HUYS ADVIES

EARTHQUAKE RETROFITTING
NON-ENGINEERED LOW-RISE BUILDINGS

Including Non-Engineered Retrofitting of Traditional Pamiri Houses in Pakistan and Tajikistan

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Abstract

Practical examples of non-engineering earthquake retrofitting techniques for traditional adobe, rubble-stone masonry, semi-dressed stone, cut-face stone, cement block construction, baked brick and other building systems in Pakistan, Tajikistan and similar areas such as Afghanistan. The Pamiri house design is detailed with retrofitting options. Preliminary building site assessment and economic feasibility of retrofitting versus total reconstruction. Structural interventions include weight/mass reduction, tie-beams, bracing, framing of walls and openings, through-stones or anchors in delaminated walls, and floor and roof diaphragms. The use of galvanised wire-mesh, gabion type wire-mesh, PP rope netting and full wall jackets is explained. Ring tie-beams with concrete reinforcement bars. Simple earthquake load calculation and estimation of stress reinforcement.

INTRODUCTION

The Technical Working Papers incorporate knowledge gained from more than 30 years experience in project development and implementation in several development countries. Much time has been dedicated to providing practical information on how to realise beneficial, low-cost solutions for the inhabitants of the mountain regions of the Himalayas.

Technologies need to be adapted to local circumstances because of socio-economic circumstances. Existing, proven technical solutions have been modified taking into consideration local customs; technical skills of local craftsmen; ease of transport; availability of materials in the local markets of the mountain regions; as well as the acceptability and affordability by the village people.

Making existing or traditional buildings more earthquake resistant is a necessity for the tens of thousands of houses and other constructions in the seismically active Himalayas. In this document simple retrofitting construction methods suitable for low buildings are explained.

> For low-income people, it is important to find appropriate solutions taking into consideration the local economy of the people. Also the possibilities of the local entrepreneurs, such as skills, tools, materials and other resources, need to be considered to create affordable products for improving living conditions and livelihood.

This Technical Working Paper #12 gives a resume of the most practical retrofitting options for low-rise buildings and reviews several constructions which were executed since 2005. The non-engineering earthquake retrofitting techniques are suitable for traditional adobe, rubble-stone masonry, semi-dressed stone, cut-face stone, cement block construction and baked brick. The paper does not elaborate in detail the earthquake retrofitting techniques for reinforced concrete constructions since these are engineering designs; only a few basic issues are explained.

This document can serve for capacity building and decision making on the subject. It remains, however, a working document and should be extended when additional information becomes available.[1]

Capacity building of technical staff, local building contractors and entrepreneurs is realised by a combination of theoretical education and practical implementation. Analysing existing examples is a good training method, as well as studying material available from the Internet.

The document can also be used as a basis for awareness development, training and as part or basis of curriculum development and vocational training.

National and international training institutes need to develop and expand on this matter with additional practical examples of retrofitting solutions. In this way, a good collection of options and building designs will be developed.

Terminology

In this paper the terminology of "retrofitting" is only used for preventive modification of the building to better withstand earthquakes or post-earthquake repair. Retrofitting in this paper is not used for other construction activities, such as thermal insulation, although they may be executed together.

When making an assessment of retrofitting a building, the cost of the operation needs to be compared with the cost of completely rebuilding the construction incorporating much stronger and lighter weight construction methods. In this adobe building, there was some damping of the earthquake impact (hysteretic absorption) due to the soft adobe, but it is not economical to retrofit the building. Generally speaking, when the retrofitting cost exceeds 40% of the new building cost, it is unwise to undertake the retrofitting.

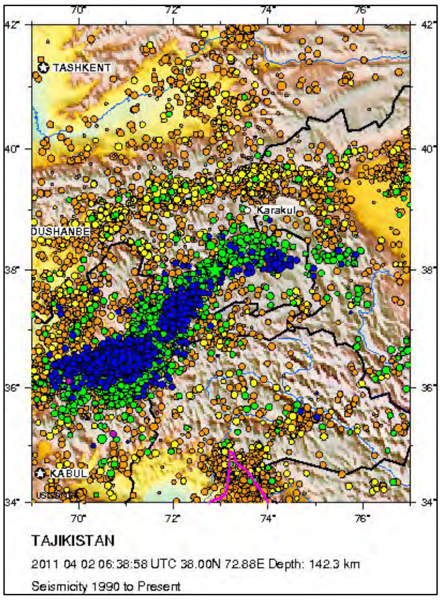
[1] Readers are invited to comment by email: #12@nienhuys.info

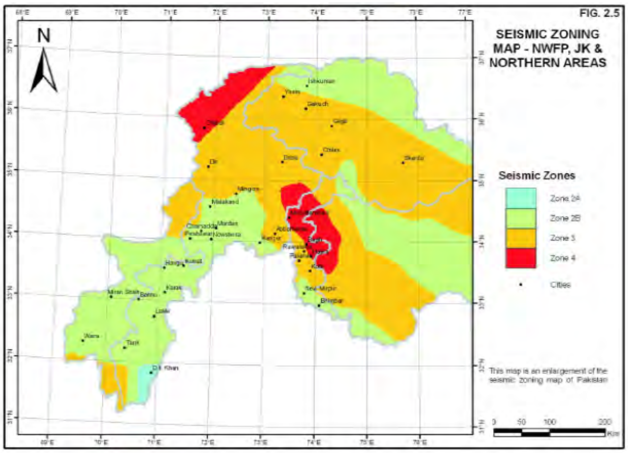
1. ASSESSMENT BEFORE RETROFITTING

The observations in this paper are limited to low-rise buildings having no more than two storeys. Ground floor only and two-storey (ground floor + one storey) buildings are currently the most common in the rural regions of the Pakistan and Tajikistan (GBAO) Himalayas.

For the purpose of seismic design of buildings, Pakistan has been divided into five zones. These zones are based on the possible peak ground acceleration according to current knowledge.

The two maps below indicate the possible intensity of earthquakes for Northern Pakistan (right) and the frequency of earthquakes in Tajikistan (left). The central part is the Gorno-Badakhshan Autonomous Province (GBAO) of Tajikistan, which has an earthquake risk similar to Zone 4 (Red) areas of Pakistan. The narrow Wakhan Corridor of Afghanistan, in between Pakistan and Tajikistan GBAO, lies also in Zone 4 (coloured red, top left of second map).





Gilgit-Baltistan (Pakistan) lies in intensity Zone 3 (Yellow).

Chitral (Pakistan) and the GBAO (Tajikistan) lie in the highest earthquake intensity Zone 4 (Red).

The force of an earthquake is related to the ground acceleration, which is different for each type of soil. Soft soils dampen the shock and thus have a lower acceleration. On the other hand, soft soils result in a continued forward and backward movement of the building, causing increased damage.

Earthquake damage to buildings is the result of several factors, such as the speed and duration of the acceleration and the height and mass of the construction. The effect of these factors needs to be reduced and all have to be considered when retrofitting or strengthening a building to better withstand earthquakes. Before retrofitting the general situation needs to be assessed:

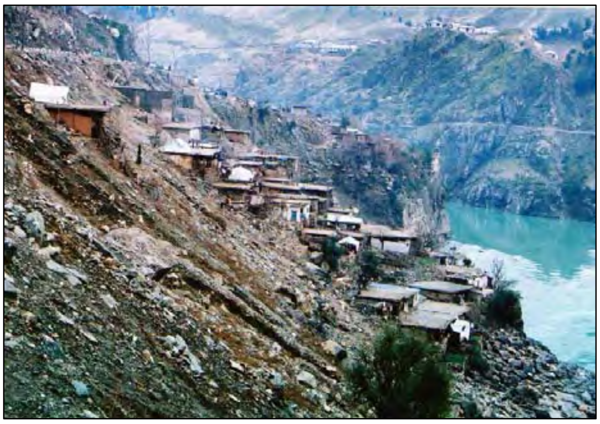
1.1 Assess the General Quality

It is not worthwhile to retrofit a poor quality building if the total cost of the retrofitting exceeds 40% of the cost of a newly constructed building. An exception to this rule would be when the building has historical or special cultural significance. The importance of preserving the building might then outweigh the higher retrofitting costs. When buildings are to be occupied by large numbers of people, such as schools and clinics, the strength should be 1.25 times the strength for housing.

This old building has a light roof, but the walls are a weak rubble construction and total rebuilding is advised. Although, some villagers attached historic value to the building, they are not prepared to pay the retrofitting costs.

1.2 Assess the General Environment

When the building is located in a high risk area, such as being prone to rock fall, landslides and flooding, being constructed on very soft or liquefying soil, etc., it would be better to relocate the building all together and prohibit construction on the existing building site. Buildings constructed on slopes of 30% or more need to be relocated, while on slopes between 25% and 30% only lightweight (timber) houses should be allowed to be built.

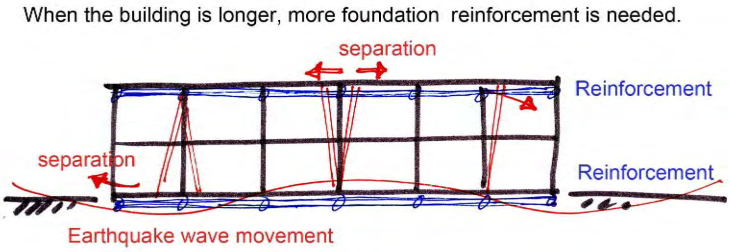


In the Kashmir earthquake nearly all buildings that were constructed on slopes of more than 30% collapsed. The remaining lightweight one-floor timber houses were severely damaged.

1.3 Foundation Stability

The coherence of the foundation itself is important. A long weak foundation can rip the building apart from below during an earthquake wave. Full plate foundations or beam foundations need to be assessed on their ability to hold the building together. Very long buildings (length = >4 x the width) need to be divided into smaller sections of maximum 3 x width.

When the soil lifts the centre of a building during an earthquake, the roof will crack open. When the sides are lifted, the foundation will crack. With long buildings, the foundation and roof reinforcements should be additionally strong.



1.4 Reduce the Mass

<u>The force of an earthquake is directly related to the mass of the construction.</u> The heavier the construction, the larger the horizontal and vertical forces will be on the construction during an earthquake. Constructing lightweight is therefore very important. Reducing the mass of the building as part of the retrofitting activity is a very important element to increase relatively the strength of the building.

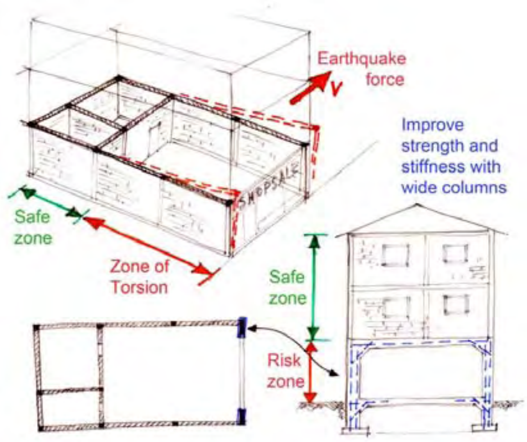
*The mass of traditional soil roofs is very large. The weight of 30 cm of moist soil layers on a traditional house of 8 m x 8 m is approximately **40,000 kg**.*

*With an acceleration force of 25%, the horizontal load on that roof is **10,000 kg**.*

*A lightweight metal sheet roof with a total weight of only 800 kg has a horizontal load of **200 kg** and will not damage the walls.*

1.5 Avoid Non-Symmetric Construction Designs

Non-symmetric construction designs, either in the horizontal plan or vertically, need to be avoided or adjusted to symmetric designs. When the building needs to be non-symmetric for user utility, the strength and stiffness of the building components should be compensating the non-symmetric design.



In the shop building on the right, the wide front opening needs to be substantially reinforced to create structural symmetry in strength. The columns to the side of the opening should be moment resistant.

1.6 Review the Structure of the Walls

The actual compressive strength of a wall and the coherence of the wall construction against delaminating or bulging (splitting between the two faces of the wall) determine to a large extent the resistance of the wall against vertical loads and vibrations.

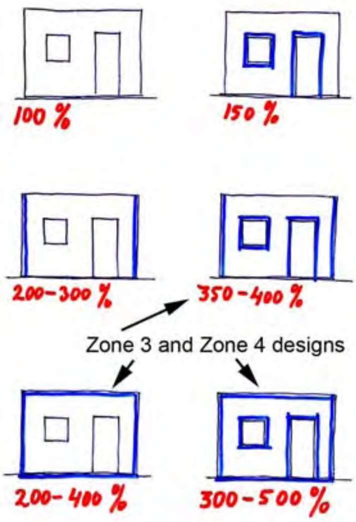
Adobe has a low compressive strength, but compacted adobe or stabilized soil blocks can perform well for single storey buildings. Although stone has a very high compressive strength, those walls depend on the tailoring of the stone and the binding agent, such as clay soil (very low) or cement mortar (good).

Many stone walls have no bonding between the two faces and can easily delaminate under vertical vibrations. This will be accelerated when the stones are round (not straight cut) or when they are masoned in clay soil only. Cut-face stone walls look very nice from the outside, but when not fully cement mortar masoned, will easily delaminate, bulge and fall apart.

Cement blocks or baked bricks are often cement mortar masoned, but when the walls are long or very slim, their vertical resistance can be greatly reduced.

1.7 Review Openings and Piers

The strength of buildings is strongly and negatively affected by door and window openings. When retrofitting is being considered, it needs to be assessed whether these openings would require closing or replacement to create stronger shear wall sections.



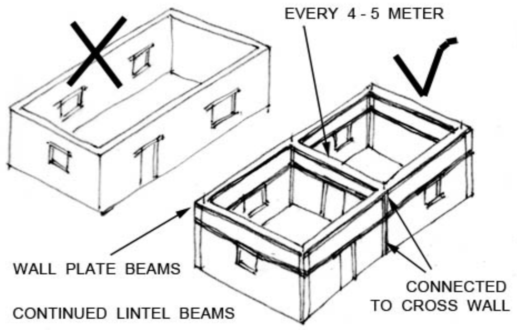
For Zones 3 and 4 earthquake areas, all openings and wall endings should be completely framed to enhance overall wall strength.

In many cases, retrofitting goes together with remodelling of the building, including larger windows. The piers between the openings need to be sufficiently wide to function as shear walls.

The framing around openings, small shear wall segments and wall endings does substantially improve the overall strength of the building.

1.8 Improve the Strength

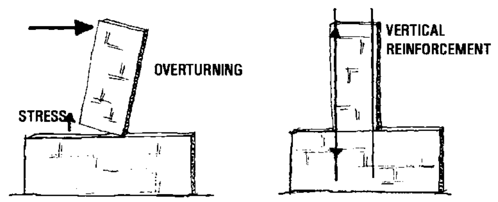
The strength of the building needs to be increased to withstand the expected maximum horizontal and vertical earthquake forces.



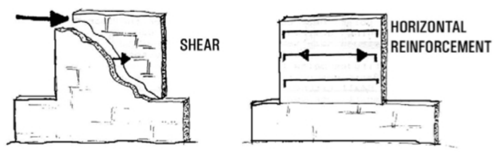
This means that sufficient shear walls (connected to cross or bracing walls) have to be present in the building. Shear walls need to be positioned perpendicular to other (cross) shear walls.

The long room is divided with a cross (shear) wall. The two long walls are strengthened and connected with tie-beams to the side walls and the new central wall.

Tie-beams need to continue over doors and windows and be at floor/roof level.



Narrow shear wall sections need to be framed with adequate vertical stress reinforcement. When the piers are narrow (height = >2 x width), they tend to overturn without the framing stress reinforcement. This means that small piers next to windows and doors have to be converted to column structures. This framing can be done by adding angle iron profiles or with wire-mesh wrapped around the section.



Shear walls being about as wide as high need horizontal reinforcement to avoid diagonal cracks. The horizontal reinforcement needs to be anchored in the vertical framing. In the square or wider wall sections, the horizontal reinforcement is three times as effective as vertical reinforcement.

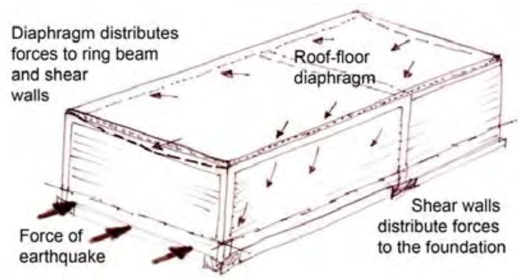
In this house, the smallest wall sections of the building, between the corner of the building and the window, show diagonal cracks. With horizontal reinforcement anchored to vertical reinforcement along the wall ending and the window, this wall would not have cracked.

In a retrofitting exercise, the reinforcement can be fitted on the outside and inside faces by means of a full wire-mesh wrapping and tie-beams over all the walls.

The all-adobe house in the picture, however, is of very poor quality and the retrofitting cost would be very high. Even after incurring the retrofitting expense, it would unlikely be strong enough to support a second storey in the future.

All floors need to be made as diaphragms anchored to all surrounding tie-beams and walls.

The load from the upper building or roof should be transferred through the walls to the foundation. This means that the walls should have compressive strength and stress resistance, and should be supported in their perpendicular direction by other shear walls.

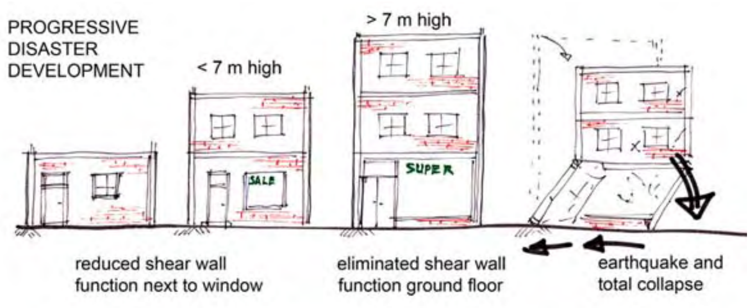


All elements should be tied together by tie-beams, especially the joining walls and the floor diaphragms, as well as the walls to the floor and roof diaphragms.

1.9 Plan for the Future

In many cases, retrofitting is undertaken when the following applies:

- The house owner wants to extend the building with another section or storey.
- The building changes ownership and other building activities are being considered, such as adding a room, additional storey, renovation, etc.
- The building is slightly damaged during an earthquake.
- Building inspection certifies that the earthquake resistance of the current building is too low for the location.
- The house owner realises that the building is unsafe when an earthquake occurs.



When an existing building must be able to carry an additional storey or when enlarging openings on the ground floor adds serious risks, retrofitting of the structure is important.

