# Seismic Retrofitting of Traditional Stone Masonry Houses in Rural Nepal

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***Abstract*— The Gorkha earthquake affected 1,048,574 homes across Nepal; of these, an estimated 500,000 damaged houses can be retrofitted. To cater to this large need for retrofitting, an intervention in which a pre-engineered retrofit design is developed for a certain building type and applied to multiple buildings that meet a narrow applicability criteria, was found to be most effective in addressing these houses, taking into account the constraints in cost and availability of experienced structural engineers. Stone masonry in mud mortar buildings are the most prevalent construction typology for housing in rural Nepal. A large portion of these traditional houses are very similar in overall size, configuration, connections and member sizes. Built with low-strength, random rubble load bearing masonry walls and timber diaphragms, these buildings are highly vulnerable in earthquakes. The resulting retrofit scheme was designed based on the typical damages and failure sequences observed in this building type in the 2015 Gorkha earthquake and based on relevant building codes. Most of the common failures were due to out-of-plane forces on the walls, weak connection of diaphragms to walls, weak interconnection of the wythes of thick and unsupported walls, and inadequate connection of adjacent walls at corners. Retrofit elements were introduced to address the deficiencies that led to the observed failures and damages; strong backs to brace the walls against out-of-plane loads and to connect the walls to the diaphragm; reinforced concrete slab strips to strengthen the diaphragm and its connection to the walls; through concrete to connect the wythes of the thick walls; and light-framed gables to replace heavy masonry gables. The design parameters used were validated by experimental tests. Some of the key findings were the compressive strength of masonry walls and the push out failure strength of through concrete from the wall. The retrofit design was piloted with the purpose to adapt the theoretical design to suit local preferences, resources and skills of the local builders. This also helped validate the affordability, acceptability, and scalability of the retrofit design to homeowners and local builders.***

***Keywords*— *Retrofit; Gorkha earthquake; Rural Housing; Stone Masonry in Mud mortar***

## I. BACKGROUND

The Gorkha Earthquake, magnitude 7.8 on the Richter scale hit Nepal on the 25th April, 2015[1]. After the main earthquake struck at 11:56HRS Local Time, aftershocks occurred at regular time intervals, with one aftershock, occurring on the 26th April, 2015, registering as a 6.7 on the Richter scale[2]. The most severe intensity was VII MMI. This earthquake, and subsequent aftershocks brought about severe devastation, killing more than 8,857 people, injuring 21,952 and leaving 3.5 million people homeless[3]. The estimated damages caused by the earthquake was USD $10 billion[4]. The damages were spread across 31 districts in Nepal, centering from the epicenter, in Barpak, Gorkha.

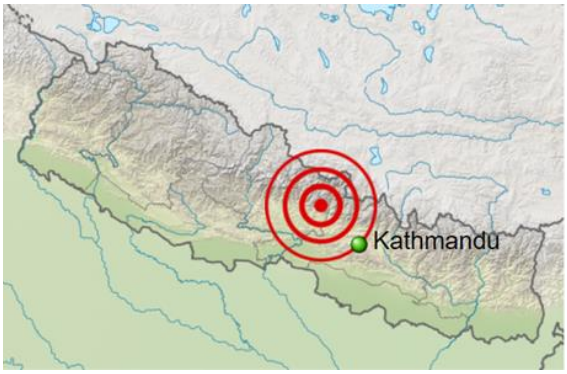


Fig. 1. *Epicenter Barpak, Gorkha located near Gorkha*

Rural areas of Nepal suffered maximum devastation, where stone masonry in mud mortar construction is most prevalent. From the 14 districts that were hardest hit, approximately 1,048,574 houses were damaged, out of which 73 percent were houses of Stone Masonry in Mud mortar (SMM) Typology[5]. The Government of Nepal (GoN) National Reconstruction Authority (NRA) categorized earthquake damaged houses on a scale of 1 to 5. Grade 1 houses have negligible-to-slight damage that is non-structural. Grade 5 houses are classed as destroyed, with near or total collapse[5].

