A CASE STUDY ON RETROFITTING OF STONE MASONRY IN MUD BUILDINGS IN POST GORKHA EARTHQUAKE RECONSTRUCTION

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Abstract

The 7.8 Mw earthquake that jolted Nepal and the region on April 25, 2015 resulted in 256,697 partially damaged and 498,852 fully damaged houses in Nepal [1]. The earthquake damage proved the existing vulnerability of masonry buildings in Nepal, as 67.7% [1] of the partially damaged buildings comprised of low strength masonry buildings, prominently found in rural areas. However, accessibility as well as economic conditions of the affected households in these areas demand for cost effective retrofitting techniques and materials, which is seen as one of major hindrances in expediting the process of repairing and retrofitting partially damaged houses in the current reconstruction campaign. Tests and experiences in retrofitting of school buildings of low strength masonry prior to the 2015 Gorkha Earthquake identified splint and bandage using GI welded wire mesh as the most cost effective and feasible technique for retrofitting of masonry buildings [2]. However, implementation of the technique on a wide scale in rural masonry buildings had not been done, which raised a question regarding its applicability and suitability on a wider scope. This paper focuses on the learnings gained from the experiences of retrofitting in low strength masonry buildings in the aftermath of the 2015 Gorkha Earthquake, prominently stone masonry in mud buildings through splint and bandage method using galvanized welded wire mesh at critical locations and addition of galvanized iron wires mesh to prevent local failures. To improve the box behavior of the building, the connection between different elements were provided, such as walls to walls, walls to floors, walls to roofs, etc. This paper also highlights several technical issues that arose during the implementation of the proposed designs especially in maintaining adequate connectivity between the elements, sloping foundation, large openings, etc. and the solutions that were provided. As an outcome, several stone masonry in mud buildings with varying degrees of technical challenges were successfully retrofitted using this technique. Conclusively, welded GI wire mesh Splint and Bandage technique can be widely promoted and used as the most feasible and economic technique for masonry buildings due to its low cost, ease in construction and wide range of applicability.

Keywords: 2015 Gorkha Earthquake; Low Strength Masonry; Reconstruction; Retrofitting; Welded wire mesh

1. Introduction

The 7.6 Mw Gorkha Earthquake on April 25, 2015 and its subsequent aftershocks had devastating effects in Nepal as it resulted in huge damage to infrastructures worth billions and claimed nearly nine thousand lives with other multiple folds injured [1]. It was the worst disaster to hit Nepal in the aftermath of Nepal-Bihar Earthquake that occurred more than eighty years ago. Among various sectors affected by the earthquake, damages to private houses accounted to more than half of the total losses, with nearly 750,000 [1] houses fully or partially damaged. A higher share of these damages was in rural areas, where low strength masonry is abundant. These houses lacked seismic resistant construction as neither the building regulations were in place nor trained construction workforce were available.

Low strength masonry buildings are typically constructed of stone, sun dried and burnt clay bricks or soil blocks, often in mud-based mortar and are one of the most prominent construction techniques in Nepal. These materials have been widely used in the construction of residential, public, cultural as well as historical buildings such as palaces, temples. Although the use of burnt bricks is widely increasing, the higher hilly and mountainous regions of the country, especially those that lack adequate access to road network still use stone masonry as the major construction material with mud mortar or as dry walls, as it is locally available and cheaper than most of the alternative materials. These buildings are typically two to three floors, as shown in Fig. 1, with additional attic space for storage, constructed with heavy walls and are laid over with timber roofs and covered with CGI sheets or thin slates [3]. Furthermore, they are characterized by low seismic capacity due to higher mass, low ductile strength and brittle nature.

Fig. 1 - Typical stone masonry houses in mud mortar in rural Nepal. (©NSET)

1.1 Damage Due to Earthquake

The vulnerability of these masonry buildings was evident during the event of different earthquakes across the region. A study of the casualties of earthquakes in the 20th century showed that nearly two-thirds of fatalities were due to collapse of buildings, most prominently masonry buildings [4]. In Kashmir earthquake of 2005, the highest levels of damages were incurred in undressed stone masonry buildings [5]. Most closely in Nepal, the high vulnerabilities of these buildings were clearly evident during the 1988 Udaypur, 2011 Sikkim and 2015 Gorkha earthquake sequences where catastrophic failure occurred at relatively lower intensities of VII and VIII. In the 2015 Gorkha earthquake alone, damages to low strength masonry buildings accounted to 95% among fully damaged and 67% among partially damaged buildings as shown in Table 1. To date, ongoing detail survey conducted by National Reconstruction Authority in the earthquake affected districts identified 69,973 residential houses as retrofittable houses [6]. Besides, myriad of buildings is present throughout the country lacking earthquake resilient elements. Hence, there is a high need of retrofitting in Nepal.

