Comparing Seismic Retrofitting Approaches of Traditional Stone Masonry in Mud mortar Buildings in Nepal

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Abstract

The 2015 Gorkha Earthquake in Nepal took the lives of more than 8,000 people with over a million houses being partially damaged or completely destroyed. 74% (Central Bureau of Statistics, 2015/16) of the damaged houses were of low strength masonry such as adobe and stone masonry in mud mortar (SMM) often found across the mid hills of Nepal. Such low strength non-engineered masonry construction is built using traditional construction practices, with minimal seismic-resistant features and results in buildings that are unable to withstand code level earthquake forces. However, retrofitting these buildings has shown to substantially increase their seismic performance whilst also providing additional benefits like maintaining the living area of the existing house at a much cheaper cost. This paper investigates the advantages and disadvantages of retrofitting an existing building rather than constructing a new house within the context of Nepal. From the authors experience retrofitting could provide many benefits over new construction and be more widely adopted by the population, but it is imperative that implementers understand when retrofitting is a suitable approach.

Keywords: retrofitting, stone masonry mud mortar

1. Introduction

Retrofitting is a viable option not only for Stone masonry in mud mortar (SMM) buildings that are affected by the earthquake but also as a preventative measure for buildings that are vulnerable to future earthquakes or other natural hazards but have not sustained any damage to date. Following the 2015 Gorkha earthquake, more than 75,000 (Central Bureau of Statistics, 2015/16) houses were considered as partially damaged and categorized as being eligible for retrofitting by the National Reconstruction Authority (NRA) of Nepal. In addition, there are approximately 3.5 million SMM houses across Nepal (Central Bureau of Statics, 2011) that requires some extent of seismic retrofitting to make them more resilient to future earthquakes.

The Government published Repair and Retrofit Manuals cater to the large number of buildings that needed retrofitting within the earthquake affected areas. This manual included 4 different retrofit designs for SMM buildings and in addition, the government approved a further type design for SMM buildings and for dry stone masonry (DSM) buildings.

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A Department for International Development (DFID) funded, United Nations Office for Project Services (UNOPS) led project has supported the construction of 290 retrofits across the earthquake affected districts. Two retrofit approaches for SMM houses were adopted as part of this project, the splint and bandage approach based on the manual and the strong back type design approach. Both retrofitting approaches aim to reduce the structure’s susceptibility to out-of-plane failure, provide confinement to the structure and increase the in-plane capacity of the masonry walls. As part of the project, 206 houses were retrofitted using the strong back approach, 18 with the splint and bandage approach and 66 using a timber retrofitting method.

The paper presents a critical review of the two retrofitting approaches for SMM buildings; and where relevant; compares them to new construction. The retrofitting approaches are compared across 4 criteria; constructability, durability, cost and environmental impact.

The comparison is done based on experiences of implementing both technologies in the field. The feedback obtained from the design team, the site team, the builders that were involved and the homeowners whose houses were retrofitted is used in this paper. These feedbacks have been compiled over a period of over three years in various districts. For cost comparisons, the costs incurred in the actual sites were used as a basis for calculation of cost of example buildings. This was important to do as in case of SMM houses, the walls are not plain, hence, the use of materials for plastering and other construction work could differ from theoretical bill of quantities calculations.

2. Traditional SMM buildings

Stone in mud mortar construction is one of the oldest construction practices in Nepal. The stones are usually mined from the shores of the river or from the rocks extracted from the stone quarries in the mountains. The locals do not have to pay for the stone but they need to pay for the labor required for extraction and transportation. Depending on the location, the practice could be using dressed, semi-dressed or random rubble stones for masonry work. The timber used is generally of good quality and found locally.
The traditional SMM buildings are generally two stories plus an attic and rectangular in shape. The low story height and thick walls in these buildings compensate for the low strength of the masonry itself. These buildings have mud floors that consist of a central timber beam that runs in the center of the floor and supports the timber joists that in turn support the mud floor. The central beam is supported by timber posts that occur at approximately the same position at each floor and eventually continues upwards to support the ridge beam of the roof. At the two extreme ends, the central beam is supported by the transverse walls.