When the openings are enlarged and the adjoining piers become narrower than half their height, these piers need to be reinforced to become moment resistant reinforced (concrete) columns.

With reinforced concrete columns, the maximum moment areas must have cage reinforcement to contain the concrete when the earthquake forces exceed the construction strength.

For each extension of the building, it needs to be considered whether it is in structural symmetry with the rest of the building. This photo below shows one of the most common errors (source: Internet). See also the sketch in paragraph 1.5 (page 4) on a similar situation and possible retrofitting design.

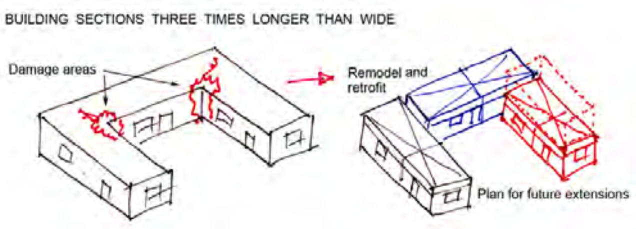
If these basic structural controls and improvements are not considered, the resulting economic disaster can be very high.

Buildings are supposed to last for many years. It is not the question **IF** an earthquake arrives, but rather **WHEN** it happens.

1.10 Review the Layout of the House

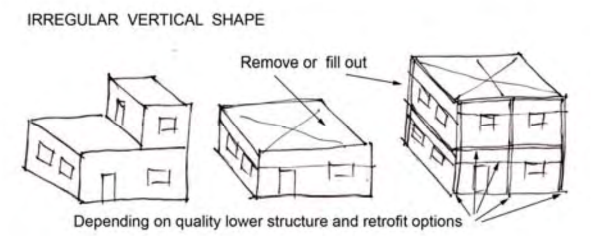
After studying the general site layout and before retrofitting, the house layout should be analysed. This can mean that some narrow window piers need to be made wider or stronger, or closing windows. The points raised below are related to earthquake Zones 3 and 4.

(a) It is better to split or fully separate long sections or attached side buildings from the main building. Are there plans for adding another storey to one or more of the sections in the near future?

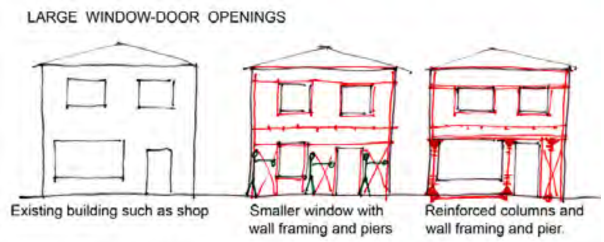


(b) The building needs to have a symmetrical floor and vertical plan.

Can the existing lower floor be made strong enough to bear an additional upper floor? Can a new upper floor be made lightweight to cause little earthquake forces?

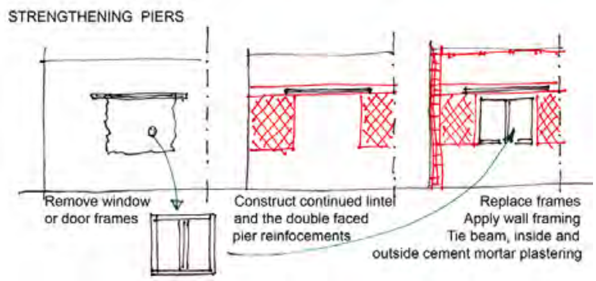


(c) If the width of the piers next to doors and windows are ≤1.20 m, they need to be widened or converted to reinforced columns. The reinforced columns have to be fully caged at all maximum moment areas, such as at windowsill level. Wall framing and tie-beams are necessary.



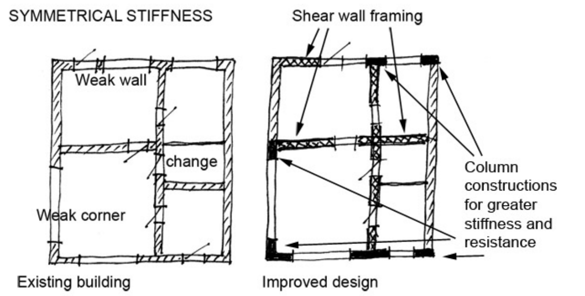
(d) Are all the piers fitted with wall framing, especially for houses with upper storeys?

In some cases, this means removing the existing window or door frame, applying framing of the wall section, and replacing the window or door frame. Wall framing is to be anchored into the lintel and tie-beams.



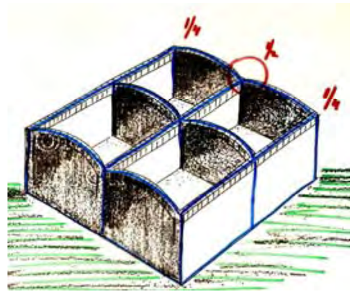
(e) Are the larger shear wall sections evenly distributed over the floor plan and in both horizontal (perpendicular) directions?

Often it is necessary to replace inside doors to make a better distribution of the larger shear walls. Walls can be repositioned to provide continuity in force lines. If there are large openings on one side, stronger columns need to be made to compensate for strength and stiffness.



(f) Can the inside walls and tie-beams take most (50% or more) of the total horizontal earthquake load and bring that load down to the foundation?

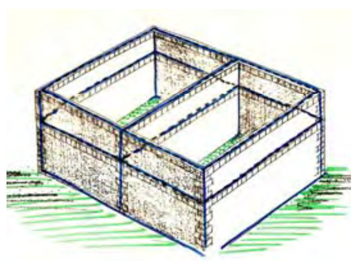
In the house sketched right, the inside separation walls take approximately half the load from the inside and outside cross walls, and the load from the floor or roof. Good anchorage of the internal load bearing walls to the outside walls is important. To realise these wall tie-beams and make a diaphragm at the same time, the floor/roof often needs to be reconstructed.



(g) Are all door and window lintels connected and form a closed seismic band around the house? Are these lintel tie-beams also connected over the inside walls?

(h) Are all the floor beams anchored to the wall tie-beams and form together a diaphragm in both directions?

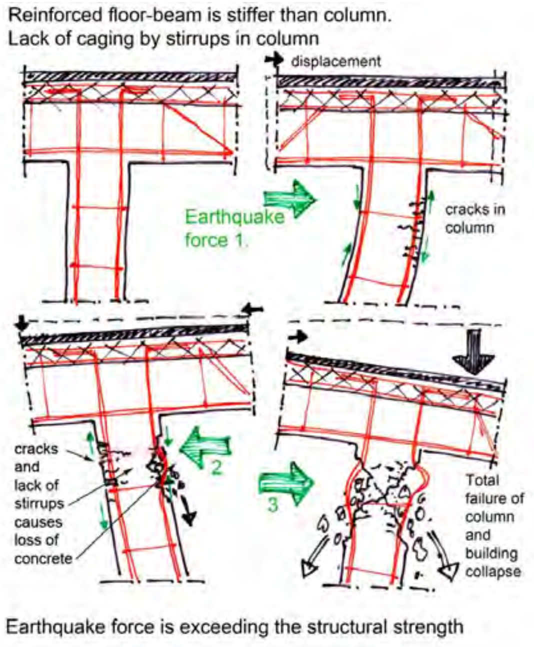
The floor or roof beams running parallel to the walls also need to be connected to the walls. Connections of floor diaphragm with tie-beam anchors have to be made all around the building.



1.11 Ductility of the Structure[2]

This paper does not detail the retrofitting of reinforced concrete constructions. However, in low-rise and non-engineered constructions, a lot of reinforced concrete is being used. Reinforced concrete is a very heavy materials (>2200 kg/m^3), and when poorly dimensioned or from poor quality, it creates an additional hazard.

An 8 m x 8 m (64 m^2) x 12 cm thick reinforced concrete floor or roof with a 4-5 cm layer of cement has a weight of more than 20 tons. During an earthquake, this can generate an alternating horizontal shock load of 25% = 5 tons.



The support structure needs to continue to function, even when the maximum design forces of the concrete have been exceeded by the earthquake.

Structures should not be brittle or collapse suddenly. Structures that bend or absorb large forces (damping) by some deformation are preferred.[3]

When the steel bars bend, the concrete will fall away, causing the structure to fail. This can be avoided by caging the maximum moment areas with stirrups.

Although a structure might need to be reconstructed when it gets extensively deformed, its toughness (binding together) minimises instant collapse and allows people time to escape.

Reinforced concrete constructions are typically heavy and brittle designs that collapse instantly when the earthquake forces exceed the construction design. The reinforcement does not hold the broken concrete together. At the maximum moment area, a large number of stirrups are needed to avoid sudden collapse.

Existing column constructions need to be assessed:

A. Where will the maximum moment force occur in the construction?
B. What steel reinforcement is present inside the concrete columns?
C. What additional reinforcement needs to be realised to improve the situation?

In these cases, it is necessary to contact a structural engineer for proper advice.

[2] The ductility or damping is also called "absorption of forces" or "hysteretic response of the structure". The effect is that although the structure gets damaged, part of the earthquake forces is absorbed in the process.
[3] This is also hysteretic movement.

1.12 Escape of the Occupants

When a heavy earthquake continues for a minute or longer and the building still remains upright, the occupants can sometimes escape to the outside. The door openings must remain open. For buildings with many occupants, the doors need to be wide and open outwards for safety.

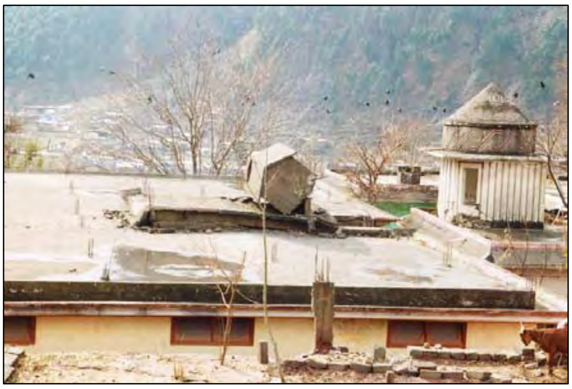

In the left photo, there was no chance for escape because the reinforced concrete columns did not have the required caging and the building collapsed instantly under the very heavy concrete roof. The vertical reinforcement from the column is visible in the centre of the picture. It has been pulled out clean from the poor quality concrete. Five design mistakes: column reinforcement without caging, no internal shear walls, too much weight, no ductility and poor concrete quality.

In the right photo, the loosely piled traditional rubble stone wall fell outwards during the earthquake. The lightweight roof, however, hung together and in this building the occupants escaped.

When framing wall sections around door openings, the most likely escape routes should be additionally strengthened, especially in buildings where many people can be gathered.

1.13 Furniture Straps and Braces

A lot of injuries occur during earthquakes because of falling ceilings and household furnishings, such as cabinets, water tanks and refrigerators toppling over.



In this photo, the concrete water tank on the roof has toppled over during an earthquake. Hot water tanks inside the house should be well fixed to the floor or at least onto two walls, preferably with its own support. Hot water tanks fitted to the stove should be stable, allowing 50% of their weight as horizontal force.

1.14 Calculate the Horizontal Load Factor

The horizontal load factor on the building is the most critical. When the building resists this static horizontal load, a minimum level of safety is achieved. The weight or mass of all the building components therefore needs to be calculated. For houses, the importance factor (*I*) is 1, but for clinics and schools, the importance factor (*I*) is 1.25.

Considering the variables in the construction quality, it can be simply stated that:

- Gilgit-Baltistan (Pakistan) needs to consider a horizontal load factor of 20% of its mass (W) times importance (I).
- Chitral (Pakistan) and GBAO (Tajikistan) need to consider a horizontal load factor of 25% of its mass (W) times importance (I).

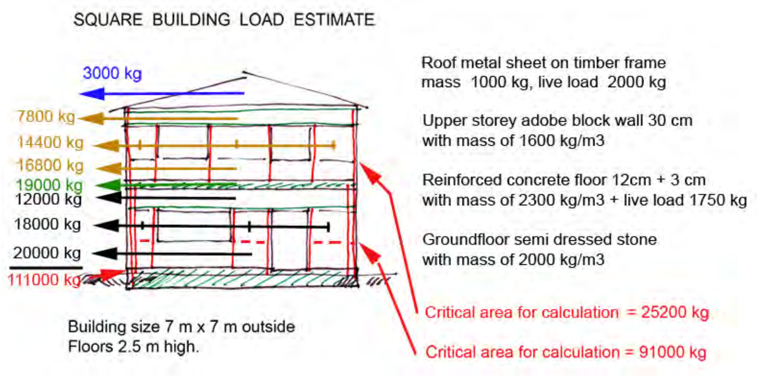
The building mass and live weight is calculated from the top floor down. Each floor must be able to carry the full load of its upper zones. All students should be taught how to calculate the mass of a building; that is not engineering.

The horizontal load must be carried down to the foundation through the shear walls and piers. Since it is generally unknown from which side the earthquake will come, the walls in two horizontal perpendicular directions need to be calculated.

The building in the sketch is square with the approximate mass and live loads estimated. The live load for the roof includes snow, but can be assumed lower.

Including inside walls, the total mass and live load of the building is over 100 t.

The most critical areas are determined and calculated. The reinforcement is to be calculated on these sections.



Under the upper floor window level, the total earthquake load for a house in Zone 4 is 25% of the mass or 6300 kg. The stress reinforcement in the walls at this level should resist that force. Under the ground floor window level, the total earthquake load is 25% of 91000 kg = 22750 kg.

The stress force needs to be absorbed by stress-resistant materials. Four different gauge values exist for galvanised steel wires; determined by the strength per mm^2. When the length wire is knotted, the allowable stress force is reduced by 25%. Galvanised wire thinner than Ø 1 mm is not recommended for structural purposes.[4]

Diameter	S.W.G. Gauge	Section	Strength/mm^2	Breaking Force	Knotted Wire
Ø 1.0 mm	19	0.8 mm^2	35 kgf/mm^2	28 kgf	20 kgf/wire
Ø 1.2 mm	18	1.1 mm^2	40 kgf/mm^2	40 kgf	30 kgf/wire
Ø 1.4 mm	17	1.5 mm^2	40 kgf/mm^2	60 kgf	45 kgf/wire
Ø 1.6 mm	16	2.0 mm^2	40 kgf/mm^2	80 kgf	60 kgf/wire
Ø 1.8 mm	15	2.5 mm^2	40 kgf/mm^2	100 kgf	75 kgf/wire
Ø 2.0 mm	14	3.1 mm^2	45 kgf/mm^2	140 kgf	100 kfg/wire
Ø 2.3 mm	13	4.1 mm^2	50 kgf/mm^2	207 kgf	150 kgf/wire
Ø 2.6 mm	12	3.3 mm^2	50 kgf/mm^2	265 kgf	200 kgf/wire
Ø 2.9 mm	11	6.6 mm^2	50 kgf/mm^2	330 kgf	250 kgf/wire

Concrete reinforcement bars and angle iron can be calculated in a similar way:
When used inside good concrete, the calculated value is about half the breaking strength.

Diameter	Type	Section	Strength/mm^2	Breaking Force	Calculate With
Ø 6.0 mm	Mild steel	28 mm^2	25 kgf/mm^2	700 kgf	300 kgf/bar
Ø 7.0 mm	Mild steel	38 mm^2	25 kgf/mm^2	950 kgf	400 kfg/bar
Ø 8.0 mm	Cold deformed	50 mm^2	35 kgf/mm^2	1750 kgf	800 kgf/bar
Ø 10.0 mm	Cold deformed	78 mm^2	35 kgf/mm^2	2730 kgf	1200 kgf/bar
Ø 12.0 mm	Cold deformed	113 mm^2	35 kgf/mm^2	3955 kgf	1800 kgf/bar

Different suppliers can have different qualities in strength and galvanisation. Cold deformed and ribbed steel has better adherence to concrete than smooth mild steel bars. Welding points weaken the bars. All steel bars need to be cast in strong quality cement mortar or concrete.

Glass fibre mesh[5] is woven in two directions and is used as external reinforcement in plasterwork (light mesh) and dry-piled cement block construction. It can also be used as earthquake reinforcement and is commonly used in high buildings and skyscrapers.

[4] S.W.G.. stands for Imperial (British) Standard Wire Gauge. Non-galvanised wire has different sizes.
[5] VITRULAN Technical Textiles GmbH, maze 6 mm x 7 mm, Panzer Fabric®, 325 g/m^2, strength >800 kg/10 cm width. Special Panzer Fabric manufactured for earthquake wall reinforcement with maze 20 mm x 12 mm, strength > 1000kg/10cm.

1.15 Calculate the Reinforcement Amount

Based on the above figures, the minimum stress reinforcement in the upper level is as follows:

Reinforcement	Strength	Number	Total Load	With 3 Walls = 6 Wall Faces
Ø 2.3 mm GW	150 kgf/wire	42	6300 kg	14 per wall = 7 per wall face
Ø 2.9 mm GW	250 kgf/wire	25	6250 kg	8 per wall = 4 per wall face
Ø 8.0 mm TOR	800 kgf/bar	8	6400 kg	3 per wall = 2 per wall face
Ø 10.0 mm TOR	1200 kgf/bar	6	7200 kg	2 per wall = 1 per wall face
Panzer Fabric	800 kg/10 cm	80 cm	6400 kg	27 cm/wall = 15 cm/wall face

Comparing the above values and solutions, Ø 2.9 mm GW or Ø 8.0 mm TOR are the best options and simple to apply. The reinforcement should be placed vertically along the smallest window piers.

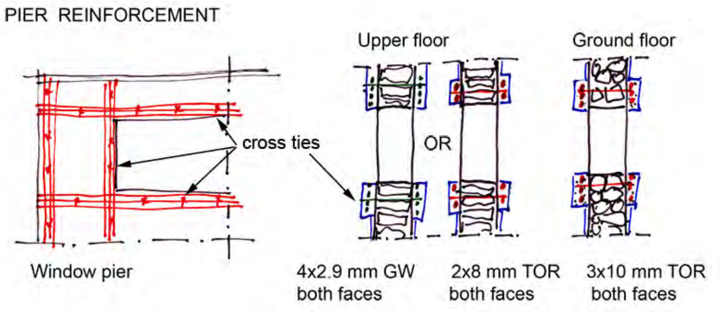
For the lower level, the forces are substantially larger, partly due to the heavy floor:

Reinforcement	Strength	Number	Total Load	With 3 walls = 6 wall Faces
Ø 2.3 mm GW	150 kgf/wire	152	22800 kg	51 per wall = 26 per wall face
Ø 2.9 mm GW	250 kgf/wire	91	22750 kg	30 per wall = 15 per wall face
Ø 8.0 mm TOR	800 kgf/bar	28	22400 kg	9 per wall = 5 per wall face
Ø 10.0 mm TOR	1200 kgf/bar	19	22800 kg	6 per wall = 3 per wall face
Panzer Fabric	800 kg/10 cm	284 cm	22750 kg	90 cm/wall = 45 cm/wall face

Comparing the above values and solutions, Ø 10 mm is the best option and simple to apply. The reinforcement should be placed vertically along the smallest window piers. Instead of TOR bars, angle irons can be used with as minimum the same stress resistance.