Unreinforced stone masonry in mud mortar (SMM) houses with flexible timber flooring have been used as one of the main construction typologies in Nepal for a long time. SMM houses are non-engineered buildings where the construction practice has evolved over time including through several large earthquakes in Nepal's history. Hence, partial evidence of the installation of good lateral load resisting features within SMM houses can be found, however a large percentage of recently built SMM houses seem to be missing these features. Thus, the more recently constructed houses are more susceptible to the effects of earthquakes than their older counterparts. Through field work, it is hypothesized that some of the reasons that newer houses lack the earthquake resistant features is because of the relative increased cost for these elements, such as horizontal bands and that as time passes between earthquakes, people become less vigilant about installing these features to their house. The Nepal National Building Code (Published 1994) includes guidelines on the construction of new stone masonry and mud mortar buildings, however, these guidelines were not enforced in rural areas until after the earthquake [6].

There is a broad degree of similarity in configuration and size between a large number of existing SMM houses across the mid hill regions of Nepal. Due to these similarities in construction, the observed effects of the Gorkha earthquake on SMM buildings is largely the same. Through analysing the effects of earthquakes on this specific building type a singular retrofit 'type design' was developed that is applicable to SMM buildings that fall within earthquake damage grades 1 to 3 and that meet a set of defined criteria, or characteristics. The developed type design is presented in this paper.

There is also potential to expand the scope of retrofitting activities to SMM houses that fall outside of the 31 earthquake affected districts. Most existing traditionally built SMM houses cannot withstand National Code-level forces even when they are undamaged, hence, this type design can be used for preventive retrofitting as well, and need not be limited to only damaged houses.

## II. Traditional Stone Masonry in Mud Mortar Buildings

A typical Stone Masonry in Mud mortar (SMM) house in rural Nepal is 2 stories with an attic as shown in Fig. 2 and Fig. 3. The bottom floor is used as a barn, the first floor is used for sleeping and the attic floor is used as the kitchen and for grain and produce storage. Two stories and attic space is essential for the homeowner's agrarian lifestyle. The structure typically consists of 450mm thick SMM load bearing walls composed of two faces of placed stone with a rubble filling in the center of the wall cavity. The floor, usually mud, is supported by a timber framing diaphragm.

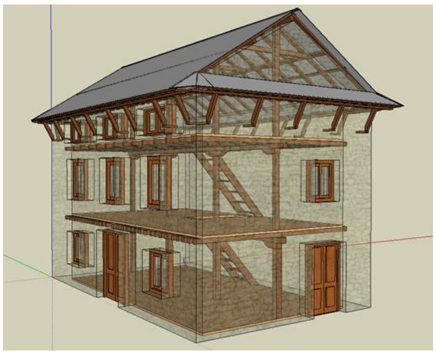

Fig. 2. *Typical SMM building in Nepal*

Fig. 3. *An SMM building in Kavrepalanchowk district*

The timber floor framing diaphragm consists of joists supported on the longitudinal walls and a central longitudinal girder. The joists are normally well embedded into the walls. The timber girder is supported on timber posts and typically embedded into the transverse end walls. Typically a house has four posts supporting the middle girder – one at each end and two in the middle, usually spaced at more or less equal distance apart, as seen in Fig. 4 and Fig. 5. These wooden posts occur at each floor in approximately the same location, ultimately supporting the ridge beam of the roof. The transverse wall is usually connected to the floor framing only through this middle girder, as see in Fig. 6.