There is sometimes a timber band at the floor level but it is usually discontinuous around the building. The roof is supported by the ridge beam at the center and the eaves at the other end.

It is generally observed that the joists are well embedded into the masonry walls. In windy area, it is general practice for buildings to either use heavy roofing materials like stone or clay tiles, or use light corrugated galvanized iron (CGI) sheets but weigh it down with stones or other heavy materials.

There are generally two major types of SMM houses depending on the use or location of such houses. One is a house near market places where the ground floor is used as a store front and hence has larger openings in the ground floor. The other is a house which is only used for residential purpose and has opening sizes around 35% of the wall length.
These SMM buildings are similar in construction across the mid-hill region of Nepal and therefore demonstrated similar damage patterns following the 2015 earthquake. The damages that were commonly observed in these kinds of buildings are discussed in the following sections:

Delamination of walls: The in SMM buildings are generally 450mm or thicker. The practice of laying stones is such that the larger stones are arranged along the two outer faces of the walls and the gap between these two stones are filled with mud and small pebbles. There is generally no through connection between these two outermost wythes. Hence, when there is lateral shaking, the wall behaves as two slender walls instead of one thick wall resulting in delamination of the two layers and eventually collapse of the wall.

Gable wall collapse: The SMM houses typically have stone masonry gables above the attic walls which extend up to the roof. There is no positive connection of this wall to the roof and is supported only by the weight of the roof in normal conditions. During earthquakes, due to the lack of positive connection of these walls to the roof, these walls collapsed, sometimes also facilitating the subsequent collapse of the transverse wall below. This was one of the most common damages observed across all the districts.
Transverse wall out of plane damages: Out of plane damages were observed more frequently in transverse walls. This could be due to the fact that the joists span between the long walls but the floor is connected to the transverse walls only with the central beam and not properly restrained by the diaphragm. Hence, we could see the transverse walls with out of plane damages and in some cases the wall had completely pulled out and collapsed.

Parapet walls out of plane damages: Since the roof is not resting directly on the parapet walls in the attic, the wall lacks restraint or bracing at the top. In cases where the parapet walls were stout, this was not observed, but in cases of taller attic walls or in case of houses without attic, this type of failure was more frequently observed.

Diaphragm deficiency: The floor joists in SMM buildings usually rest directly on the walls. The wall plates are usually absent to restrain the joists at the edges and act as a tension chord element. Hence, we could observe vertical cracks formed at the floor level in many of these buildings.

3. Strong back design approach

The strong back approach is based on the type design approved by the Central Level Project Implementation Unit (CLPIU), Building division, under the National Reconstruction Authority (NRA) of Nepal. The strong back design comprises a system of reinforced concrete strong backs placed at corners and at locations along the length of the wall, connected at the floor level by slab strips and ring beam at the top of the walls. The strong back is connected to the walls with the help of through anchors. The function of the strong back is to brace the walls out of plane and provide a load path for the out of plane wall loads to reach the diaphragms above and below. The strong backs also acts as a buttress to break the horizontal span of the wall.

At the floor levels, a slab strip is provided around the inside perimeter of the wall and across, connecting opposite strong backs. The function of the slab strip is to improve connectivity of all walls to the diaphragms and to each other, creating a box effect. Also, it is connected to the joists and functions as a chord element at the edge of the diaphragm increasing the diaphragm stiffness.
and strength. A reinforced concrete ring beam is provided at the top of the walls to provide connectivity and restraint to the walls at the top.

Through concrete is provided at a spacing of 600mm center to center all over the walls. The through concrete connects the inner and outer wythes of the thick walls preventing it from delamination and hence increasing the overall out of plane capacity of the walls. Finally a cement sand plaster is applied to the walls on the internal and external surfaces to increase the in-plane strength and stiffness of the walls.

Heavy gable walls made of SMM is dismantled and a light CGI or timber gable is provided with good connection to the roof and the ring beam. In addition, improvements to the connections with the existing timber elements are provided with the help of CGI straps.

