GALVANISED WIRE REINFORCEMENT (GWR) TECHNOLOGY

Earthquake Reinforcement for Non-Engineered Stone and Earth Constructions

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Abstract: Earthquakes negatively affect many low-cost houses of low-income people due to poor material choice and construction techniques, especially in non-formal settlements and housing development. In the remote village areas of high mountains such as the Himalayas and the Andes the introduction of cement and steel reinforcement bars for reinforced concrete constructions is very costly and often not affordable for the local villagers. Galvanised Wire Reinforcement (GWR) is an earthquake reinforcement for thick, non-engineered dressed and semi-dressed stone walls, adobe, soil block and rammed earth building constructions. In remote mountain areas masonry with cement mortar is only marginally done due to the high cost of cement, sand and aggregates. The 2.3 mm and cross-welded or knotted GWR provides lengthwise and crosswise reinforcement within the wall thickness and vertically along the borders of all openings such as doors windows and wall endings. The special advantage of the Hot Dip Galvanised Wire is that it does not require a high concentration of cement in the concrete or cement mortar to prevent corrosion of the wires. Villagers can apply the reinforcement throughout the wall construction applying only low-cement mixtures, thus keeping the construction cost low. L-shaped and U-shaped cement blocks provide hollow space for the vertical reinforcement consisting of folded up GWR strips, facilitating construction and providing an aesthetic architectural design. The cement blocks can be cast on site with a simple operated mould and hand compacting, also allowing low cost production techniques. The GWR strips or ladders can equally be used in adobe wall constructions either made with blocks or rammed earth. In addition it is an adequate reinforcement for solid cement block walls. Practically speaking the GWR strips can be applied in every alternating course or stone or block masonry, thus creating adequate stress reinforcement throughout the wall structure and having contact with all stones or blocks.

Key words: mountains, remote, housing, earthquake reinforcement.

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1. Introduction

<u>Earthquakes and Remote Mountain Areas</u>

The western wing of the Karakorum Range of the Pakistan Himalayas, comprising the Northern Areas and Chitral District, is under the influence of plate tectonics that culminate beneath Afghanistan. Earthquake movements are frequently registered in the entire area. A very large earthquake occurred in October 2005, leaving 75,000 people dead and destroying more than 100,000 houses. Building to withstand these tremors is therefore extremely important in saving human lives and minimising economic disaster. Road access to remote villages is by donkey trail. Bringing cement, long concrete reinforcement bars, sand and aggregate is extremely difficult and expensive.

Lack of natural resources, such as timber, have affected the building practices over the last generation. This aspect, combined with rapid population growth, has resulted in a severe deterioration of building quality, especially in areas where no alternatives to traditional stone constructions have been developed. BACIP has introduced the Galvanised Wire Reinforcement (GWR), providing an economically feasible and technically sound method to reinforce traditional dressed stone, semi-dressed stone and soil block constructions in remote mountain villages.

<u>Non-Masoned Semi-Dressed Stone and Rammed Earth Construction</u>

Galvanised barbed wire was first used in 1970 with the reconstruction of low-cost *bahareque* houses (timber frame, bamboo mats and soil plaster construction) in Guatemala by CARE. The use of wire-mesh in stone masonry was used by the author in the earthquake reconstruction programme after the devastating earthquake of 1982 in Dhamar, Yemen Arab Republic.[1] The galvanised wire-mesh technology was particularly suited for the horizontal reinforcement of 18" wide dressed stone walls. In the Dhamar reconstruction project, rolls of pre-manufactured <u>double</u> galvanised cattle fencing were used for rapid application. The openings in this wire-mesh ranged from 6 cm to 20 cm.

The central plateau of Yemen has good quality clays. Two to four-storey houses are traditionally built from rammed earth, having 2-3 ft. thick walls. Before casting and compacting a higher layer of rammed earth between a wooden formwork, a new strip of the cattle wire-mesh is laid from corner to corner. By doing so, a horizontal reinforcement is realized at 1 ft. vertical intervals, providing an even distribution of reinforcement throughout the walls. With the slimming of the walls, the wire-mesh is cut in narrower strips, keeping the length wires along the sides of the wall about one inch from the external face.

<u>Plaster or Cavity Wall</u>

A GWR strip can be made with three length wires. Two wires consist of the main wall reinforcement, while the third external wire is used to create a cavity wall. Cavity walls create some thermal insulation whereby comfort is enhanced and firewood savings realised. Especially in the desert climates and high altitudes, such as on the Yemen plateau, Pakistan, North India, Nepal, Tibet, China and Mongolia, cavity walls are economically and thermally efficient. In wet climates, when the outer cavity wall is made of durable materials, it keeps the inner wall dry.

<u>Insulating Inner Wall</u>

A thin insulating inner wall can be fixed on a third inner parallel wire. Insulating walls are made with cavities, insulation material and reflecting foils. The inside of the inner walls can be finished with gypsum board or plaster on fine wire-mesh.

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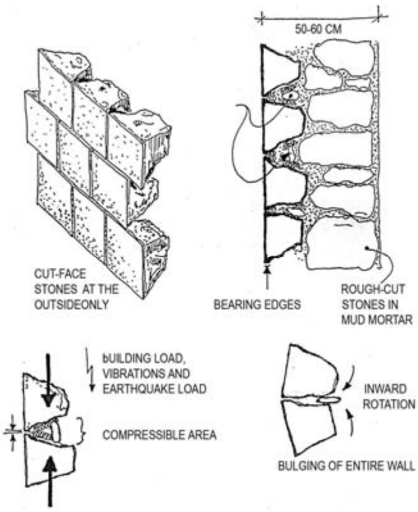
[1] Project financed by the Netherlands Directorate for International Cooperation (DGIS) and DHV Consulting Engineers, The Netherlands. The use of wire-mesh is common in reinforced masonry designs (burned brick).