For example:
When the building is made from lighter construction materials, the amount of reinforcement can be less.

For buildings in a higher safety category, such as schools and public buildings, the load factor needs to be increased by 25%.



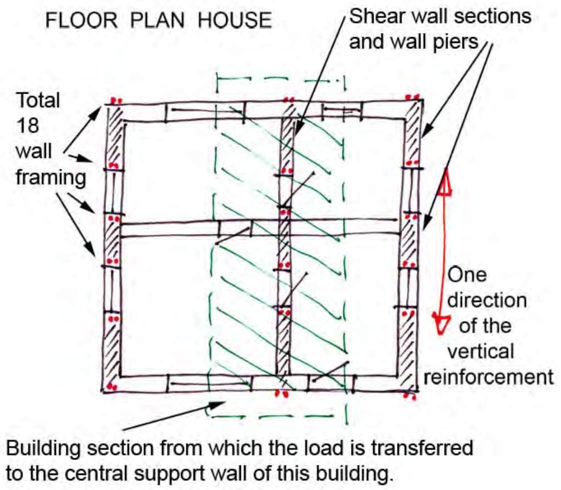
In the case of the above symmetric building, 50% of the load is taken by the internal walls. This is especially so when the reinforced concrete floor is anchored to all walls and functions as a solid floor diaphragm. When these inside walls are cement mortar masoned and have long shear wall sections (width = height or width > height), the amount of reinforcement can be reduced. However, when the building is not very symmetric or the inside walls are not well cement mortar masoned, reductions should not be made. For buildings which are not (almost) symmetric in their floor plan, the load factor needs to be calculated in the two main horizontal perpendicular directions.

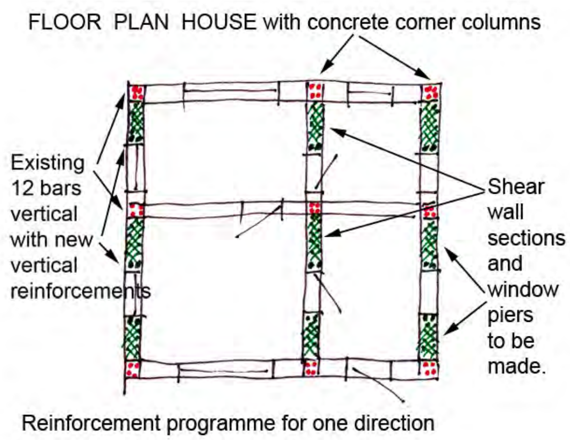
In the decision making about the amount of reinforcement, it is necessary to know whether or not an additional storey is going to be built on top of the retrofitted construction. If so, the construction design and weight should be known and the additional reinforcement applied in the ground floor construction.

- Vertical reinforcement is taken to be the same amount as the horizontal reinforcement.
- When applying square type wire-mesh, PP netting mesh[6] or Glass fibre Pantzer Fabric®, the same calculation system can be used.
- When applying gabion or chicken wire type mesh with wires in an angle for both horizontal and vertical reinforcement at the same time, 40% strength increase is required.

[6] From the PP netting as depicted in paragraph 2.1 page 15, no technical information was found. Pre-stressed PP strip (cable) has a much higher elasticity than galvanised wire, steel bar or glass fibre. The wall deformation will be larger causing cracks, but hysteretic movement will also be larger, creating more shock absorption.

- The mesh should be filled in and plastered over with non-compressible plaster. This plaster transfers the forces between diagonal, horizontal and vertical stress reinforcement.
- Vertical reinforcement can be taken as being the same amount as the horizontal reinforcement. This is stress reinforcement for wall framing and anchoring of the horizontal reinforcement.





The 7 m x 7 m floor plan above is used as an example. The left sketch shows the reinforcement in one of the two horizontal directions. In total, 18 wall framings are needed in the three walls. When referring to the above two tables, only 3 x Ø 2.3 mm GW is needed for each wall ending in the upper floor or 5 x Ø 2.9 mm GW for each wall ending in the lower floor. Alternatively, 2 x Ø 8.0 mm TOR can be used in the lower floor wall endings.

The first sketch also shows that about 50% of the load of the building is carried by the central wall. Because a reinforced concrete floor is very stiff, in this case the horizontal load will be evenly distributed over the three walls. When the floor diaphragm is not very stiff, more load will be carried to the central wall as per the sketch.

The right-hand sketch is the situation when the building has been made with reinforced concrete in the corners of the walls. In such a case, these column reinforcements will function as stress reinforcement. When for each wall section 12 bars of Ø 8.0 mm TOR are already present in the columns, the difference with the requirements for the upper floor is zero. The difference for the ground floor is 6 x Ø 8.0 mm TOR. However, to obtain a good force distribution, double bars should be used in the non-reinforced openings, both for the ground floor and upper floor; otherwise the piers or shear wall sections do not work because the horizontal reinforcement has no connection.

The above calculation shows that making very thick columns in wall corners is not very economical and does not avoid the need for making vertical reinforcement along the window openings.

The following recommendations can be made in relation to wall reinforcement:

(a) Centrally located walls inside the building will play a major role in transferring the earthquake load to the foundation, especially with a non-stiff floor diaphragm.
(b) A very stiff floor diaphragm better distributes all the building loads to the support walls.
(c) The amount of horizontal and vertical wall framing should be the same.
(d) Wall framings should be similar on both sides of the openings to optimise resistance.
(e) Making thick columns only in the wall corners does not provide wall section framing.
(f) All outside and inside wall framing and tie-beams should be linked together.
(g) The reinforcement amount needs to increase with the possible earthquake load; hence a separate calculation should be made for each storey.
(h) The weakest horizontal section should be determined as critical calculation area (windows).
(i) Asymmetric buildings need to be compensated with extra strong elements to avoid torsion.
(j) When diagonally woven wire-mesh is used for both horizontal and vertical reinforcement, the calculated strength should be increased by 40%.

2. BUILDING SYSTEMS

Buildings can be classified into several construction categories, each having specific technical options for retrofitting. When the post earthquake damage is extensive, it is most often more suitable to rebuild the house entirely, especially when the reconstructed house can be made much lighter and therefore relatively stronger than the repaired damaged house.

When the retrofitting cost exceeds 40% of the new building cost (including building materials), it is wiser to totally reconstruct the house.

The reconstruction or retrofitting cost depends not only on material costs, but labour as well. In remote villages the labour cost is often low and most houses have been built by the house owners themselves. House construction is usually a joint effort with family and neighbours lending a hand and undertaken during the period when there are few agricultural activities. The retrofitting method should therefore facilitate construction in the non-agricultural seasons. Construction work using cement mortar or (reinforced) concrete can only be realised when the average daily temperature is above 15°C and there is no night frost. Usually this coincides with the agricultural period when people are very busy.

Given the scarcity of land in most mountain areas and the need to relocate a large number of people who live in unsafe site locations, the reconstructed houses should include the possibility of ground floor plus one or two storeys to house several or larger families.

Non-cement mortar masoned walls lack resistance to any stress forces. For walls masoned with cement mortar, the allowable stress forces will quickly be exceeded. For the calculation of structures, it must therefore be assumed that cement masoned wall structures do not absorb any stress forces. Hence all walls require stress reinforcement.

Improving the ability to absorb stress forces requires stress-resistant materials, such as steel (flat strip, angle irons, steel concrete reinforcement bars, galvanised wire, wire-mesh), bamboo, timber or synthetic fibres (nylon, polypropylene-PP, glass fibre). Although timber and bamboo can resist stress forces, these materials are becoming scarce and costly. The use of timber is currently limited to supporting columns and beam structures.

Since earthquake forces are vertical and horizontal from various opposing directions, the stress reinforcement must be applied to all walls in both vertical and horizontal perpendicular directions. Most thick, non-cement mortar masoned stone wall constructions also need to be reinforced internally to resist vertical loads and bending loads perpendicular to the face of the wall.

2.1 Adobe Houses

Generally, adobe houses should be rebuilt entirely. Only ground floor only adobe houses can be reinforced to withstand Zones 3 and 4 level earthquakes.

Most adobe houses will fail during an earthquake, even when not located near the epicentre.

Because the adobe material does not have good compressive strength (<3 kg/cm^2) and hardly any tensile strength (<0.3 kg/cm^2), in combination with a large mass and seldom a foundation, most of these houses will collapse in an earthquake of average strength.

Hand-built adobe soil houses have 40-50 cm thick walls, a large mass >1600 kg/m^3 and large shrinkage cracks. The compressive strength of hand-built adobe is maximum 3 kg/cm^2, being very low for construction purposes. When these walls are constructed with courses of galvanised wire-mesh every 30 cm high, they can resist substantially large forces without immediate collapse. The reason is that the adobe wall will absorb part of the shock by deformation.

Good reinforcement or retrofitting can be achieved simply by applying a reinforcement mesh on both faces of the wall and galvanised wire through-the-wall anchors every 60-70 cm (staggered) to connect the inside mesh to the outside mesh. The mesh used can be PP, nylon or galvanised chicken wire. Non-galvanised wire-mesh should not be used. The roof construction should be lightweight. Retrofitted houses with double mesh (inside and outside) are still unsuitable for having a second storey in Zones 3 or 4 earthquake areas. [7]

Rammed earth adobe houses are substantially stronger (<15 kg/cm^2) because the dryer soil is well compacted and has a higher pressure resistance. With a shear wall design, tie-beam and floor diaphragm, they can resist Zone 2a and 2b earthquakes. These houses are not found in the Western Himalaya area under review.

Adobe block houses are usually masoned with dried blocks (<10 kg/cm^2) in wet adobe soil (<3 kg/cm^2). Houses with substantial wall piers in both horizontal directions can be retrofitted by making shear walls and reinforced piers. Adobe block houses should not have a second storey in Zones 3 and 4 earthquake areas.

The adobe block house in this picture has far too slender piers next to the windows, no tie-beam and no floor diaphragm. In the corner by the windows, a supporting column can be reconstructed to support a roof tie-beam running around the entire house. Inside the house, perpendicular shear walls need to be created to transfer the roof load towards the foundation.

The upper adobe construction should be totally removed. Not only because the adobe house should not have a second storey, but also because it creates an asymmetric load.

The non-window sections of the lower walls should be converted to shear walls by applying chicken/gabion wire-mesh or PP/nylon/glass fibre mesh on both inside and outside faces, going around the window openings. This should be done for all four sides of the house and a new tie-beam should be connected over the inside walls.

Reconstructing the building with Galvanised Wire-Mesh Reinforcement (GWR)[8] inside the new wall probably is less costly. The GWR or PP/nylon/glass fibre mesh is a product that needs to be paid for. The amount of steel for the rolls of GWR for internal wall reinforcement is far less than the amount of chicken/gabion wire-mesh on the two faces for making the shear walls.

Handmade adobe blocks have a low compressive strength (<10 kgf/cm^2) and for that reason their resistance to earthquakes is not very high. Their resistance to stress forces is negligible. Without stress reinforcement, adobe block walls will simply break apart, first at the corners and then collapse. Small piers between windows will fail (see photo on Introduction page).

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[7] Getty Reinforcement of Adobe Buildings (2005?), 11 pages, 1.13 MB. Good description, but not very relevant for Himalayan area. www.getty.edu/conservation/publications_resources/pdf_publications/gsap_part1c.pdf

[8] Details on using GWR wall reinforcement are given in the document, Galvanized Wire-Mesh Reinforcement (GWR) (latest revision, October 2010).

Retrofitting with wire-mesh reinforcement on and around all corners, linking inside walls to outside walls, and fitting a full roof diaphragm will substantially improve earthquake resistance. The wire-mesh reinforcement can be of galvanised metal wire (GWR), glass fibre wire (VIRTULAN Panzer Fabric®) or polypropylene (PP) netting. The mesh or netting applied on the two faces of the walls needs to be stitched through the wall and fixed to the other face reinforcement. This can be done with galvanised wire (sketch page 17).

The PP netting construction technology was presented at the Proceedings of the 11th International Conference on Non-Conventional Materials and Technologies (NOCMAT 2009) held on 6-9 September 2009 in Bath, UK.

Inside and outside netting must be connected every 60-75 cm with through-anchors (galvanised wire). The entire building must then be cement plastered inside and outside, making the application expensive.

Based on self-help construction labour and common sense cost analysis in a village environment, reconstructing an adobe house with a lightweight roof would be more economical.

The compressive strength of adobe blocks can be increased by adding 10-15% volume gypsum (not with cement), resulting in a compressive strength of respectively 40-50 kgf/cm^2. Adding horizontal stress reinforcement in the newly masoned construction is essential in all cases. Two-storey constructions should consider closely positioning all openings and perpendicular shear walls. However, two-storey adobe constructions are not advised in a Zones 3 or 4 earthquake risk areas.

2.2 Compacted Earth Blocks

Strongly compacted earth blocks (<50 kgf/cm^2) and compacted cement-stabilized earth blocks (<100 kgf/cm^2) have much higher compressive strengths than adobe blocks. With an existing proper shear wall design, these types of earth blocks can be further improved by applying total framing of openings and walls in combination with floor diaphragms. Currently the use of compacted or compacted and stabilized soil blocks is unknown in the Pakistan or Tajikistan regions.[9]

Making of compacted earth blocks can be done with the CINVA ram and motorized presses. The hand-operated machines give varying results without constant quality control, and the process is labour intensive. Self-locking or dry stacked interlocking bricks can be made and bamboo wall reinforcement is often applied. The bamboo needs treatment for conservation. When assessing compacted earth block buildings, the block strength and internal reinforcement must be verified.

Hand-operated CINVA ram machine with hollow core for placing vertical reinforcement. Stabilized (5% cement) and compacted earth blocks can reach a compressive strength of 50 kgf/cm^2. Profiled and interlocking blocks are manufactured as well.

[9] Stabilized and machine compacted earth blocks were extensively used in the post-earthquake reconstruction of Bam in south Iran (23 December 2003 earthquake) as this is a dry climate.

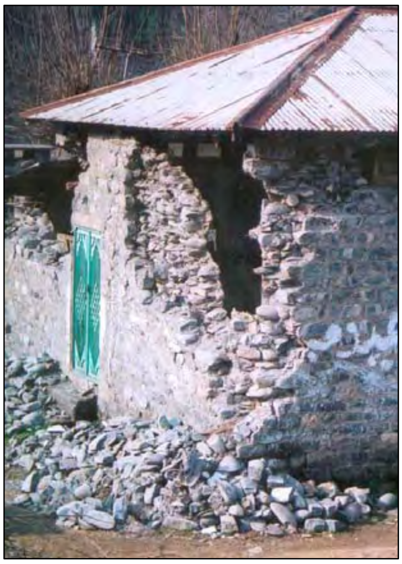
2.3 Rubble Stone and Soil Masonry

Houses built of rubble stone and clay soil masonry are almost worse than adobe houses and preferably should not be retrofitted. It is generally more economical to pulled down the construction completely and rebuild.

The internal bonding inside the heavy walls is totally inadequate, while an occasional timber or reinforced concrete beam does not provide sufficient bonding in any direction. Lime or cement mortar plastering inside and outside will hardly improve the structural strength but does limit the amount of erosion by rain and wind.

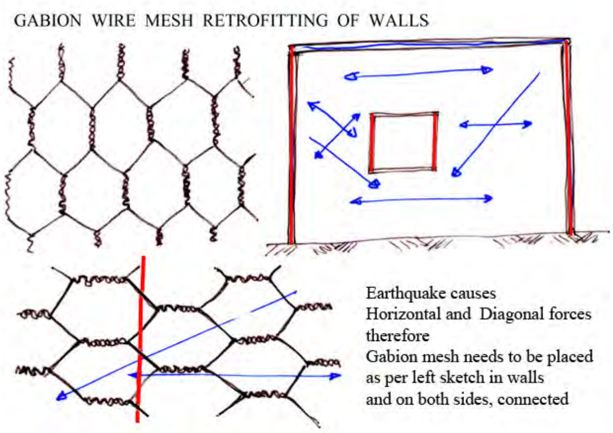
However, if retrofitting is undertaken, such type buildings can be retrofitted with external netting or wire-mesh, through-anchors and cement plastering, similar to adobe constructions. However, such an operation is relatively costly and the construction will not be able to bear a second storey.





Left photo: *Shows the loose bondage in the clay masoned rubble stone wall.*
Middle photo: *Shows the lack of bonding of timber tie-beams.*
Right photo: *Shows that although the stones are cement mortar masoned on the outside, there is no bonding between the inside and outside faces, leaving a weak construction. The only reason why the house did not collapse completely was that the lightweight roof construction held the walls together.*

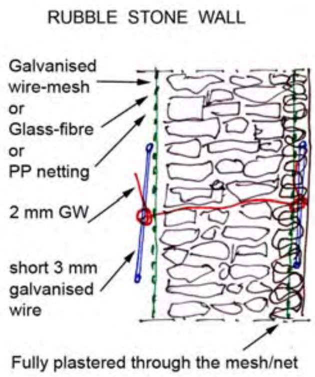
Wrapping the wall sections in galvanised wire-mesh and placing through-anchors at regular intervals to connect the inside with the outside wire-mesh has a triple reinforcement effect: (1) it holds the two faces of the wall together and (2) it provides both horizontal and (3) vertical reinforcement.

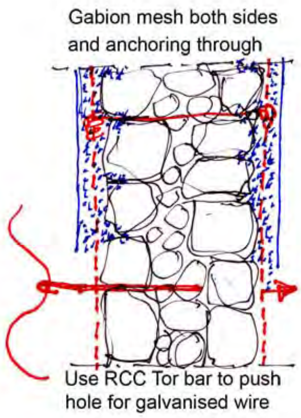



In the above construction, no separate horizontal or vertical reinforcement has been made; the calculated steel section should be 40% higher than the calculated single horizontal reinforcement.