![Figure 6: Schematic of Strong Back approach](image1)
![Figure 7: Actual house retrofitted with Strong Back approach](image2)

**4. Splint and bandage design approach using welded galvanized iron (GI) wire mesh**

The splint and bandage approach considered in this paper is based on Repair and Retrofit manual published by the NRA.

The splint and bandage design consists of vertical splints, at building corners, wall intersections and on either sides of the openings, and horizontal bandages, at sill, lintel and floor levels. The wall area not covered by the splint and bandages are covered by wire mesh that confines the walls. Galvanized iron wire mesh was used for the splints and bandages. Although there are other options for splint and bandage also mentioned in the Repair and Retrofit Manual such as reinforced concrete, timber, etc., this paper will consider the use of the galvanized iron wire mesh as it was found to be cheaper and more practical to install.
The function of the splints is to add in-plane capacity and stiffness to the walls. The splints at the edge of the piers, provides tension capacity to the walls. The splint comprises galvanized iron wire mesh installed on either side of the wall. The wire mesh installed on the inside and outside is connected by rebar anchors at regular intervals. The wire mesh thus installed is fixed at the bottom by a plinth beam. The function of the bandage is to tie the walls together to provide box action. The bandages are similar to splints in terms of materials used and details but are horizontal instead of vertical bands.

The function of the plinth beam is to anchor the rebar in the splints and confining reinforcement and connect it back to the wall foundation. The confining reinforcement consists of a galvanized wire mesh that helps to contain the masonry wall in case of shaking during earthquakes, preventing disintegration. The inside and outside confining reinforcement is connected to each other with the help of wire anchors.

Cement sand plaster is applied on the outside and inside of the walls to cover all the reinforcement. The cement sand ratio used in splint and bandage design is richer in cement compared to strong back approach.

Other works such as replacing heavy gables with light well connected ones and overall improvement in connection of existing timber members were done similar to strong back approach.

5. Constructability

The SMM houses across Nepal are very similar in terms of their shape, size and structure. However, depending upon the skills of local builders and local construction practices, slight variations do exist. Hence, in these structures the theoretical designs might need to be adapted.
for site conditions. During construction of the retrofits some issues have been identified with both approaches and these are detailed below:

**Condition of existing building**
The first step in the construction process for both retrofit methods is to remove the existing mud plaster from all walls – assuming it is present. Site engineers have reported that during this process, large masses of mud mortar can unintentionally detach from the wall, leaving large voids within the masonry, this is later filled in with cement slurry or plaster. The quality of masonry in SMM buildings in Nepal is extremely variable. Some buildings have good quality masonry characterized by regular blocks, a low mortar:stone ratio, and some have irregular stones but low mortar:stone ratio. However, in some cases the quality of the masonry is extremely poor, with small stones and a very high mortar:stone ratio. The condition of the stone is relevant to the retrofitting approach chosen and the constructability of the retrofit.

*Figure 10: SMM house with rubble and high mortar:stone ratio*

*Figure 11: SMM house with shaped stones and low mortar:stone ratio*

*Figure 12: SMM house with angular stones and low mortar:stone ratio*
**Masonry walls are not always aligned vertically:**
The masonry walls are not always aligned vertically or horizontally. This can be due to design intentions, for example the walls might be thicker at the base and the inner face of the wall steps in at each floor reducing the thickness as you go up the building, or due to poor workmanship.

The strong backs are constructed to be vertical, therefore a filler material needs to be added between the strong back and the wall increasing cost and also adding complexity. For the splint and bandage approach the wire mesh can be installed to a non-aligned wall profile, however, extra labour is required to bend the wire mesh which could increase the cost of intervention.

**Splicing of existing timber posts**
The strongback retrofits require the timber posts supporting the central floor beam to be spliced and continuous to the ring beam at the top of the attic wall. The timber splicing requires extra timber elements and connections. Sometimes the timber posts in different floors might not be aligned vertically, which adds additional complexity to the details. These elements are not required in the splint and bandage approach.

**Installation of wire mesh:**
The splint and bandage approach requires working with galvanized welded wire mesh which is difficult to work with due to thicker diameter of the wires necessitated by the designs in the repair and retrofit manual. This makes constructability of installing splints at corners and at wall stepping sections very difficult and time consuming.