Table 1 - Damage due to 2015 Gorkha earthquake based on building typology [1]

SN	Building Typology	Fully Damaged	Partially Damaged
1	Low Strength Masonry	474,025 (95%)	173,867 (67.7%)
2	Cement Based Masonry	18,214 (3.7%)	65,859 (25.6%)
3	Reinforced Concrete Frame	6,613 (1.7%)	16,971 (6.7%)
Total		498,852	256,697

The damages to stone masonry buildings during the 2015 Gorkha earthquake followed similar patterns of typical masonry buildings. The most common failures seen were the out of plane failure of walls and the separation of orthogonal walls at corners, resulted from lack of adequate bonding and structural integrity. Similarly, diagonal cracks originating from the corner of openings and by in-plane failure of structural walls was also prominently seen. Other common forms of failures such as collapse of gable walls, failure of flexible diaphragm and delamination of walls due to lack of bonding between two layers of walls were seen, although in smaller proportions. These damages to stone masonry buildings during the earthquake can be attributed to lack of integrity in structural walls due to absence of through and corner stones, lack of proper connection between orthogonal walls, lack of adequate anchorage between walls and diaphragm, slender unsupported walls and lack of earthquake resistant elements such as horizontal and vertical reinforcements which cause the buildings to undergo brittle failure which are shown in Fig. 2.

(a) Out of plane failure of orthogonal and gable walls.

(b) Delamination caused due to separation of two layers of walls followed by out of plane failure.

(c) Failure of masonry gable walls and separation of corners

(d) Diagonal cracks propagating from the corners of openings

Fig. 2 - Typical damages seen in stone masonry in mud mortar (SMM) buildings during the 2015 Gorkha Earthquake (© NSET, 2015)

1.2 Retrofitting Techniques for Masonry Buildings in Nepal

There have been previous studies on the effectiveness of different retrofitting techniques and options for strengthening low strength masonry buildings. In Nepal, retrofitting of masonry buildings was widely accomplished in school buildings, starting as early as in 1999. The effectiveness of these techniques was summarized based not only on the cost of strengthening but also the time required for interventions, the adoptability by the local craftsmen and communities and the suitability to masonry buildings existent in the country. Among the various techniques, Splint and Bandage technique was considered to be the most appropriate for masonry buildings constructed with moderate to high strength mortar [7].

A further study conducted on the retrofitting of masonry buildings using the splint and bandage and jacketing methods using various materials such as welded wire mesh, reinforced concrete, steel bar mesh and polypropylene (PP) bands ascertained that although jacketing using PP bands was the most cost effective method of retrofitting, its inadequate strength and ductility limited its suitability to single storied masonry buildings. The study established retrofitting using GI welded wire mesh splint and bandage as the most effective and efficient technique in case of buildings with adequate mortar strength. However, for low strength masonry buildings, jacketing of walls was considered the suitable option [2].

These studies were mostly based on the experiences of retrofitting in school buildings, where constraints on financial resources aren't as significant as for private rural buildings. Especially in the aftermath of the 2015 Gorkha earthquake, a large number of buildings are to be retrofitted in communities with low economic capacity, where the need to attain maximum safety at minimum cost plays a significant role. However, as discussed earlier, one key aspect of low strength stone masonry buildings is the lack of adequate bond strength among the masonry units which causes delamination resulting in brittle collapse of the building. Hence, it is crucial to provide appropriate solution to prevent local failure as well. One solution of this is the jacketing of structural walls, with nearly 50% higher cost than splint and bandage [2]. Another solution however, is use of welded wire mesh or rebars as splints and bandages at critical locations which enhance global strength of the building, and jacketing using gabion wires in the portion of uncovered walls to prevent local failure [8]. This allowed for retrofitting designs to maximize safety of the buildings at minimal cost.

This method consists of additional elements with higher strength and ductility at critical locations in comparison to gabion wire knitting used by M. Wang et al. (2017) to retrofit random rubble stone masonry wall, one of the wall samples of his study [9]. His study showed that inplane deformation of wall increased by up to 275 %, ductility by 195%, maximum force increased by 13% and also evinced that out of failure of wall is curbed. This study provides additional backing to use splint and bandage method with provision of gabion wires to prevent local failure as a suitable method to retrofit low strength masonry buildings.

