



EXPERIMENT-BASED EARTHQUAKE RESISTANT PROTOTYPE DESIGN OF RESIDENTIAL BUILDINGS IN NEPAL

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1 Abstract

The damage and destruction caused by the 2015 Gorkha earthquake triggered the development of a new breed of earthquake-resilient designs for residential buildings in earthquake-affected areas of Nepal. These designs aimed to maximise the use of abundantly available local materials such as stone and mud while minimising the use of “imported” materials, such as rebars and cement, which are unsuitable to the setting of rural and impoverished areas. Instead, materials such as wire, wire mesh, and welded wire mesh were used in these designs because of their easy transportability by animals and humans. The proposed designs include one and two-storey buildings constructed of stone in mud loadbearing masonry buildings with a light metal roof and timber floor. The stone masonry building walls incorporate horizontal welded wire mesh and surface containment steel wires on both surfaces of the walls. The containment wires were tied together by cross-links. Experimental testing methods were employed to demonstrate their compliance with the Nepal National Building Code (NBC). This elicited an extensive experimental campaign that included shock table tests of multiple half-scale building models representing the prototypes. The shock table is a cost-effective dynamic testing tool where the platform is shaken by impulse loading. The models were subjected to multiple base excitations with increasing amplitudes. The one-storey model building survived multiple and intense shocks but suffered significant damage. The strengthening measures were further improved in case of two storey model which survived intense shocks without triggering any unstable modes of failure, thereby confirming compliance of the proposed designs to the NBC. Based on the findings of the experimental campaign, detailed designs were prepared which have since been approved by the Government of Nepal (GON) for construction/ reconstruction of residential buildings and are being implemented in the earthquake-affected areas of Nepal. To facilitate the construction process, pictorial guidelines have been developed, and training to masons and engineers has been delivered.

Presented herein is the evolution and implementation of the proposed earthquake-resilient building system implementation including experimental testing methods, high-level findings, and methods used to disseminate this building system.

Keywords: building reconstruction, shock table, stone masonry, containment, earthquake safety

2 Introduction

The Mw 7.8 2015 Gorkha earthquake and associated aftershocks damaged or destroyed approximately 750,000 houses, 6,000 government buildings, and 30,000 school classrooms [1]. Among the damaged or destroyed residential houses more than 90% are estimated to be constructed of low strength masonry such as stone or fired brick in mud mortar or adobe [2]. For ‘proofing’ against future earthquakes, the Post Disaster Needs Assessment, an actionable and sustainable Recovery Strategy planning for mobilizing financial and technological resources, recommended the construction of earthquake-resilient construction [3].

Most of the earthquake-affected areas are highly inaccessible by vehicular transport and marred with a poor economy. Consequently, importing industrialised construction materials such as cement, structural steel



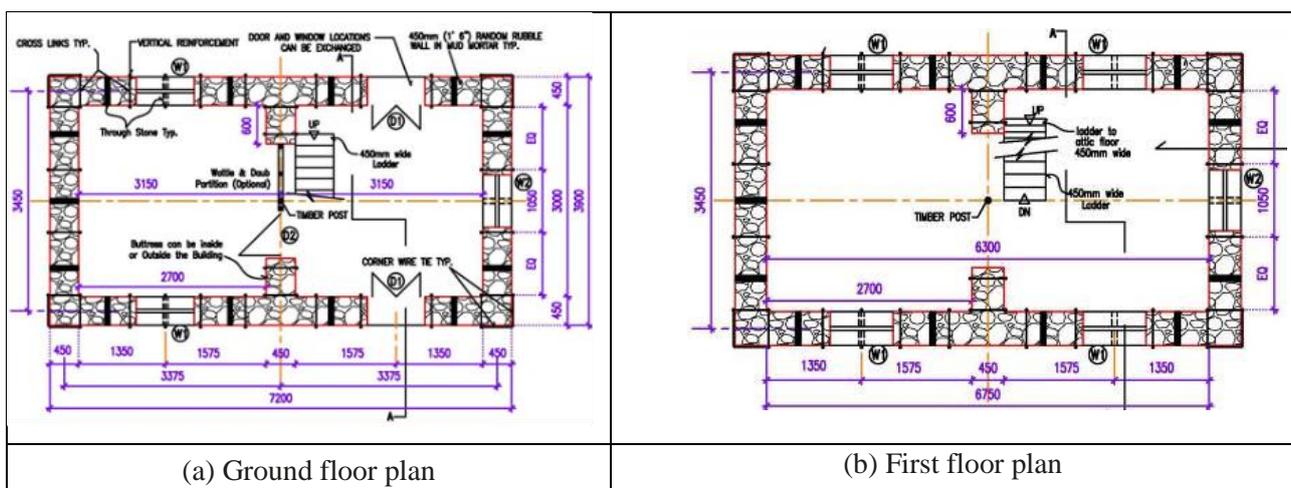
and reinforcing steel bars (rebar), though considered essential for earthquake-resilient construction, are generally not feasible. The only construction materials that are economically and physically available in abundance in such areas are stone and mud, materials generally considered unsuitable for earthquake-resistant construction.