The GI wire mesh on the inside and outside of walls needs to be connected either by anchorage bars or GI wires at regular spacing. However, drilling of GI wires through the wall is difficult due to uneven mud mortar level and multiple wythes of masonry. It is also difficult to push GI wires through the mortar joint as the wires are not very stiff. In comparison installing the anchorage bar is easier as the bar can be hammered or pushed into the mortar portion of the masonry.
Cement Sand Plaster
Due to the surface of SMM walls being uneven it is difficult to apply plaster and often results in the thickness of the plaster being uneven across the whole of the surface. Unfortunately, this can’t be avoided, although it can be reduced using trained and experienced masons. The problem is exacerbated when plaster is applied over wire mesh as the gap between the mesh and stones needs to be filled and this often requires two layers which requires more labor and materials.

Based on the field experience, the splint and bandage retrofits end up with an average of 50 mm thick plaster on both sides of the wall whereas the strong back approach has an average thickness of 40mm of plaster.

Constructability comparison
Workmanship in Nepal can often be of lower quality and therefore requires close supervision by trained engineers who can enforce quality standards. The quality issues detailed above in respect to reinforcement, concreting and plastering are in no way insurmountable and are likely to improve as engineers and builders become more familiar with improved construction techniques.

Considering the issues described above, and discussions with site engineers who have supervised both strongback and splint and bandage retrofits, there is not one scheme which is the easiest to construct. Masons are generally more accustomed with rebar and cement rather than wire mesh, however, thorough training can overcome this and in the end each approach lends itself to different existing building configurations:

- Splint and bandage approach: more suitable for straightforward buildings where there are limited additional walls (e.g. cross walls and buttresses) and for buildings where the masonry is of lower quality and needs confining.
- Strongback approach: best suited to larger houses, with multiple walls/cross walls/projections and where the piers are vertically aligned

6. Durability
As the traditional SMM houses are made up of stones, mud mortar and timber, there are some issues with regard to durability of some of the elements used in the construction mostly due to interaction of those elements with moisture, which can lead to rot. There has been little research carried out or evidence found validating the long term durability of retrofitting in SMM
buildings. This section discusses durability issues that are present in some of the elements in SMM buildings and challenges to mitigate those issues through retrofitting with either approach.

**Durability of wooden joists, beam and vertical posts**

As a natural material, timber is vulnerable to rot and insect attack if left untreated and exposed to damp conditions. In most traditional SMM houses, the timber used is untreated, unseasoned softwood which has very little natural durability.

In the majority of houses the floor rests on wooden joists which are embedded into the masonry wall where the timber interacts with moisture inside the wall. The timber posts supporting the central floor beam are embedded into the mud floor, sitting on bed stones, and therefore also in contact with moisture.

The major challenge with retrofitting lies in increasing the durability when the existing timber joists are embedded in the masonry wall, which is then covered in cement sand plaster as recommended in either design (See Error! Reference source not found.). The cement sand plaster creates an impermeable layer on either side of the wall which prevents natural evaporation of moisture within the wall. Hence it keeps the mortar damp which then interacts with timber making it more susceptible to rot. A solution to this may be to wrap the surface of the embedded timber in a locally available impermeable membrane (such as plastic sheets) or to treat embedded timber either by painting (black japan paints available locally at low cost) or varnishing it. Periodic change of wooden joists or vertical posts, retrofitting it by painting or varnishing and reinstalling it also increases the durability of the timber. This would require that part of the existing wall be dismantled to facilitate access and has yet to be implemented in practice. An alternative solution would be to plaster the wall in a more compatible permeable mortar such as lime or mud. These plasters would not provide the required protection to the wire mesh of the splint and bandage, but it could be a suitable option for the strongback solution where no mesh is provided.
Figure 14: Deterioration of timber member at the base
Figure 15: Timber member embedded in cement plastered SMM wall

Durability of the cement based plaster
The cement sand plaster acts as an impermeable layer, preventing moisture from evaporating naturally which leads to the build-up of water in between the inner and outer cement plaster. In cold climates, this can be detrimental due to freeze-thaw induced cracking and in warmer climates; it can cause erosion of the mud mortar within the wall.