2. Implementation of Retrofitting

Owing to the large number of partially damaged buildings to be retrofitted as a part of the reconstruction campaign, the National Society for Earthquake Technology Nepal (NSET) retrofitted 49 SMM buildings in earthquake affected three districts in the span of a year; a huge endeavor considering that only less than 30 buildings were retrofitted before the start of the demonstrations. This paper studies the retrofitting of 16 of those buildings, and covers typical stone masonry buildings incorporating the most common architectural and structural varieties. Table 2 shows the general information of the buildings that were chosen as part of the case study.

Table 2 – Architectural and structural existing details of stone masonry buildings

S.N.	Building Index	No. of Storey	Wall thickness (Inches)	Height (feet)	Plinth Area (PA), sq. feet	Built up Area (BA), sq. feet	Wall Area (WA), sq. feet	Gable wall
1	A	One	17.7	10.83	260.33	260.33	817.71	Light partition gable
2	B	One	17.7	8.69	446.37	446.37	1646.62	SMM gable wall
3	C	One	17.7	9.84	565.94	565.94	2015.04	SMM gable wall
4	D	One	17.7	9.24	426.51	426.51	1351.86	Light partition gable
5	E	One + attic	17.7	11.89	233.36	350.04	1273.28	SMM gable wall
6	F	One + attic	17.7	14.11	369.78	554.66	1491.23	Light partition gable
7	G	One + attic	17.7	13.37	392.34	588.51	1621.92	Light partition gable
8	H	One + attic	17.7	13.37	462.46	693.69	1804.21	SMM gable wall
9	I	Two	17.7	13.53	417	834.00	1843.79	SMM gable wall
10	J	Two	17.7	15.17	474.22	948.44	1915.08	SMM gable wall
11	K	Two	17.7	14.68	539.27	1078.54	1906.80	SMM gable wall
12	L	Two	17.7	15.72	606.55	1213.10	2792.96	SMM gable wall
13	M	Two + attic	19.7	20.18	367.425	918.56	1877.89	SMM gable wall
14	N	Two + attic	22.6	17.50	462.205	1155.51	2950.56	SMM gable wall
15	O	Two + attic	17.7	20.62	465.01	1162.53	2642.80	Light partition gable
16	P	Two + attic	18.1	19.24	479.37	1198.43	2125.10	SMM gable wall

2.1 Analysis and Design

Linear static procedure was used to determine the stresses and deformations induced in the elements of the building in a seismic force suggested by NBC 105: 1994 for 300 years return period. The design is done for the elastic response of building considering compressive capacity of masonry walls whereas splints and bandages were placed at critical locations for taking tensions developed in buildings. Either welded wire mesh (WWM) or rebar was considered as splints and bandages at critical locations, such as corners, jambs of openings, at sill and lintel/ floor level. In addition, galvanized iron (GI) wires were employed as a jacketing to prevent the local failure in both methods. When WWM is used, the method of retrofitting is referred hereafter as WWM Method, and Rebar Method if rebar is assumed as a tensile material at critical locations. Details of WWM method and Rebar method are shown in Fig. 3 and Fig. 4 below.

From design philosophy, use of rebar is suggested when it is necessary to enhance the ductility as well as strength whereas WWM is recommended when more weightage need to be given for ductility than strength. However, it is crucial to carry out cost sensitivity analysis to decide which material to opt. From the analysis, it was observed that all sixteen residential buildings taken under study have thick walls demanding no additional compressive strength. In addition, walls of these residential buildings are not slender with respect to height and length of wall; hence, any of the WWM Method or Rebar Method could be employed to retrofit these buildings. Therefore, design and subsequent cost sensitivity analyses were carried out which established use of WWM Method would be economical to retrofit these residential buildings. Conclusively, WWM Method was employed to strengthen 49 SMM residential buildings. Fig. 5 depicts before, during and after retrofitting of a building, one of the buildings among considered samples for this case study.

For the purpose of connections, GI through wires were provided to connect inner and outer meshes whereas 4.75 mm anchorage bar passing more than half width of wall connect meshes with walls. These crucial keys were placed alternately and staggered at spacing not greater than 600 mm apart from each other. Moreover, 4.75 mm anchorage bars were provided to anchor the tie beam with the foundation wall at spacing not greater than 300 mm c/c.

In order to improve the integrity between floors and walls, metal angles 3 mm thick or folds of plain sheets of equivalent thickness were used to connect all the walls with floors. As an alternative to metal angles, wooden keys were also used. Moreover, GI wires were used to tie different members of a roof. In addition, GI wires from jacketing was used to tie wall plates at eaves level.