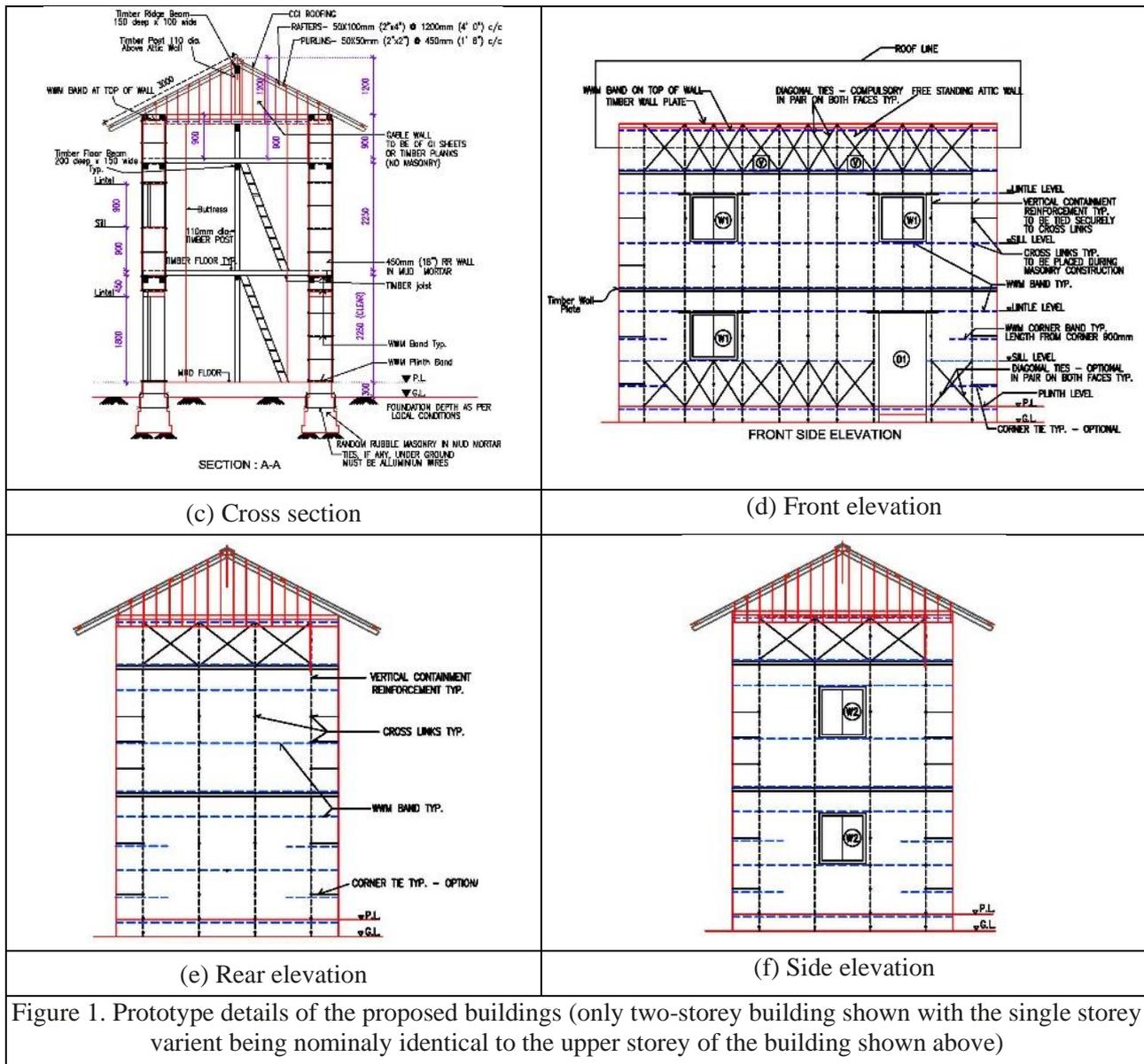
The Nepal Building Code (NBC) permits the use of stone masonry in mud mortar for residential houses but provides very limited options. The options include the provision of reinforced concrete and timber bands, vertical rebars in strategic locations for improving their earthquake resilience. Hard wood is generally not available in the earthquake-affected areas, and softwood is not suitable for reconstruction because of its short life. The poor economy and inaccessibility of the areas prompted a search for cost-effective building options which maximise the use of locally available materials and minimise the use of imported materials. Furthermore, any materials imported in these inaccessible areas would have to be easily transported by humans and animals. This triggered an experimental campaign, which included a series of shock table tests on stone masonry buildings.

