKEA estimated that the cost could go as low as $1,000 if the items were mass-produced[24]. The structures were deployed to refugee camps in Ethiopia in 2013.

[23] http://www.ikeafoundation.org/programmes/refugee-children/
[24] http://www.fastcoexist.com/1682416/a-new-ingeniously-designed-shelter-for-refugees-made-by-ikea

Figure 6.8. United Nations and IKEA Foundation Refugee Shelter

The advantages of using a structures such as this are:
- easily transportable (lightweight)
- thermally insulated
- generate electricity
- structures are built to last approximately 60 months

The disadvantages of using a structure such as this are:
- these structures were designed for refugee camps, and their structural performance against natural hazards is unknown
- the original cost of $10,000/unit would be too high, although if the structures were in mass production at $1,000/unit the cost may be more reasonable for construction
- the shelter is not in character with existing structures in Nepal
- all materials come from outside of the country

6.1.5. Bamboo structures - semi permanent solution (Indonesia 2009)

A series of semi-permanent bamboo-framed structures were built after the September 2009 earthquake in West Java, Indonesia as shown in Figure 6.9[25]. The dimensions of the structure were 6m x 4m in plan, and the structural system consisted of concrete foundations, terracotta roof tiles, bamboo columns and bracing, and bamboo matting walls.

[25] International Federation of Red Cross and Red Crescent Societies 2011. *Transitional Shelters: Eight Design.* http://www.ifrc.org/PageFiles/95186/900300-Transitional%20Shelters-Eight%20designs-EN-LR.pdf

Figure 6.9. Semi-Permanent Bamboo Structures

The benefits to using a bamboo structure such as this in Nepal are:

- bamboo is readily available in many regions in Nepal
- the structure is low-cost and can be constructed rapidly
- the foundations can be constructed with concrete-filled buckets
- the shelter can be easily moved by unpegging the frame from the foundations and the materials can be reused as part of more permanent construction
- the structure can be used for temporary or longer-term shelter

The disadvantages include:

- bamboo needs to be properly treated to avoid durability problems and potential insect attack
- a light-frame roof should be used to avoid a large mass on top of the structure
- these structures provide little to no thermal insulation

6.1.6. Tents

The quickest, yet most temporary option for the people of Nepal to have emergency shelter is by using tents. Tents are commonly used at refugee camps, but they provide little protection from the rain, and do not have adequate thermal insulation for cold weather. Following the 2005 Kashmir earthquake in Pakistan, many displaced persons who were given tents, preferred to stay in the tents for extended periods of time, and saved the construction materials given to them, like CGI sheets, and material salvaged from collapsed structures, for later reconstruction. Therefore, no matter the shelter strategy implemented, tents may be a residence of choice for many families[26].

6.2. Retrofitting Surviving Structures

The overarching goal of developing retrofit strategies for existing structures in Nepal is to tie the structure together to resist seismic loads as a single body. As previously mentioned, many structures failed since the structural components acted independently. The retrofit strategies

[26] "Rural Housing Reconstruction Program Post-2005 Earthquake." 2013. 22 May. 2015 <http://reliefweb.int/sites/reliefweb.int/files/resources/RHRP_PAKISTAN_WEB.pdf>

described herein are aimed to tie the structure together. The retrofit options discussed within this section include simple architectural changes that can increase the strength and stiffness of walls and structural components.

6.2.1. Polypropylene strip retrofit of brick masonry structures

One retrofit strategy for non-engineered masonry structures in rural Nepal uses polypropylene packaging strap meshes on the exteriors of mud brick structural walls, as investigated by Joshua Macabuag, Ramesh Guragain, and Subhamoy Bhattacharya[27]. With the addition of the mesh, the walls could sustain larger deformations, thus lowering their collapse risk.

Compressive and shaking table tests validated the improved performance of the walls with mesh. In addition to testing, pilot programs were conducted in Bhaktapur, Nepal in 2008, in which masons were trained in retrofitting with the polypropylene band technique. Additionally, structures were retrofit in Nangkhel, Nepal in 2009. A tested specimen is shown in Figure 6.10 and improved force versus deformation response is shown in Figure 6.11.

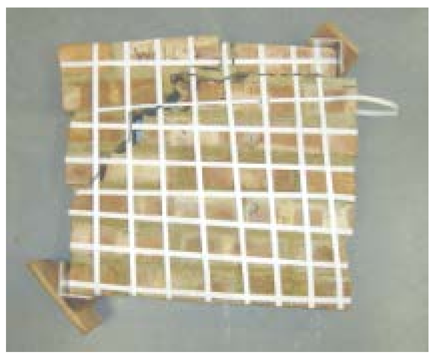


Figure 6.10. Tested brick panel with polypropylene strips

[27] Macabuag, Joshua, Ramesh Guragain, and Subhamoy Bhattacharya. "Seismic retrofitting of non-engineered masonry in rural Nepal." *Proceedings of the ICE-Structures and Buildings* 165.6 (2012): 273-286.

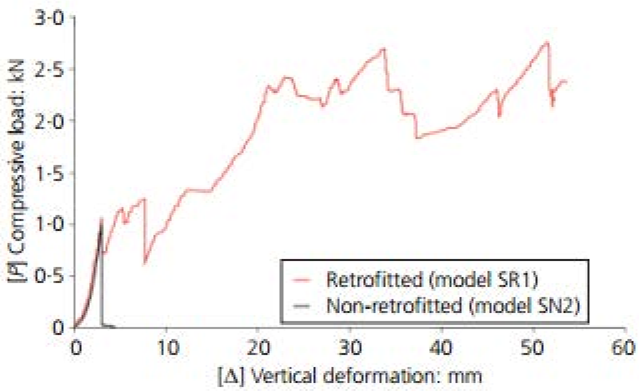


Figure 6.11. Force versus deformation of retrofitted and retrofitted with polypropylene strips panels

One NSET technician, two masons, and two unskilled laborers conducted the work over four weeks, with a material cost of the retrofit at $250. Construction is shown in Figure 6.12.

Figure 6.12. Retrofit of a house with polypropylene strips

While polypropylene is a very cheap plastic, locals may have difficulties melting it to the proper strip shapes. Additionally, low quality cementitious material would limit the effectiveness of the confining strips.

6.2.2. Addition of RC/timber seismic bands to masonry structures

This retrofit technique involves tying structural members together in order to enhance stiffness of the entire structure. Bands of reinforced concrete or wood act as tie beams when placed and secured to the top of stone or brick masonry walls, so that all walls of the house act together to resist seismic loads. "A seismic band is the most critical earthquake-resistant provision in a stone masonry building," according to the Earthquake Engineering Research Institute[5]. Where timber is used to form a band, knee braces, or 45 degree diagonal members can aid the two adjoining wall members in responding together during a seismic event (see Figure 6.13). Alternatively, for existing walls where this may not be practical, bandages, consisting of steel wire mesh attached to the wall with nails, layered with mortar, can be added as shown in Figure 6.14. Semi-skilled labor is required for this type of retrofit, however the skillsets required currently exist in Nepal.