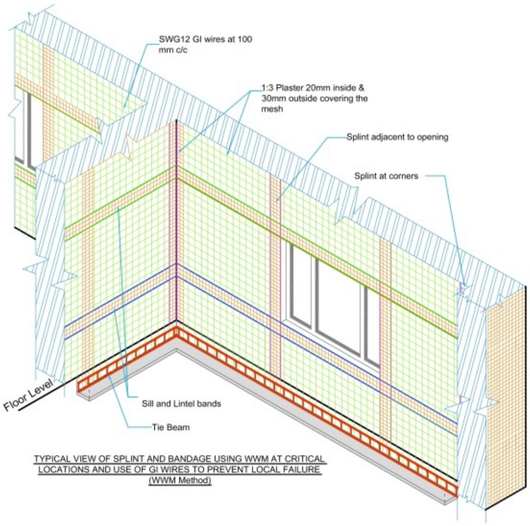

Fig. 3 – Typical design output of retrofitting for stone masonry wall using WWM Method (© NSET, 2015)

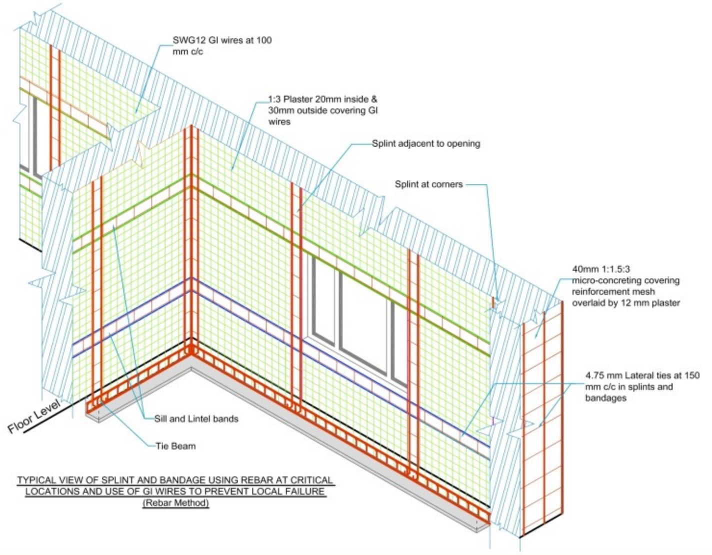

Fig. 4 – Typical design output of retrofitting for stone masonry wall using Rebar Method (© NSET, 2015)

Fig. 5 – A building before (left), during (middle) and after (right) retrofitting (© NSET, 2015)

3. Results and Discussion

Several key results were obtained through the analysis, design and implementation of the retrofitting of the SMM buildings that provide ample learnings. This paper studies two of the major results and learnings of the process; one regarding the cost of retrofitting and second regarding the technical challenges faced during implementation and their appropriate solutions.

3.1 Cost of Retrofitting

Various factors are considered to ascertain the suitability of retrofitting and affects the decision making process such as a) Direct cost of retrofitting including materials and manpower, b) Indirect costs associated with loss of income and rent during interventions, c) Time required for interventions, d) Importance of the building and e) Remaining life of the building. Among all these mentioned factors however, direct cost of retrofitting plays the most significant role. Past experiences of retrofitting in Nepal have suggested that retrofitting of a building is economical if the cost falls under one-third of the cost of construction of similar new structure to be earthquake resistant. While this general information might not be applicable for all cases, the notion that retrofitting must be cost-effective is of paramount importance, especially in Nepal considering the socio-economic status of those that are in need of such interventions.

Therefore, one of the key results derived from this study is the direct cost associated with retrofitting of stone masonry buildings, using WWM Method and Rebar Method. The cost of retrofitting a building using most common aforementioned materials was done to ascertain which technique was more economical along with establishing the average cost of retrofit construction. For this, different rates of retrofitting were calculated based on plinth area, built up area and wall area of buildings. The results of the analysis of cost are shown in Table 3 and Fig. 6.