One storey plus attic (one-storey) and two-storey plus attic (two-storey) stone masonry buildings in mud mortar were designed based on a traditional layout in order to accommodate for the aforementioned needs. To improve the buildings' seismic resilience, welded wire mesh, and containment wires were used. To verify the buildings' seismic resilience, shock table tests of 1/2 scale stone masonry model buildings were conducted. For smooth implementation of the proposed designs, training to masons and engineers were delivered and pictorial guidelines developed. Discussed herein are the design concept, findings of the experimental work and dissemination of the technology.

3 Design of buildings

Based on the building typology survey in the earthquake-affected areas, typical building layout, wall thickness, height and construction materials, one-storey and two-storey buildings were designed. The proposed one and two-storey buildings had the same floor plan. Stone in mud mortar has been proposed for walls and timber structure has been proposed for floor structure. The layout of openings, doors, and windows were sized and located to be representative of a range of typical construction practices. The commonly used heavy slate or tile roofing material was replaced by metal roofing sheets on timber structure to reduce building weight. Similarly, considering high toppling risk of stone masonry gables, these were replaced by light timber structure clad with metal sheets (Figure 1).





In the absence of established earthquake resistant design standards for stone in mud mortar masonry (low strength masonry (LSM)) buildings [4], [5], the design concepts for of the building was prepared based on available prescriptive guidelines [6], [7], [8]). The bands proposed in the aforementioned guidelines were replaced by welded wire mesh embedded in the masonry mud mortar. Further to this, vertical and horizontal wires were provided on interior and exterior wall surfaces (containment wires)) tied together by cross-links passing through the walls. Considering the loss of integrity between masonry units and building components as one of the major threats to survival of LSM buildings [9], [10], [11] (Figure 2), special focus was placed on maintaining integrity between building components during earthquake shaking. Once the concept design was finalised, the structural design (Figure 3) of the buildings was completed following classical mechanics and simplified engineering methods. For the structural design, the design seismic force was estimated following the relevant seismic standard [12].



(a) Delamination and bulging of wall wythe, 2015 Gorkha earthquake, Nepal



(b) Out-of-plane collapse of wall led to collapse of roof and floor, 2015 Gorkha earthquake, Nepal



(c) Out-of-plane collapse of walls, destruction of top storey, 2015 Gorkha earthquake, Nepal