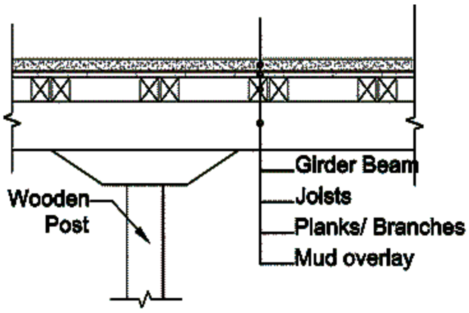


Fig. 4. *Intermediate wooden post to floor connections*

Fig. 5. *Wooden posts, Girder beam and joists in a typical SMM house in Kavrepalanchowk*

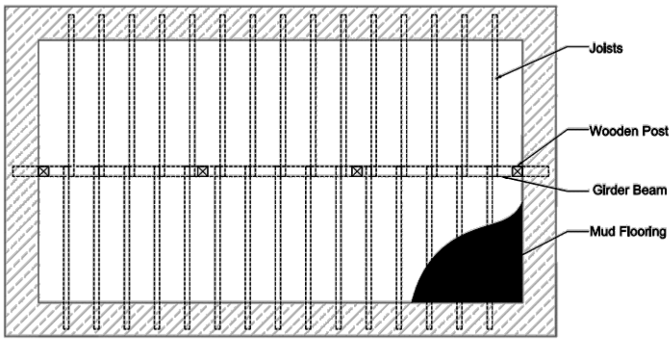


Fig. 6. *Floor plan showing joist and Girder beam placements*

### A. *Common Damage Observed after Earthquake*

The damages observed in these traditional SMM buildings were found to be very similar and comparable throughout different earthquake affected locations in Nepal. This was expected as the construction practices observed were also found to be similar throughout the earthquake affected regions. The damages due to out-of-plane loading was found to be most prominent. Damages due to in-plane action of the walls had very low observed occurrence in SMM buildings.

*a) Delamination of walls*: The width of these walls on average is 450mm. As described above, the walls are built with two faces and lack the connections between the inner and outer wythes, this causes the wythes to behave as two separate slender walls under out-of-plane shaking. This resulted in frequently observed delamination and led to subsequent damage or even out-of-plane collapse in some houses. This could be clearly observed in damaged buildings as shown in Fig. 7.

Fig. 7. *Cross section of a SMM House showing the dual layer of stones*

*b) Gable wall collapse:* The stone masonry in the short walls is typically extended up to the roof line, forming the triangular gable walls, which directly support the outermost roof trusses at each end of the house. This gable wall, although adequate for gravity loads, is unbraced and unreinforced. During the Gorkha Earthquake this unreinforced wall was prone to collapse due to the out-of-plane lateral shaking. Gable wall collapse often initiated or facilitated the subsequent collapse of the transverse walls below. A typical gable wall failure can been seen in Fig. 8.

Fig. 8. *Gable wall damage after earthquake*

*c) Short wall out-of-plane damages:* There was high occurrence of damage to the short walls of SMM type buildings as shown in Fig. 9. The floor diaphragm is only connected to the short walls through the girder beam at the middle point of the walls, while it is connected to every embedded joist along the longitudinal walls, leaving the short walls significantly less braced out-of-plane than the longitudinal walls. This, in combination with the effect of the collapsing gable wall peeling away above, led to a concentration of wall out-of-plane damage observed on the short walls of the building. In addition, the wall corners did not have sufficient capacity to transfer forces from one wall to the adjacent which also caused wall separation at the corners, leaving the short wall with even less bracing against out-of-plane loads.

Fig. 9. *Short wall damage*

*d) Unsupported parapet walls:* The top of the attic walls, which are essentially a tall perimeter parapet above the attic floor, walls are usually not tied together nor are they directly connected to the roof framing. The lack of bracing for these cantilevering unreinforced walls led to observed out-of-plane failure in the earthquake.

*e) Diaphragm Deficiency*: The floor joists are directly embedded in the walls and there is typically no element to serve as the perimeter diaphragm chord. Due to the lack of a tension-carrying chord element at the edges of the diaphragm, significant diaphragm deflection likely occurred, leading to the observed vertical cracks at the face of the walls as shown in Fig. 10.

Fig. 10. *Vertical cracks observed at floor level in a typical SMM house*

### B. *Positive Attributes*

While the typical SMM house has many seismic deficiencies, there are some positive attributes to this traditional construction type.