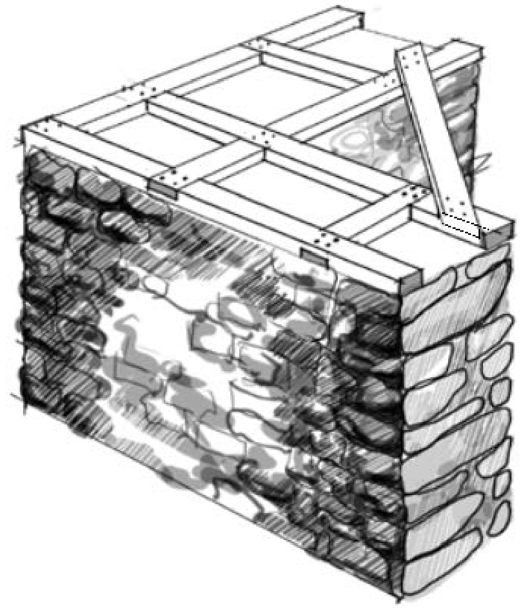


Figure 6.13. Timber knee brace[4]

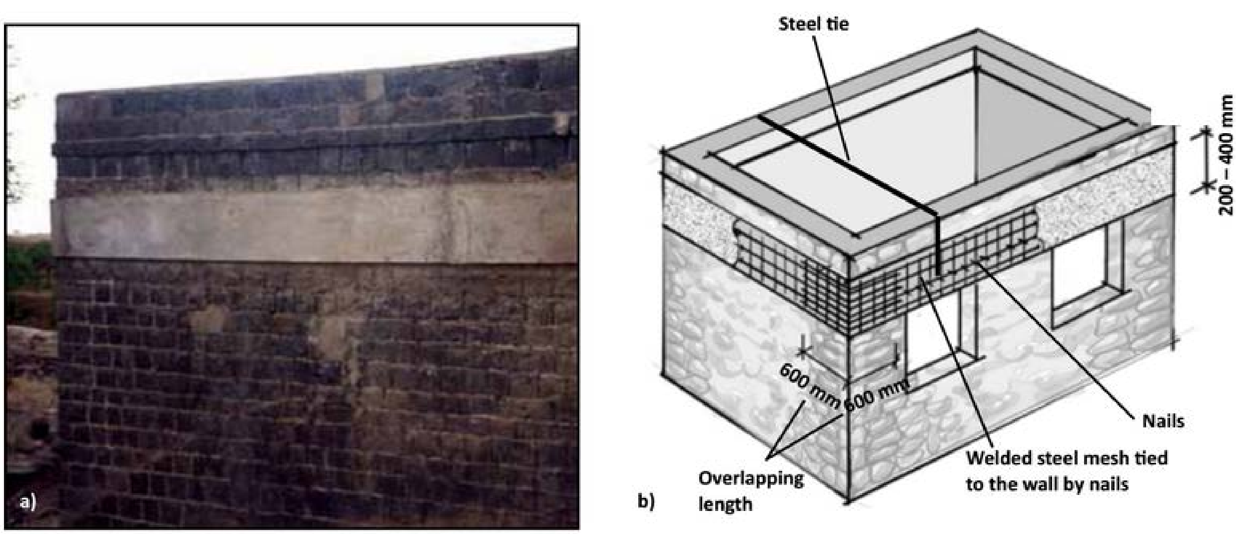


Figure 6.14. Reinforced concrete tie bands[4]

Unconfined masonry houses that have withstood the earthquake may be susceptible to the next seismic event. Another means to tie walls together is by anchoring them together at the corners. Techniques include a wire-reinforced mortar splint system, anchors and plates, or post-tensioned rods (Figure 6.15(a)-(c), respectively).

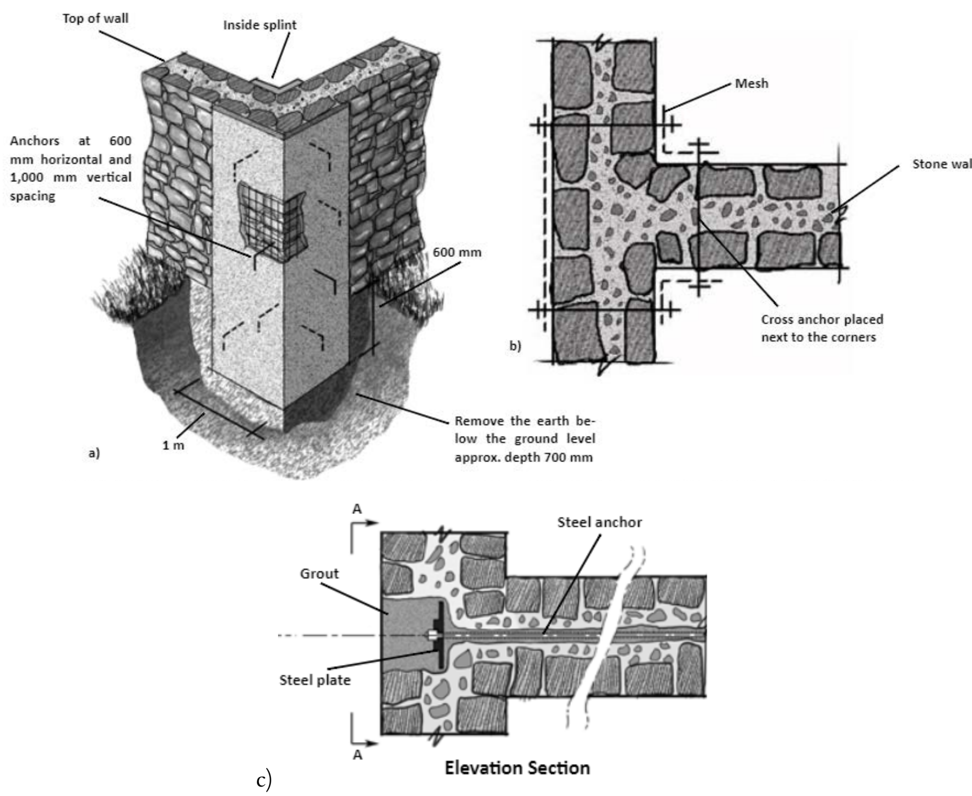


Figure 6.15. Corner wall (a) anchors and splint, (b) anchor plates, and (c) post-tensioned steel anchors[4]

6.2.3. Securing/Strengthening Floors

Besides tying the walls to each other, the walls of a house should be secured to each floor and the roof for added diaphragm action. Floors, if made of timber, can be secured to the walls by means of steel straps. Figure 6.16 (a) and (b) show examples depending on whether the floor beams run perpendicular or parallel to wall of interest, respectively.

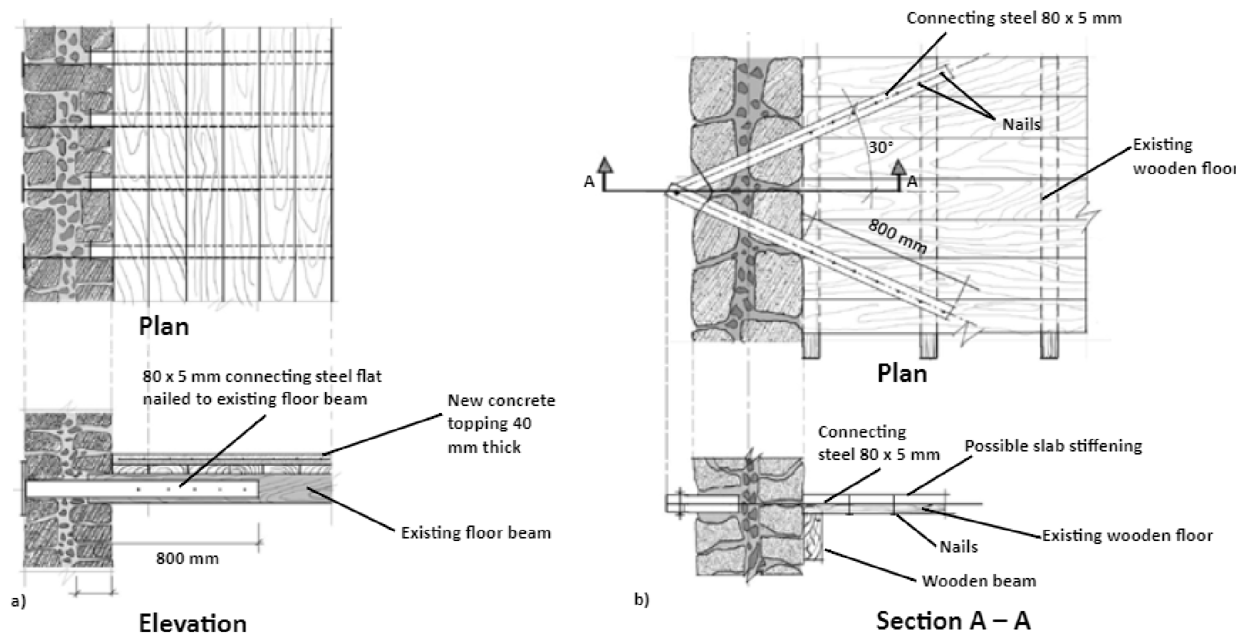


Figure 6.16. Steel straps tying floor beams (a) perpendicular and (b) parallel to the exterior wall[4]

An alternative measure to installing steel straps is to pour a concrete floor or roof. The existing flooring system can act as a form, and a minimum thickness of 40 mm is recommended per [5]. Prior to the concrete pour, nails should be hammered up through the bottom of the existing floor to act as shear studs and enforce compatibility between the existing floor and the new concrete slab as shown in Figure 6.17.