(d) Destruction of a house, 2005 Kashmir earthquake, Pakistan



(e) In-plane wall and corner damage, 2005 Kashmir earthquake, Pakistan



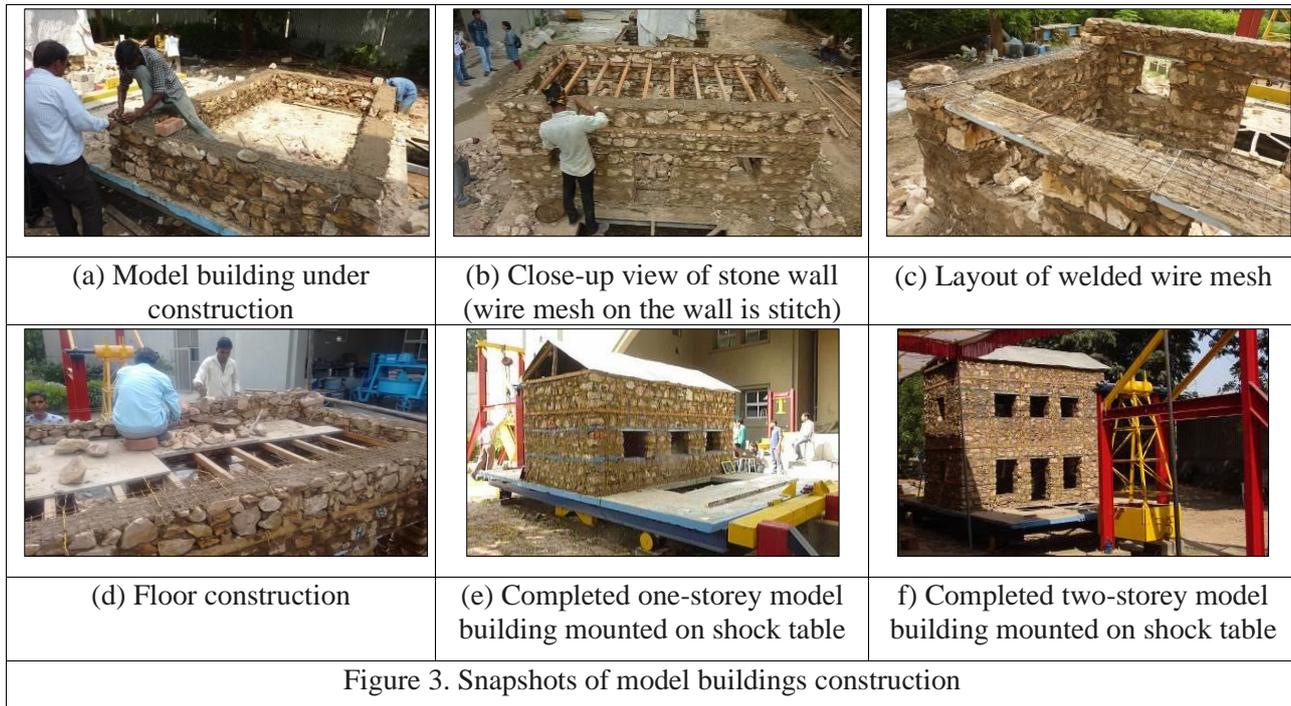
(f) Roof collapse due to absence of wall-roof connections, 1999 Chamoli earthquake, India

Figure 2. Typical failure modes of stone masonry building with weak mortar

4 Experimental verification of design

4.1 Design and construction of the model buildings

In order to show that the designs can be considered as earthquake resistant and provide life safety during a seismic event, dynamic shock table tests were performed on $\frac{1}{2}$ scale models of a one-storey and a two-storey building. For the construction of the model buildings, the geometry of the building and its elements (including wire diameters) were linearly scaled down to $\frac{1}{2}$ the size of the prototypes. This scaling resulted in a 3.42 m (L) \times 1.98 m (B) \times 2.21m (H) for the one-storey and 3.42 m (L) \times 1.98 m (B) \times 3.20 m (H) for the two-storey model buildings respectively. The building models were constructed using nominally the same materials for the two building prototypes. The stones were also scaled down to $\frac{1}{2}$ scale to suit the scaled model buildings so that the number of bedding planes remained the same as for the prototypes. Timber lintels were provided to span window and door openings. The roof was constructed using lightweight metal roofing sheets supported by a timber structure. Diagonal wire bracings were installed under the suspended floors to help stabilise the walls under the face loading. Bracings at the eaves and in the roof were not provided. Attempts were made to simulate the field conditions of the earthquake-affected areas of Nepal while constructing the model buildings. Refer to Figure 3 for photographs of the building models under construction.