*a) Walls*: Looking beyond the deficiencies in wall construction, the overall low slenderness of the stone masonry walls gives much stability to the building. The thick walls increase the ability of the walls to span between points of support, either vertically between floors, or horizontally between cross-walls and also provides rocking resistance against in-plane forces.

*b) Timber elements:* The floor is generally supported independently by wooden posts and beams. Large and long timbers are used throughout, many dating back to when high quality hardwood such as Sal wood (Shorea Robusta) was commonly available. The timber components are typically in good condition. Consequently these have been reused in temporary or permanent reconstruction, or salvaged and stored for future use. The current availability of timber of the same quality and size is considerably rare. The connection of the central timber girder to the independent posts supporting this beam also seem to have delayed the complete collapse of the structure despite severe damage or even collapse of some of the walls, as illustrated in Fig. 11.

Fig. 11. *A damaged house in Sindhupalchowk where the entire short wall is collapsed but the house is still standing*

## III. RETROFIT DESIGN PRINCIPLES

- The retrofit scheme was designed based on the following principles:
- Designed as per all applicable Codes of Practice.
- Has minimum impact on the exterior architecture of the building.
- Has minimum impact on the available interior space of the building.
- Is affordable and cost effective compared to available alternatives.
- Uses locally available materials as much as possible.
- Is constructible in relatively short time and using locally available manpower.

### A. *Retrofit Type Design Approach*

It is estimated that there are nearly 448,005 houses that are partially damaged and can be potentially retrofitted [5]. To cater to this huge need for retrofitting, it is appropriate and beneficial to use a type design approach by which a single design is applicable to many existing buildings that conform to a narrow set of pre-defined criteria, or characteristics.

The SMM buildings in most rural settlements in the middle region of Nepal are similar in terms of their configuration and structure. Moreover, consistent and similar damages were seen on these types of buildings throughout districts such as Kavrepalanchowk, Sindhupalchowk, Sindhuli, Ramechap and Syangja. This enabled the adoption of a deficiency based approach to designing the retrofit solution for this type of house. In this approach, the deficiencies in the building were studied based on the damages observed. Retrofit interventions were then conceptualized to correct these deficiencies so that the collapse of the buildings in future earthquakes due to the observed deficiencies is reduced.

In the post-earthquake context of Nepal, a type design approach for retrofitting is very suitable. The added advantage of a type design approach is that it allows the retrofit design to become available and affordable to the rural population. In addition, a complete implementation package, such as the design, the corresponding construction quality requirements, qualified mason training, and supervising engineer training can be easily developed for each type design to address a large number of houses as a group, and is not developed individually, case by case. This has significant benefits not only in reducing time in the process but in quality control and assurance.

To arrive at a type design for a narrow range of building characteristics, an iterative approach was employed, taking into consideration different critical cases within the scope of the type design. Only by running the complete iterative analysis of the houses in consideration, limiting parameters are determined. These parameters are then used to define the applicability criteria for the type design. The different considerations taken into account while determining the critical cases can be broadly defined as follows:

- Range of variation in overall length and breadth of the building.
- Range of variation in pier sizes where the window height is governing.
- Range of variation in pier sizes where the door height is governing.
- Considering maximum percentage of opening in both long and short directions.
- Considering maximum openings in both wall lines in the same direction.
- Considering one wall line without opening and the other wall line with maximum opening.

### B. *Applicability Criteria*

The applicability criteria is a narrow set of parameters that is used to identify SMM houses for which the described type design would be an appropriate retrofit solution. The criteria is set based on the limiting parameters assumed during design such that all buildings that conform to this criteria can be safely retrofit following the proposed type design.

A applicability criteria for the considered type design would be as follows:

- The building is a house, with four exterior walls constructed of stone masonry and mud mortar, with wood floor and roof framing.