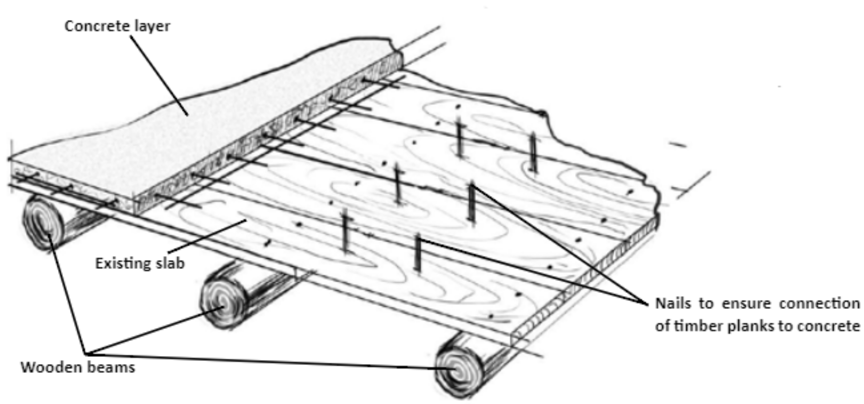


Figure 6.17. Steel Straps Typing Floor Beams a) Perpendicular and b) Parallel to the Exterior Wall[4]

6.2.4. Addition of interior walls and buttresses

Out-of-plane collapse is a common failure mode for masonry walls, and is depicted in Figure 6.18. As discussed a number of times previously, overall building integrity is critical for the seismic performance of masonry buildings, i.e. structural components must stay connected to each other. When cross-walls parallel to the direction of shaking are far apart, the central areas of long walls are subjected to significant out-of-plane vibrations, and are susceptible to collapse. This is exacerbated by inadequate connections between the walls at corners, between the walls and the diaphragms/roof, and the presence of flexible diaphragms/roof.

Figure 6.18. Out-of-plane failure of a stone masonry wall

To prevent out-of-plane failure of long walls, one retrofit solution is to add interior walls perpendicular to the long wall at regular intervals. It is critical to ensure these walls are well connected to the long wall. Another solution is to add buttresses at regular intervals to stiffen the wall in the out-of-plane direction. These options are illustrated in Figure 6.19. Buttresses can be constructed using unskilled labor, but interior wall construction requires skilled labor to ensure adequate connections to the long wall.

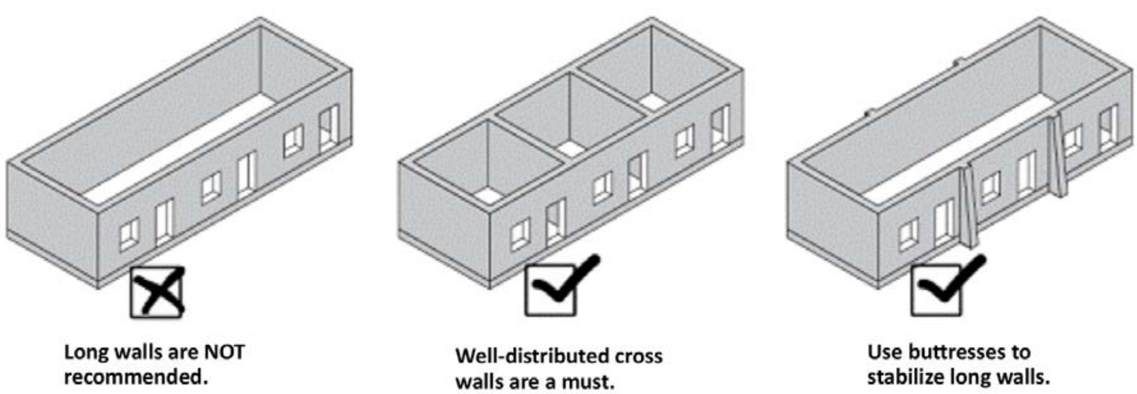


Figure 6.19. Addition of interior walls and buttresses to stiffen long walls in the out-of-plane direction

6.2.5. Injecting grout

Stone masonry walls can be strengthened by injecting cementitious grout into air voids. The hardened grout is effective in bonding the loose parts of the wall together into a solid structure. The injected grout is prepared by mixing Portland cement and pozzolana with water in the right proportion. The grout is injected into the wall at low pressure using tubes and nozzles, which are inserted into the joints between the stones, uniformly over the entire wall surface. A masonry wall prepared for grout injection is shown in Figure 6.20. More details about this technique can be obtained from [28] and [29].

Figure 6.20. Masonry wall prepared for grout injection

6.3. Reconstruction Methods

Experience from previous earthquakes in similar communities, e.g. the 2005 Kashmir earthquake, indicate that residents begin reconstruction activities early, while policies and strategies on reconstruction usually lag behind[30]. Ensuring policies, standards, and technical advice are made available in a timely manner following the disaster can smoothen recovery. The emphasis of the reconstruction effort should be on "building back better". Achieving this goal would first require a detailed survey of prevalent construction materials and methods, and an assessment of common vulnerabilities due to defective design and construction practices. The suitability and effectiveness of earthquake-resistant housing solutions employed in other earthquake-prone regions would need to be analyzed, while considering local materials and knowledge. Affordability of proposed reconstruction techniques is a key consideration. This provides an opportunity to train masons and

[28] Tomazevic, Miha. *Earthquake-resistant design of masonry buildings*. World Scientific, 1999.
[29] "Housing Report: Rubble-stone masonry house - World Housing Encyclopedia" 2012. 21 May. 2015 <http://www.world-housing.net/wp-content/uploads/2011/06/stone-masonry-report-58.pdf>
[30] "Rural Housing Reconstruction Program Post-2005 Earthquake." 2013. 20 May. 2015 <http://reliefweb.int/sites/reliefweb.int/files/resources/RHRP_PAKISTAN_WEB.pdf>

artisans on earthquake-resistant construction techniques, and to promote structural systems like confined masonry, that have been proven to be extremely effective against earthquakes in high seismic regions around the world.

6.3.1. Confined masonry construction

The confined masonry construction technology was developed by the structural engineering community in response to the observed poor seismic performance of unreinforced masonry (URM) structures and reinforced concrete (RC) framed structures with masonry infill walls, both of which are popular in many developing countries, including Nepal. Although well designed RC framed structures can be effective in resisting seismic loads, typical non-engineered RC framed structures tend to have non-ductile detailing (e.g. inadequate splicing of reinforcement, widely spaced stirrups, poor concrete confinement in joints), which results in brittle behavior that is, at best, only marginally safer than URM construction (Figure 6.21). Even engineered RC framed structures are, more often than not, incorrectly designed as pure RC frames, although the addition of masonry infills completely changes their dynamic characteristics. The EERI World Housing Encyclopedia[31] identifies RC framed buildings with masonry infill walls as a popular construction technique in both urban and suburban areas in Nepal. It is also locally perceived to be the safest and strongest form of construction when compared to other prevalent construction techniques.