2. Materials and Method

The need for simple-to-apply earthquake reinforcement for self-help stone constructed houses was highlighted after the December 1982 earthquake in Dhamar, Yemen Arab Republic, where tens of thousands of traditional dressed stone houses collapsed during the earthquake.

Photos of traditional buildings and their damage can be viewed in my paper on site selection see: http://www.nienhuys.info/mediapool/49/493498/data/Dhamar_Site_Selection.pdf

The pictures in the above-mentioned document illustrate the problems related to the technique of making nicely dressed cut-face stones for “dry” masoned stone wall constructions.



The volcanic stones can be finely shaped with enough time and skill (cost), but many masons apply the cut-back technique whereby the face of the stone is tailored with straight sides and the rear side is cut back to minimize the joint in the façade of the building.

The stones are supported with rubble. Vibrations, such as with earthquakes, cause the cut-face stones to bulge outwards and come loose from the rubble masonry of the inside of the walls.

No published information was available on appropriate solutions given the remote mountain situation of the Mahgrib Ans. Therefore, generally available earthquake-resistant construction technology was used, mainly from sources such as the American Concrete Institute (ACI) building codes (ACI 318) and a number of publications from the Indian Institute for Earthquake Engineering (IIEE) on the technical reinforcement of simple houses using reinforced concrete confinement along all wall endings and bringing in tie beams through the windows and at floor level. Roof diagram constructions would be realised on every floor. The details are explained in the following chapters.

The working method was to assess the available building materials in Yemen and the possibility to transport these by light 4WD truck to the building sites, some of them only reachable by donkey and man power. Reduction of weight, transportability and the versatility of the reinforcement were some of the determining factors.

Three other important factors for remote mountain areas, such as in the Himalayas, were:

(1) The possibility to shift part of the manufacturing cost of the reinforcement to the village where the material was to be used.

(2) The use of the steel reinforcement in low cement masonry or even in mud-clay soil masonry. The use of heavy and costly cement was commonly minimised by the house owner and the masons.
(3) The reinforcement should be well distributed throughout the construction because making reinforced concrete columns was costly and the concrete quality generally was substantially below the minimum recommended resistance value due to adverse aggregate, water quality and poor construction practices.

In Pakistan, Northern Areas, the choice fell on 2 mm hot-dip galvanised wire, having ample strength to withstand large tension forces and sufficiently pliable to knot into a mesh structure to enhance adherence in between the stone masonry layers.

The material could be easily transported in rolls of 50 kg and a series of simple hand tools were designed to rapidly knot the wires to make a long roll of mesh having the width of the stone wall – 50 cm, 60 cm or 80 cm.

It is recommended to make factory point welded bands (strips) of reinforcement wire. Post-welding the rolls should be by means of a hot-dip galvanised technology. Rolls of 20 m long are used. GWR can be effectively used in natural stone, adobe and cement block houses.

A small stock of factory welded and post welding hot-dip galvanised wire-mesh in one of the BACIP storage sites in the Northern Areas of Pakistan.
Author with a stack of adobe blocks. When the wire-mesh rolls are slightly smaller than the width of the wall, they should be placed in very soft clay joining paste at every alternating layer.

When the wire-mesh bands are connected at all intersection walls and to vertical corner and door/window side reinforcements, good horizontal and vertical wall reinforcement is obtained. A roof tie beam and roof diaphragm will complete the construction, providing a fairly safe home able to withstand a considerable earthquake without fatal collapse.

A roll of hand-made wire-mesh manufactured for a large house in the mountains. The roll weighs about 100 kg and can be transported in a small 4WD pick-up truck that is able to reach the construction site via the mountain tracks. Smaller rolls can be carried by donkeys.

In remote areas where access is very difficult, rolls of 2 mm wire and the small tools can be hand-carried to the village. After a short training, the wire-mesh can be manufactured on the building site. Women can make the rolls of wire-mesh as well.

3. Theory of the Reinforcement

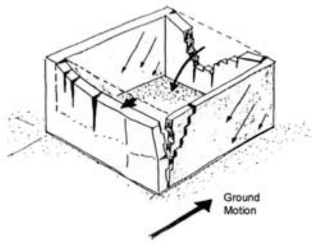
The objective of the GWR is to provide internal stress resistance to walls lacking sufficient natural bonding to function as shear walls or when the bonding is exceeded by an earthquake jolt. Stress resistance is traditionally obtained with wooden tie beams laid in the walls. In modern building technology, iron reinforcement bars are applied by imbedding them in a layer of concrete. This "modern" building technique has a number of serious disadvantages when applied in remote mountain areas because the correct sand and stone aggregates are unavailable, cement is very expensive, and mixture and curing processes are often deficient. Improperly realised concrete constructions become an additional earthquake hazard in themselves due to their massive weight.

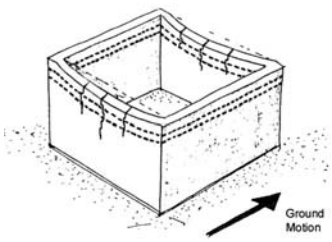
The amount of reinforcement required is determined by the expected earthquake forces; these are directly related to the mass of the construction (weight). The expected horizontal forces caused by an earthquake can be derived from a standard earthquake code.[2] This force varies from 20-30% of the mass of the construction. For public buildings a multiplier of 1.25 or 1.5 is used, depending on its importance. These values are used for low-rise buildings up to four storeys.