- The building should not have significant distortion in diaphragm and significant damage to short walls.
- The building should not be subject to other hazards such as proximity to fault lines, landslides, flood, steep slopes.
- The building should not be retaining soil on any side.
- The building should not be higher than two stories plus attic.
- The longitudinal dimension of the building should not exceed 9 meters.
- The transverse dimension of the building should not exceed 5 meters.
- The length to breadth ratio of the building should not exceed 3.
- The story height at each level structure should not exceed 2.1 meters.
- The total length of openings in the longitudinal direction at each level should be less than 35% of the total length of the building.
- The total length of openings in the transverse direction should be less than 25% of the total length of the building.
- The openings should be aligned at all floors.
- The height of the attic wall should be less than 1.2 meters.
- The walls should be at least 450mm thick.
- The minimum length of pier between openings should be 1 meter.

## IV. RETROFIT INTERVENTIONS

### A. Through Concrete

Through concrete is provided to bond the inside and the outside wythes of the SMM wall. Providing through bonding elements to interconnect the stones throughout the width of the wall helps to prevent delamination. A through bonding element of concrete and rebar is used as shown in Fig. 12; these are effective as a secure bond to the existing stones can be created. The through concrete is approximately 150mm diameter. In the type design, these are placed at a spacing of 600mm center-to-center in horizontal and vertical directions along all walls, as shown in Fig. 13.

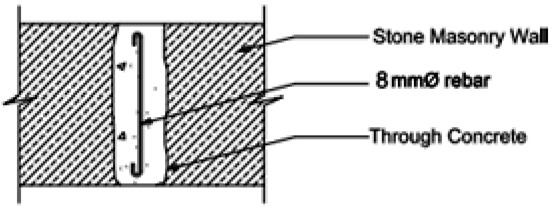


Fig. 12. *Through wall concrete in an existing SMM wall*

Fig. 13. *Installed through wall concrete connections*

### B. Ring Beam

In order to facilitate connection between the long attic walls and the adjacent short walls, and to ensure the attic walls are adequately braced out-of-plane, the retrofit design calls for a new reinforced concrete ring beam at the top of attic wall, below the roof, as shown in Fig. 14. The ring beam connects the walls together and promotes a box effect. The ring beam in the type design is directly connected with dowels to the new strong backs.

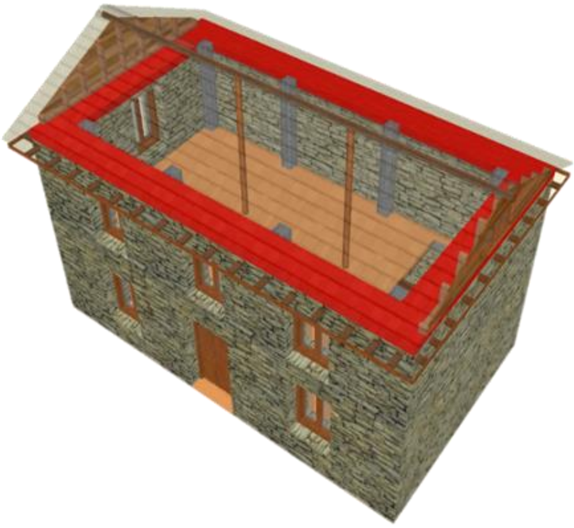

Fig. 14. *Ring Beam highlighted in red is installed at the top of the attic wall*

### C. Strong Backs

Vertical strong backs are attached to each wall pier and connected to the slab strips at each diaphragm level and ultimately to the ring beam at the top of the walls. The strong backs brace the walls against out-of-plane forces and facilitate connectivity of the walls to the diaphragms. These members are designed with the intention of carrying seismic out-of-plane loads from the walls to the levels above and below. They are connected to the masonry walls at two equally spaced points between each floor level by rebar dowels that are grouted into the wall, as shown in Fig. 15.

The strong backs are provided at the corners of the house and at each wall pier, as shown in Fig. 16. The corner strong backs help to inter-connect the orthogonal walls to prevent corner separation. The type design provides the option to construct the strong backs constructed out of either reinforced concrete or good quality timber.