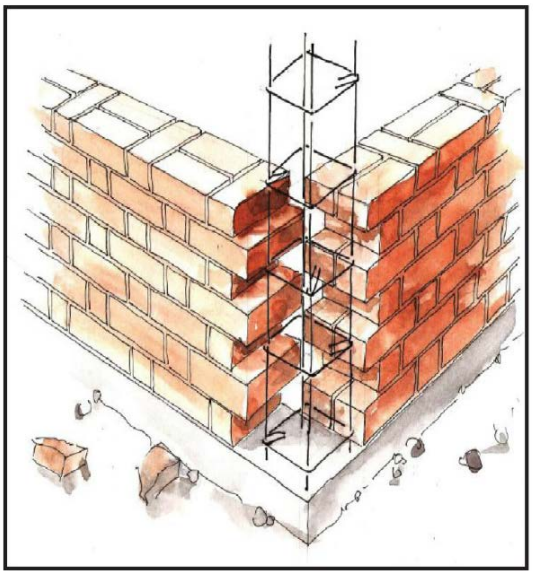
(a) (b)

Figure 6.21. Failure of (a) non-ductile vs. (b) ductile RC framed buildings

Confined masonry offers the advantage of using all the same materials used to construct an RC framed building with masonry infill (cement, reinforcing steel, and aggregate), but only following an improved design philosophy and construction sequence. To construct a confined masonry building, the masonry walls are erected first in the same manner as traditional URM construction, with the small difference of leaving empty toothed, vertical slots in the walls every 3-4 meters, as per the developed structural design. Steel reinforcement cages and formwork are then placed in the vertical slots and horizontally along the tops of the walls, before casting concrete in the forms of

[31] "World Housing Encyclopedia — an EERI and IAEE project." 2002. 20 May. 2015 <http://www.world-housing.net/>

“tie-columns” and “tie-beams” respectively (Figure 6.22). Although this results in a structure that looks a lot like an RC frame with masonry infill, the concrete binds firmly with wall, thus providing adequate confinement and allowing the entire structure to act as a unit when resisting seismic loads. This results in dramatically improved seismic performance than traditional RC framed structures, whose frame is constructed before the infill wall is placed, thus resulting in both components acting as separate units under seismic loading. Confined masonry construction is more cost-effective than RC frame construction due to its smaller member sizes and lesser reinforcing steel required. The two forms of construction and their lateral load resisting characteristics are compared in Figure 6.23.



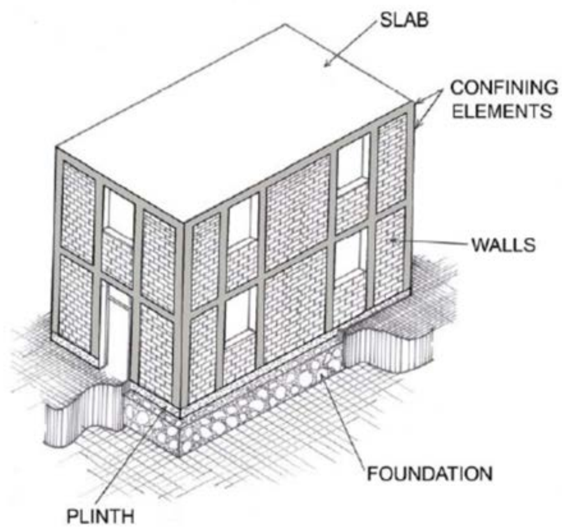


Figure 6.22. Construction and layout of a typical confined masonry structure

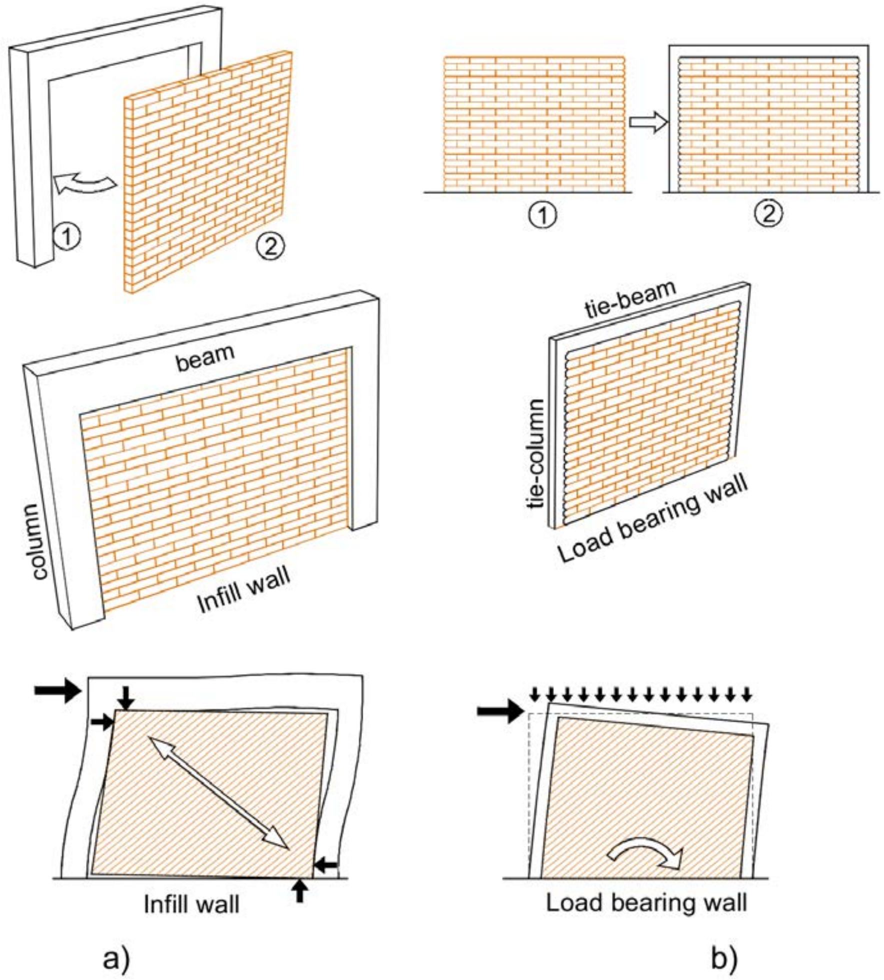
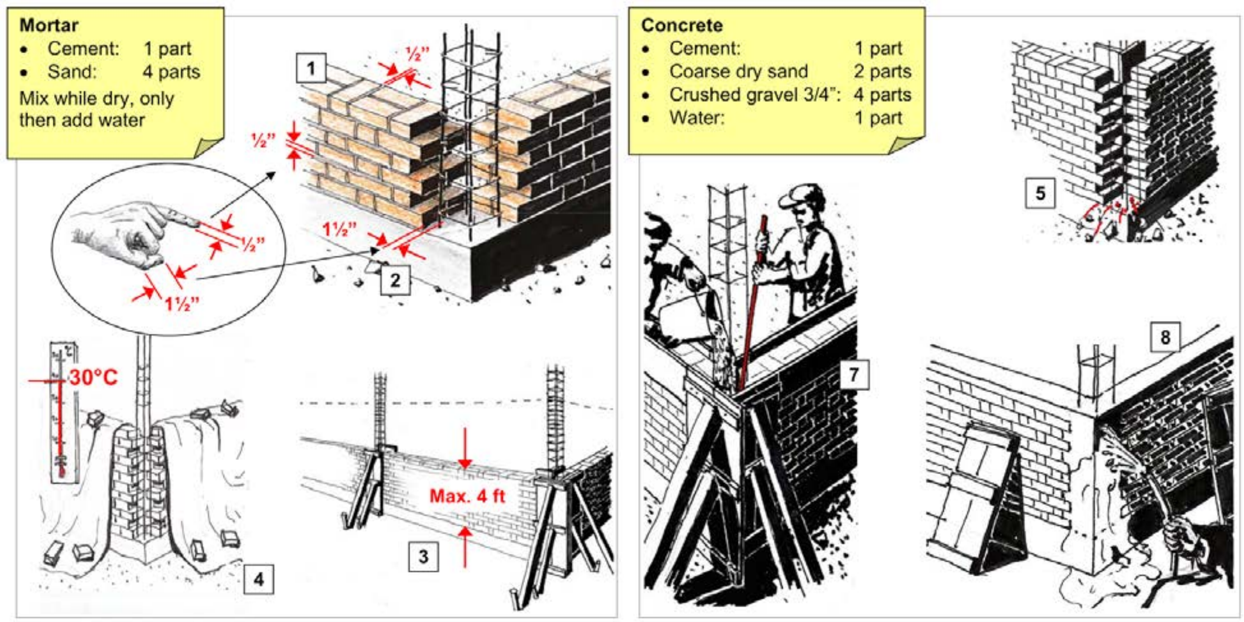