Table 3 – Cost comparison of WWM Method with Rebar Method

Cost per square feet of, (NPR[1] in hundreds)							Rebar Method costlier than WWM Method (%)
	Plinth Area		Built up Area		Wall Area		
Storey	**WWM Method**	**Rebar Method**	**WWM Method**	**Rebar Method**	**WWM Method**	**Rebar Method**	
1	6.8- 8.3	7.5- 9.8	6.8- 8.3	6.8- 9.8	2.1- 2.5	2.3- 3.1	18
1.5[2]	8.1- 11.2	9.7- 13	5.4- 7.4	6.5- 8.7	2- 2.1	2.3- 2.7	22
2	7.1- 10.1	8.1- 14.1	3.5- 5	4- 7	2- 2.2	2.3- 3.2	27
2.5[3]	9.3- 12.5	12.7- 16.2	3.7- 5	5.1- 6.5	1.9- 2.2	2.5- 3.1	37
Std. deviation	1.7	2.8	1.5	1.6	0.2	0.3	

From above Table 3, in an average, retrofitting of residential SMM buildings using Rebar Method is costlier by 26 % than retrofitting using WWM Method. In the Fig. 6 below, the intercept between curves of either PA, BA and WA is gradually increasing with increase in number of stories. This is because retrofitting using Rebar Method is uneconomical for building stocks which require no additional strength but need improvement in ductility. In other words, all the sixteen building samples are not slender with respect to height and length of the wall. Hence, these buildings need enhancement of ductility rather than strength. In both retrofitting methods, most of the materials are almost the same except the materials required in splints and bandages. Here, with the increase in number of stories, the material required in splints and bandages increased. Consequently, the total cost incurred in the uneconomical method gradually piled up with increase in number of stories resulting the increase of intercept as shown in Fig. 6.

From Table 3 and Fig. 6, it is clear that the usual trend of reporting the cost of retrofitting SMM buildings either per square feet of PA or BA does not give the real picture of the cost. Meanwhile, the standard deviation in cost per square feet of WA using WWM Method and Rebar Method is only NPR 20 and NPR 30 respectively for the whole building stocks ranging from one to two and attic story. Therefore, retrofitting cost deducted per wall area having minimum standard deviation is the best index to report the average cost. One of the reasons why cost per wall area has minimum standard deviation is because most of the retrofitting interventions are carried out in wall. This wall area includes both inner and outer surfaces of walls excluding openings. In other words, wall area is function of many parameters which alter the cost of retrofitting works; these parameters are percentage of openings, materials in gable (light partitions or SMM), story height. Moreover, same floor area can have variation in wall areas due to variation in number and size of the rooms. Cost per wall area also takes account of this variation and the consequent cost of tie beams, anchorages.

Meanwhile, cost per BA is decreasing by a quadratic relationship as shown in Fig. 6. However, the later part of the curve of cost per BA consisting two, and two and attic story has a constant nature. This is because the ratio of WA to BA for most of these buildings is nearly the same which is depicted by the Fig. 7. Despite this

[1] 1 USD: 114 NPR

[2] 1.5: One plus attic

[3] 2.5: Two plus attic

study established cost per WA as an accurate index to represent retrofitting cost of SMM buildings, the advantage of an index, cost per BA, cannot be discarded. This is a useful index to give a quick response of an approximate cost that can incur in retrofitting SMM buildings. According to study conducted by R. Guragain et al. (2018) in the region, two and three storied buildings represent about 80-90% of SMM buildings [3]. Hence, it can be discussed that the majority of SMM buildings in the region require NPR (350 - 500) per square feet of BA while retrofitting using WWM Method.

Furthermore, Fig. 6 shows the gradual increase of the cost per PA in each method with increase in number of stories. This is because ratio of WA to PA is increasing with increase in number of stories which is depicted in Fig. 7.