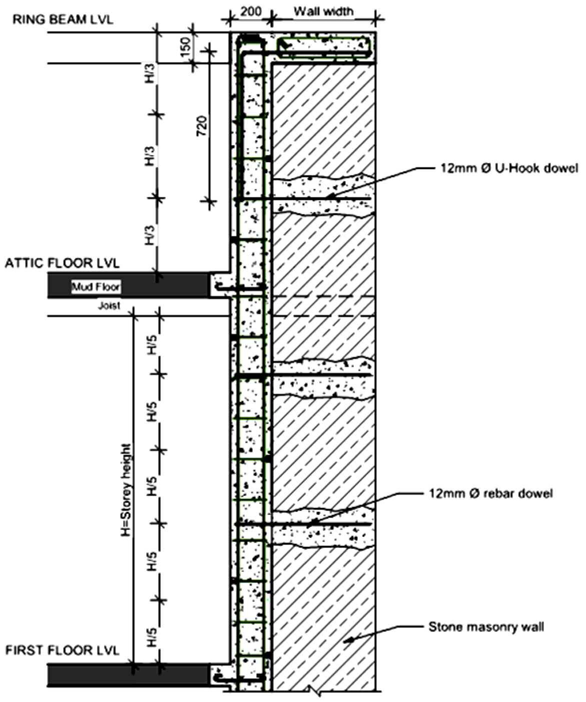


*Fig. 15. Detail of strong backs*

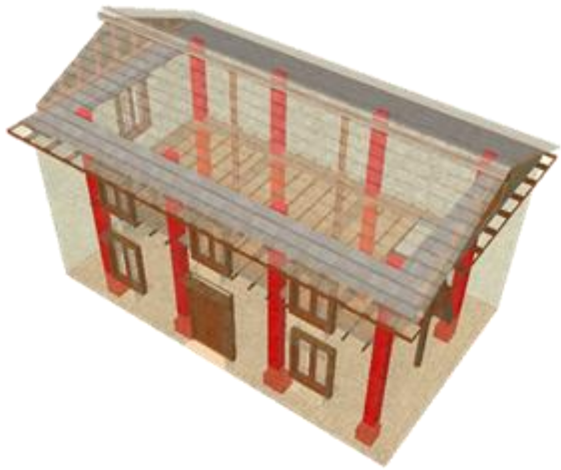

*Fig. 16. Strong backs highlighted in red*

## D. *Slab strip for diaphragm strengthening*

In order to strengthen the floor diaphragm and provide chord and cross-tie elements, as well as strengthen the connection of the walls to diaphragm, reinforced concrete slab strips are installed along the inner perimeter of the walls and cross connecting intermediate strong backs. The slab strips aid in distributing the out-of-plane loads to the perpendicular walls.

The slab strips are connected to the existing joists through rebar dowels. Dowels are also placed along the perimeter strips at a spacing of 600mm center to center and embedded with grout in the adjacent wall as shown in Fig. 17 and Fig. 18.

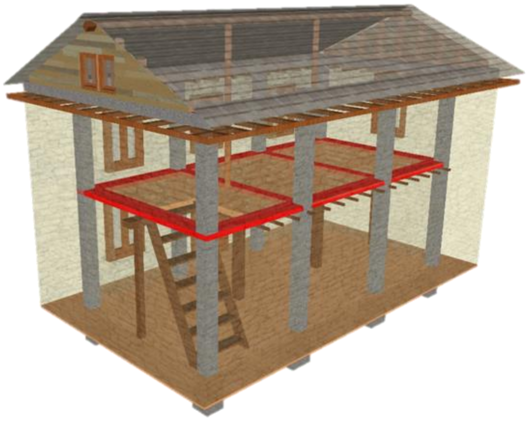

Fig. 17. *Slab Strip (indicated in red) connects the diaphragm to the walls as well as interconnecting the strong backs*