Figure 6.23. Construction and lateral load resisting characteristics of (a) RC frame with masonry infill vs. (b) confined masonry structure adapted from [28]

Over the last 30 years, the confined masonry construction technique has been widely implemented in a number of countries with extremely high seismic hazard like Mexico, Chile, Peru, Colombia, Iran, Algeria, Indonesia, and China. Well built confined masonry structures have an excellent track record of surviving major earthquakes without collapse, and in most cases, even without significant damage. The use of good confined masonry construction practices has been widely attributed as the reason for the limited damage and death toll following the magnitude 8.8, 2010 Chile earthquake (only 10 deaths in confined masonry structures). They also have a broad range of applications, ranging from single-family houses to medium-rise apartment buildings.

A guidebook on confined masonry construction with easy-to-understand illustrated instructions (e.g. Figure 6.24) was prepared to train masons and artisans during reconstruction following the 2005 Kashmir earthquake[32]. This guidebook could be translated into Nepali for local use.



1. Mortar beds and joints must not be thicker than ½ inch.
2. Keep end bricks 1½" away from the stirrups to leave room for the concrete of the tie-columns.
3. Don't build higher than 4 feet per day.
4. Protect the wall in warm weather with a plastic sheet or wet cloth so the mortar will not dry out.
5. Clean the column space of all rubbish before adding the formwork.
6. Pour the concrete for the bands and the columns at the same time.
7. Compact the concrete vigorously with a stick to get the air pockets out of the mix. Also, hammer against the formwork to compact the concrete. Don't add water to make concrete 'go down'.
8. Water the concrete twice a day for at least 3 more days. Cover with a plastic sheet in summer or in a dry climate.

Figure 6.24. Example of illustrated step-by-step instructions available in the guidebook for confined masonry construction [27]

Detailed information on confined masonry construction is also available in the Seismic Design Guide for Low-Rise Confined Masonry Buildings, published by EERI and IAEE[33]. Some guidelines outlined in this manual include:

- Avoiding irregular building plans (Figure 6.25)

[32] Schacher, T. "Confined Masonry for One and Two Storey Buildings in Low-tech Environments-A Guidebook for Technicians and Artisans." *National Information Centre of Earthquake Engineering, Kanpur, India (www. nicee. org)* (2009).
[33] Confined Masonry Network. "Seismic Design Guide for Low-Rise Confined Masonry Buildings." *World Housing Encyclopedia, EERI & IAEE* (2011).

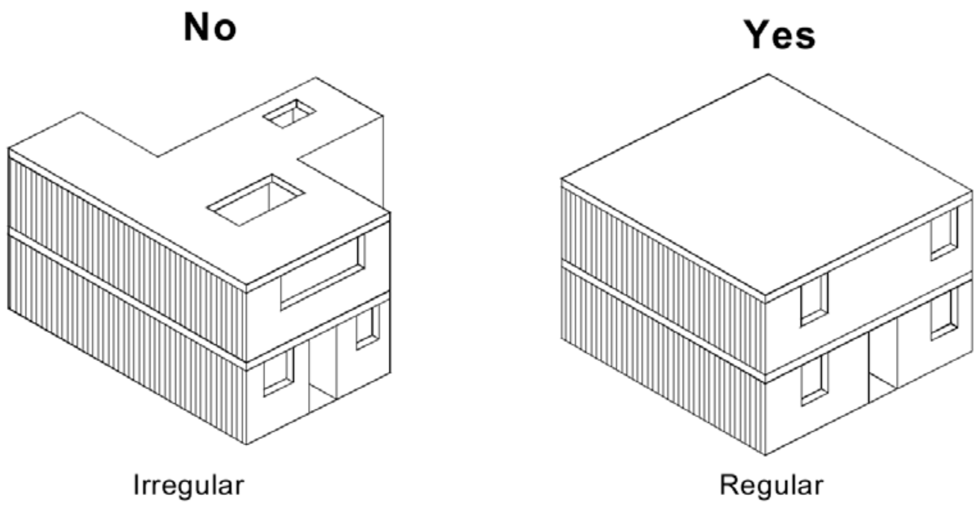


Figure 6.25. Avoid irregular building plans

- Avoiding large aspect ratios (building length-to-width ratios) (Figure 6.26)

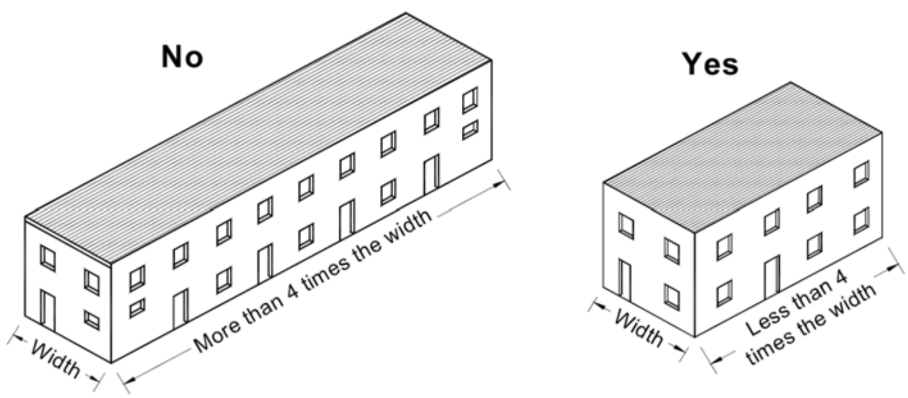


Figure 6.26. Avoid large aspect ratios

- Avoiding unsymmetrical internal wall layouts since they attract torsional forces under earthquake loading (Figure 6.27)

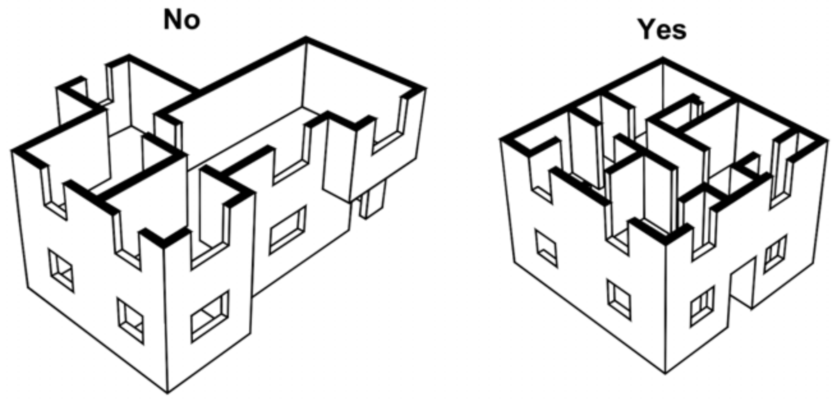


Figure 6.27. Avoid unsymmetrical internal wall layouts

- Providing sufficient internal walls in both perpendicular directions (Figure 6.28)