To limit the erosion induced by the cement sand plaster, finding an alternative more compatible mud or lime plaster could be the solution. However, this is not ideal for the splint and bandage retrofit where the galvanized wire mesh requires additional protection due to the poor quality of the galvanizing. This can be rectified by protecting the mesh by applying bitumen paint (Black Japan) or by improving the production of galvanized wire mesh. In addition to protecting the mesh further testing would need to be carried out on whether the wire mesh can develop sufficient in plane strength if covered in a lime or mud based plaster.

Durability comparison
The issues associated with durability affect both retrofitting approaches due to the concerns regarding the compatibility of the cement plaster with the mud mortar and timber. It would be more suitable for SMM buildings to be plastered with a material that does not allow moisture to be trapped inside. However, further research is required to investigate potential materials for both approaches.

7. Cost
The total cost of construction for a new building and retrofitting can be broken down into three important categories; materials labor and transport. For purposes of comparison, transport costs are excluded in this study as they can hugely vary depending on exact location of the building.

In order to compare the retrofitting costs for each approach, a theoretical SMM house measuring 8m x 5m, 2 storey plus attic was considered and all the required materials and labor (in man days) calculated. These were in turn compared to a new building using Stone Masonry in Cement mortar (SMC) measuring 6.75m x 6.75m, based on designs and Bill of Quantities (BOQs) in the DUDBC design catalogue (Nepal Reconstruction Authority, 2015). The comparison had to be made with an SMC building as a two storey with attic building can no longer be constructed using SMM. The rates used for materials and labor are the same across all houses and based on average market rates across different districts.
As expected, figure 11 shows that a new SMC 2.5 home is significantly costlier than either retrofit solution, coming in at almost four times the cost of a splint and bandage retrofit and almost five times the cost of the strong back retrofit. Whilst the strong back retrofit is the cheaper of the two retrofitting options.

Figure 16: Cost of retrofitted houses compared to the cost of new design catalogue houses

Figure 17: Cost per square meter of livable space for retrofitted home compared with design catalogue homes
However, the SMC 2.5 house is somewhat larger than the house that the retrofit costs were based on. Therefore, it is more appropriate to compare the cost in terms of cost per square meter of livable space. This comparison is presented in Figure 14.

![Cost comparison chart](image)

**Figure 18: Cost of materials for Strong back and Split and bandage solutions**

**Cost comparison**
The cost data presented in this section shows that retrofitting is significantly less expensive than new construction both as a total cost and also per square metre of living space. The two retrofitting approaches are approximately equivalent in cost with the splint and bandage being slightly more due to the high cost of wire mesh, if this cost could be reduced then the difference would be marginal.

For retrofitting, a large proportion of the cost is due to amount of cement used. Further research should be done on the potential for reducing the quantity of cement or replacing the concrete members with non-cementitious material (e.g. lime based plaster)

**8. Environmental Impact**
The construction industry is one of the largest global contributors to emissions of greenhouse gases so it is vital to consider the sustainability of the retrofitting options. There is a wide range of performance indicators that can be used to measure sustainability within the construction industry (Kamali & Hewage, 2015), but within the scope of this research, only environmental criteria are considered.
Global warming potential (GWP) will be used as an indicator to compare the environmental impact of strong back, splint and bandage, and new construction. GWP is a measure that enables comparison of the global warming impact of different gasses. It is defined as the amount of energy that one ton of a gas will absorb over a given time relative to one ton of carbon dioxide (USEPA, 2017). The GWP values used in the comparison have been obtained from the database of construction materials developed for India (IFC, 2017), which is thought to be the most relevant data to Nepal. Any gaps in information have been filled using the Inventory of Carbon and Energy (ICE) database (Jones & Hammond, 2019), which although developed for the UK market, has a much wider range of materials. Since the Indian database assumed carbon capture for wood and other natural materials, the GWP values for timber have been obtained from the ICE database. Stones and mud have been assumed to be sourced locally and to have zero GWP.