Well masoned houses with tie beams, floor diaphragms and consisting of no more than two storeys with proper distribution of doors and windows are usually strong enough to withstand minor earthquakes. In general, these houses are non-engineered, meaning that no special calculations are made. Non-masoned and non-reinforced houses will fail in any major earthquake and cause numerous casualties, as well as great economic loss. For non-masoned (non-bonded masonry) houses to be earthquake resistant, the following is required:

(a) Rectangular cut stones that are fully supported by lower stones.
(b) Minimal one through-stone per square meter of wall.
(c) Floors and roof beams anchored into the walls in two directions, making diaphragms.
(d) Openings that are at least one meter away from the junctions of the walls.
(e) Short freestanding wall lengths (without cross walls) and low unsupported walls.

The diagram right shows the effect of an earthquake on a room made in masonry having no stress capacity.[3]

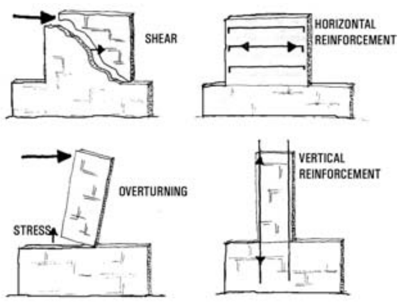




The effect of simple stress reinforcement in the higher parts of the wall is illustrated left. The better the stress reinforcement is embedded in the wall and distributed over the higher part of the wall, the less cracks will appear in the unsupported central part.

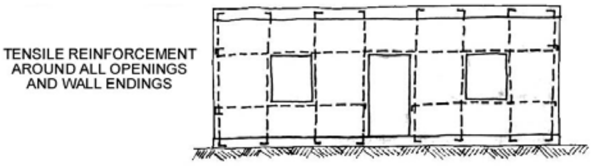
GWR or reinforced concrete tie beams provide such a distributed stress reinforcement in semi-dressed stone or soil block constructions.

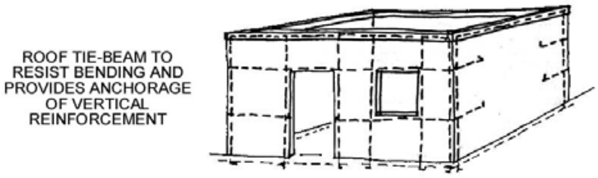
The four diagrams right give an idea of the shear forces in small wall sections, such as those between doors and windows. With the occurrence of an earthquake, diagonal cracks will appear in the walls as indicated in the first diagram. To withstand the horizontal forces, stress reinforcement should be brought into the wall in several layers, crossing the diagonal line of failure (second diagram). The third diagram shows the overturning of a narrow wall section. Here stress reinforcement needs to be placed vertically as indicated in the last diagram. L-shaped and U-shaped cement blocks at wall endings and corners provide room for placing such vertical reinforcement.



The combination of the above two principles of wall reinforcement requires narrow wall sections to be fully framed along their outside borders. With the use of L- and U-shaped blocks, slender stiffener columns can be integrated with the extremities of the walls, connecting the foundation to the upper tie beams. The schematic presentation of such a reinforcement pattern is present in sketches below.

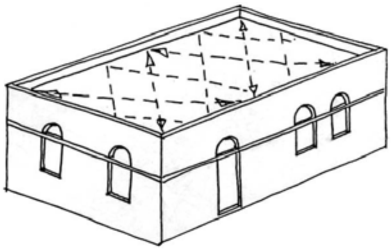
[2] The American ACI 318 and the Indian Earthquake Code are rather similar in their calculation methods.
[3] Sketches on pages 5-7 are copied from Indian Earthquake Research Institute documents, 1976.





When the above reinforcement pattern is combined with a tie beam reinforcement in the top of the wall, it will provide an overall reinforcement pattern as indicated in the right-hand sketch.

The stability of a house not only depends on the reinforcement of individual wall sections, but on the overall coherence of the construction as well. Long walls need to be supported with either reinforced buttresses or anchored cross walls. All floor and roof beams need to be properly anchored into the wall tie beams to create floor/roof diaphragms that function in all horizontal directions. In addition, all inside walls need to be anchored into this floor/roof diaphragm.



The method of reinforcement described can be used for one or two-storey buildings without load bearing reinforced concrete columns. However, the higher the building, the greater the amount of reinforcement required in the lower walls. For buildings with a few storeys, the strength of the shear walls in the lowest part of the building should be more than in the top floors.

The window and door openings should be distributed in the façade in such a way that sufficient wall segments or piers remain to form shear wall sections. For non-engineered constructions, the total section of piers in the lower floor walls should increase with the height of the building. When a two-storey building is planned, but will be built in stages, the amount of piers and internal wall reinforcement should conform to that higher design of the future.

> Earthquake disasters occur when a storey is added on top of a ground floor construction that was not designed for additional floors. This is aggravated when shear walls on the ground floor are eliminated to make room for shops.

The quality control of house construction in villages depends entirely on the knowledge of the house owner. Building advice should provide general rule-of-thumb guidelines to ensure sufficient safety to withstand earthquakes. These guidelines must be understood by both the house owner and the locally available skilled labourers. Some guidelines found in earthquake building codes are:

- No window or door opening should be made within one meter of the corners of the building.
- When the width of a wall section between openings is smaller than its height (piers), the vertical sides of these wall sections need to be reinforced.
- The piers next to a door or window opening should have a minimum width equal to half the height of the opening. For example, if the door opening is two meters high (6 ft.), the pier should be minimum one meter (3 ft.) in width.
- When numerous window openings are required, it is better to make one large opening with a strong shear wall rather than several small openings with many piers. Depending on the design, reinforced columns can be considered instead of several piers.
- For the top floor where there will be <u>no future construction above</u>, the cross section of the shear walls should be a minimum of 40% of the original wall section (without the openings).