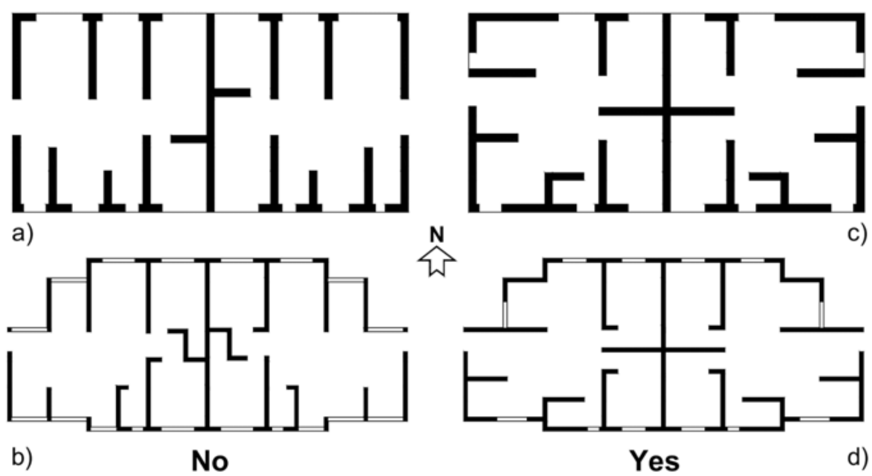


Figure 6.28. Provide sufficient internal walls in both perpendicular directions

- Placing the internal walls continuously over one another (Figure 6.29)

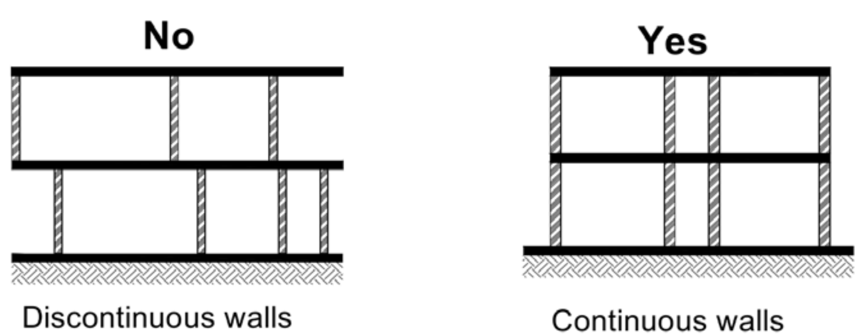


Figure 6.29. Place internal walls directly above one another

- Placing openings (doors and windows) in the same position at every floor (Figure 6.30)

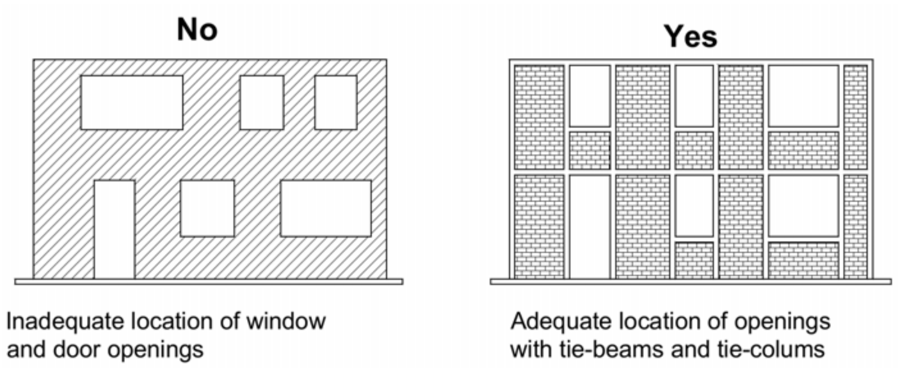


Figure 6.30. Place openings in the same position at every floor

Detailed guidelines are also provided on the types of materials to be used, e.g. bricks, mortar, concrete, reinforcing steel, their respective strength and quality requirements, the design of foundations and diaphragms, etc.

6.3.2. Stone masonry construction

The EERI World Housing Encyclopedia identifies uncoursed rubble stone masonry construction (Figure 6.31) as a popular construction technique in rural Nepal, especially in the central mid-mountain region[34]. Traditional stone masonry dwellings are built by the owners themselves or local builders without any formal training. These non-engineered structures attract large seismic forces due to their large weight, but are unable to withstand these lateral forces due to a number of design and construction deficiencies. They are, therefore, extremely vulnerable to earthquake shaking, and lead to unacceptably high human and economic losses, even in moderate earthquakes[35]. Most of the 74,000 deaths in the 2005 Kashmir earthquake, 13,800 deaths in the 2001 Bhuj earthquake, and 8,000 deaths in the 1993 Maharashtra earthquake have been attributed to the collapse of stone masonry buildings. These statistics are expected to be similar for the 2015 Nepal earthquake as well. Nonetheless, since this is a popular construction technique in many communities around the world, significant research effort has been invested in identifying the underlying causes of their poor seismic performance, and developing techniques to improve the performance of both existing and new buildings. These techniques have been proven in field applications, are relatively simple, and can be applied in areas with limited artisan skills and tools.

[34] "HOUSING REPORT Traditional oval-shaped rural stone house." 2011. 21 May. 2015 <http://www.world-housing.net/WHEReports/wh100081.pdf>
[35] Bothara, J. and Brzev, S. "Improving the Seismic Performance of Stone Masonry Buildings" 2011. <http://www.world-housing.net/wp-content/uploads/2011/06/Stone_Masonry_English.pdf>

Figure 6.31. Example of uncoursed rubble stone masonry building

The following is a summary of the recommendations on earthquake-resistant stone masonry construction described in Bothara and Brzev (2011)[30].The seismic performance of an unreinforced masonry building depends on how well the walls are tied together, and anchored to the floor and the roof. Unconnected walls vibrate individually under ground shaking, thus leading to in-plane and out-of-plane instability, and subsequent collapse (Figure 6.32b). Walls that are well connected to each other, and to a rigid roof, vibrate as a monolithic unit, thus providing better seismic performance (Figure 6.32b).

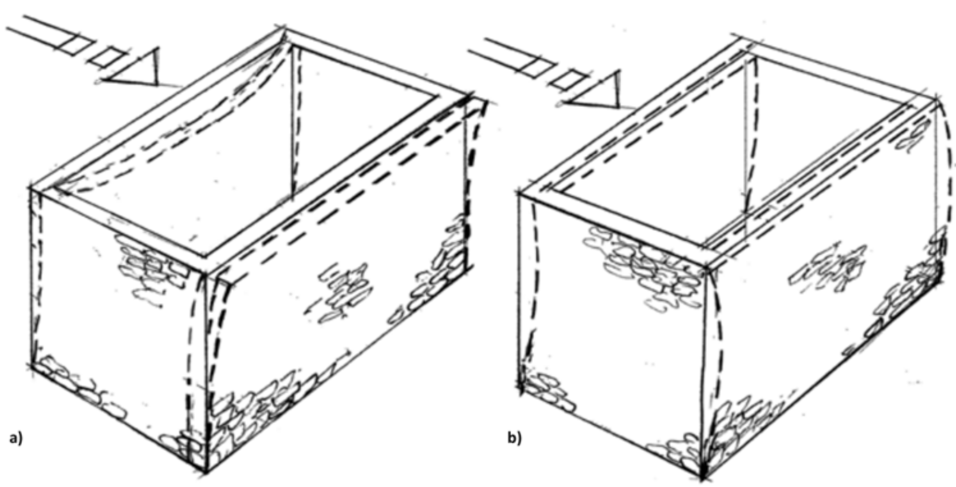


Figure 6.32. Comparison of the seismic behavior of masonry buildings with (a) loosely connected walls and no roof slab and (b) well connected walls with a rigid roof slab

Flat sites should be preferred over sites near steep slopes for construction. As outlined for confined masonry structures above, buildings with simple, regular, and symmetrical plans and small aspect ratios should be preferred. Long walls that cannot be avoided should be adequately supported by buttresses or internal walls at regular intervals. Setbacks and vertical irregularities are not recommended. Cement mortar should be preferred, but mud mortar stabilized with a pozzolanic material may be used. The key design requirements for ensuring structural integrity and monolithic box action under seismic loads is summarized in Figure 6.33. The broad theme of these recommendations is ensuring good connections between all structural components: foundations, walls, floor, and roof. The presence of a continuous ring beam (band) at the lintel level (directly above the openings) is one of the most critical requirements for ensuring structural integrity. This seismic band could be constructed of reinforced concrete or timber. Seismic bands could also be provided at the floor and roof levels. Detailing requirements for these bands are described in the document. Stone masonry buildings with seismic bands have performed well in past earthquakes.