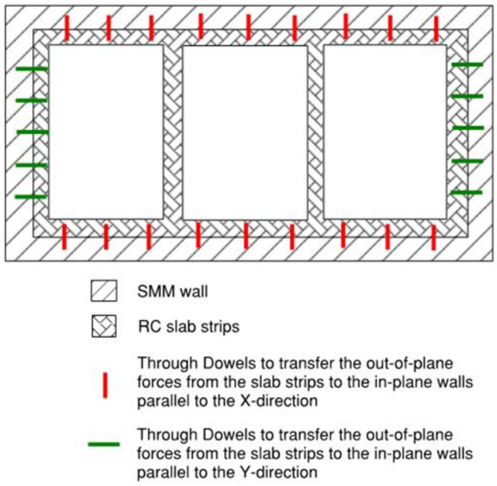


Fig. 18. *The red and green lines indicate dowels spaced at 600mm that connects the slab strip to the walls*

## E. *Plastering of walls*

The SMM walls are plastered at the exterior and interior face. The plaster together with the through concrete, helps to increase the capacity of the wall in the in-plane direction [7].

## F. *Improving existing timber connections*

The existing timber connections are generally acceptable for gravity loads but not for wind and lateral loads. So, simple improvements in connections using galvanized iron wires and/or corrugated galvanized iron straps are provided to the roof, as shown in the photo in Fig. 19.

Fig. 19. *Improvement of existing timber connections*

## V. LABORATORY TESTS

### A. Compressive Test

Compressive tests were carried out on Stone Masonry in Mud mortar samples as per the specifications in ASTM C1314 in order to better understand basic properties of the masonry walls [8]. The samples were constructed in the laboratory with materials procured from, and with a mason from, Kavrepalanchowk district. This district is where a significant amount of houses are built using Stone Masonry in Mud mortar and the mason was very familiar with this construction technique.

The test was carried out on a Universal Testing machine, as shown in Fig. 20. The displacement gauge was placed at the loading plate of the UTM, due to which it was only possible to observe the loading till failure and not beyond the ultimate failure point.

Fig. 20. *Compressive test carried out*

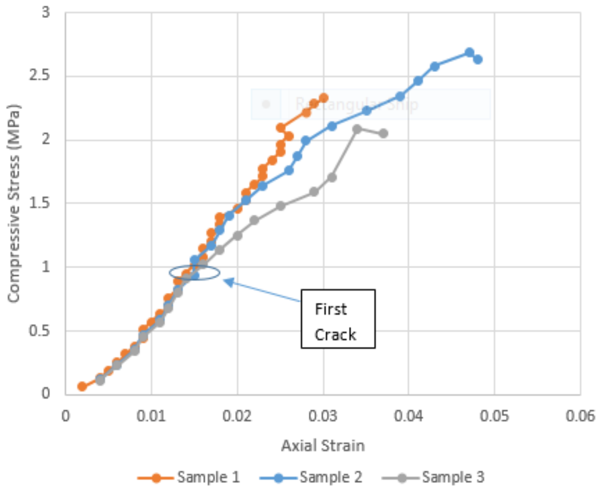


Fig. 21. *Compressive stress vs Axial stress*

The failure observed was brittle failure, the stresses drastically dropped off after the point of failure below which the sample was unable to resist further loading. The average compressive stress at failure was found to be 2.367 MPa, as seen in Fig. 21, a plot of the recorded stress-strain curves for each specimen.

### B. Push-out test

Tto support the design of the strong backs, testing of the strong back-to-wall connection was carried out. the possible modes of failure for a strong back to wall connection are:

- pull out of rebar from the concrete dowel
- pull out of concrete dowel from the wall
- failure of strong back in bending

Ppreliminary capacity calculations indicated the critical failure mode to be due to the pull out of the concrete dowel from the wall. the pull out capacity of the dowels from the wall was tested and factored into the design of the dowels and strong backs.

SMM wall specimens were of size 1.2m x 1.2m x 0.45m, and through concrete was inserted into each at approximately the center of the wall specimen.

The objective of the push-out test was to examine the behavior of the through concrete when pushed out of the wall. the sample wall was restrained at the top and the bottom. the through concrete was then pushed out with the help of a hydraulic plunger, as see in fig. 22 and fig. 23.