- For the floor where there will be only one floor constructed above, the cross section of the shear walls should be a minimum of 50% of the original wall section (without the openings).
- For the floor where there will be two floors constructed above, the cross section of the shear walls should be a minimum of 60% of the original wall section (without the openings).
- When the openings in the lowest floor of a three-storey building consist of more than 30% of the original wall construction, then reinforced column constructions need to be realised.
- For buildings higher than three storeys, engineering calculations should be made.
- The above-indicated percentages can be taken over the entire wall section of the floor only where both the inner and outside walls have a fully integrated network of linked up tie beams, floor and roof diaphragms.
- When horizontal or vertical loads are applied on walls, good bonding from face to face of the wall should avoid internal separation.

In traditionally built houses without the traditional wood framing, the above-indicated conditions seldom exist. <snip drawing>

4. Practice of Dry Stone Construction

Traditional houses in the Northern Areas of Pakistan use four to seven heavy wooden columns in the centre of the room, supporting massive roof beams and having in-filled stone walls on the periphery. These dry stone (non-cemented) exterior walls often have internal wooden posts supporting the heavy roof construction. The roof consists of tree trunks, branches, twigs, grass, birch bark and various layers of clay soil. Adjacent to the central living area, various stores are built having a solid wall construction (no window openings). The only light comes through a central opening in the roof, doubling in function as a smoke outlet.

In the event of a major earthquake, the pillared construction would remain standing, but periphery non-masoned walls would eventually fall out of their framing. If the walls of the adjacent rooms (stores) fail to withstand the earthquake, the pillars would topple sideways causing the whole massive roof to collapse, burying the inhabitants under the heavy roof and rubble. <snip drawing>

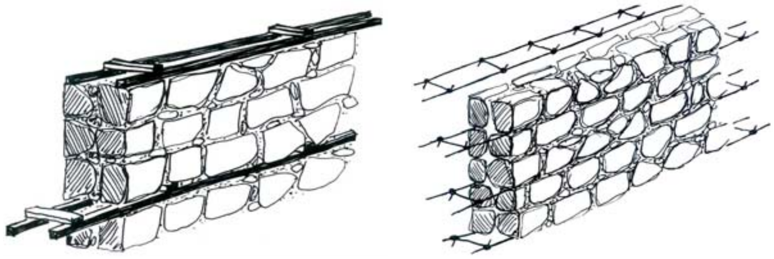
TRADITIONAL HOUSE ~ COLUMNS JUST MANAGE TO KEEP THE HEAVY ROOF UP.
WITHOUT THE REMAINING BRACING WALLS, THE STRUCTURE WILL COLLAPSE FURTHER.

In the past, a wooden tie beam construction was made in the length of the wall consisting of two parallel (fruit tree) wood sections connected to each other with short sleepers. In some cases, these lengthwise wooden strips have been applied in the corners of the walls only.

Population growth has created a high demand for new construction and this has led to an over-exploitation of available forests for building materials and firewood. The result is the non-availability of fruit trees for construction and scarcity of quality wood for the traditional house design with the central columns. The limited hardwood available in the market is unaffordable for wall reinforcement. In the absence of an alternative, villagers are constructing walls without any reinforcement. This makes all such houses highly vulnerable to earthquake jolts and does not allow for the building of two-storey houses.

The GWR replaces the traditional wood reinforcement in dry wall stone masonry.

Sketches: Lateral wall reinforcement ~ traditional method and new GWR solution.

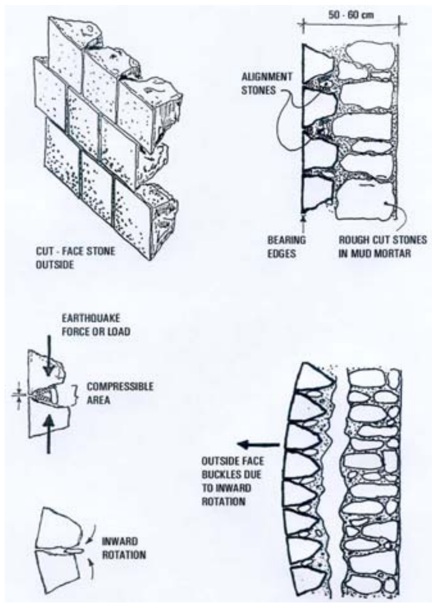


Modern dressed and semi-dressed stone constructions have particular disadvantages in relation to earthquake movements. The worst are nicely cut-face stone works.

a. Earthquake forces are directly related to the mass of the construction. Traditional 18-20" (46-50 cm) dressed stone walls generate tremendous earthquake forces that can only be resisted with either very strong or very stable constructions. Non-masoned stone constructions have neither of those two characteristics.