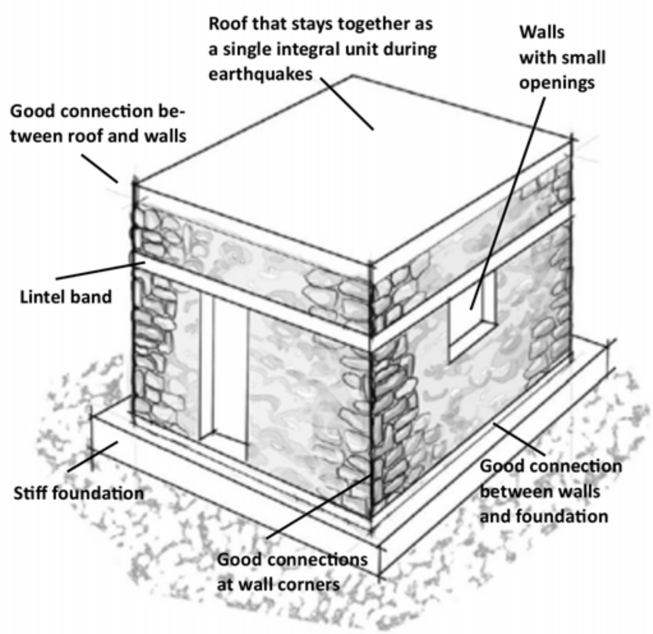


Figure 6.33. Key design requirements for ensuring monolithic box action under seismic loads

Delamination is one of the main causes of collapse of stone masonry walls in earthquakes, and is illustrated in Figure 6.34. Through-stones (also known as bond stones) are long stones placed through the wall to tie wall wythes together and prevent delamination. The presence of through-stones make the wall wythes perform like hands with interlaced fingers. The proper placement of through-stones in a masonry wall is illustrated in Figure 6.35. Contrary to their name, through-stones can also be made of concrete, wood, or steel bars with hooked ends embedded in concrete.

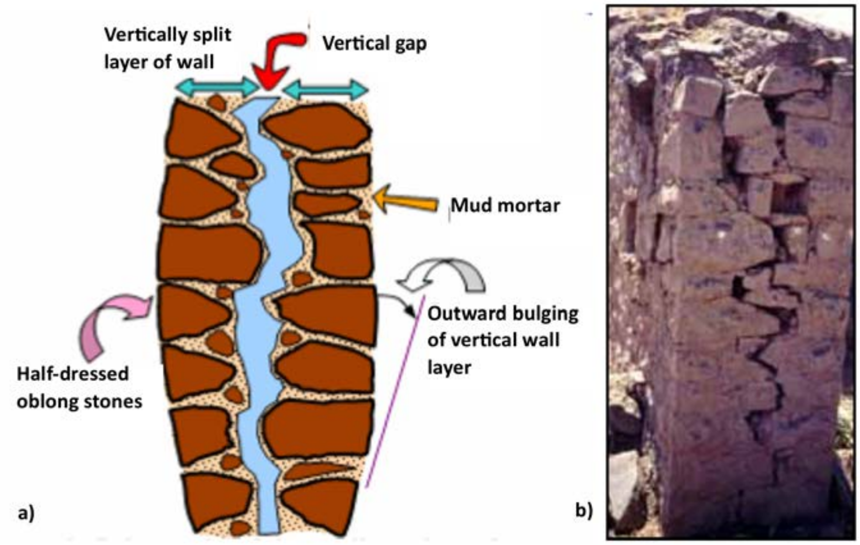


Figure 6.34. Delamination of stone masonry wall wythes

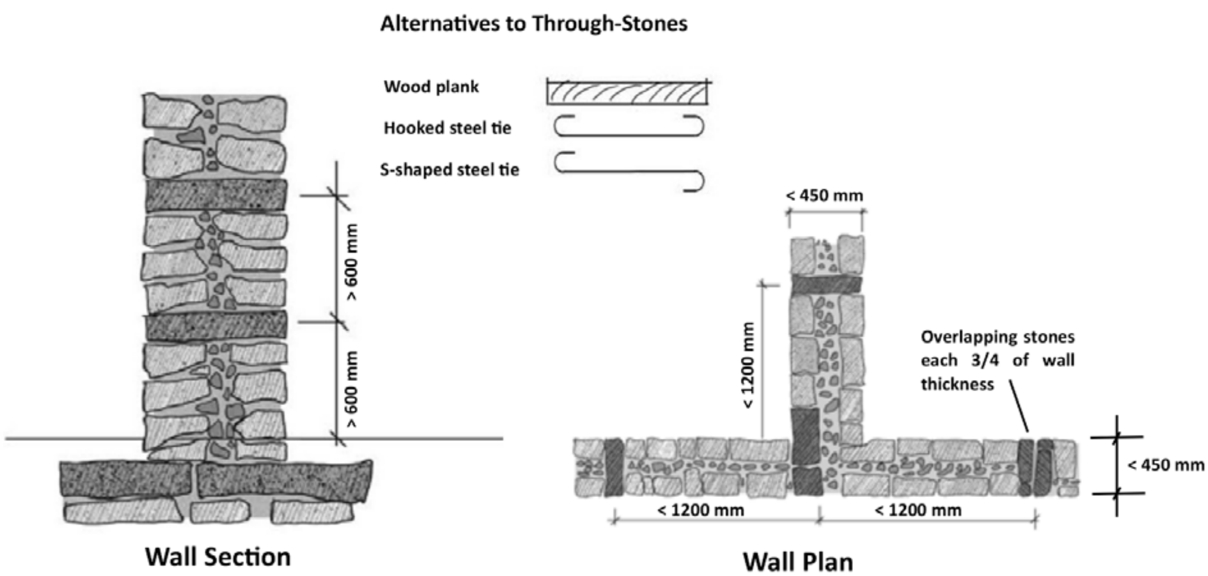


Figure 6.35. Proper placement of through-stones in a stone masonry wall (adapted from GSDMA 2001[36])

Wall intersections should be strengthened with stitches to ensure integral, box action of the building. These stitches could be constructed using long stones, RC bonding elements, steel mesh, or timber. Figures illustrating the use of each type of wall stitches are available in the document.

[36] GSDMA, 2001. Guidelines for Reconstruction and New Construction of Houses in Kachchh Earthquake Affected Area of Gujarat, Gujarat State Disaster Management Authority, Government of Gujarat, India.

Floor and roof structures should be as light as possible, but stiff and securely fastened to the lintel or roof level seismic band. Diagonal bracing of timber or steel floor and roof structures provides sufficient in-plane stiffness. Bamboo is a cheap and strong alternative for framing roof structures.

Stone masonry foundations with RC plinth bands are recommended to avoid differential settlement. The use of mortar as a binder between the foundation stones is recommended.

The advantages and disadvantages of different types of mortar: cement mortar, mud mortar, stabilized mud mortar, lime mortar are discussed in the document. Guidelines on the recommended quality of other construction materials like concrete, reinforcement, stone, and sand are also provided.

It is worth noting that a number of these recommendations are also described in the Nepal Building Code.