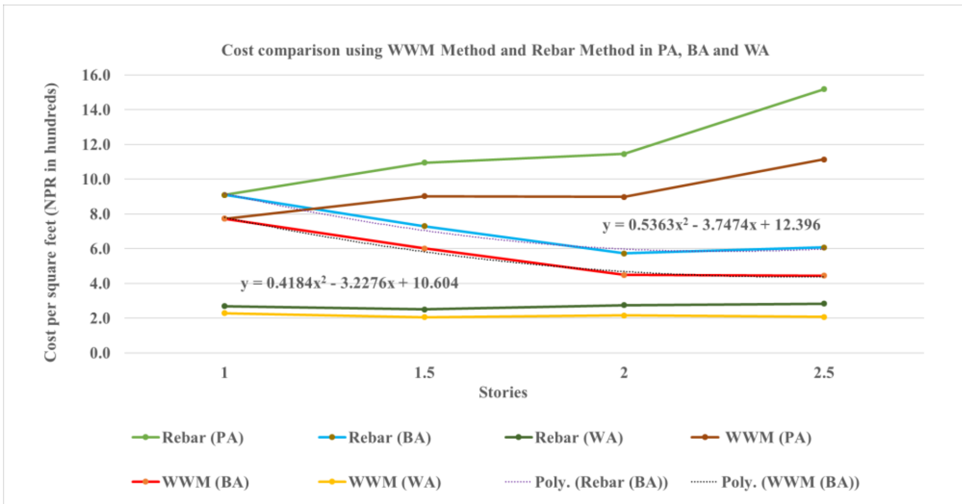

Fig. 6 – Comparison of cost trends shown by two methods studied

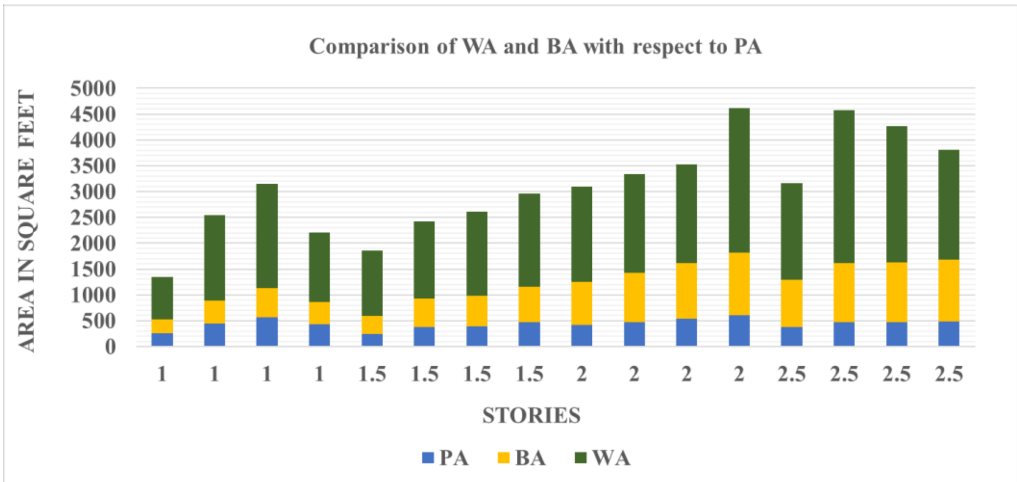

Fig. 7 – Comparison of WA and BA with respect to PA for building samples

3.2 Technical challenges in implementation and solutions:

Needless to say, numerous challenges were encountered while retrofitting low strength masonry buildings. Amongst challenges involved on accomplishing the retrofitting of 49 SMM buildings using WWM Method, several crucial challenges and their implemented solutions are discussed below:

a) Usually it is suggested to cast tie beams stretching horizontally over the ground at normal depth. However, due to presence of slope terrain at outer of either side elevations of some buildings, tie beams were placed at a slope of not exceeding 1:6, as shown in Fig. 8, which would meet horizontally running tie beams at front and back side of the building. Although it is possible to excavate and place horizontally at the recommended depth, it increases additional cost. The purpose of tie beams, simply, is to anchor splints and GI wires provided to prevent local failure of masonry units. Placing tie beams at a slope still fulfil the required purpose.

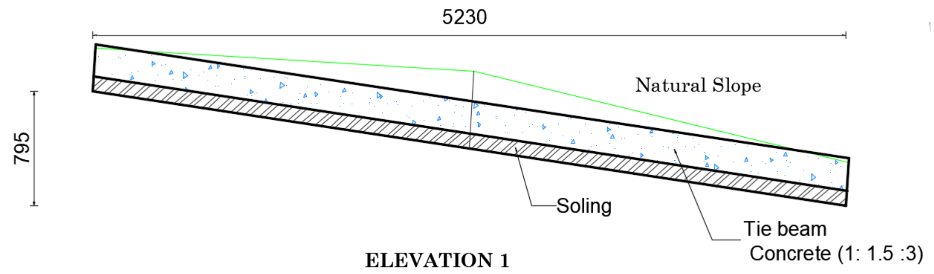

Fig. 8 – Placement of tie beams at slope

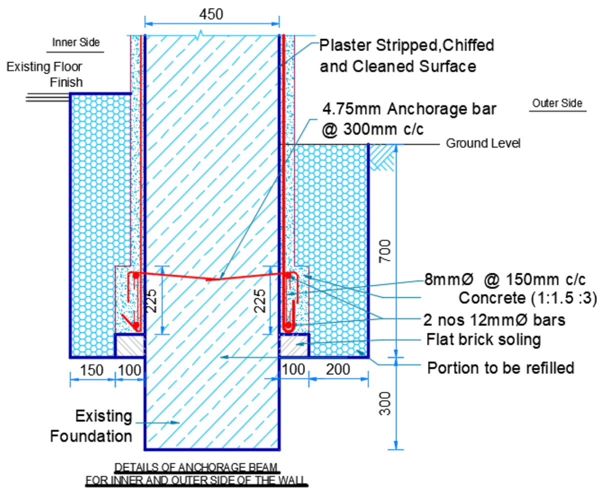

Fig. 9- Placement of inner and outer tie beams at same level to compensate required footing width