The amount of galvanised wire-mesh or glass fibre mesh or the strength of other reinforcement material can be determined by calculation as provided in paragraphs 1.14 and 1.15. Since rubble stone walls are heavy (2000 kg/m^3), the most convenient material thickness is Ø 2.0 or Ø 2.2 mm galvanised wire or the glass fibre mesh.

VITRULAN Panzer
Openings 12 mm x 20 mm
1000kg/10 cm stress resistance





To connect both sides of the mesh reinforcement together, Ø 2 mm galvanised wire can be stitched through the wall with the aid of a Ø 10 mm iron bar needle. A short section of Ø 3 mm galvanised wire can be used to hold the glass fibre or PP mesh (middle sketch).

This above example of a ground floor only building shows the cement plaster after the application of the gabion wire-mesh. The plaster avoids that the openings in the wire-mesh are pulled closed when a stress force is applied on the metal. For the same reason, the other types of mesh also need to be plastered.

2.4 Cut-Face Stone Walls

Cut-face stone walls are often unsafe. Although such walls look very nice from the outside, they can be a great earthquake risk when lacking connection between the faces.

Assessing such buildings requires breaking open a wall section. From the outside the buildings look strong, but without verification of the interior structure of the wall, no assessment can be made. The inside face of these walls are often plastered, but the wall itself is constructed from rough stones and waste material from the cut-face stone manufacturing. Other internal walls are often made from rubble masonry as well.

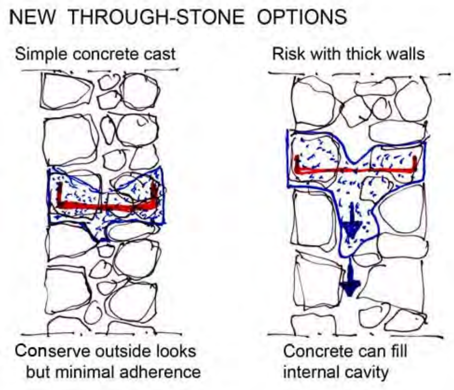
Often a lot of strong cement mortar is used to make nice looking joints. The added cement does not necessarily make the building stronger. The building needs to be structurally analysed from the floor plan, each façade and the walls internally.


This building was partially held together by the lightweight roof diaphragm. The photo shows that there is no connection between the inside and outside wall. Internal wire-mesh wall reinforcement connecting the two faces would have avoided the wall collapsing.

Through-Stone Option

To retrofit cut-face stone walls, holes have to be cut into the wall every 60-75 cm both horizontally and vertically (staggered) and then through-stones or galvanised steel anchors masoned into the wall with cement mortar, connecting the inside with the outside face.

Replacing a cut-face stone with a concrete cast with reinforcement bar creates and new through-stone. Care must be taken that the concrete does not fall in the cavity and the steel reinforcement bar is fully covered with a high cement-sand (1:3) coating to avoid corrosion.



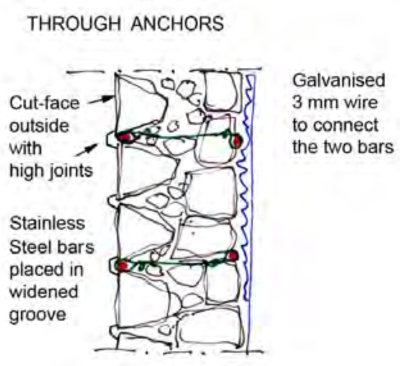
Through-Anchor Option

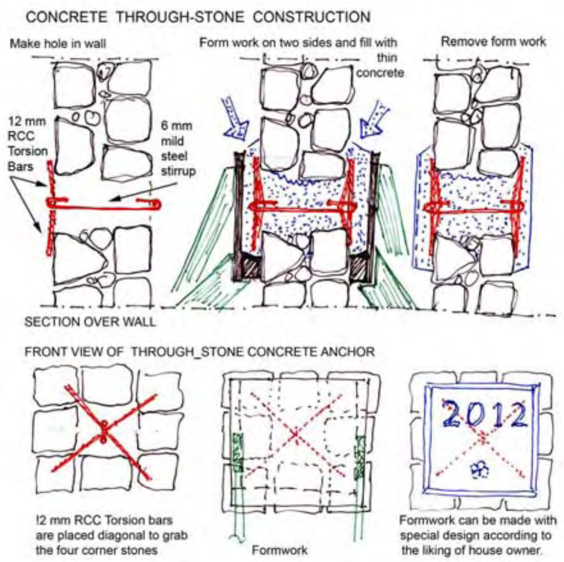
When using stainless steel bars, six cut-face stones together can be anchored using a 3 mm galvanised connector through the wall.

Based on the new appearance, cost of the materials and the amount of work, a decision can be made on the technology.

Concrete Through-Stone Option

When the outside presentation of the wall does not have to be exactly conserved, larger through-stone constructions can be made, anchoring four stones with the concrete and another four stones with the 12 mm TOR cross bars. In this way, less through-stones are needed, but the formwork is additional work. The resulting plaques on the façade of the wall can be decorated to the liking of the owner of the building.





In all cases, work should start from the top with temporary support of the lower wall. A limited number of holes should be made and completed each day to minimise the risk of the wall collapsing.

2.5 Semi-Dressed Dry-Stone Walls

Many buildings in the area have 40-50 cm thick semi-dressed dry-stone walls. When some of these stones are over the whole thickness of the wall, the coherence between the inner and outer face may be adequate, but these walls have ZERO stress resistance in the plane of the wall. Placing a single tie-beam over the outside wall hardly improves their structural strength. Retrofitting these buildings with the above-mentioned technologies (wire-mesh and through-stones) is most likely very costly. Due to the large mass of these stone wall constructions, they remain unsafe.


Once the above dry-stone buildings are finished with cement plaster, it will be difficult to determine the construction quality visually. For example, it will be impossible to know whether the foundation of the house (left photo) has any stress reinforcement. The market building (right) does not have a continued lintel construction, while the solid cement blocks of the columns have no internal reinforcement.

To retrofit these types of constructions, the entire building (inside and outside walls) needs to be wrapped in the appropriate amount of galvanised wire-mesh along with through-stone connections to obtain reasonable earthquake resistance.

The house below is an example of an owner-built house after his former adobe house was damaged in an earthquake. In this construction, the family will not survive another earthquake.


Plastering the house with clay soil will not increase its strength. Plastering inside and outside with cement mortar will enhance the strength a little, provided there are many through-stones in all walls. It is not economical to try to retrofit such bad quality houses.

A question is: “Why do local authorities allow such faulty and poorly earthquake-resistant structures to be rebuilt after an area has suffered from a strong earthquake?” In this case, the new house is probably less earthquake resistant than the lost adobe house.

The house pictured right, under construction in 2010, is a similar construction but with two storeys. The following problems can be easily detected as the house has not yet been plastered:

- ☒ There is no foundation beam structure.
- ☒ There are no continuing lintels over windows and doors.
- ☒ There is no wall sector framing.
- ☒ The piers next to the windows are too narrow and have no vertical framing reinforcement.
- ☒ There is no tie-beam over the inside and outside walls.
- ☒ There is no floor or roof diaphragm.

The only advantage is that the roof is lightweight.

Retrofitting this structure will be rather expensive as all the above-indicated shortcomings need to be addressed.

- ➢ The inside walls need to be verified as to whether these can carry the load after retrofitting or need to be repositioned.
- ➢ The mud plaster needs to be removed from the outside and inside faces of the ground floor walls.
- ➢ Full wire-mesh wrapping of <u>all walls and piers</u> of the building, including many through-stone connections.
- ➢ Inside and outside tie-beams need to be constructed at floor and roof level and through connected.
- ➢ After completing the wire-mesh reinforcement, the walls need cement mortar plaster.
- ➢ The floors need to be made as diaphragms connected to all the walls.

2.6 Square-Dressed Dry-Stone Construction

The advantage of the square-dressed dry-stone construction is that the stones are better bearing than the semi-dressed stones, resulting in an excellent vertical bearing capacity for the walls. In addition, the long deep stones are overlapping in two perpendicular horizontal directions, providing bondage. Normally, longer through-stones are placed at regular intervals, approximately one per 1 m^2 face of the wall.

This construction technology requires a lot of labour and can therefore be expensive. The amount of labour also depends on the stone quality that can be found because certain types of stones may be more difficult to tailor.

This building technology is not found in the area.

2.7 Dry-Stone Walls with Reinforced Concrete

Buildings of dry-stone walls with reinforce concrete are common. Often they have thick walls and equally thick reinforced concrete beams at floor/ceiling level (photo next page). These houses are frequently built two storeys high. These constructions usually have the four-fold structural problem of:

(1) A very weak wall construction; thus unable to function as shear walls.
(2) A very large mass or weight; thus invoking very large earthquake forces.
(3) The concrete is of poor quality with poor adhesion to the reinforcement bars; thus unable to function as supporting beams or columns when the wall fails.
(4) The column-beam reinforcements have few stirrups; thus no ductility with excess forces.

On the outside corner of the left photo, a linking column of 45 cm x 45 cm section joins the walls. The right-hand photo is the same building, showing the much lower field level.

Although in the above photos thin cement layers are visible, these do not include wire reinforcement and provide only a small amount of binding between the two faces of the wall. The new layer of semi-dressed stone is laid on the hardened cement layer, thus having zero adherence with this cement layer. The binding in the length of the wall cannot be counted as the cement plaster does not resist any substantial amount of stress.

The house in the above photos is already 1.5 storeys high on the low side of the slope. The planning is to add another storey similar to his neighbour (photo right). The current structural design of these two houses will not resist Zones 3 and 4 earthquake forces.

A house owner would most likely be unwilling to dismantle the house and rebuild it with internal reinforcements as a substantial investment in the building has already been made. This includes the massive amount of cement and concrete for the very thick columns and beams.

The follow are some opinions expressed by house owners:

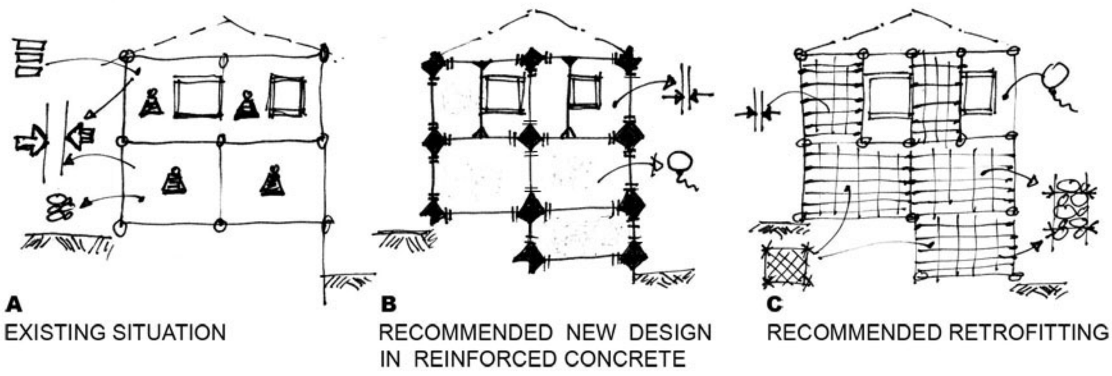
- "There might not be any earthquakes."
  This is totally incorrect because in Zones 3 and 4 earthquakes occur frequently, actually almost everyday. The issue is where the next epicentre will be.

- "There might not be a large earthquake nearby."
  When building with more durable materials, such as reinforced concrete, the lifetime of the building increases to over 100 years and with that the risk increases of a larger earthquake affecting the building.

- "I have used reinforced concrete."
  The reinforcement used in the above buildings is not designed or calculated on strength, is very heavy and weak, does not support the building, and is not ductile with large forces. The concrete columns and beams only work as wall framing, but these walls are loose and have no internal binding. Poor quality concrete design can increase the risk of collapse during an earthquake.

Because the building in the picture has no framing around the openings, these pier wall sections do not work as shear walls. The left sketch (next page) represents the current situation and the right sketch the possible design for retrofitting. The foundation under the house needs attention.[10]

[10] For details of the symbols used in the sketches, see Annexe I.



Schematic design is applicable in two perpendicular horizontal directions and the building plan should be symmetrical

Left: *When the earthquake movement is left-right, the right column will not hold the building.*

Centre: *Suitable design for Zones 2 and 3 earthquake areas. It has a light moment-resistant space frame with lightweight infill walls. The maximum moment areas in the column and beam connections are caged to make them ductile in case of exceeding forces. Modifying the existing construction to the second sketch is impossible.*[11]

Right: *To make the building suitable for Zone 4, the foundation needs to be made as a shear wall that can carry the entire horizontal load of the building. Removing all the adobe walls from the upper floor and placing lightweight walls will reduce the total mass. The semi-dressed stone walls of the ground floor have to be made shear walls with two sided wire-mesh and plaster.*

In this house with a lightweight roof, the columns are about 40 cm x 40 cm thick but do not have caging of the reinforcement in their maximum moment areas. The resistance of the building largely depends on the rubble-stone and clay masoned wall sections **A** and **B** of the ground floor, and on the adobe block wall section **C** of the first floor.

For the four outside walls, framing should be done along the openings. The wall sections at the corners should be fixed on both sides with gabion wire-mesh and through-anchors. The inside walls should be treated the same and be linked to the two tie-beams.

This house is already better than the house above because of the framing of the wall sections alongside all the openings.

However, because of the large mass of the stone, concrete and adobe materials, it is recommended that the corner constructions of the house are made full shear walls with inside and outside connected gabion wire-mesh.

In addition the inside walls need the same strengthening because these will receive about 50% of the building load during an earthquake.

[11] Technical Working Paper #12 does not cover retrofitting of reinforced concrete constructions. For various non-destructive testing methods on non-destructive concrete reinforcement bars see: www.acme.pwr.wroc.pl/repository/282/online.pdf

2.8 Dry-Stones and 3 Thick Concrete Beams

An improvement over the construction methods of paragraph 2.6 and 2.7 above is the realization of three reinforced concrete beams in the height of the storey and the tie-beam. However, by not applying cement mortar in between the stones, the construction allows deforming of the walls or hysteretic movement with large shocks.[12]

The result will be that the small stones fall sideways out of the wall and the heavy beam structures with the above walls settles lower and off plumb. The advantage is that the building will not suddenly collapse in an earthquake. However, because of its large mass and reinforced concrete, it can only be repaired by masoning it higher for the distance it sank (if sunk vertically).

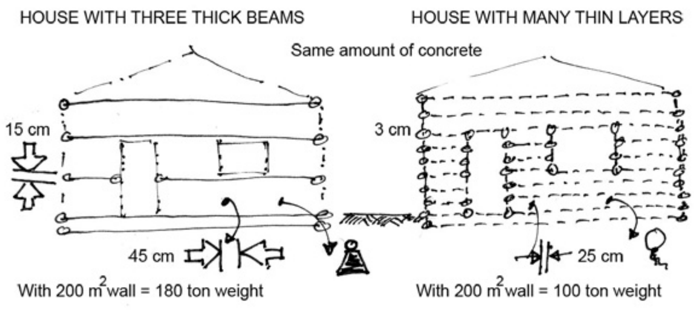
Improving this design is by applying wall framing.

Although this three-beam-per-storey design is substantially stronger than the one-beam-per-storey designs indicated in paragraph 2.7, it has three problems:

(1) The mass of the walls is very large.
(2) The masonry is loose dry-stone.
(3) There is no framing of the openings.

Using the same amount of concrete in more layers and slender wall framing around the openings would further improve the building resistance and allow for a more slender and lighter weight wall construction.

To provide covering for a single layer of mild steel, TOR bar or galvanised wire-mesh, only 3-4 cm thick concrete is needed.



The right-hand design with multiple layers of wire-mesh in thin cement mortar courses and framing along all openings is at least 200% stronger than the left-hand design, as well as having lower building costs.

Retrofitting this type of design requires vertical framing reinforcement along all the openings and linking the vertical reinforcement to the horizontal reinforcement of each beam. This means cutting the thick concrete beams open along all openings and wall endings.

[12] By alowing hysteretic movements, the energy of an earthquake shock is greatly absorbed. Rubber dampers will reposition themselves, but with non-bonded dry-stone construction, the sideways movement will remain and increase with each following shock.

2.9 Baked Brick or Cement Block Construction

The special advantages with cement block or baked brick masoned walls are that they have a substantially lower weight than stone walls and are usually masoned with cement mortar, substantially increasing their wall strength in three directions.

The baked clay brick house below has slim reinforced concrete framing along all openings. This is a more economical use of reinforced concrete wall framing than thick columns. In most cases, only two reinforcement bars are needed for wall framing along the openings.

When horizontal reinforcement has also been placed inside the masonry, and the tie-beams of the inside walls are well connected to the ring tie-beams, this house is highly earthquake resistant. Without the horizontal reinforcement, the outside four corner sections of the ground floor need to be reinforced as shear wall sections.

Whether or not this house requires more retrofitting depends on the configuration of the inside walls and if they can take most of the horizontal earthquake load.

When baked brick masoned houses have structural cracks in the walls, they can be retrofitted with long stainless steel torsion bars, which are masoned into the horizontal joints. For this purpose, the joints are swan opened with a cutter. Depending on the calculated forces, different sizes of SS bars can be used. The SS bars are necessary because the thickness of the joint does not allow sufficient cement covering of the common TOR bars to avoid corrosion.

Because of the high machine and SS material costs, this kind of retrofitting is usually only done for historical buildings having a very exclusive brick architecture.

The cement block house below has a lighter and stronger wall construction than non-cement mortar masoned stone constructions, but does not have framing of all the openings; required in Zones 3 and 4 earthquake areas. Additional wall framing around the windows is needed.

Wall framing around the window and door openings will be necessary when one or more storeys are added. The inside walls from left to right <u>are not in one line</u> and therefore have much less capacity of transferring the horizontal load to the foundation.

In the front side of the house, the upper <u>tie-beam should be continued</u> over the veranda area to provide continuity. A reinforced concrete floor will have the same effect, but would cause a very heavy horizontal load during an earthquake.

Retrofitting of these buildings is best done by applying concrete reinforcement wall framing or jackets and tie-beams throughout the construction at those places where there are no columns or wall framing already.

2.10 Solid Cement Block and Concrete Beams

Although solid cement block houses with concrete beams do have reinforced concrete, it is not a self-supporting reinforced concrete space frame. The advantage of such constructions is that the solid cement blocks are masoned together with cement mortar, making the infill walls highly compression resistant and function adequately as shear walls.

In the house pictured, the foundation is on flat land and very strong. The columns are most likely four bar with few stirrups, while the roof structure is lightweight.

