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 impovrished 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].

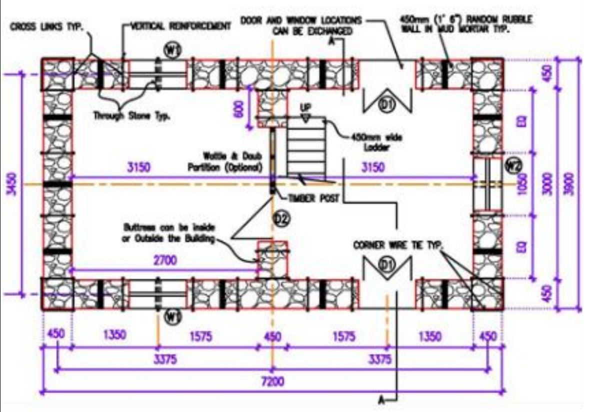
Most of the earthquake-affected areas are highly inaccessible by vehicular transport and marred with a poor economy. Consequently, importing industrialised construction materials such as cement, structural steel and reinforcing steel bars (rebar), though considered essential for earthquake-resilient 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.

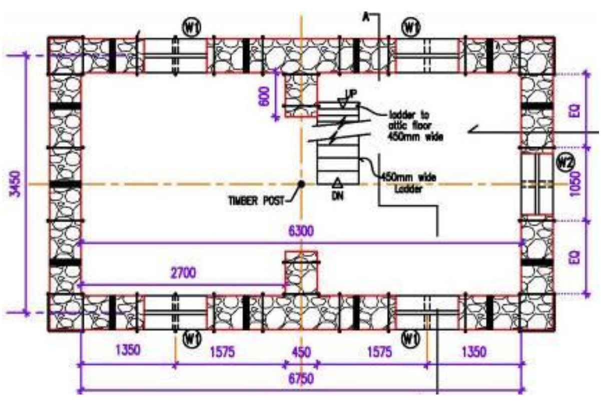
One storey plus attic (one-storey) and two-storey plus attic (two-storey) stone masonry buildings in mud mortar were designed based on a traditional layout in order to accommodate for the aforementioned needs. To improve the buildings' seismic resilience, welded wire mesh, and containment wires were used. To verify the buildings' seismic resilience, shock table tests of ½ 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

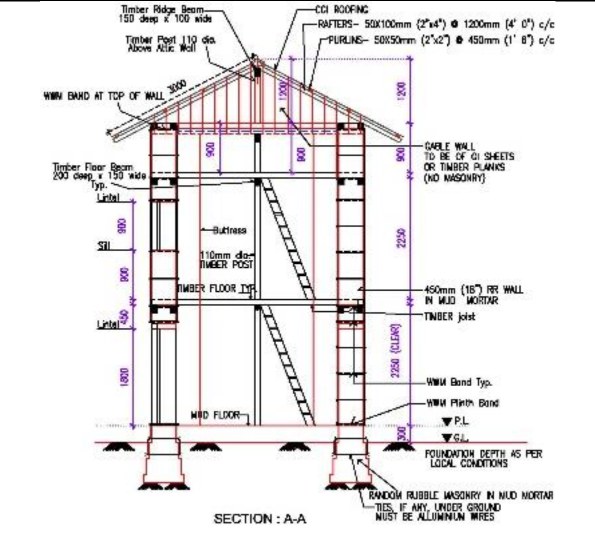
Based on the building typology survey in the earthquake-affected areas, typical building layout, wall thickness, height and construction materials, one-storey and two-storey buildings were designed. The proposed one and two-storey buildings had the same floor plan. Stone in mud mortar has been proposed 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).