6.3.3. Brick masonry construction

Many of the guidelines provided by the Adobe Anti-Seismic Construction Handbook[37] are similar to those mentioned above for stone masonry construction. The emphasis, in the design of these structures, is also on symmetry of building plan, ring beams at the top of the structures, and interconnection of various structural elements like walls, floor, and roof. Additional considerations include the use of vertical and horizontal reinforcement in the form of reed or split bamboo rods to help resist seismic loads (FIgure 6.36). Tips on producing, transporting, and storing quality bricks are also covered.

[37] "Adobe - anti-seismic construction handbook - Misereor." 2010. 21 May. 2015 <http://www.misereor.org/fileadmin/redaktion/Handbook%20anti-seismic%20construction.pdf>

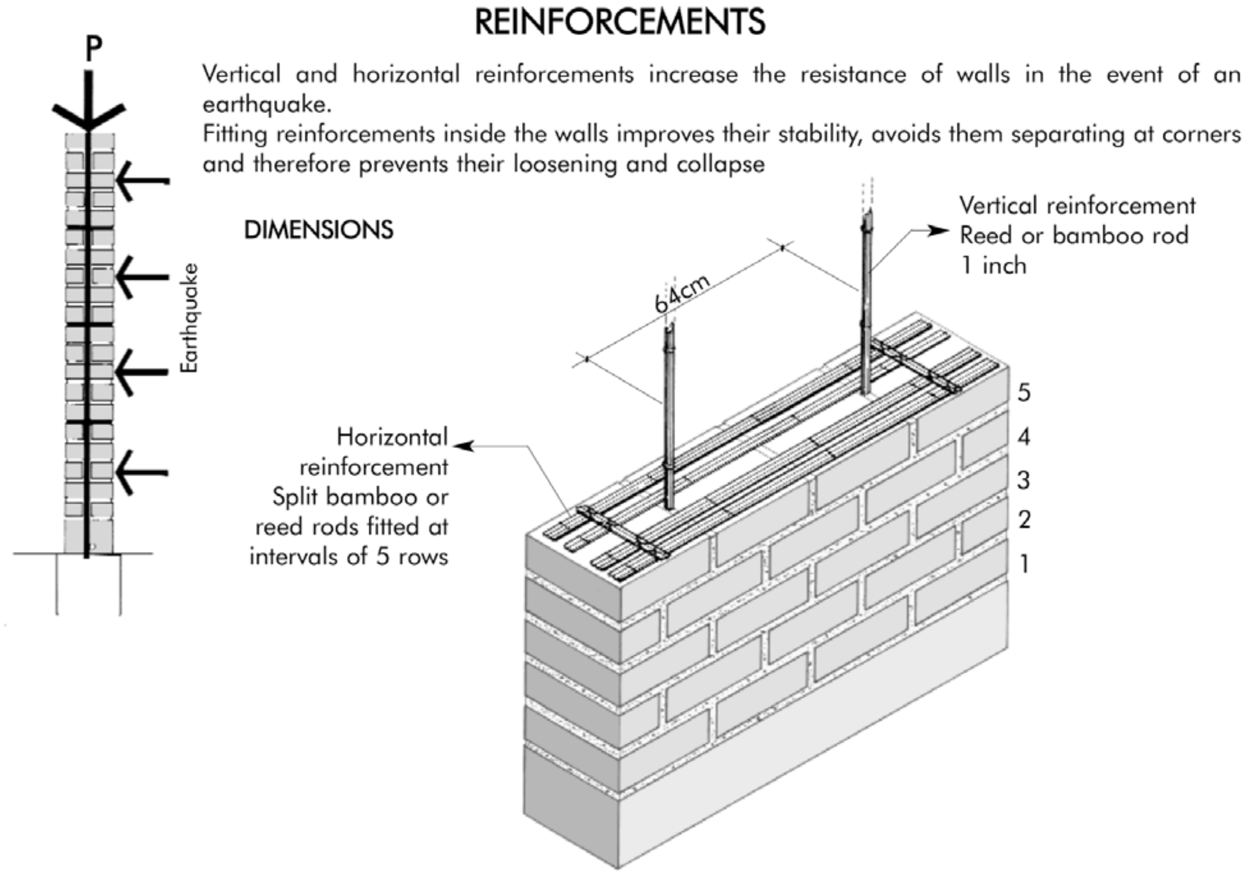


Figure 6.36. Vertical and horizontal reinforcement of brick masonry walls

6.3.4. Straw bale construction

Straw bale construction was proposed as a reconstruction technique following the 2005 Kashmir earthquake. These structures consist of compressed straw bale walls, held together by nylon fishing nets, and sandwiched between layers of plaster. The walls are supported on gravel bag foundations encased in soil cement. Exterior opposing bamboo pins provide out-of-plane support to the walls. Roofs are made of wooden trusses, covered with corrugated iron sheets, and insulated with light straw clay[38]. They attract very small seismic loads due to their light weight, and hence perform very well in earthquakes. Their seismic performance has been demonstrated by a number of experimental tests conducted at the University of Nevada, Reno[39]. Straw bale construction has additional advantages of being extremely low cost, making use of easily available materials, having excellent thermal insulating properties, and being fire-resistant and vermin-proof. To date, Pakistan Straw Bale and Appropriate Building (PAKSBAB) has trained about 60 people and built 27 straw bale houses in Northern Pakistan. Figure 6.37 shows a few construction details and a finished straw bale house.

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[38] "PAKSBAB - Pakistan Straw Bale and Appropriate Building" 2007. 21 May. 2015 <http://www.paksbab.org/>
[39] "Straw Bale House - NEES - University of Nevada, Reno." 2013. 21 May. 2015 <http://nees.unr.edu/projects/straw-house>

Figure 6.37. Straw bale construction

In addition to the construction methods proposed above, a number of other earthquake-resistant construction methods have been developed and proposed by researchers. Although some aspects of the proposed designs are specific to different geographical regions, since they were designed to use locally available materials, they follow the same principles of earthquake-resistant design, and could be easily adopted for use in Nepal (e.g. low cost base isolators). Some such designs are summarized in Figure 6.38, which is adapted from [40].

[40] "How Impoverished Nepal Can Rebuild for the Next Earthquake" 2015. 21 May. 2015 <http://news.nationalgeographic.com/2015/04/150430-nepal-earthquake-rebuilding-construction-science>

Figure 6.38. Alternative earthquake-resistant construction techniques proposed by researchers

7. Summary

Extensive damage to the housing stock from the April 25, 2015 M7.8 earthquake threatens both the health and prosperity of the people of Nepal. Preliminary damage reports from both engineers evaluating houses and from the media indicate that in urban areas, many housing structures are uninhabitable. In the rural regions near the epicenter of the earthquake, overwhelming percentages of houses have been destroyed. Much of the damage to structures occurred because of fundamental weaknesses in material properties and architectural layouts, and the lack of elements tying wall and floor diaphragms together. Stone and brick masonry structures have sustained substantial damage because their components act as individual units instead of structural systems when they are unreinforced.

In this report, the authors have consolidated information on shelter, retrofit, and rebuilding methods from previous natural disasters, particularly earthquakes, in the hopes that the information will assist in expedient selection of a response strategy to rebuild the housing stock of Nepal. Temporary structures that can provide shelter for the people of Nepal were presented based on structures that have been deployed after natural disasters with economic means similar to that of Nepal. The temporary structures reviewed were chosen because they are made of materials that may be easily accessible to Nepal, or can be rapidly deployed to regions of Nepal.

Retrofit and reconstruction methods were also discussed. The aim of the retrofit strategies discussed in this report will help prevent structural components from acting independently from one another, and will help tie the structure together to act as one-body. Reconstruction methods discussed in Section 6.3 are aimed at using materials and building systems that are similar to those currently in practice in Nepal. Slight modifications in design or construction practice were discussed to increase the redundancy and robustness of the structures in Nepal.

Following a large earthquake that takes a devastating toll on the building stock of a country, it is important to rebuild quickly, while being mindful of the resiliency and character of the community. Constructing in the same fashion as has traditionally been done invites future catastrophes.