The wall sections next to the window and door openings are wide enough (>1.2 m) to function as shear walls.

The overall strength of this house would be excellent when the block masonry is anchored horizontally into the columns.

This house complies with the recommendations for earthquake Zone 3. If the inner walls are fully connected to the outside walls, and if no additional storey is added, it also complies with Zone 4.

2.11 Cement Masoned Buildings

The following example is from a one floor school building, but the same solution can be used for other well cement masoned walls, such as in houses.

Because the wall structure has a high compressive strength, framing of the wall sections and adding tie-beams is adequate. The dimension of the reinforcement bars need to be calculated according to the earthquake load (20% or 25%) and the type of building (public +25%). The building below has a timber frame and lightweight galvanised iron roof construction and therefore needs only a small amount of retrofitting.

The photos show the left and right sides of the school building with the ongoing retrofitting of the additional end-wall framing.

The making of the floor-foundation tie-beam and the tie-beam under the window has already been completed.

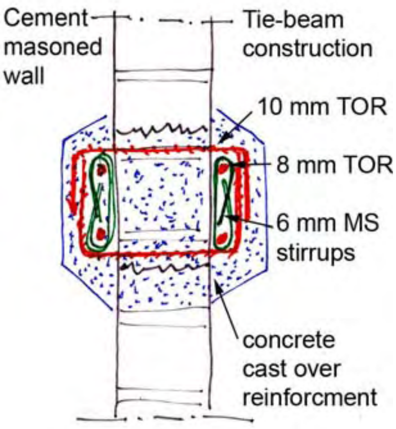
The tie-beam over the windows is under construction.

The interior photo (right) shows the lintel tie-beam on the inside of a construction similar to the outside of the building above.

The inside and outside reinforcements are connected through the wall with Ø 12 mm TOR bars, thus forming a wide reinforced concrete lintel tie-beam above and below the windows. The side framing along the windows is done in a similar way, connecting the inside bars with the outside bars. These side framings are connected to the tie-beams.

The corner wall framing, the window side framing, and the tie-beams below and above the windows and doors are all connected together and cast in concrete. This way many shear wall segments are created, providing ample stability. The wider column in this picture is needed to connect the horizontal reinforcement on each side of the interior cross wall.

The connection between the inside and outside reinforcement should be done with double bars to create a wide beam (sketch). The distance between the cross ties should be about 1.2 m.



The tie-beams should also enclose (wrap around on the outside) the vertical reinforcement along the window openings and the wall endings.

If the building has a reinforced concrete roof that functions as a diaphragm and an upper lintel tie-beam, the additional reinforcements need to be made along the window openings (photo below).

Especially in public buildings, the escape routes should be large (wide) enough to allow many people to rush out of the building. The doors should open outwards and not be locked when the building is in use.

Steps directly at the entrance behind the door should be avoided as this will result in people falling when exiting in a rush.

2.12 Timber Houses

In some areas old timber houses can be found, but due to current lack of timber, these house designs are not being built anymore. Because of their small mass, as well as their ductility, these houses can withstand large earthquake forces.

The timber frame of the house needs to be checked for the existence of diagonal bracing in both horizontal directions and whether the joints are well connected. If needed, they can be reinforced with metal straps.

2.13 Plastered Timber Lattice Houses (Finnish Houses)

These buildings have a timber support frame structure. A crossed diagonal lattice work is then nailed over the inside and outside of the timber frame.

Both inside and outside lattice constructions are plastered. In between the two plastered lattice faces, an air cavity is created which functions as thermal insulator. The buildings are lightweight and the diagonal lattice work serves at the same time as stress-compression diagonals, providing resistance against horizontal loads. The wall structure is not very stiff and during an earthquake the plaster may crack.

These houses have a small mass, but do require some maintenance to repair the plasterwork (picture). It is important that the timber remains dry to prevent rot.

2.14 Prefabricated EPS Panel Buildings

Expanded Polystyrene (EPS) panels, 10-15 cm thick, are protected on each side with a painted, thin metal sheet. The metal sheets make the EPS strong and stiff in the plane of the panel.

The lightweight panels are often used for temporary buildings, but can also be used for lightweight upper storeys (photo right).

Their extreme low weight makes then not vulnerable for earthquake forces.

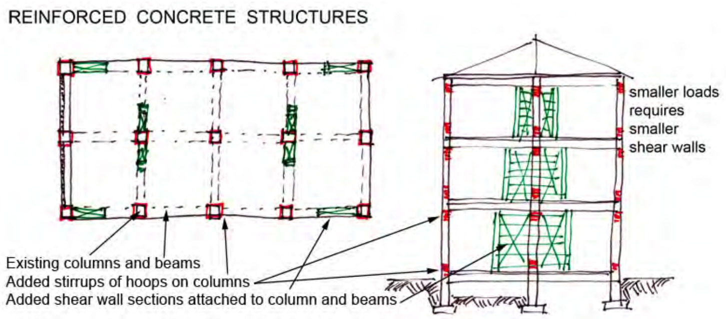
These prefabricated lightweight systems should not be fitted with a heavy roof construction.

2.15 Reinforced Concrete Buildings

According to the latest earthquake code specifications, <u>no reinforced concrete space frame buildings are allowed</u> for Zones 3 and 4. However, in the past many reinforced concrete constructions were realised as space frames without integrated shear walls. In several cases, this will imply changing the façade of the building or the inside partitions to construct these shear walls.

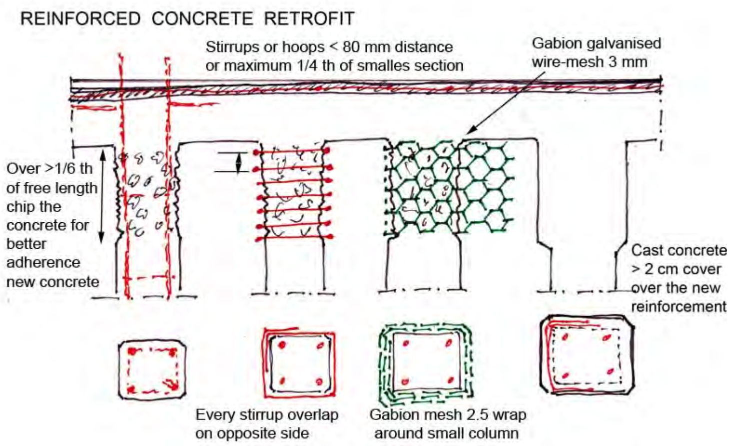
These reinforced space frame buildings can be improved with two basic measurements:

A. Constructing symmetric shear walls that are fully attached to the column and floor beam reinforcements. These symmetric shear wall designs should be related to the possible load factor in each (perpendicular) horizontal direction. If the building is twice as long as wide, the shear walls in the length direction should be also twice as strong.



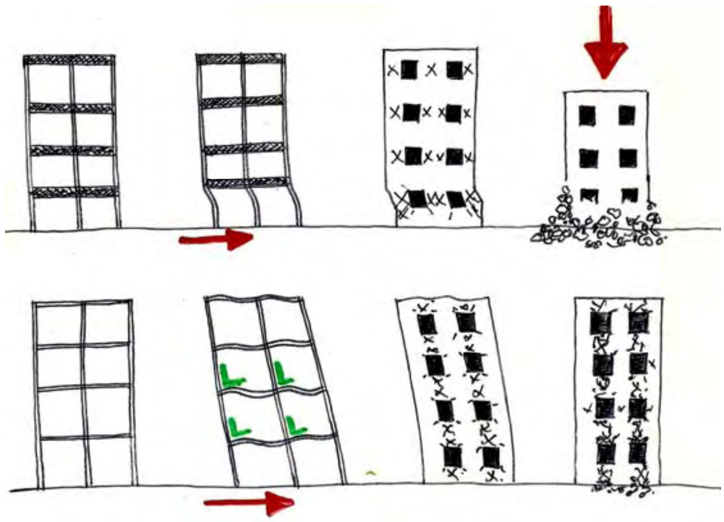
B. Assuring that the free columns have adequate caging in their maximum moment areas, which are usually the feet area and the top over >1/6th of their free length. When stirrups or hoops are used, the maximum spacing should be <1/4th of the smallest column section or <80 mm c-c.

Gabion wire-mesh wrap can be used, but the wrap should be at least 2.5 times around the column and even more for large columns (to calculate).



Stiff Beams or Floors
When the floor construction is very stiff or thick, such as with high (integrated) beams, the caging of the columns at their maximum moment areas is even more important than with a flexible floor-beam construction because the columns may fail first, leading to a total collapse of the building.

With a flexible floor, the building floors (including the façade) may get damaged but would not immediately collapse.



Change of Maximum Moment Area
When windows are constructed against the columns, the maximum moment area in the column is possibly shifted to the level of the lower window sill due to the support of a strong infill wall. In such a case, the stirrups or caging around the column should be made in that maximum moment location. If not, the stiff infill wall should be removed and replaced with a lightweight and compressible structure.

Recalculation of Buildings
Large reinforced concrete constructions need to be recalculated with the <u>real values of the concrete quality</u> to re-assess their earthquake resistance. This needs to be measured on site. In some cases, it will mean that the building needs to be stripped of the heavy solid cement block interior and exterior walls and new lightweight insulated walls be made.

3. PAMIRI HOUSE DESIGN

The traditional Pamiri house is a timber support construction, having a heavy soil roof and walls of semi-dressed stone and rubble masonry in clay soil.

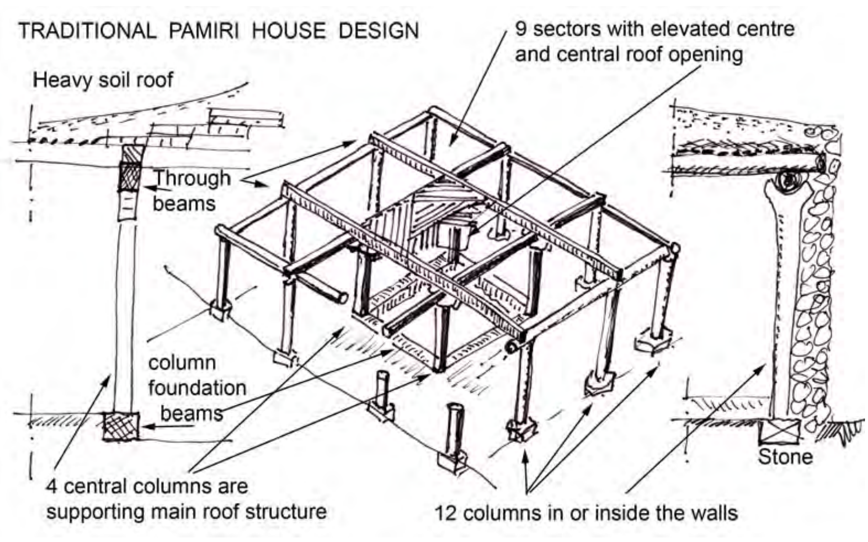
All traditional Pamiri houses have a similar main room configuration consisting of a square floor plan with a double column after the room entrance. Around the central area, five large timber posts support the central roof section. Along the four sides of the room, other posts (visible in the room or embedded into the thick wall) support the perimeter roof beam. The skylight has four concentric square box-type layers made from crossed timber beams tightly fitted together, forming a solid structure (Gasirkum).


Depending on the age of the Pamiri houses, the roof-to-wall connections are different because in the more recent houses, fewer and thinner supporting timber is used.

The old traditional Pamiri house has a relatively small earthquake risk because:

(a) It is a ground floor only house.
(b) It has almost no windows and therefore closed side wall constructions.
(c) The (heavy) roof is fully supported by a strong massive timber column support system.
(d) The building has a symmetric floor plan.

Making the <u>roof lighter</u>, providing horizontal stability and avoiding that the walls collapse inwards are the primary retrofitting elements.



In recent times, the stone walls have been cement pointed on the outside, but this hardly improves their resistance to lateral forces.

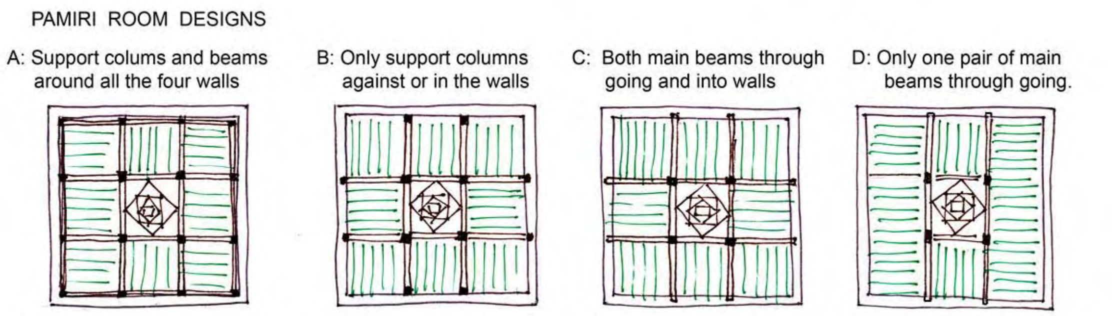
The concept of totally pulling down and reconstructing the walls of the ancestral house can receive strong resistance by many house owners. In reality, however, pulling down the stone and clay soil walls can be done in a few hours and then be rebuilt with cement mortar to look the same.

New Pamiri Design Houses

In the three regions of Pakistan, Afghanistan and Tajikistan, several new Pamiri house designs have appeared due to the decreasing amount of timber available.

Newly built Pamiri design houses are at larger earthquake risk because flimsy timber is used, the perimeter supports are missing and windows are being introduced in the side walls.

Because of the high cost of timber, the more recent low-cost houses do not have the 12 outside posts and the roofing beams are now directly supported in the surrounding wall. When this wall is not fully cement masoned and the roofing beams are not anchored into the tie-beam of that wall, it creates an unstable situation.

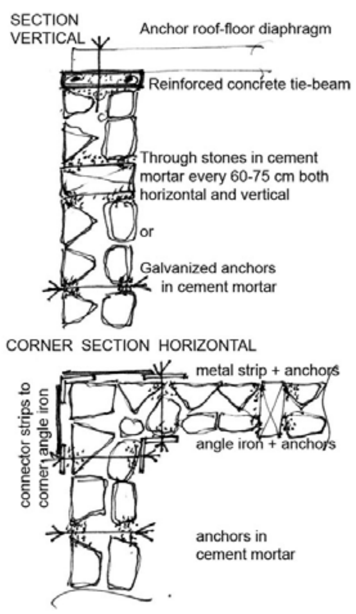


All central squares and diogonally closed roofs ("Gasirkum design") are loose beams layd each layer on top of the lower layer.

- Design A is the oldest with at least 16 support columns and roof support beams all around the inside of the perimeter walls. The central Gasirkum ceiling design is of loose, thick beams fitted together (photo front page). The roof beams are also loosely fitted onto the support beams, spanning the shortest distance. The roofing sticks/planks are not tied or otherwise connected to the roof support beams. The walls are commonly masoned in rubble stone and clay soil. The other three designs are the result of the scarcity and increasing cost of timber. The least amount of timber is used in the last design.
- In design B, the two main beams are supported on columns located against the perimeter walls. All the roof beams are directly supported on the perimeter wall. Usually only one set of the main beams are continuing and the other set is interrupted.
- Design C is without the columns against the perimeter wall.
- Design D only has one set of main beams continuing, while the supporting columns are sometimes made from two columns fitted together (photo page 35). In addition, the timber dimensions are so small that the support beams start bending (paragraph 4.6). For this design, the walls can be made of cement blocks and cement mortar masoned.

The retrofitting methods for the four above designs are about the same, but the old design with the support columns in the perimeter wall would be safer with diagonal bracing and when the roof load is greatly reduced.

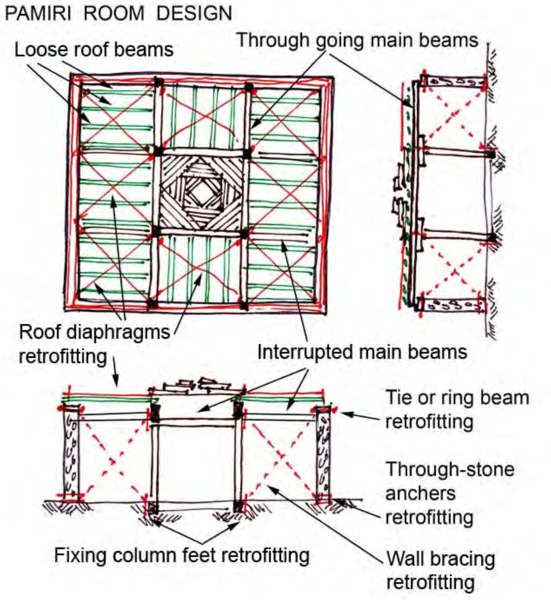
Generally, the whole roof has to <u>be taken off</u> and reassembled as a diaphragm, creating a connection from one side of the roof to the other. After the roof is off-loaded from the heavy soil layers and the covering or insulation materials are removed, a thin reinforced concrete tie-beam should be cast over the walls and fitted with 3 mm galvanised anchors to tie the roof beams (sketch right).



Through-stones need to be made lower in the perimeter walls to improve the coherence of the structure. These should be placed at 60-75 cm intervals and staggered over the height of the construction. Diagonal bracing profiles should be linked to the tie-beam and lower through-stones. When making this diagonal inside framing, the outside corner columns can be made according to the sketch (right).

The basic measurements of retrofitting the Pamiri room are indicated in the sketch. The central Gasirkum design needs to be fixed vertically onto the four main beams below. In many cases, the central opening is increased to place a roof (hatch) window to allow more light and solar heat intake.

The roof squares around the central portion need to be made as diaphragms. In many old houses, the first layer on the support beams consists of branches.



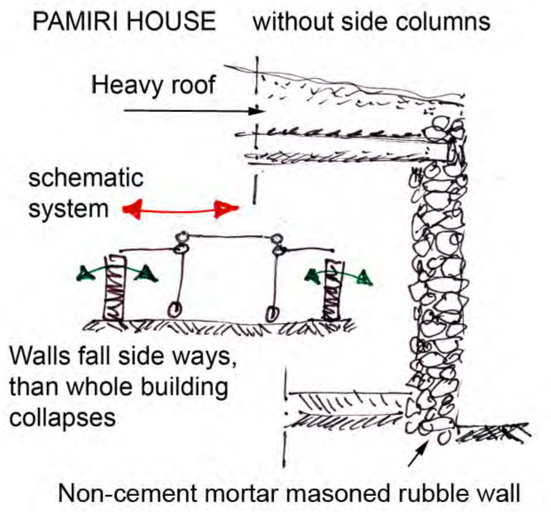
Various options are possible:

- Nailing planks diagonally in two directions over the support timbers. This, however, requires a substantial amount of timber.
- Nailing or screwing plywood over the support beams. For remote villages, plywood may be difficult to transport and may be as expensive as the planking.
- Nailing gabion wire-mesh over the beams.
- Connecting 2.2 mm galvanised wire diagonally to the corners of the squares and ensuring tight connections to the tie-beam and central vertical posts.