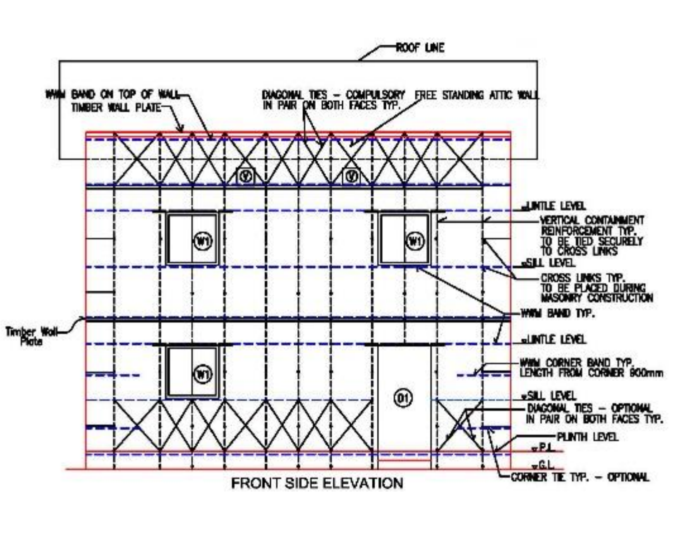
(a) Ground floor plan



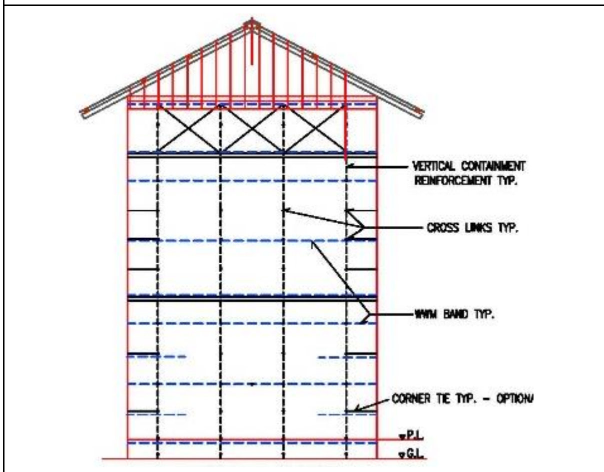
(b) First floor plan



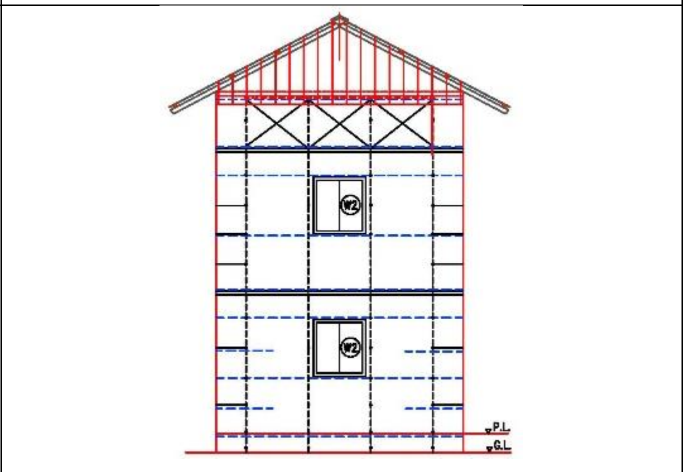
(c) Cross section



(d) Front elevation



(e) Rear elevation



(f) Side elevation

Figure 1. Prototype details of the proposed buildings (only two-storey building shown with the single storey varient being nominaly identical to the upper storey of the building shown above)

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 ½ 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 ½ the size of the prototypes. This scaling resulted in a 3.42 m (L) × 1.98 m (B) × 2.21m (H) for the one-storey and 3.42 m (L) × 1.98 m (B) × 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 ½ 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.

		
(a) Model building under construction	(b) Close-up view of stone wall (wire mesh on the wall is stitch)	(c) Layout of welded wire mesh
		
(d) Floor construction	(e) Completed one-storey model building mounted on shock table	f) Completed two-storey model building mounted on shock table

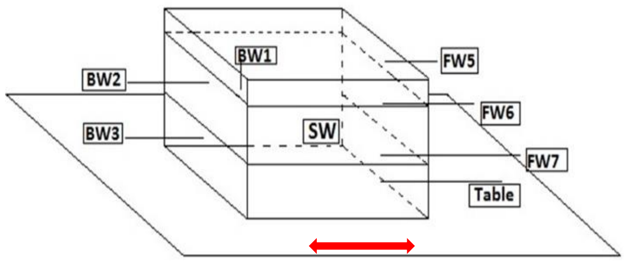
Figure 3. Snapshots of model buildings construction

4.1.1 Experimental set-up and loading protocol

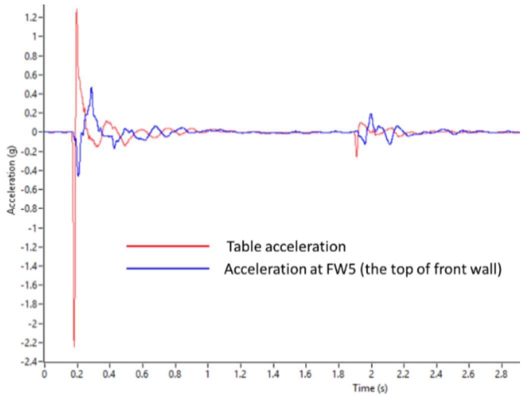
All building models were constructed on 3.0 m x 6.0 m shock-table platform. A shock-table consists of a simple platform that typically works under impulse type motion generated by striking the platform. The three main components of the shock table are: (i) a table platform supported by wheels, sliders 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/documented 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) Acceleartion time history for Shock # 14 for two storey building when using a pendulum angle of 70º.