It is assumed that GHGs produced during construction are low to negligible due to an absence of machinery on-site and that carbon emissions throughout the life of the building are negligible, since many homes lack electricity and where they do, do not have mechanical heating or cooling. Transport of materials to site has not been considered in this analysis, however, it should be noted that the transport of materials has the potential to be a significant contributor to GHG emissions, especially when materials can’t be sourced locally.

![Figure 19: GWP for each retrofitting technique](image)

**Error! Reference source not found.** Figure 14 presents the results of the GWP analysis broken down by constituent materials. The most significant contribution to GWP is due to the presence of cement. Note that Portland Pozzolana Cement (PPC) (cement with 15-25% of fly ash) is used for the plastering; while Ordinary Portland Cement (OPC) is used for all other concrete elements (e.g. ring beam, foundation improvement, slab strip, strong backs and cement mortar in SMC home). Comparing the two retrofits, the materials required for the splint and bandage has a
higher GWP than those for the strong back. The primary reason for this is the plaster, which is significantly thicker than for the strong back and has a higher proportion of cement compared to sand. However, both retrofits produce approximately 60% of the GWP than a similar floor plan SMC2.5 house does. For the SMC structure the GWP due to cement alone is significantly higher than both retrofits in their entirety and this is not even including any cement based plaster being applied.

Environmental impact comparison
Retrofitting has an approximately 60% lower environmental impact that a new SMC structure and when comparing the two retrofits the splint and bandage has a higher GWP due to the greater thickness of plaster and higher proportion of cement used.

As the cement plaster has a very high environment impact a key area for further research would be to investigate alternative options for plastering the wall that reduce or omit cement. Further research is also recommended to investigate other options for the mesh in the splint and bandage system, or make use of recycled materials.

9. Conclusion and Recommendation

Retrofitting is a viable option to preserve traditional architectural heritage in the community and to maintain the living space that is required for agrarian life. However, as it is a relatively new approach to increase the resilience of building stock in Nepal scaling of the technology across the whole nation poses many challenges. These include clear government policy, creating awareness among the home owners, capacitating government and private sector engineers, enhancing skill of local masons and availability of tools and materials to name some of them.

Based on the experience of implementing both approaches, each one has its distinct advantages and lends itself to a particular situation:

- In the splint and bandage approach the wire mesh acts to constrain the stone walls, and is therefore more suitable for buildings where the masonry is of lower quality. However, it lends itself to straightforward buildings where there are limited internal walls, buttress walls or external projections, as these all increase the cost and complexity of construction. There can also be difficulties obtaining the wire mesh from rural markets and this might impact the overall cost of construction.

- Strong back: This approach is best suited to larger houses, with multiple walls/cross walls/projections, where cost and/or global warming potential is a significant factor for the homeowner. This approach is more suitable also in cases where the piers are vertically aligned as this leads to reduced intervention and subsequent cost.
In comparison to constructing a new house, retrofitting is a much more cost effective and environmentally friendly solution, and is more attainable for the general population. However, the cost of retrofitting is still more than what homeowners are ready to invest, making it necessary to either produce alternative, cheaper, approaches or come up with financing schemes that can make retrofitting more affordable. This would be key in enabling the scaling of retrofitting across Nepal.

Both the Government approved retrofitting options that is available is heavily based on iron and cement, neither of which are local materials. More research should be done into developing retrofitting options using timber or bamboo. More research into using an alternative to plaster also needs to be looked into.

Most importantly, a long term approach to making retrofitting more affordable to the wider population is required. Incremental retrofitting breaks down the two existing retrofitting approaches into distinct phases, addressing primary deficiencies first and then addressing other deficiencies in the following phases. Doing this would reduce the barrier to finance and hopefully entice more homeowners to start the process of retrofitting their homes. Additional research needs to be done to quantify the risk reduction as well as the cost benefit that would be attained by each phase of retrofitting for both of these approaches. Further study also needs to be done to identify how these phases can be incentivized for the homeowners to move up from one phase to the next.

10. References


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