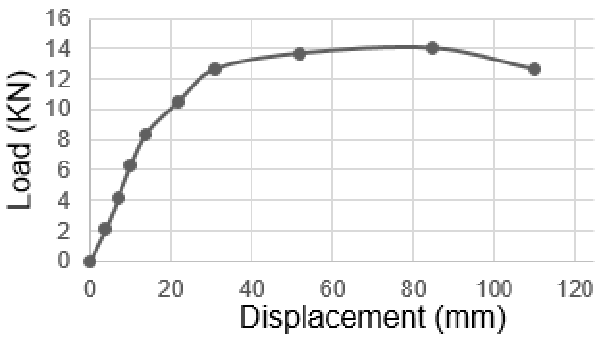


Fig. 22. *load displacement curve for push out of dowels*

Fig. 23. *dowel push out tests setup*

the failure push out strength for a concrete dowel from the sample of stone masonry in mud mortar wall was found to be 14 kn.

## VI. CHALLENGES FOR RETROFITTING IN RURAL AREAS

Because the majority of the damaged, but repairable and thus retrofittable houses are located in remote parts of rural

Nepal, there are various challenges related to geography (such as the accessibility to the location, nearby vendors for procurement of materials, and monsoon season) and skill set of the local masons. Some of the challenges related to the construction of these retrofits, which were considered in the development of the type design are:

### A. *Availability of materials*

Due to the difficult geographical topography and diverse spread of settlements, ensuring a constant and reliable supply of the material inputs for the retrofits from a local supplier was hard, this included items such as threaded rods, GI wires, bolts as seen in Fig. 24.

Fig. 24. *Showing GI wires, threaded rods and metal plates used in the construction*

### B. *Ensuring Safety at the Construction Site*

Due to these houses being damaged in the earthquake, they are very fragile and need to be adequately shored before work can commence, which can include both internal and external shoring systems as shown in Fig. 25. The availability of local timber and/ or bamboo is essential to allow the shoring process to start at the construction site. Prototype shoring designs were developed to accompany the type design.

Fig. 25. *Shoring of SMM house prior to the commencing of retrofit activities*

### C. *Restoring the cracked building and crack repair*

Most of the houses have mud plaster over the external and internal faces of the house, this often is cracked, like the house shown in Fig. 26, and needs to be repaired in the retrofit process. The crack repair requires stripping of mud mortar, exposing the stones (making V-notch) and grouting it with stabilized mud mortar. This crack repair process requires the availability of materials for the scaffolding at the site as well as the proper compaction of mortar within the cracks to ensure proper restoration.

Fig. 26. *Damaged house prior to retrofitting*

### D. *Availability of skilled masons*

Some of the skills required to implement the retrofit construction are beyond traditional practice or knowledge, such as shoring installation, construction of timber post splices, or insertion of through concrete. The availability of skilled masons to undertake these activities is one of the major challenges for adopting retrofitting at scale over the earthquake-affected districts. Targeted mason or builder training is essential to complement the type design.

### E. *Availability of good quality materials*

Due to the remoteness of the retrofitting sites, there is often difficulty procuring good quality construction materials such as sand and aggregates as they are often mixed with mud and other impurities. The difficulty in ensuring the quality causes additional problems during the construction process.

## VII. CONCLUSION

When the need for retrofitting is high and the available resources to cater to this need are limited, a type design approach for retrofitting is a viable option. Similar buildings of the same typology, meeting a well-defined criteria of applicability can be retrofitted using a type design approach.

The deficiency based design approach can be used for design of retrofit schemes of buildings. It helps in conceptualizing the retrofit elements to be used in the design based on the true behavior of such buildings during earthquake and ensures that any shortcomings are addressed so as to minimize similar damage to the buildings in future earthquakes.

The challenge in this process was not just to produce a design that was structurally sound, but to find a solution that was also socially desirable and financially feasible. Costs are minimized by ensuring that the proposed design is constructible by the semi-skilled local masons using locally available materials. From a social perspective, it was important that the design maintain the core function and corresponding value of the house for the homeowner.

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