Figure 4: Instrumenation and typical recorded time hostory 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	

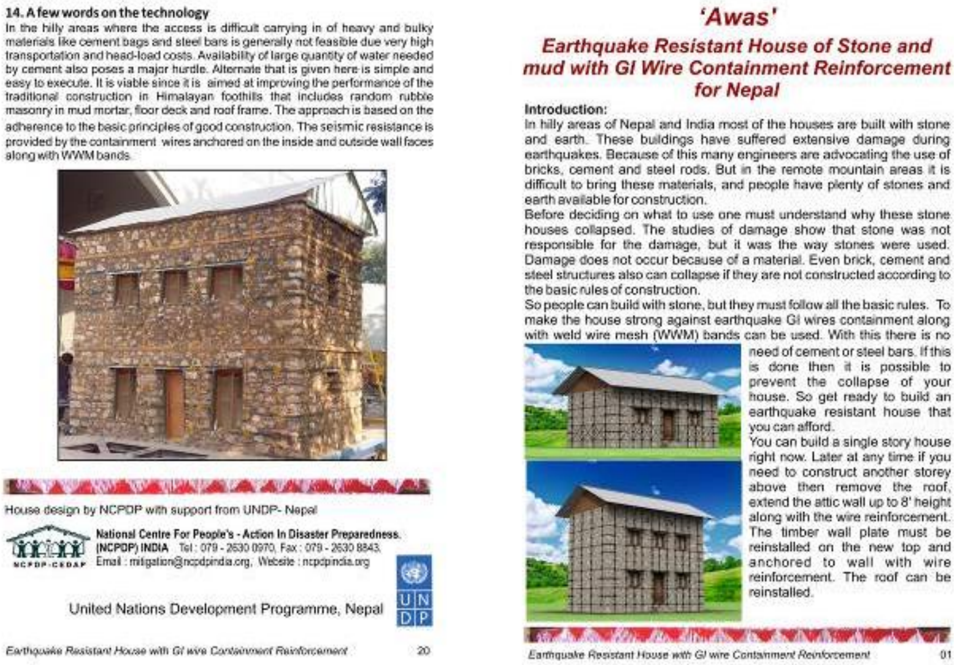
One-storey building			Two-storey building		
Shock No.	Pendulum angle (degrees)	Camera Position 1	Shock No.	Pendulum angle (degrees)	Camera Position 1
4	35		4	25	
5	35		5	30	
6	35		6	30	
7	40		7	35	
8	45		8	35	
9	45		9	40	

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	

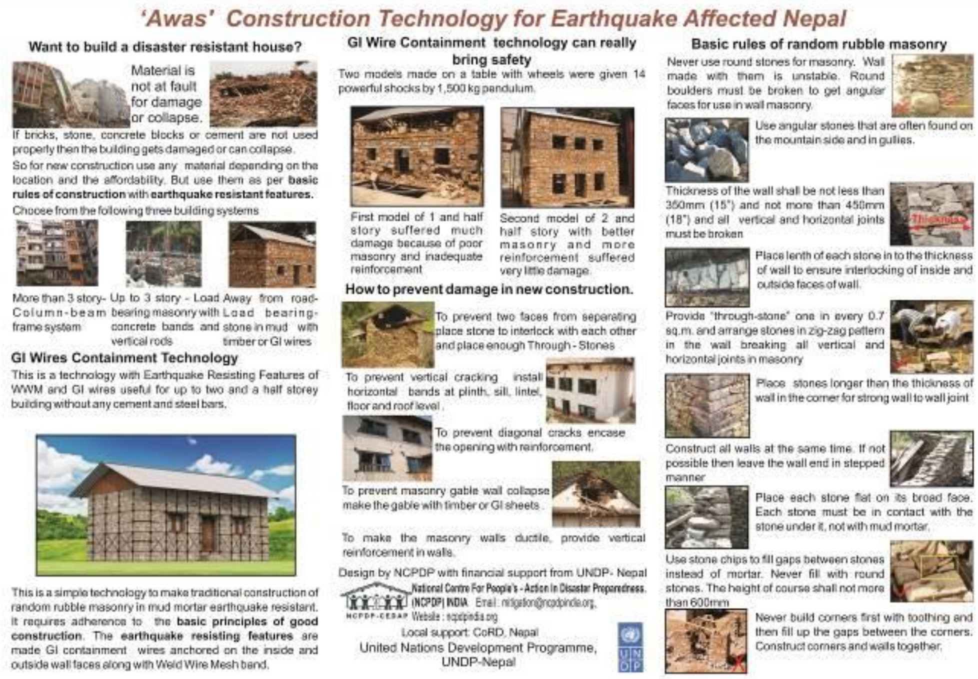
Figure 5. Photographic images of observed progressive damage (arrows indicate the direction of shaking of the table)

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.



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



(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) Anogther 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 experimentaly validated building desings

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 ½ 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.

7 Acknowledgments

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