CROSS-SECTIONS OF TRADITIONAL WALL AND COLLAPSED STRUCTURES SHOWING LACK OF BONDING BETWEEN FACES, BUT WITH THE USE OF A LARGE AMOUNT OF CEMENT MORTAR AND PLASTER. LACK OF ANCHORAGE OF WALLS.

b. Traditional stone walls are composed of two lines of semi-dressed stones (inner and outer faces). Small pointer stones are used throughout the construction (both on the inside and outside faces) to balance the stones vertically in the façade of the wall. When some of these pointer stones fall out due to erosion or vibration, the wall becomes unstable and eventually will bulge and collapse.
c. For a straight uniform finish of the façade, the stones are dressed to even height and size. The stones are cut backwards from the cut-face into a conical shape so they can be easily aligned. The façade stones are supported inside the same wall with roughly cut stones, rubble and clay. Cut-faced stones will resist some vertical vibrations, but the inside of the wall is compressible. The result will be a rotation of the cut-face stones, breaking them loose from the inner wall and fall away in an earthquake.
d. To provide binding between the inner and outer wall faces, through-stones need to be placed providing about one tie per square meter wall. This is insufficient to withstand many tremors over a long period of time.
e. When the 18" two-stone wall is masoned with cement mortar for additional strength and bonding between the two faces, large amounts of mortar are required (30% of wall volume). When steel reinforcement bars are masoned into this cement work, the quality of the cement mortar covering the steel bars is often inadequate and. the steel reinforcement bars will corrode.
f. Steel reinforcement bars embedded in natural stone masonry are always over-dimensioned in relation to their adherence to the stones around them. Many thinner reinforcement wires or GWR provide a better spreading of the stress resistance throughout the construction.



5. Result: Galvanised Wire Reinforcement

The GWR technique provides a simple, cost-effective solution for making houses better resistant to earthquakes. Although binding of stone walls with cement mortar is the best method for making dry stone masonry more earthquake resistant, the disadvantages of using cement mortar in remote mountain villages outweigh the advantages for many inhabitants:

- Cement is costly, heavy and difficult to carry, making transport additionally expensive.
- For loose stone construction, a large quantity of cement mortar (30% of stone volume) is required.
- Reasonable sand quality is required for the cement mortar. Not all riverbeds have the quality and quantity of sand required, and those that do often are located at considerable distance from the villages.

Considering the above problems in remote mountain villages, a reinforcement technique is required that can be applied in:

1. Dry stone masonry using stabilised mortar only.
2. Construction of soil block walls.
3. Adobe and rammed earth constructions.
4. Masoned constructions in which stones, bricks or cement blocks are used.

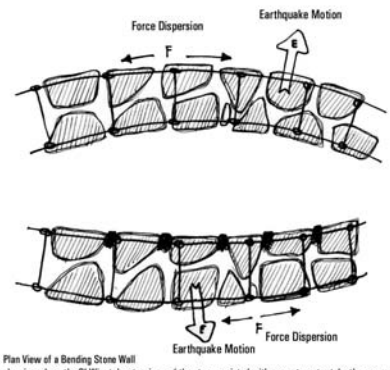
Steel bars used to reinforce masonry constructions require strong cement-sand mortar (minimum 1:4) or concrete (1:2:3). When the concrete or mortar quality is poor, steel reinforcement bars will eventually corrode and break the surrounding masonry.

The GWR does not require masonry with strong cement-sand mortar (only 1:10) and can be used in square-cut dry stone construction or adobe walls without the immediate danger of corrosion of the wires. Corrosion protection is adequate with double galvanisation, such as used for barbed wire and fencing wire.

Good adherence between the wires and the wall is necessary. To achieve this adherence, a long ladder-like strip is made from galvanised wire. The many cross wires and knots grip the surrounding stone construction or adobe masonry at regular intervals (1 ft.).

The amount of light sand-cement mortar (mix 1:10) required to fix the cross wires between the stones is considerably less in comparison to other masoned constructions. Less cement mortar results in considerable material and financial savings. Stabilised cement mortar is a large improvement over clay-mud masonry and avoids wind and rain erosion of the joints.

The GWR works best when the reinforcement is placed along the faces of each wall. Thick walls are heavier, but in a thicker wall, the distance between the wires is also increased and the increased moment-arm of the reinforcement will be more resistant to bending. The GWR is difficult to apply in very thin walls; instead, the thin wall sections should be properly framed.



Plan View of a Bending Stone Wall
showing where the GI Wire takes tension and the stones pointed with cement mortar take the compression.

An earthquake motion perpendicular to a wall will bend the wall between the supporting cross walls. With the GWR inside the outer faces of the wall, stress forces will be applied to the reinforcement, resisting the bending force. The alternating forces of an earthquake make the outside placed wires work in alteration.

To improve resistance against compression, the open spaces between the stones of both faces need to be pointed with cement mortar. Cement mortar is needed because the outside face is subject to wind and rain erosion. Thick walls have more benefit from the GWR than thin walls. <snip text>

6. Calculation of the GWR Technique

The maximum horizontal earthquake forces (kgf) in the shear walls of a simple building can reach up to 20% of the weight of the stone mass (kg). A stone wall of 4 meters in length, 2.5 meters high and with a thickness of 50 cm (18 inch plastered) has a volume of 5 m^3 and a mass of nearly 9000 kg. The section of one Ø 2.3 mm GWR wire is 4 mm^2. The stress resistance of the cold-deformed wire is around 1500 N/mm^2 or 150 kgf/mm^2, giving one wire a resistance of well over 600 kgf. Practical stress tests indicated that a double 2.3 mm wire would break at well above 1200 kgf.

Distributing the mass of the above wall over a number of wires indicates that only 8 horizontal wires are needed or five layers of double wires. This is achieved by placing the GWR in every alternating layer. In practice, the forces in a stone masoned wall are partly absorbed by micro-shifting of the stones during a major earthquake and first resisted by the wall itself. The GWR is important in holding the two faces of the wall together; if this is not done, these walls will cause early failure.

The vertical framing reinforcement is created by folding the ends of the wire-mesh up into the hollow of the L- and U-shaped corner blocks. Several double wires will be collected vertically and overlap. Six stress reinforcement wires provide 3600 kgf, being equal to two concrete reinforcement steel bars Ø10 mm, the common reinforcement and adequate for framing.