b) Inner and outer tie beams were recommended to place with their top surface levelled with the existing floor level and ground level respectively. This typical provision was suggested to minimize the excavation works. However, theoretically, when footing width does not meet the required width, it is necessary to increase the bearing area below the existing footing for better distribution of gravity loads. Ironically, it is almost impossible to intervene at this level in rural region since it requires sophisticated equipment which will call out high cost. Due to this, it is suggested to place anchorage beam with its bottom at the same level with the bottom level of an existing footing. This solution is also not economically feasible as it involves huge excavation; hence, anchorage beams of required width were provided at a required depth below the ground level. Such case was encountered in one of the one and attic storied buildings and the solution as shown in Fig. 9 was implemented. This new assembly is similar to footing with shear key which prevents tilt, settlement and sliding [10].

c) In some buildings, the position of joists at the floor level hinders the continuation of full width of splints as shown in Fig. 10. When such problem encountered, the full width of splint was continued up to possible top level. A lapping splint that could pass through the available gap was placed by overlapping with lower story splint and upper story splint. Furthermore, to compensate the width of splint, number of lapping splints were used such that the sum of width of lapping splints would not be less than the recommended width of splint. Moreover, bandages at the top level of lower story and at the bottom level of upper story tied these splints. Although throughout continuation of splints and bandages is of prime importance to achieve ductility which was targeted by a design, this was the most practical alternative that could be implemented. Likewise, a challenge with continuation of bandages was solved when encountered.

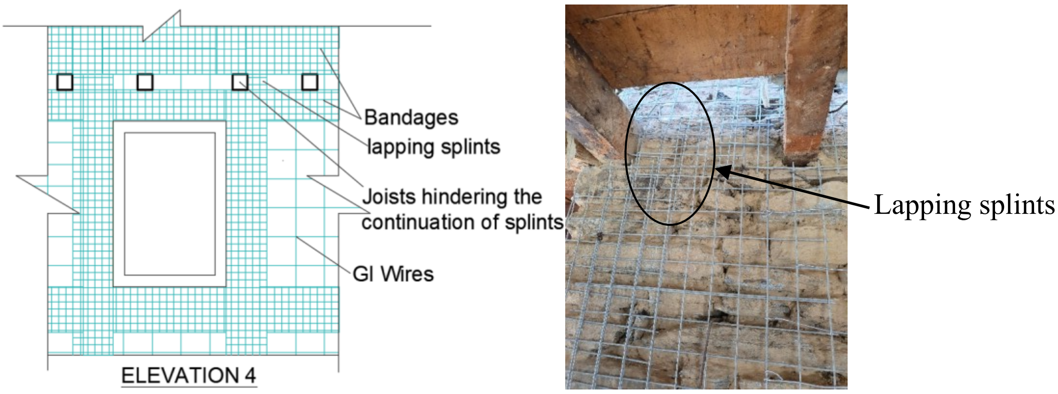

Fig. 10 – Drawing showing joist hindering the continuation of splint (left) and similar picture taken while implementing (right) (©NSET)

d) In most of the buildings, wooden keys restraining lateral movement of timber members, such as joists, rafters, beams were not found. In such case, wooden keys were fixed with the timber members as shown in Fig. 11.

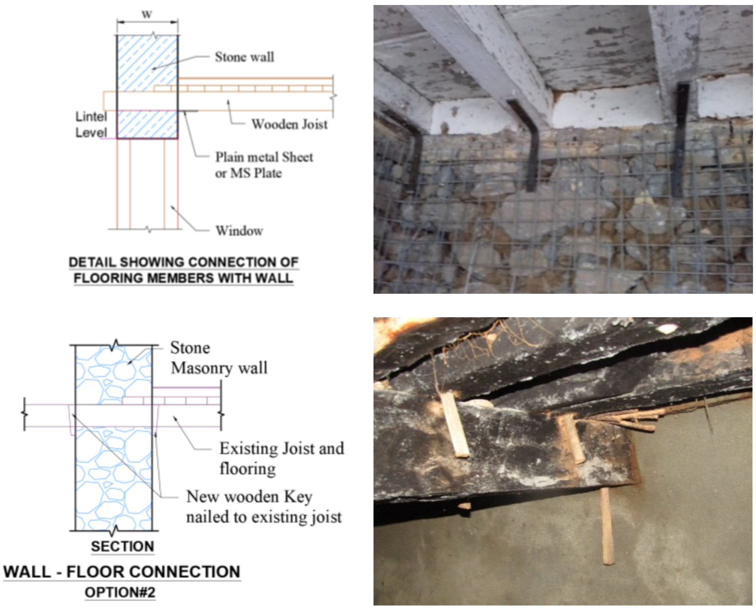

Fig. 11 – Drawings showing installation of Keys to connect floor and wall (left) and similar picture taken while implementing (right) (©NSET)