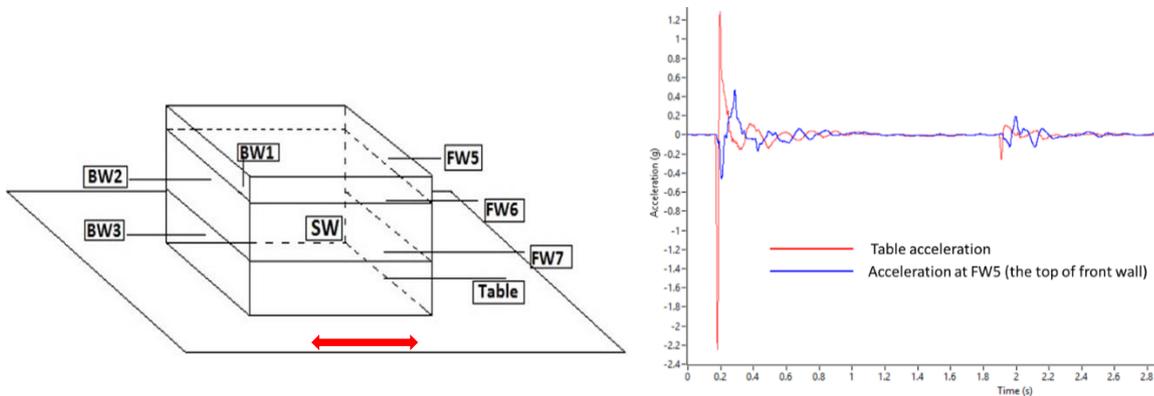


4.1.1 Experimental set-up and loading protocol

All building models were constructed on 3.0 m x 6.0 m shock-table platform. A shock-table consists of a simple platform that typically works under impulse type motion generated by striking the platform. The three main components of the shock table are: (i) a table platform supported by wheels, sliders or floating mechanism on which test specimens are mounted, and (ii) impact mechanism to create an impulse load to the table platform, and (iii) a reaction beam to provide a reverse shock. The testing procedure consists of imparting ‘shocks’ to the table platform by means of striking the platform by a swinging pendulum. The shock-table thus receives main shocks from the pendulum and the reverse shocks from the reaction beam and can be used to simulate the cumulative effects of ground motion by subjecting it to a series of base impacts [13]. The testing procedure reported herein consisted of imparting ‘shocks’ of increasing intensity (by varying pendulum angle) of to the table platform by means of striking it using a 1.5 ton swinging pendulum mounted on a steel tower.

All the tested model buildings were shaken in the transverse direction considering the high vulnerability of the long walls (refer Figure 4) when subjected to face loading. The model buildings were constructed on top of the table platform and were subjected to a gradually increasing intensity of base shocks by increasing the angle of release of the pendulum, which caused progressive damage to the model. Figure 5 presents the damage history of both one and two-storey model buildings.

Eight accelerometers were mounted, one on the shock table and seven at different levels of model walls (Figure 4 (a)). During each shock test, the acceleration response was obtained by using high-speed data acquisition system. Prior to the base shock test, free-vibration tests were conducted to obtain the dynamic properties and damping in the models. Figure 4 (b) presents recorded peak accelerations on the shock table and at the top of front wall. Every test run was documented on video by two strategically placed video cameras and photo cameras. After every test run, the models were inspected for possible damage which was recorded/documentated in the form of visual observations, still photographs and continuous recording through video cameras.



(a) Location of accelerometers for two storey building (BW: back wall, FW: front wall, SW: side wall)

(b) Acceleration time history for Shock # 14 for two storey building when using a pendulum angle of 70°.

Figure 4: Instrumentation and typical recorded time history for a two storey building

4.1.2 Visual observations

The one-storey model was constructed and tested first followed by the construction and testing of a two-storey model. Under extreme shaking, models exhibited significant cracking, sliding and rocking both locally and globally, which caused the structure to undergo large lateral deformations. Even under the extreme shaking, the model buildings survived without triggering any toppling or slumping of walls, which are the commonly observed reasons for the failure of stone masonry buildings when subjected to lateral loading.

The one-storey model suffered damage in the form of falling of stones off the walls. The wall junctions, and walls below the sill and above the floor level of the one-storey model suffered extensive damage (refer Figure 5). Based on these observations the construction of the subsequent two-storey model was improved by strengthening wall junctions, adding one timber band at the roof level and diagonal wires added to the walls to the two-storey model. Further to this, stone masons were employed for model construction, whereas the one-storey model was constructed by brick masons. At the ultimate shaking levels, the two-storey model did not suffer falling of stones, but did experience extensive cracking throughout the structure.

The good performance of the models confirmed that the proposed designs had the capabilities to be considered as earthquake resilient structures in the context of Nepalese construction.