The GWR as applied by local masons in remote mountain villages is not an exact calculable technology, as much as the actual force of the earthquake cannot be established for the housing site. The purpose off the GWR is to hold the stone construction better together than loose wooden beams (which do not exist) and with that provide better safety for the inhabitants of the house.

The GWR strips can be pre-manufactured, point-welded, double galvanised and supplied in rolls of a few standard sizes. Winding the cross-wire extensions can be done quickly on-site using a small hollow tube tool.

Width of GWR

The width of the GWR depends on the type of building materials, as follows:

- Adobe and Soil Block Walls: For 16-inch walls, 14-inch wide GWR. For 12-inch walls, 10-inch wide GWR.
- Semi-Dressed Stone Walls: For traditional 18-inch walls, 16-inch GWR with light cement mortar in the joints (mortar mix 1:10).
- Cement Block Walls: Hollow 6-inch cement blocks are preferably used in light wall constructions, providing stability and some thermal insulation. For the 6-inch hollow cement block walls, 5-inch wide GWR is recommended.

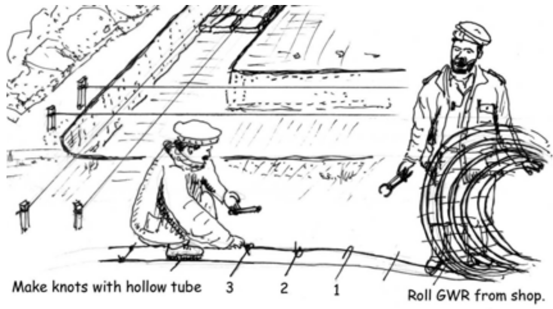
Factory-Produced Point-Welded

When the wire strips are factory point-welded, pre-manufactured rolls of 100-200 m can be marketed in the same way as rolls of barbed wire. The cross wires should be thinner (2 mm) than the length wires (2.3 mm). The point-welding process needs to be carefully controlled so that the actual section of the length wire will not reduce to less than 2 mm.

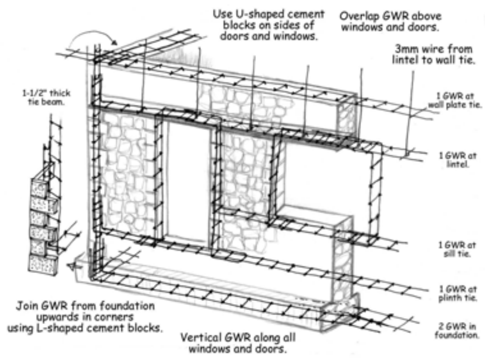
Double Galvanisation after Welding
The cross wires (2 mm) are straight and stick 2 inches out from the length wires. After the welding process, the wire strip needs to be double galvanised conform the treatment for good quality barbed wire. The GWR can be rolled to facilitate transport (200 m = 10 kg).

Requirement for a Core House
Minimal 400 m wire (20 kg) is required for a 50 m^2 core house. Each layer in a 50 m^2 core house requires 50 m length of GWR. An earthquake-resistant ground-floor-only house requires six layers of GWR: 2 x foundation, 1 x plinth, 1 x windowsill, 1 x lintel and 1 x roof tie. In addition, vertical reinforcement is recommended along all door and window frames, overlapping above the openings.

On-Site Application
The GWR is unrolled on the building site and cut to length. This length is longer than the wall sections to allow overlap and anchorage to the next section. The mason who applies the GWR in the walls is required to wind the 2-inch extension twice around the main wire or to joining sections of the GWR. This winding will enhance the friction and adherence in adobe constructions and, with a little cement mortar on the winding, it will greatly enhance the linkage with semi-dressed stone constructions. The metal winding tool is about the size of a thick ballpoint pen.



As indicated in Chapter 3, shear wall reinforcement requires vertical reinforcement to be at the ends of the walls and along all window and door openings. The GWR needs to be folded upwards at the corners of the walls and along the doors and windows. The upward folded GWR will meet other GWR sections coming from lower layers. The overlapping strips of vertical GWR form the vertical wall reinforcement.



L- and U-shaped cement blocks have been designed for easy masonry work. These cement blocks are placed in the wall corners and along the sides of door and window openings. The cement blocks have three important advantages:

1. With the placement of the cement blocks, straight vertical edges are first masoned upwards at all corners and allow easy in-fill of the cut-stone masonry. A string is stretched between the raised corners. This saves substantial time in masonry work.
2. The vertical GWR can be pulled upwards in the space between the cement blocks and the stone masonry. The cement blocks will function as formwork allowing easy filling of the space between the blocks and the stone wall with light mortar and small stones.
3. The architecture obtained by the combination of the corner cement blocks and cut-stone in-fill work is aesthetically very appealing.

Various moulds can be used for making the L- and U-shaped cement blocks. One manual type of mould is described below – the rack mould. Large quantities of good quality cement blocks can be rapidly made with this mould.

The rack mould consists of a 2 mm sheet metal mould (open at both the top and bottom) and a rack with a compacting angle iron fitted to it. The mould is placed on a flat, sanded cement floor and filled to the rim with fairly dry aggregate cement mortar (8:1). The rack is then lifted over the mould and set down with force onto the mortar in the mould, compacting the mortar. An additional amount of mortar mix is added to the mould and the compacting with the rack is repeated. Once firmly compacted, the mould is lifted while the rack holds the freshly compacted cement block down. When the mould is free from the freshly cast block, the mould and rack together are further lifted and placed aside to make the next block. The mould may not be tapered inside, otherwise it cannot be lifted.