Out of plane failure of walls is prominent in the walls through which joists members do not pass. In other words, walls parallel to joists are more prone to out of plane failure. None the walls parallel to joists had any connections with the floor members. However, it was found that most of the buildings have joist members at an inch gap from these walls. Hence, MS plates were used to connect these walls with joists members as shown in Fig. 12.

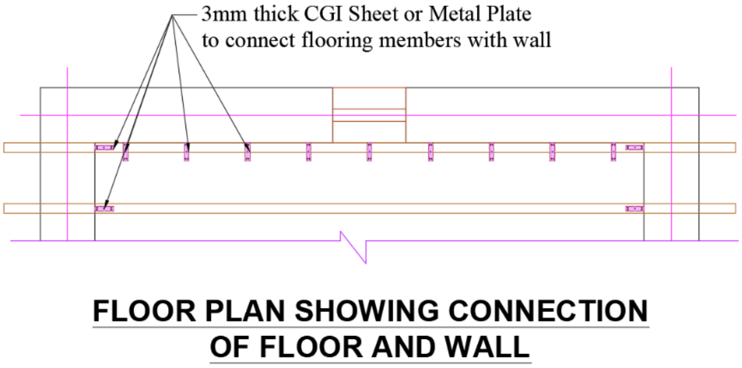

Fig. 12 – Drawing showing installation of Keys to connect floor and wall which is parallel to joists

e) Sometime, it is necessary to install an opening for lighting and ventilation. Installation of an opening in existing SMM buildings involves high level risk causing even collapse of walls. However, it was accomplished working cautiously. First of all, horizontal wooden planks, which would be supported by inclined shoring, were provided from both inner and outer side as shown in the Fig. 13. Cautiously, stone units were withdrawn to insert horizontal through members which would be supported by vertical shoring from both sides of wall. Furthermore, stone units were withdrawn to insert vertical cross member followed by insertion of horizontal cross member. Thus, after ensuring sufficient props, units were withdrawn and simultaneously window frame was installed.

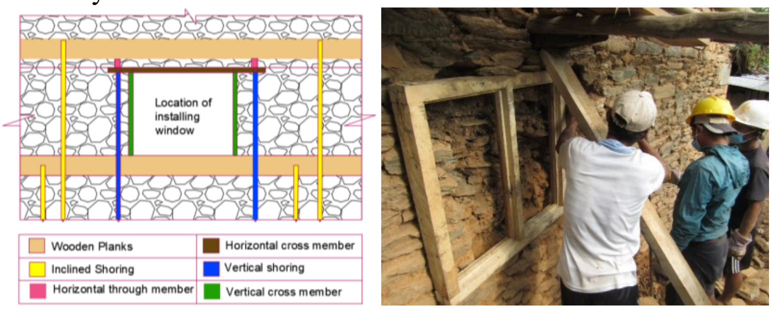

Fig. 13 – Drawing showing shoring provided while installing a window (left) and a picture of similar case while implementing (right) (©NSET)

4. Way Forward

While the reconstruction of fully damaged private houses in the aftermath of the 2015 Gorkha earthquake has progressed significantly, the retrofitting of the partially damaged buildings has not gained momentum. Among various issues hindering the progress, the lack of understanding of appropriate method and cost of retrofitting among the affected house owners and technical personnel are most crucial. This study shows that retrofitting of rural masonry residential buildings will be economical by using WWM Method. The method is also widely feasible due to less time of construction, easy transportation of materials, easier handover of technique to local masons and preserves the vernacular look of the building. This study suggests an accurate index and an average rate for calculating estimated costs of retrofitting for a wide range of stone masonry buildings; however, the development of norms for cost analysis of retrofitting is seen as a crucial support to engineers and builders. Similarly, the Government of Nepal's National Reconstruction Authority has published a manual to support the design and construction of retrofitting, but it doesn't incorporate the key technical challenges that can be met as detailed in section 3. As such, it is crucial to draft construction handbook covering all the technical challenges that may be encountered while implementing retrofitting and their equivalent solutions. These further works if develop will help to scale up and expedite the retrofitting of partially damaged buildings.

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6. Copyrights

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