One-storey building			Two-storey building		
Shock No.	Pendulum angle (degrees)	Camera Position 1	Shock No.	Pendulum angle (degrees)	Camera Position 1
2	25		3	25	



One-storey building			Two-storey building		
Shock No.	Pendulum angle (degrees)	Camera Position 1	Shock No.	Pendulum angle (degrees)	Camera Position 1
4	35		4	25	
5	35		5	30	
6	35		6	30	
7	40		7	35	
8	45		8	35	
9	45		9	40	



One-storey building			Two-storey building		
Shock No.	Pendulum angle (degrees)	Camera Position 1	Shock No.	Pendulum angle (degrees)	Camera Position 1
10	45		10	40	
11	45		11	40	
12	50		12	65	
13	50		13	70	
14	55		14	70	

Figure 5. Photographic images of observed progressive damage (arrows indicate the direction of shaking of the table)

5 Dissemination of building system and reconstruction efforts

To facilitate earthquake-resilient residential building construction, maintenance of quality control and realisation of the standard of construction, illustrative guidelines and posters were prepared as a resource for the practicing structural engineers, site foremen and artisans . These guidelines provide step-by-step detailed



explanations and procedures for implementing the developed and experimentally validated designs. Figure 6 presents these dissemination materials prepared by NCPDP for UNDP, Nepal.

14. A few words on the technology
 In the hilly areas where the access is difficult carrying in of heavy and bulky materials like cement bags and steel bars is generally not feasible due very high transportation and head-load costs. Availability of large quantity of water needed by cement also poses a major hurdle. Alternate that is given here is simple and easy to execute. It is viable since it is aimed at improving the performance of the traditional construction in Himalayan foothills that includes random rubble masonry in mud mortar, floor deck and roof frame. The approach is based on the adherence to the basic principles of good construction. The seismic resistance is provided by the containment wires anchored on the inside and outside wall faces along with WWM bands.



House design by NCPDP with support from UNDP- Nepal
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 United Nations Development Programme, Nepal

Earthquake Resistant House with GI wire Containment Reinforcement 20

'Awaz'
Earthquake Resistant House of Stone and mud with GI Wire Containment Reinforcement for Nepal

Introduction:
 In hilly areas of Nepal and India most of the houses are built with stone and earth. These buildings have suffered extensive damage during earthquakes. Because of this many engineers are advocating the use of bricks, cement and steel rods. But in the remote mountain areas it is difficult to bring these materials, and people have plenty of stones and earth available for construction. Before deciding on what to use one must understand why these stone houses collapsed. The studies of damage show that stone was not responsible for the damage, but it was the way stones were used. Damage does not occur because of a material. Even brick, cement and steel structures also can collapse if they are not constructed according to the basic rules of construction.

So people can build with stone, but they must follow all the basic rules. To make the house strong against earthquakes GI wires containment along with weld wire mesh (WWM) bands can be used. With this there is no need of cement or steel bars. If this is done then it is possible to prevent the collapse of your house. So get ready to build an earthquake resistant house that you can afford. You can build a single story house right now. Later at any time if you need to construct another storey above then remove the roof, extend the attic wall up to 8' height along with the wire reinforcement. The timber wall plate must be reinstalled on the new top and anchored to wall with wire reinforcement. The roof can be reinstalled.

Earthquake Resistant House with GI wire Containment Reinforcement 01

(a) One of the pages from Field Guide showing step by step building construction

'Awaz' Construction Technology for Earthquake Affected Nepal

Want to build a disaster resistant house?

Material is not at fault for damage or collapse. If bricks, stone, concrete blocks or cement are not used properly then the building gets damaged or can collapse. So for new construction use any material depending on the location and the affordability. But use them as per basic rules of construction with earthquake resistant features. Choose from the following three building systems

More than 3 story- Up to 3 story - Load Away from road- Column-beam bearing masonry with Load bearing-frame system

GI Wires Containment Technology
 This is a technology with Earthquake Resisting Features of WWM and GI wires useful for up to two and a half storey building without any cement and steel bars.

This is a simple technology to make traditional construction of random rubble masonry in mud mortar earthquake resistant. It requires adherence to the basic principles of good construction. The earthquake resisting features are made GI containment wires anchored on the inside and outside wall faces along with Weld Wire Mesh band.