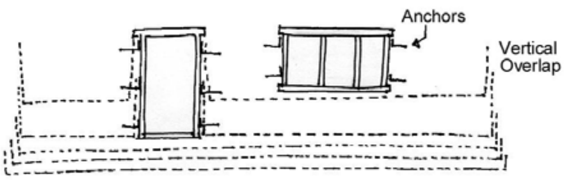
7. Building a House

Foundation

Traditional houses constructed on slopes often have high foundations built in rough stone masonry. The space inside the foundation is frequently used as cattle sheds or storage for fodder and firewood. Although this basement may not be sophisticated enough for living quarters, the walls have to bear the superstructure as it will receive the first horizontal impact by an earthquake jolt.

Depending on the soil type and boulders in the subsoil, reinforcement of the foundation is important to prevent any settlement cracks in the higher walls. The GWR needs to be applied in every layer of the foundation and cover its whole width. For wide foundations, wide GWR strips are used or several strips can be joined lengthwise, overlapping each other.

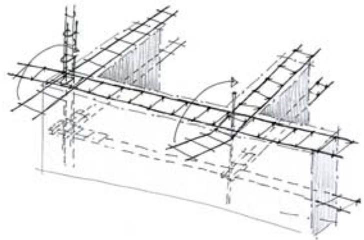
To provide anchorage for the vertical wire reinforcement at the wall ends, several GWR strips are bent upwards at the corners, overlapping for 1-2 ft. to create the corner columns. This vertical reinforcement will run upwards inside the L- and U-shaped cement blocks.



IN FOUNDATION, IN EVERY LAYER

Wall Junctions and Corners

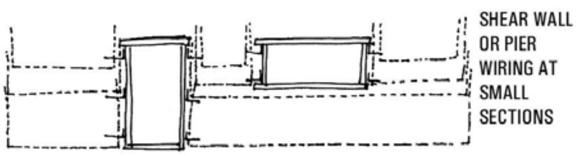
The horizontal GWR is folded over at the corners to make a turn or folded over the cross strip; thus anchoring one wall to the other. This applies to corners and T-junctions.



FOLDING THE EXCESS LENGTH OF THE WIRE-MESH BACK TO IMPROVE ANCHORAGE WITH VERTICALS

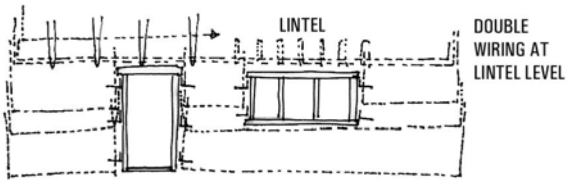
Shear Walls

Between wall ends and openings, shear wall reinforcement needs to be applied. When the wall sections are narrower than the height, pier reinforcement has to be created. Shear wall reinforcement consists of several layers of GWR over the height of the wall section and the bent-up ends of the wall reinforcement into the vertical columns. Pier reinforcement is created by doubling or tripling the vertically folded-up GWR strips along the sides of the doors, windows and wall ends, thus making reinforced columns.



Door and Window Lintel Tie Beams

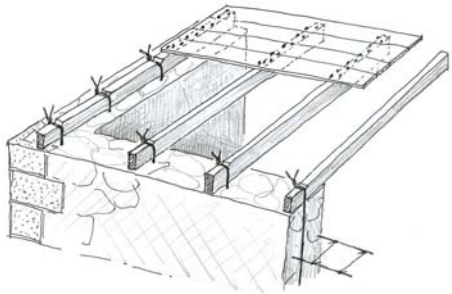
All door and window lintels need to be connected throughout the building; also over inside walls. For door and window lintels, the GWR is doubled, depending on the span, and loops of 3 mm wire are attached to the GWR at short intervals. The 3 mm wire loops are hooked into the GWR and between the hoops, a solid line of stones or cement blocks is masoned as pressure zone.



STRAPS FOR FLOOR BEAMS

Floor / Roof Beams – Diaphragms

Starting at the door and window lintel level, a 3 mm galvanised wire is hooked into the GWR to provide anchorage for floor and/or roof beams and wall plates. The beams need to be notched over the middle of their supports. The two ends of the 3 mm wire are tied down over the notches to avoid that (in case of a major earthquake) the beams slip out of these anchors. The floors and the roof should form a diaphragm with all walls, providing full bracing at every floor level and the roof.



The 3 mm wire straps are tied together over the notches in the floor beams. To provide a connection between the wall running parallel to the floor beams and the floor beams themselves, a wall beam is tied onto the parallel wall. The flooring or roofing is nailed to this wall beam and also over all the floor beams; thus creating an integral floor diaphragm. <snip text and many drawings>

8. Discussion

When discussing the calculation concept of the GWR with the Pakistan Institute of Engineers (PIE), the staff agreed on the concept, but due to the nature of the vernacular house building practice in the remote mountain areas, precise figures could not be verified. The conceptual thinking about how to reinforce non-engineered constructions was in strong contrast with their detailed knowledge on reinforced concrete design drawings, where steel reinforcement and concrete quality could be precisely defined on paper in order to dimension the construction and its reinforcements.

The professional staff of the PIE agreed that the design value of reinforced concrete quality would seldom be reached in practice due to lack of on-site supervision of the contractor and adverse climate conditions, and similarly the actual construction quality of village mason-built dressed stone houses could not be defined in precise figures.

Nonetheless, the PIE staff agreed that the concept of the GWR was valid. On the other hand, they commented that this building method could not be applied by professional engineers or architects because the methodology was **"not taught at schools, not documented and approved by international testing institutes, and not approved as building practice in Pakistan"**. It was pointed out by the author that by adhering to such criteria, building innovation would not be possible.