Waterproofing and new thick thermal insulation can be applied over the diaphragm construction. The new roof should be constructed to drain rainwater well over the support walls.

Static Design

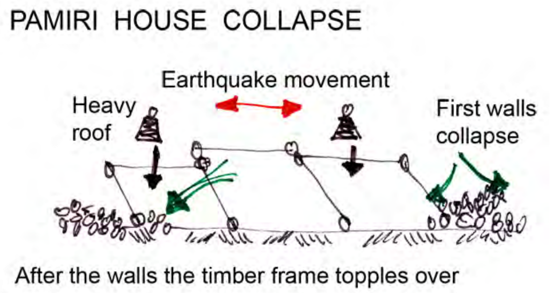
The floor plan of the house is 8 m x 8 m = 64 m^2. With an average soil roof thickness of 30 cm, the load by the moist soil layers is 40 tons or more.



During an earthquake, this heavy roof can cause a horizontal shock and load of 10 tons (= 25%). The column-to-beam connections are not moment resistant. The side walls will be pushed over and collapse, and then the timber frame structure will fall sideways.

For a picture of a partly collapsed Pamiri house see page 3. Here part of the rear remained upright because of some additional cement masoned cross walls, but the front side of the house totally collapsed under the roof weight.

Because in many cases the walls are only rubble masonry in clay soil, they do not withstand vertical vibrations and even less the horizontal shocks.



After the collapse of the walls, the timber frame will fold down because the <u>connections between the timber members are not moment resistant</u>.

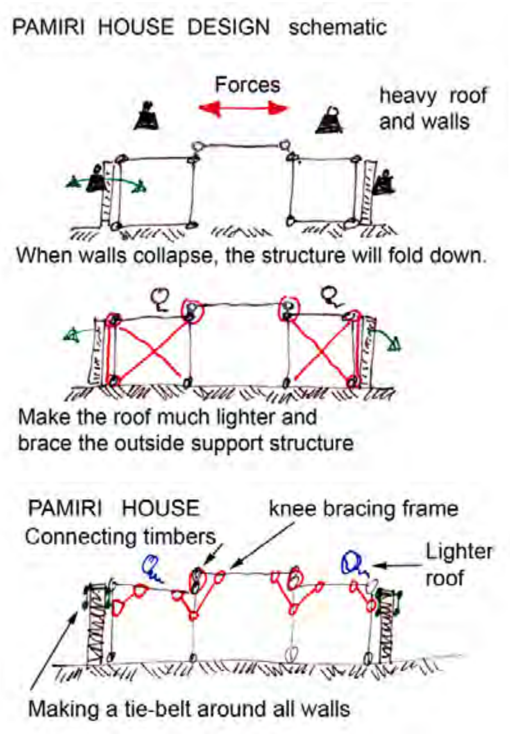
Retrofitting these houses can be done in two levels. In the first level it is avoided that the outside walls collapse towards the inside and the timber support frame folds down. In the second level the outside walls do not collapse and assist in keeping the structure up.

The following is also required to make the design highly earthquake resistant:

A. Connecting the timbers together and making diagonal bracing along the four corners (8 outside wall sections) of the room (second sketch). This can be done with steel bars or galvanised wire. The reinforcement can be covered later with thermal insulation or plastered. This way the bracing does not affect the interior design. The metal connectors between the beams can be kept out of view from the centre area.

Or:

B. The connections between the columns and the roof beams can be made moment resistant with timber knee-bracing diagonals from either timber or metal angle irons. The perimeter walls can be reinforced with a tie-beam all around, while the roof beams should be connected to this tie-beam. The internal architecture of the structure, however, will be affected with these diagonal reinforcements (lower sketch). For low roofs, it limits the circulation area around columns.



Or:

C. A combination of the whole wall section bracing (as per A, second sketch) together with a tie-beam construction (as per B). The side roof sections are to be anchored into the perimeter walls, whereas the walls are to be cement masoned.

Metal Profiles and Strip Framing

Option B above is rather simple and can be executed in different ways. Retrofitting according to this model consists of five measurements:

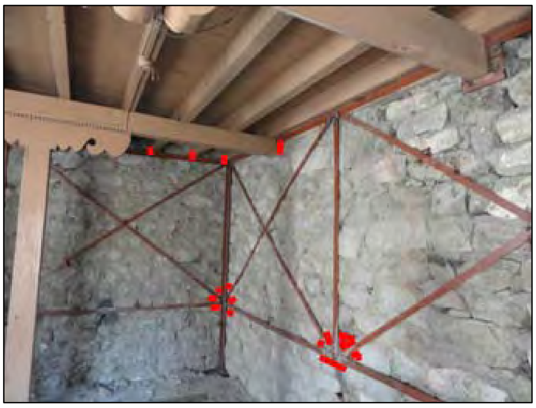
(1) Lightening the roof by removing all the clay soil layers, adding thermal insulation (also an insulating roof window) and making it fully waterproof.

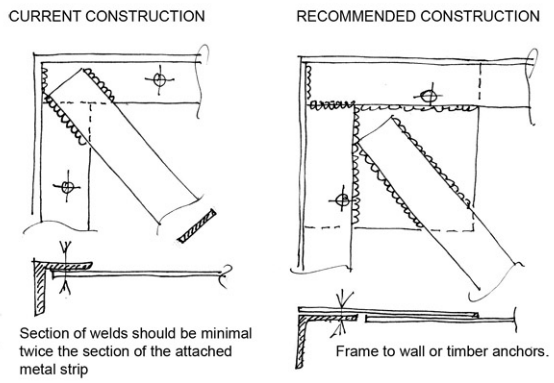
(2) Ensuring the roof functions as a full diaphragm, anchoring the perimeter beams to a tie-beam all around the room. The tie-beam can be made of a double angle iron (50.50.5), which is connected over the top.

(3) Making an inside wall framing with other angle irons in the four corners (40.40.4). Welding diagonal metal strips to the squares or attaching 3 mm galvanised wire diagonals.

(4) Through-stones fitted into the walls about 1 per m^2.

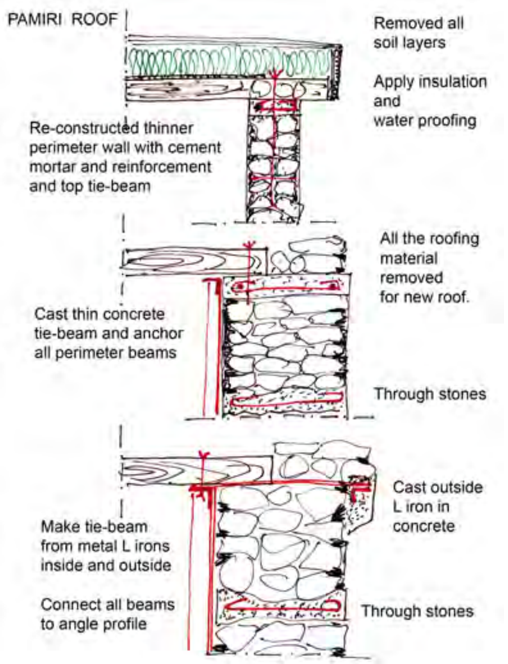
(5) Cleaning the joints and cement mortar pointing the outside and inside faces.





Inside view of the wall reinforcement using flat steel strips and angle irons. The top side of the metal strips are connected to the roof beams; the bottom corners to through-stones in the wall (red marks). After welding the iron strips in place, the welds need to be cleaned and given a corrosion protection.

The three most economical options are presented in the sketch (right).



The top sketch is the reconstruction of the perimeter walls with a cement masoned and wire-mesh reinforced wall. The wall insulation can be applied either inside or outside, each option having advantages and disadvantages.

The middle sketch is the reconstruction of the roof (first removing the soil layers) and casting a thin reinforced concrete tie-beam over the wall. The roof beams are anchored onto this tie-beam. The diagonal inside bracing is connected to the main timber frame components.

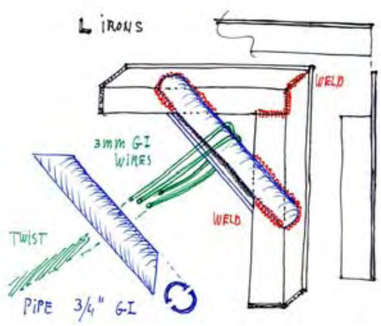
The bottom sketch is also with removing the soil layers, but the tie-beam is made by an inside and outside angle iron and all beams are connected to the inside angle iron. To prevent corrosion, the outside angle iron is cast into concrete.

The choice between the solutions depends partly on the local labour situation and the possible supply of the angle iron reinforcement.

The angle irons must provide wall framing around door and window frames. The inside metal angle irons are anchored below into the wall and above into the tie-beam. The angle irons are bolted into the lintel and additionally into the door or window frames (photo right). Additional through-stones need to be placed in cement mortar to increase the stability of the wall.

The option of inside framing with angle iron is feasible in towns with electricity, but it is not always possible in mountain villages for the following reasons:

(1) In most mountain villages, the existing masonry is only with clay soil, not providing any binding aspects between the stones.
(2) The cost of the steel framing and welding is high and <u>almost impossible to weld</u> in a remote village without bringing one's own power generation and welding equipment. It is far cheaper to pull down the old walls and rebuild them with wire-mesh reinforcement.
(3) The welding needs to be done with sufficient welding length so the maximum tension forces from the diagonals are transmitted by those welds. Welding plates improves the connection.
(4) If the metal is touching the cold wall, condensation can settle on it. To protect the <u>metal framing against corrosion</u>, the welded points need to be cleaned and treated on all sides before fitting in place.



It is possible to replace the metal strip diagonals with a few strands of 3 mm galvanised wire because the strips are only functioning as stress braces. With the application of the galvanised wire, the connection point should be made around a section of ¾-inch GI water pipe to avoid that the sharp sides of the angle iron cuts into the wires.

The small section of water pipe is cut lengthwise in half and welded to both sides of the angle profile frame. This way a stronger corner connection is made and the GI 3 mm wires are wound around the GI pipe.

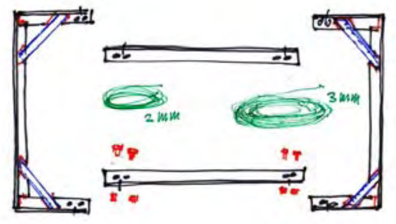
Each wall of the Pamiri room weights about 0.4 m x 2.5 m x 5 m x 2000 kg/m^3 = 10,000 kg. One third of the mass force will be carried directly to the ground. The diagonal wires should resist a force of about 25% x 1.41 x 2/3 x 10,000 kg = 2.3 ton. Each 3 mm wire has a section of 7 mm^2 and resists about 350 kg. A minimum of 7 wires is necessary. Using a double wire, the total will be four for each diagonal. There are two frames in each wall section, thus eight x 3 mm GI wires.

The wire bundle is stretched after fixing by torsion in the middle. Once the two wire bundles have been stretched, the central twisting points on the X are bound together with 2 mm GI wires.

The advantages of the GI wire braces are:

- ✓ Easier to transport rolls of the 2 mm, 2.2 mm and 3 mm galvanised wire.
- ✓ Lower material costs than the metal diagonal strips.
- ✓ Ability to adjust the bundles to the required stress forces on site.

The system can be partially systematized by pre-manufacturing of the vertical sections of the frames. Each wall can be measured and the width of the bracing frame noted. In a central workshop, the profiles can be cut and fitted with a few galvanised bolts and nuts. This way the amount of cutting and welding at the house is reduced and the frames will be more durable. Standard frames can be made of 40.40.4 angle iron, 50.50.5 angle iron and 60.60.6 angle iron, depending on the size and weight of the house.



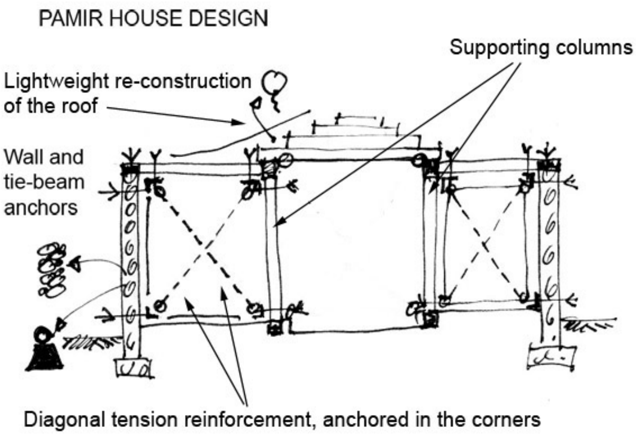
The methodology is **NOT recommended** for houses or rooms that do not have a self-supporting roof structure similar to the Pamiri traditional house.

Diagonal Solutions

The maximum force calculation shows that only the four corners of the Pamiri room need to be braced to resist the horizontal load in the event of an earthquake.

The corners of the inside bracing diagonals, however, need to be anchored into the wall (through-stones) and into the ceiling construction when the roof is a full diaphragm.

The black dotted lines show the positioning of the diagonals.



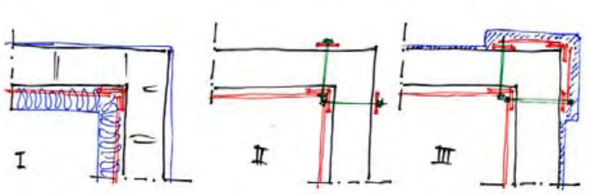
Strengthening Wall Corners

The inside angle iron needs to be linked horizontally in two perpendicular directions for stability.

(I) Simple design with only inside bracing and the insulation added.

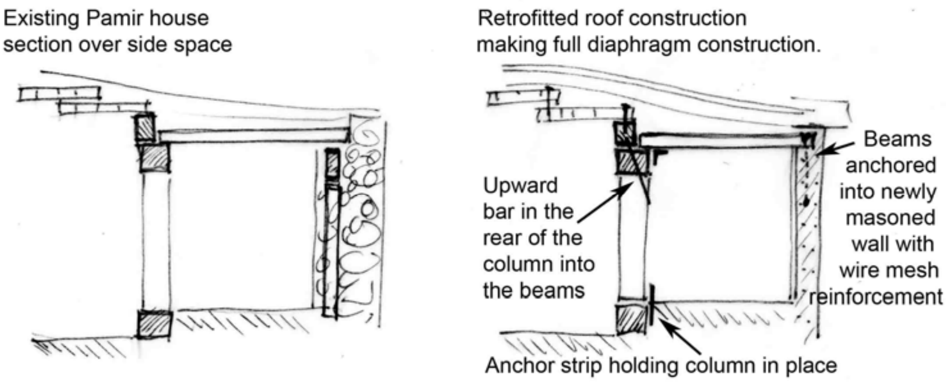
(II) Placing an outside metal strip or angle profile and bolting this through the wall with the inside.

(III) An angle profile on the outside corner connected horizontally with strips and through the wall with the inside angle iron; thereby creating a full column.



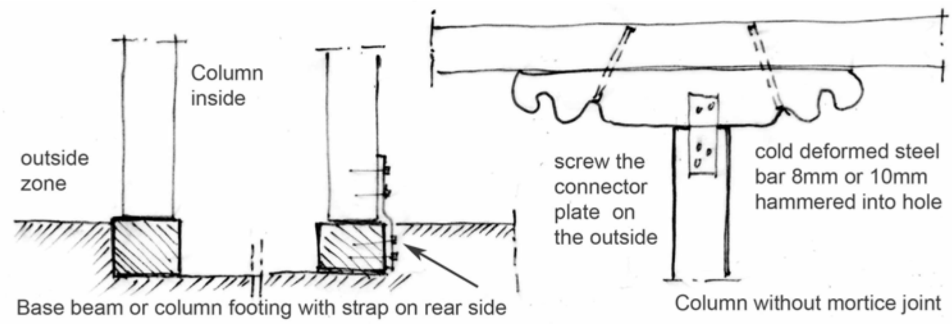
Roof Structure with Metal Connectors

The traditional Pamiri roof needs to become one diaphragm. All timber elements need to be fixed together by means of metal straps or pins when not otherwise connected. Traditionally the plank flooring over the roof beams is not nailed down. With the reconstruction of the roof, it is necessary to create a continued connection from one tie-beam to the opposite other tie-beam.



A stress-resistant connection should exist from the tie-beam on one side of the room to the tie-beam on the opposite side of the room. The plank flooring over the beams resists compression. Central section has through connections to the inner ring beam and outside tie-beam.

Timber mortise connections can withstand both vertical and horizontal movements during an earthquake. For each house, it needs to be assessed whether or not the existing mortise joints are adequate. If these are not strong, the strapping can be done on the rear side of the column-beam connection with a single plate or between the column and the floor plate (left sketch below).



Placing the straps on the rear side of the columns would give a better aesthetic appearance.

In column capital constructions, it cannot be always seen whether there is a linkage between the capital and the supported main roof beam. In this case, two holes can be drilled from below and a short Ø 8 mm or Ø 10 mm cold deformed concrete reinforcement bar hammered through the capital and into the upper beam. This way the connection is hardly visible (right sketch above).

The metal angle irons are coming through the plaster. The small vertical supports under the beams should not be able to function like hinges.

The metal (T) straps can also be placed on the rear of the columns. When the diagonal roof beams are tightly packed together, they only need to be fixed onto their support beams.

Tie-Beams

In modernized traditional (Pamiri) houses, the house owner often wants to place windows in the walls during a reconstruction activity. This will cause an interruption of the shear wall function of these walls. In such a case, it is necessary to create a through going tie-beam in the wall as per paragraph 2.11 with cement masoned buildings.

When new building sections are connected to the old Pamiri room, the tie-beams or lintel beams also need to be connected to create continued stability. In many houses, the lintels over doors and windows are individual and need to be linked into one tie-beam construction (photo left).

Roof

The roof constructions in some old Pamiri rooms consist of rough beams, covered with branches. In such a situation, the application of gabion mesh or galvanised wire for making the diaphragm is more practical.