GI Wire Containment technology can really bring safety

Two models made on a table with wheels were given 14 powerful shocks by 1,500 kg pendulum.

First model of 1 and half story suffered much damage because of poor masonry and inadequate reinforcement

Second model of 2 and half story with better masonry and more reinforcement suffered very little damage.

How to prevent damage in new construction.

- To prevent two faces from separating place stone to interlock with each other and place enough Through-Stones
- To prevent vertical cracking install horizontal bands at plinth, sill, lintel, floor and roof level.
- To prevent diagonal cracks encase the opening with reinforcement.
- To prevent masonry gable wall collapse make the gable with timber or GI sheets.
- To make the masonry walls ductile, provide vertical reinforcement in walls.

Design by NCPDP with financial support from UNDP- Nepal
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 Local support: CoRD, Nepal
 United Nations Development Programme, UNDP-Nepal

Basic rules of random rubble masonry

Never use round stones for masonry. Wall made with them is unstable. Round boulders must be broken to get angular faces for use in wall masonry.

Use angular stones that are often found on the mountain side and in gullies.

Thickness of the wall shall be not less than 350mm (15") and not more than 450mm (18") and all vertical and horizontal joints must be broken

Place length of each stone in to the thickness of wall to ensure interlocking of inside and outside faces of wall.

Provide "through-stone" one in every 0.7 sq. m, and arrange stones in zig-zag pattern in the wall breaking all vertical and horizontal joints in masonry

Place stones longer than the thickness of wall in the corner for strong wall to wall joint

Construct all walls at the same time. If not possible then leave the wall end in stepped manner

Place each stone flat on its broad face. Each stone must be in contact with the stone under it, not with mud mortar.

Use stone chips to fill gaps between stones instead of mortar. Never fill with round stones. The height of course shall not more than 600mm

Never build corners first with toothing and then fill up the gaps between the corners. Construct corners and walls together.

(b) Construction poster for one storey building

Figure 6. Developed dissemination materials

Extensive training was delivered to engineers, site foremen and craftspeople (Figure 7) for the smooth implementation of the aforementioned residential building designs. Training included both classroom and



hands-on training. In the initial stages and prior to starting the building reconstruction, training was delivered on building mock-ups, which involved the construction of walls of short length and approximately 2 m height. All-important building features such as fabrication and installing of cross-links, cutting and installing welded wire mesh on walls in the form of bands, installing the timber wall plate at the wall top, and installing the vertical containment wires were practiced by the trainees. Once the reconstruction efforts commenced, the training was delivered at the actual residential building's construction sites.



(a) Participants studying the detailed model



(b) Participants installing cross-links



(c) Participants installing WWM bands



(d) Participant installing vertical wires



(e) Another example of participants installing WWM bands



(f) Trainer reviewing the work

Figure 7. Photographs of on-the-job training

Following the approval of the design by the authorities in Nepal [14] and the training of local engineers, site foreman and artisans, the technology was rolled out for reconstruction of residential houses in the earthquake-affected areas (Figure 8). Considering no change from the prevailing construction practices in the area other than a few additional elements, the technology was considered simple and easy to implement.



(a) Installation of WWM band



(b) Installation of window frames



(c) Close up view of vertical wires



(d) House near completion

(e) Completed two-storey house

(f) Completed one-storey house

Figure 8. Actual reconstruction of buildings using the developed and experimentally validated building designs

6 Conclusions

Designs of residential buildings that utilise abundantly available local stone and mud as construction materials combined with the use of limited imported materials such as welded wire mesh (WWM), steel wires, to enhance the earthquake resilience of the buildings was presented herein. To confirm the earthquake resilience of these proposed designs, experimental testing of 1/2 scale constructed model building using a shock tables test were conducted. All the building models survived the applied shocks without suffering any unstable mode of failures providing sufficient evidence that well-conceived stone masonry buildings constructed using a combination of strategically positioned materials within stone in mud mortar can be made sufficiently earthquake resilient.

The proposed designs provide cost-effective solutions for earthquake resilience for economically disadvantaged populations at a very nominal additional cost. The proposed technology could be adopted to other seismically active parts of the world, particularly in developing countries which face socio-economic and inaccessibility issues similar to Nepal, thereby providing cost-effective seismic safety to the masses.

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