In addition, they suggested that the technology could not be technically approved by the PIE when the theoretical and practical field studies and testing had not been realised. The PIE required substantial external finance to realise those tests; funding from the project was unavailable. Moreover, they did not consider the certification of the GWR building method a very feasible option because the application would be totally outside the control mechanisms of the PIE and also outside that of the regular government authorities (Public Works Department). Taking the problems, earthquake risks or interest at heart of the remote rural and mountain population was not their first priority. The pressing needs of upcoming high-rise buildings in the country and the generally poor quality of currently executed concrete works all over the country were of greater concern.

After the Kashmir earthquake of 8 October 2005, the Institute of Architects of Pakistan (IAP) proposed the GWR technology in a number of their design drawings based on cement block construction. The advantage was that the cement block constructions were lighter in mass/weight and the construction could be properly calculated. New houses could be mass produced.

Approximately 75,000 people perished in the Kashmir earthquake, nearly all of them people living in dressed stone, adobe and poor quality reinforced concrete houses. Nearly an entire primary school generation died in the poorly constructed government schools (see page 13 of this paper).

The October 2005 Kashmir earthquake demonstrated the following:

- The apparent lack of understanding of earthquake-resistant design by the Public Works Department (PWD) who built the schools and other buildings, many of which collapsed.
- The need of better reinforcement designs for dressed stone constructions.
- The past total lack of any control on the building design and construction by the PWD.
- The need for intensive training of local masons on earthquake-resistant construction.
- The need for appropriate and low-cost, but durable, solutions for remote mountain people.

9. Conclusions

1. The GWR provides a low cost, but effective, galvanised metal (non-rust) reinforcement for thick **dressed stone wall constructions**. It enhances the internal bonding of the wall, especially between the faces, and provides adequate horizontal stress reinforcement when applied in alternating layers.
2. With the GWR, various widths and lengths of reinforcement can be easily applied in all types of thick-wall dressed stone masonry construction, even in the most remote mountain village because it is easy to transport and can be manufactured locally. It can also be factory pre-welded.
3. Wall constructions should be interconnected with the vertical reinforcement at all junctions and endings. Vertical reinforcement is placed within L- or U-shaped cement blocks. Because the GWR is double galvanised, only light cement mortar (mix 1:10) is used.
4. The use of horizontal and vertical stress reinforcement alone does not guarantee a better earthquake-resistant house; it is the combination of the stress reinforcement placed in the correct way and within good quality stone work. Masoning the stone work with a light cement mortar (mix 1:10) is necessary to achieve a good overall building strength. The GWR is not a magical addition; eliminating other basic precautions, such as light cement mortar masonry and anchoring of all cross walls, will result in a weak construction. Improved housing is a product of proper material use, workmanship and building site technology.
5. The application of the GWR technology in dressed stone construction will allow a first or second storey for traditionally built houses, providing an appealing architecture.
6. With large earthquake impacts, the cross wires will hold the stones in place in the two horizontal directions and absorb part of the impact. The coherence of the construction will be maintained with the vertical framing of all wall sections, the application of tie beams and floor diaphragms, and the application of light cement mortar.
7. The GWR technology should include the following:
   - Instruction manual in its use and application and how to plan a building on a safe site.
   - Manufacturing and delivery of the L- and U-shaped block-making equipment.
   - Availability of the different GWR widths in local shops, together with user guidelines.
   - Availability of 2.3 mm and 3 mm wire and cutting tools for making lintels and roof ties.
   - Assembling instructions for complicated structural designs..
8. Using the GWR in new **cement block houses**, being masoned in light cement mortar, greatly enhances the overall strength while minimising possible rust due to low cement ratios. The GWR can be used vertically or cast-on concrete framing can be used.
9. The GWR technology also greatly enhances the strength of **adobe or rammed earth constructions.** In adobe block constructions, the GWR is placed in every alternating layer; in rammed earth constructions in every layer. These adobe and rammed earth constructions exist in many countries regularly affected by earthquakes, such as Turkey, Afghanistan, Tajikistan, Iraq, Iran, Pakistan, India, Nepal, Tibet, Mongolia and China, as well as in many Andean countries, such as Guatemala, Honduras, Nicaragua, Columbia, Ecuador, Peru, Chile and Bolivia.

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Acknowledgements

The first ideas of the wire-mesh technology were developed in Yemen Arab Republic after the December 1982 earthquake and the following reconstruction programme in the Dhamar district. The technology is based on the behaviour of buildings during earthquakes described in extensive documentation obtained from several earthquake technology institutes worldwide, including India, USA, Japan, Turkey and Chile. In Guatemala in 1975, galvanised cattle fencing wire was already proposed by Care for the reinforcement of rural adobe constructed housing.

During the further development of this technology in 1999-2001, architect Sjoerd Nienhuys (author) was Technical and Programme Director of the Building and Construction Improvement Programme (BACIP), a development programme of the Aga Khan Foundation. He was assisted by Ahmed Saeed Shaikh, Deputy Director, and Qayum Ali Shah, Manager Field Operations, who built his own house using this technology.

BACIP was a project of the Aga Khan Planning and Building Services, Pakistan. The programme was financed by PAK-SID, a collaborative venture between the Canadian International Development Aid (CIDA) and the Aga Khan Development Network. In addition, the cost of the Programme Director (myself) was financed by The Netherlands Directorate General for International Cooperation (DGIS). The technology was fully developed under this programme. Pictures have been added from the Kashmir earthquake of 8 October 2005, showing the deficiency of cut-face stone architecture.

Drawings, sketches and photographs by:
Indian Earthquake Research Institute documents (1976) – sketches on pages 6-7.
Sjoerd Nienhuys – all other drawings, sketches and photographs

In order to comply with the requirements of the ICSBE-2010 , the pictures have been reduced and text sections as well as the chapter 8 on construction technique has been removed.

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