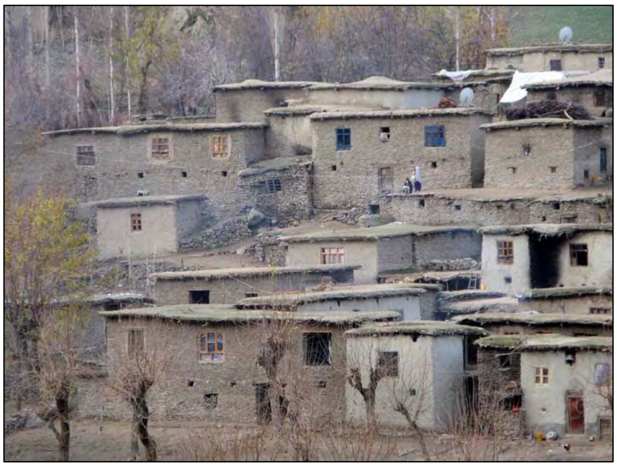
The waterproofing finish roof of the new roof surface should be draining well to outside the perimeter walls. The thin stabilized sand-cement topping avoids damage to the waterproofing material and protects it from UV light. Gargoyles should project well over the wall and splash water should not affect the lower wall or foundation.

4. EXAMPLES

This chapter presents a few examples of retrofitting or not retrofitting. The number of examples should be increased and complemented with photos, building plans and sketches. All cases can be complemented with recommendations. Building contractors can learn more from real cases than from theory alone when properly illustrated. Such a collection can become a separate document.

The tent or yurt is a very earthquake-resistant structure, mainly because it is lightweight. The yurt has the added advantage of insulation, provided by the several layers of felt.

4.1 Adobe Houses



Low-rise adobe houses are usually unsuitable for retrofitting because the reinforcement costs will be higher than building a new, stronger house.

To reinforce adobe constructions, both sides of the walls need to be packed in stress-resistant material and the two faces of the walls connected through the wall. However, the cost of applying galvanised chicken wire-mesh on both sides of the wall is out of the economic range of most villagers. In addition, most adobe houses have no foundation or are built on steep slopes and should be relocated.

Generally, most adobe houses can be taken apart by hand and the blocks re-used. In the new adobe house, galvanised wire-mesh reinforcement (GWR) can be applied inside the walls in all alternate courses (ground floor or basement only) or in all courses in the ground floor when planning a lightweight second storey. Together with vertical framing of all wall sections, more strength is obtained and the reconstruction will be at a much lower cost than retrofitting.

Recommendation

Adobe buildings should be entirely reconstructed with stress resistant foundation, wall framing using internal GWR and floor/roof diaphragms.

Full reconstruction is not always necessary when the building has an internal timber support structure such as the Pamiri house. In that case, the roof should be reconstructed as light as possible and horizontal stability created. The several layers of soil should be removed from the roof and insulation and waterproofing applied.

4.2 Cement Block Masoned School Building

The building pictured is a school block constructed half a century ago. Because it is a school, it should be reviewed for thermal insulation as well as retrofitting.

The roof is reasonably lightweight because of the asbestos sheets, but the inside ceiling has a 10 cm layer of clay soil as thermal insulation. The problem with this building was that the foundation was soaked because of poor drainage, broken roof panels and gutters, damaged floors and broken windows. In reality, this building needed a total overhaul.

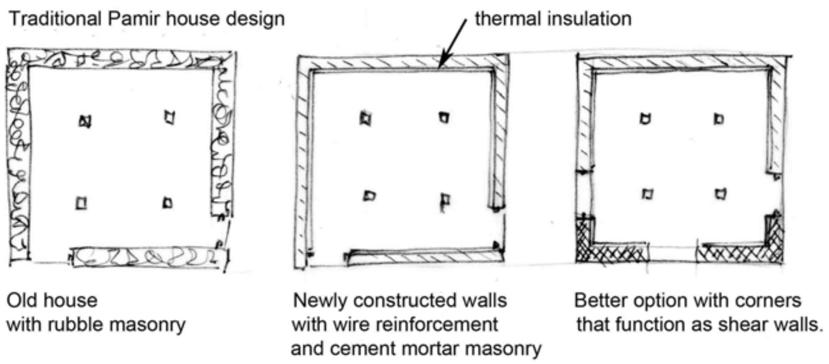
The wall sections between the windows are reasonably large. In such a case, it may still be economically possible to retrofit the structure if the walls are of good quality cement blocks. If the masonry is not good, then the whole building should be pulled down and redesigned with framed wall sections and two storeys.

4.3 Semi-Dressed Stone Village House

The options for houses built with semi-dressed natural stones are practically the same as clay soil masoned rubble stone houses. Total rebuilding is recommended with a thinner wall thickness using wall reinforcement in a light cement mortar. Wall openings need to be framed, roof diaphragms made and the roof reconstructed as light as possible.

The roof construction of this house was redone with waterproofing, gargoyles and the top of the walls newly constructed. The owner initially resisted the advice of pulling down the old thick walls. However, once convinced, the old rubble and clay soil walls were pulled down in one day and rebuilt in 3 weeks (picture right).

The walls were completely reconstructed making them thinner (and thus lighter) and stronger. Cement mortar and galvanised wire-mesh reinforcement was applied throughout the walls. In the top zone of the wall, the roof beams were adequately supported and anchored into the masonry work.

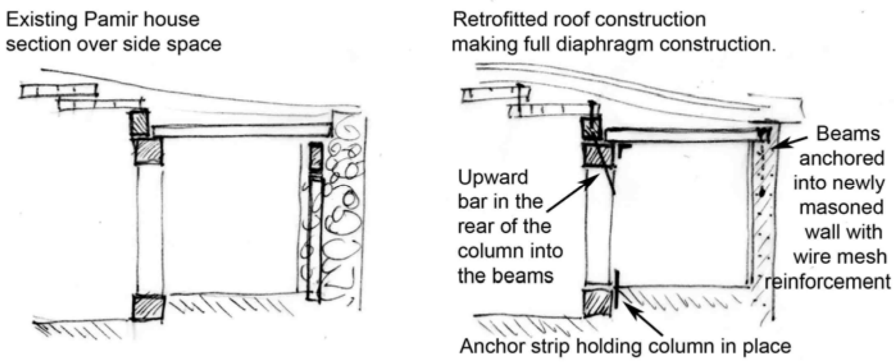


When reconstructing the walls, the position of the openings needs to be reviewed. The traditional house had two door openings, causing four non-braced wall endings. In this case, two considerations were taken into account with regard to the openings:

(1) Do not place the door or window openings at the corner, and
(2) Does the house owner want additional window openings?

By repositioning the doors, the wall corners became stronger (sketch).

The traditional Pamiri wooden roof construction was well dimensioned and after more than 100 years did not show any signs of weak areas. In this case, an 8 mm hole was drilled through the back of the column into the main roof beam and fitted with an 8 mm steel cold deformed concrete reinforcement bar (see sketch below).



Sketch of the new roof diaphragm and complete reconstruction of the side wall with the anchorage of the beams into the wall and the main beams of the inside square.

The line of the roof beams on the lower sides of the Pamiri roof were well supported and anchored with 3 mm galvanised wire straps into the new wall. The support on the inner main roof beams, however, was minimal. These short beams were fixed with a strap to the main beam, all around the room. These straps would not be visible from the central point of the room.

Although the former external side support beam had lost its function (left sketch) because the roof beams were now anchored into the new cemented and reinforced outside wall, this beam and columns were re-fitted as part of the old design. For aesthetic purposes, the decorative capitals were replaced under this side beam.

The newly constructed walls were fitted with pegs and foils to create double air spaces for thermal insulation and a plaster finish, more than tripling the insulation value as compared to the old rubble stone wall. PE foam would be applied under the carpeting, substantially increasing the comfort level of the occupants. The new and larger roof window allowed more light and was insulated.

4.4 High and Thick Dry-Stone Construction

A 100-year-old construction next to a local school and hospital was selected for retrofitting and thermal insulation. The planned designation of the building was for an early childhood development school.

The building had 2 m high windows and 4 m high walls. The size was 10 m x 20 m.

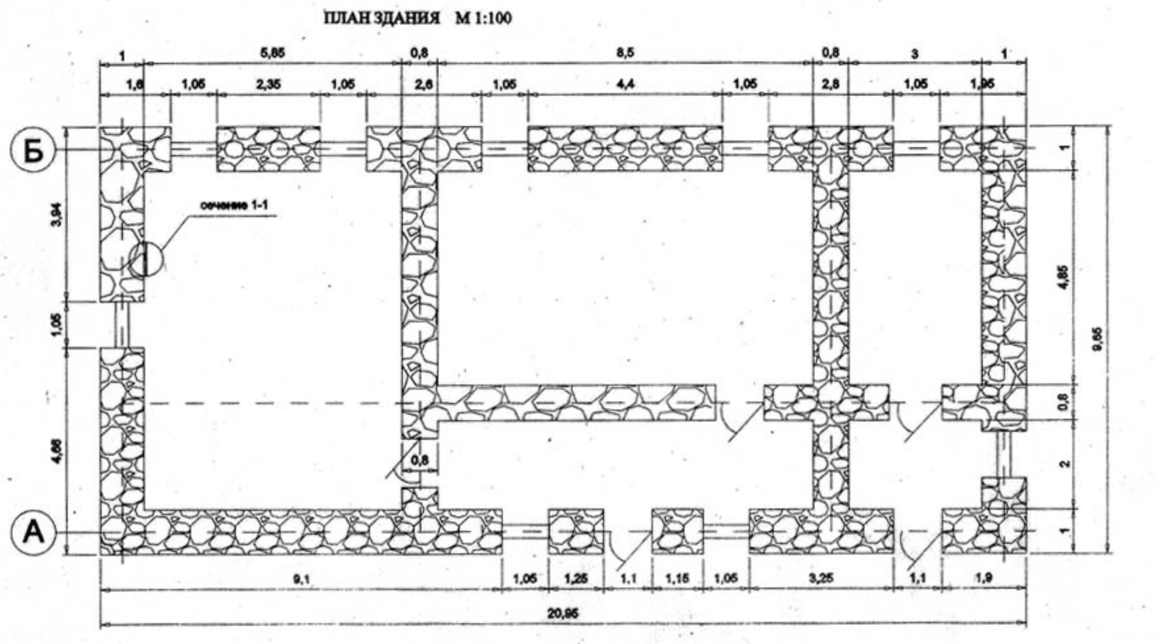
Retrofitting and thermal insulation are two different issues whereby in public buildings the decision on seismic retrofitting has the priority over thermal insulation.

Although thermal insulation would annually benefit the users with a warmer room temperature and less firewood consumption, an unsafe building remains a potential hazard for the occupants, especially for public buildings. When upgrading public buildings, it must be remembered that the strength needs to be 25% more than for common housing.

When retrofitting public buildings, the following questions should be considered:

- Will the building fatally collapse with a large earthquake?
- Will the building be structurally damaged (beyond repair) after a large earthquake?
- Will the occupants have time to evacuate the building during a prolonged seismic activity (half a minute)?
- Can the building be used for receiving earthquake victims?

For individually owned houses, it is a private decision of the house owner whether to retrofit the house or take the risk of living in a technically unsafe house (with regard to earthquakes) and opt for just only thermal insulation.



<u>Description of the Old Building</u>

The floor plan (drawing above) has an elongated entrance hall with two high windows and two large rooms, each having high windows and a 4 m high ceiling. On one side of the building, there is a separate entrance with a vestibule room leading to a smaller room. The outside walls are 100 to 110 cm thick, inside and outside plastered with cement stabilized clay soil plaster and white washed. The inside walls are 80 cm thick. The foundation is 10 cm wider on both sides, whereas the plaster on the outside was damaged up to one foot above this foundation. The general soil condition around the building is sandy clay with slow drainage, but fairly dry and with a good run-off alongside the foundation.

The wall structure was loose, non-dressed rubble stone masonry in the sandy clay soil. Inside the wall, i.e. behind the removed doorframes, it could be observed that the stone structure was totally loose and airy; small stones could be removed by hand without any difficulty (picture right). The smaller room at the end of the building showed <u>bulging of the inside of the external wall</u>, signifying internal separation of the two faces of the wall.

Occupants of this smaller room would have <u>little chance of survival</u> during an earthquake. The main dividing wall between the two larger rooms showed separation from the outside wall. The four external corners of the building were 10 cm thicker on the outside, creating a visual column, but it could not be assessed whether the internal structure was masoned with a better quality of mortar.

Extremely loose inner wall structure of rubble in clay soil; thickness 110 cm.

The ceiling and roof construction consisted of long, cleaned, round (log) wood beams, over which were branches with leaves, asphalt paper and some layers of clay soil cover about 8-10 cm thick. A pitched metal roof covered the entire building, keeping the ceiling dry. The ceiling beams were sagging as a result of the weight of the roof and have fully dried out in that position.

Original Plan

It was planned to place two steel U profiles at 4 m high, running along the top of the wall, inside and outside. The two profiles would be connected with long 16 mm bar-bolts fitted through the centre of the U profile (150 cm c-c). This top tie-beam (ring beam) would be connected vertically to four corner reinforcements using the same profiles.

New 12 cm U steel profiles running internally alongside the top of the 4 m high, 110 cm thick rubble stone wall. Only part of the ceiling beams could be connected to the steel profiles.

The following shortcomings of this plan are:

- The loose wall structure was not contained, such as the already bulging wall.
- The tops of the inner walls would not get a tie-beam.
- Inside walls were not anchored to the outside walls.
- The high windows or the door openings were not framed.
- There was no plan to remove the heavy clay soil load from the internal ceiling.
- There was no plan for a ceiling-roof diaphragm fixing the beams together.
- The single outside door would be insufficient for fast escape of many people.
- The building would not comply with increased earthquake resistance for public buildings.

Observations

When all the roof joists are fixed to the tie-beam and together, it will prevent the roof from falling down immediately. The steel ring tie-beam reinforcement will definitely reduce the risk of immediate collapse of the roof during a prolonged earthquake, but will not prevent the walls from crumbling down.

The total mass of the walls is about 300 m^3 x 2 ton/m^3 = 600 ton.
The outside space of this building is 9.65 m x 21 m = 201 m^2.
Net floor space is 123 m^2.

By dismantling the building and reusing the materials, a lower building (240 cm) with thinner (30 cm) cement masoned stone walls could be constructed on the same outside border line of the foundation, using about one fifth of the stone mass and having a net floor space of approximately 175 m^2, being 35% more than the old building.

Simple cost estimates would confirm that retrofitting this old building far exceeds the cost of making an entirely new fully seismic-resistant building, having lower rooms and a larger useable floor area.

4.5 Low Dry-Stone Construction

This small 100-year-old building has been assessed from photos only. It is considered to be an historic monument by the villagers. The building has a community and religious meeting function and is occupied only a few hours per week. As it is a semi-public building where a considerable number of people can gather, retrofitting would require it to be 25% more earthquake resistant than common housing. This will be rather difficult and costly if the retrofitting work is done by external paid contractors.

Retrofitting

The decision to retrofit the building was influenced by the villagers who apparently did not have to pay the cost of the operation. If all the materials of the old building were reused in the reconstruction (with internal wall reinforced and cement mortar masoned walls), it would still look the same and present the historic character. However, if retrofitting is undertaken using the external gabion wire-mesh technology and covering it with plaster, the building would end up with a different appearance.

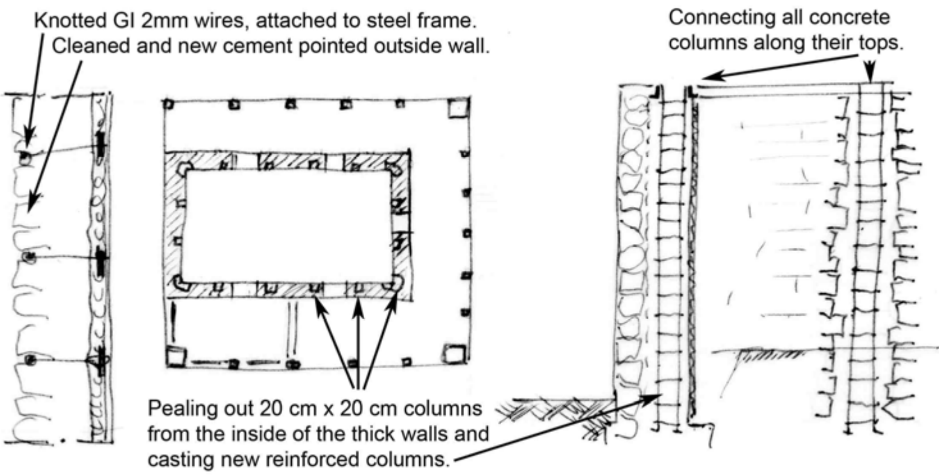
The building design with the wide veranda is highly appropriate for the adobe structures because the walls are less exposed to the climate. However, the rear side had no veranda and only little roof overhang. This wall showed extensive weather deterioration of the adobe blocks in the upper wall, erosion of the clay soil between the stones in the lower half of the wall, and structural cracks along the corner (photo). Not matter if the building is reconstructed or retrofitted, the roof overhang should be extended.

The three outside columns on the three corners were cement masoned dressed stones.

To conserve the outside appearance of the building with retrofitting, two options are possible:

I. Apply an inner steel profile frame from angle irons and strips. The wall should be attached to this inner metal frame structure with GI wires. Make a knot in the GI wire on one side, push the wire through the rubble from the outside and attach it to the metal frame. The GI knots will become invisible after the joints are pointed again with soil-lime-cement (sketch page 18).

II. Cast about 16 reinforced concrete columns of 20 cm x 20 cm into the inside of the walls. These are to be connected with a double L iron tie-beam along their tops. The slim columns will bind the old wall stones on three sides and hold up substantial parts of the walls and roof construction during an earthquake. Only two columns on opposite sides of the building should be done at the same time. After the columns are cast in place, the soil and lime mortar should be cleaned out of all the outside joints and newly pointed with soil-lime-cement mortar.



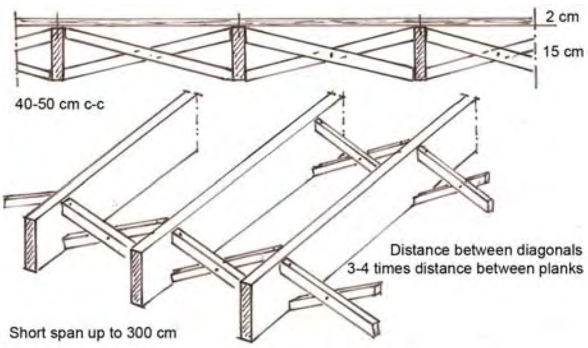
I. GI knotted wire attached to an internal metal frame and the interior being plastered after the thermal insulation.

II. The columns need to be cast in two or thee steps, using fine aggregates. The cement mortar must flow in the open joints in between the stones.

4.6 Weak Roof Construction

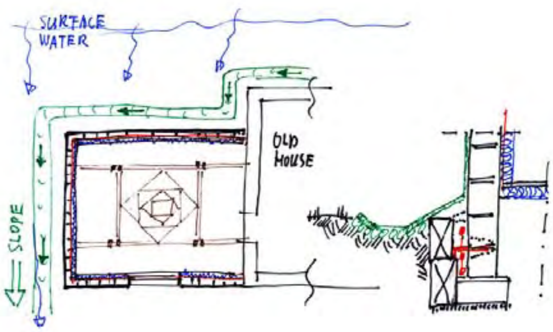
In a recently built traditional Pamiri room, the outside walls were constructed with thin cement block walls in cement mortar. At several places, both the main roof beams and the first layer of the inner ceiling square needed to be supported by means of additional posts.

The use of fresh young poplar trees, the continued roof humidity and small timber sizes caused the bending of the wood as can be seen in the above photos. Timber irregularities on the bottom sides of the beams cause breaking due to the weight of the roof. This is a common situation because large timber sizes of good quality wood are no longer available.



Rectangular section provides relatively more stiffness and can be used for the short spans in the side ceiling sections of the Pamiri room.

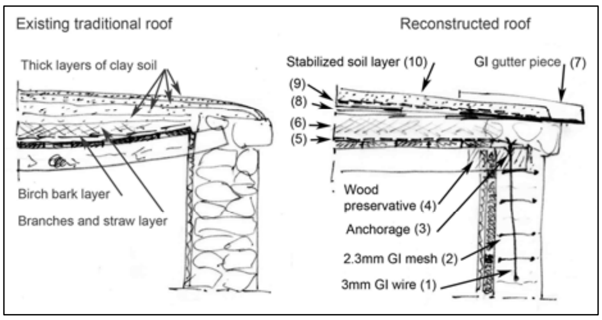
Foundation
Settlement in the foundation has caused large cracks in the floor and a large crack in the side wall. Because of the other flimsy characteristics of the building, most likely a very narrow and shallow foundation is the cause. In such a case, the foundation needs to be excavated on the outside, <u>widened and reinforced</u>.



Water infiltration coming from the higher slope needs to be blocked and diverted to the side, around the house.

Roof Reconstruction
The roof was layered with thick clay soil to stop leakage. The roof should be completely taken apart and reconstructed. The whole (bent) beams can be reused with the arched side upwards.

Roof reconstruction includes lightweight thermal insulation and waterproofing.

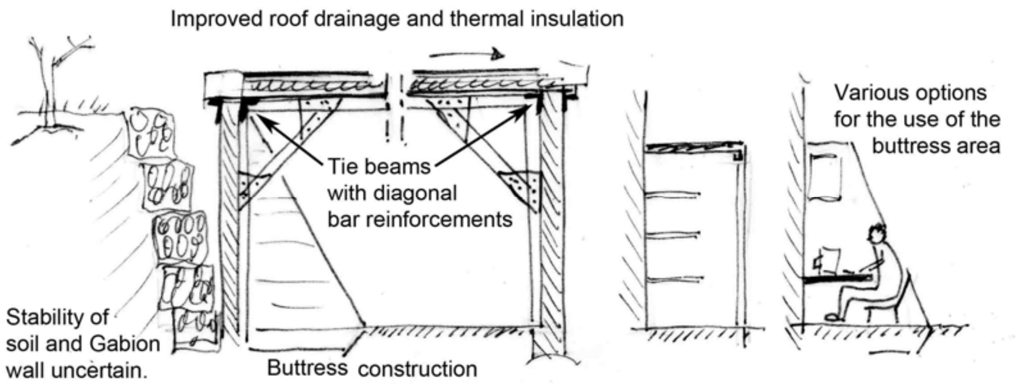


4.7 Retention Wall

The school pictured below was in an advanced state of dilapidation. The rear side of the school is built against a one-storey-high retaining wall of gabions for a higher located terrain of a large house. Single solid cement blocks have been used for the classroom walls. No foundation settlement cracks were visible in the lower part of the construction.

Retrofitting this building implies securing the rear wall of the four classrooms by masoning buttresses at 1.20 m intervals, allowing minimum 1 m spacing in between the buttresses. The buttress walls should extend at least one meter into the classrooms, be sunk into the floor and anchored into the rear wall. Three designs are possible for the upper finishing of these walls:

(1) The buttress walls are masoned inclined against the top of the rear wall, providing a sitting space in between and visually giving the classroom more space.
(2) The buttress walls are masoned straight up to 50 cm from the ceiling, creating spacious cabinets with shelving; either open or closed.
(3) Using the space in between the buttress walls for working desks.



- The classroom wall constructions require the development of shear wall sections in the corners, made by inside and outside connected L profiles and plastered.
- The window and door openings need to be framed with double 50.50.5 angle irons.
- The doors should open outwards.
- Double angle irons (50.50.5) should run as a tie-beam at the wall plate level on both sides of the external walls and connected between the L irons.
- These tie-beams should be well connected to the timber cross frames (sketch).
- The tie-beams in the corners need a diagonal reinforcement.
- The timber frames need junction reinforcement with 1.2 mm steel plates.
- The plank roofing should be fully nailed to these outer roof beams to create a floor/roof diaphragm.
- The new roof should be damp proofed over the planking, well insulated and waterproofed.

Retrofitting of this building should only be done when security against the possible collapse of the rear side retaining wall has been achieved.

4.8 Adding on Storeys

Many house owners expand their house in phases. Adding on storeys causes an increased earthquake load on the lower storey. In nearly all cases the ground floor building has not been designed to carry the earthquake load of that other storey. To keep the earthquake load minimal, the additional storey should be very lightweight. Lightweight insulated panels (EPS-timber-glass), plastered wattle with insulation, or timber and glass constructions are feasible (photo right).

Third Storey

The ground floor of this concrete frame building (photo right) is made with dry-stone masonry and partial framing of the openings. The first floor is made with cement blocks. Only the middle section of the first floor, between the two windows, is framed. There is no column or framing at the wall endings.

Retrofitting

For the ground floor, the left section and the section in between the two windows need to be retrofitted with two-face gabion wire-mesh and plenty through-anchors. This should be repeated for all wall sections of the ground floor, also the inside walls. In the first floor, the section between the two windows functions as a shear wall, but the outside left section should be retrofitted with a column or wire-mesh reinforcement and around the corner. The top floor (second floor) is lightweight, but the whole building does not comply with the minimum regulations for Zone 3 earthquake areas, mainly because of the weak ground floor.

The photo was taken when they were just starting to cover the building without structural retrofitting. The photo right is the same building a year later. The façade has been covered with plastic sheeting and a small extension has been made on the front.

The result is a nice looking building but structurally weak.

A nice finish does not guarantee a strong construction.

The building on the right has adobe walls in a concrete frame. It is in the process of being covered up with plastic panels. Adobe blocks are strong enough to cast a concrete beam on top, but are too weak to provide sufficient compression resistance needed for a shear wall for a heavy three-storey construction.

The dry-stone house on the right is fitted with new plastic windows and completely plastered over. However, the house does not have any wall framing around openings and wall endings and no continued tie-beam. Furthermore, it needs to be assessed if the inside walls are of equally poor quality and if any floor or roof diaphragms are present.

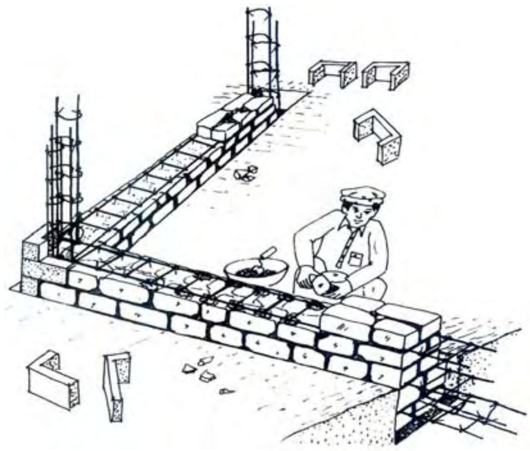
Once completed, the weaknesses of these buildings can only be exposed by removing the plasterwork or plastic panels. To protect the habitants, strong and obligatory measurements will be required to improve the housing stock.

5. SUMMARY

Based on observations from several retrofitting activities, the following points can be made:

A. When the same building materials are used in a house reconstruction, the reconstruction costs in a village situation will be approximately 20% of the value of the house; the other 80% represent the value of the building materials. This means that when a retrofitting exercise is estimated at 20% of the value of the house, it is more economical and structurally much safer to reconstruct the entire house.

B. Time-wise there will be little difference between reconstruction and retrofitting of a ground floor only house. When the walls are of rubble stone in clay or adobe blocks, reconstruction may be faster and will be stronger than retrofitting.



C. The house should be reconstructed from the foundation up. The longer the house is, the stronger the through reinforcement should be in the length direction of the foundation.

D. Water infiltration under the foundation should be avoided by seals and draining away surface water from slopes.

E. Not retrofitting or reconstructing to allow a **second or third storey** is a **lost opportunity,** considering the scarcity of land and high population growth. Reconstructing a house would provide the opportunity to plan a future second storey, being a special advantage considering the land scarcity.

F. Retrofitting is commonly decided upon in combination with other house renovations or extensions. The connections between the old and new house should be considered. The new house section should be built earthquake resistant and good for two or three storeys.

G. If partial retrofitting is done, the bedroom and other areas where people spend most of the time should be retrofitted (or reconstructed) first, rather than non-used rooms, occasional guest rooms or rooms where people commonly are awake.

Before retrofitting (or reconstructing), the following points should be considered:

5.1 **General Quality.** The planner should look at the house as a whole and should include the relocation of door openings to enhance the structural strength of walls and improve the symmetry of the construction (horizontally and vertically).

5.2 **General Environment.** The general position of the house in relation to its environment must be assessed. This includes steep slopes, possible rock fall, potential flooding, landslides, liquefying soil and other hazards. When such hazards exist, other building locations should planned with the local authorities.[13]

5.3 **Foundation Stability.** The planner needs to assess the foundation and possible water infiltration under the house. The foundation of the house needs to remain dry and built on solid (not infill) ground. This is especially important for adobe houses.

5.4 **Earthquake Resistance.** Buildings in Zone 3 earthquake areas should resist 20% of the mass as horizontal load. In Zone 4 earthquake areas, they should resist 25% of their mass as horizontal load. Public buildings and where people gather should be 25% stronger.

[13] This implies village level decision making and new accommodation in two-storey and multifamily houses.

5.5 **Reduce the Mass of the Construction.** Retrofitting or reconstruction should primarily consider lowering the mass of the construction. For the traditional Pamiri house design, this means making the traditional roof substantially lighter and reducing the mass of the heavy stone masoned walls.

5.6 **Improve Shear Walls.** Door and window positions should have framed 1.2 m walls on their sides. Shear wall sections next to openings that are <1.2 m should be converted to columns. Internal walls often take most of the earthquake load. Internal shear walls should support the horizontal forces on the building in two perpendicular directions.

5.7 **Improve Coherence.** Tie-beams, roof/floor diaphragms, anchoring of support beams to the walls and connecting lintels are all part of increasing structural togetherness. Horizontal wall reinforcement needs to be linked to all cross wall sections. Tie-beams must run over all inside and outside walls and be connected to each other.

5.8 **Adobe Houses.** These should preferably be totally reconstructed using galvanised wire-mesh reinforcement (GWR). The construction of a tie-beam, floor diaphragm and a new lightweight roof are essential elements. Foundations and walls must be kept dry. Retrofitting with gabion wire-mesh, PP rope and glass fibre mesh is possible.

5.9 **Rubble Stone in Clay Soil Masonry.** These houses should preferably be totally reconstructed making thinner cement masoned walls with galvanised wire-mesh reinforcement (GWR). Small or narrow wall sections need to be wrapped and framed. Walls should be retrofitted with plenty through-stones to avoid delaminating. The construction of a tie-beam, floor diaphragm and a new lightweight roof are essential elements. Retrofitting with gabion wire-mesh, PP rope and glass fibre mesh is possible.

5.10 **Cement Mortar Masoned Semi-Dressed Stone Walls**. The internal integrity of the walls must be assessed. Walls with clear separation between the two faces should be reconstructed or be thoroughly reinforced with at least one through-anchor per 75 cm, both horizontally and vertically. Existing lintel beams over doors and windows need to be connected. New tie-beams with beam anchors should be fixed to the floor/roof diaphragm. Retrofitting with internal-external concrete tie-beams and framing, gabion wire-mesh, PP rope and glass fibre mesh is possible.

5.11 **Pamiri Room Designs.** Roofs need to be reconstructed lightweight, insulated and waterproof. Column feet should be fixed in position and mortise connections verified for the quality of the joints. Capitals and other timber beam roof structure must be anchored to the columns. Side beams need to be anchored to the main support beams and the perimeter walls to create a full roof diaphragm. The perimeter walls need to be internally reinforced to avoid inward collapse, while the framing should be adequately secure to the horizontal stability of the roof. Retrofitting the walls with internal-external concrete tie-beams and framing, gabion wire-mesh, PP rope and glass fibre mesh is possible.

5.12 **Cement Mortar Masoned Cement Block or Brick Houses.** Vertical and horizontal wall framing reinforcement is possible with additional concrete reinforcement bars or metal profiles placed on the outside of the walls, creating through the wall tie-beams. Lightweight floors and diaphragms are needed. The application of thermal insulation is highly recommended and should be structurally incorporated. Retrofitting the walls with internal-external concrete tie-beams and framing and glass fibre mesh is possible.

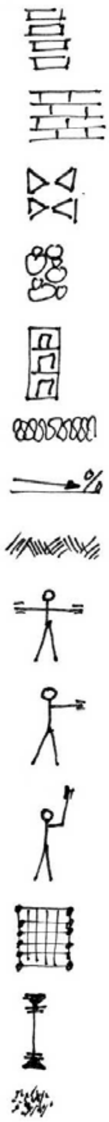
5.13 **Door Openings** in weak walls need to be additionally strengthened with framing so they remain open for escape during prolonged earthquakes. Doors should open outwards. Doors of public buildings need panic-push bars and should not be key locked when the building is occupied. There should be no steps immediately next to the opening.

5.14 **Timber Tie-Beams** and timber wall reinforcements in dry-stone walls are poor solutions compared with wire-mesh, glass fibre mesh or concrete reinforcement bars in cement masoned constructions, and should be avoided.

5.15 **Added Storeys** should be lightweight constructions with lightweight roofs.

ANNEXE I SYMBOLS

- Lightweight construction
- Heavy weight construction
- Thin construction
- Thick construction
- Stress resistant connection with hinges on extremes
- Stess-pressure resistant
- Moment resistant connection
- Wedged-in moment resistant
- Wire-mesh linked
- Cold deformed reinforcement
- Wall anchor, head and side view
- Through-stone, head, side view
- Floor/roof diaphragm
- Wrong solution
- Good solution
- Gabion wire-mesh



- Non-cement masoned (Adobe)
- Cement masoned (blocks, brick)
- Cut-face dressed stone wall
- Rubble stone wall
- Cement block wall (hollow)
- Thermal insulation material
- Roof sloop for drainage
- Infill soil (compacted)
- Minimum width 180 cm
- Minimum width 120 cm
- Minimum height 210 cm
- Shear wall section with all sides reinforcement
- Reinforced concrete column with caging in maximum moment
- Cement mortar masonry

ANNEXE II FURTHER STUDY

For additional information on the subject, the following documents can be consulted:

Guidelines for Earthquake Resistant Reconstruction and New Construction of Masonry Buildings in Jammu and Kashmir State
Training document, October 2005, Ministry of Home Affairs, Government of India. GoI – UNDP-DRM Programme. National Seismic Advisor Prof. Anand S. Arya. 3.1MB, 36 pages.
www.ndadmindia.nic.in/EQProjects/kashmir%20Final.pdf

The principles of seismic bands to reinforce newly constructed walls are well explained. However, the use of timber seismic band constructions should be replaced by Galvanised wire-mesh or thin reinforced concrete band constructions. The timber has very little bonding with the stone structures and is costly to make, while connections between the length members and cross-ties are often improperly made. Reinforced concrete band layers in between the stone constructions should be many and thin, but thick enough to provide good cement mortar cover of the steel reinforcement bars.

Seismic Design Guide for Low-Rise Confined Masonry Buildings
By EERI & IAEE august 2011, 3.4 MB, 90 pages.
http://sheltercentre.org/sites/default/files/16.02.2012_confined_masonry_design_guide_8_2011.pdf

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Earthquake-Resistant Confined Masonry Construction
By Svetlana Brzev, National Information Centre of Earthquake Engineering, 2.6 MB, 90 pages.
http://www.preventionweb.net/files/2732_confinedMasonry14Dec07.pdf

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Techniques for the Seismic Rehabilitation of Existing Buildings
Resource file, 11 MB, 105 pages.
http://www.fema.gov/library/viewRecord.do?id=2393 Also to download in three parts.

Description with models of building types including reinforced concrete and steel frame constructions.

Guidance Notes on Safer School Construction – Global Facility for Disaster Reduction and Poverty
Produced as collaboration between the International Agency Network for Education in Emergencies (INEE) and the Global Facility for Disaster Reduction and Recovery (GFDRR) at the World Bank, in partnership with the Coalition for Global School Safety and Disaster Prevention Education, the IASC Education Cluster and the International Strategy for Disaster Risk Reduction. 3.7MB, 135 pages.
http://gfdrr.org/docs/Guidance_Notes_Safe_Schools.pdf

The Annexe has various interesting references on codes, design, landslides, prevention and retrofitting.

Manual for Restoration and Retrofitting of Rural Structures
UNESCO-UNDP-GovIndia. How to Reduce Vulnerability of Existing Structures in Earthquake Affected Areas of Jammu and Kashmir (2007), 140 pages, 17,9MB.
http://unesdoc.unesco.org/images/0015/001593/15933E.pdf

Several of the presented designs of houses are not available in Pakistan, Afghanistan and Tajikistan. Extensive repair with timber will be affected by the limited availability of timber. The vulnerability assessment of Chapter 4 is relevant and useful for other earthquake areas. In Chapter 5, repairing cracks in houses does not necessarily make them better earthquake resistant; it mainly makes them more aesthetic.

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