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**State of knowledge and identification of research
priorities for the scientific validation of disaster resistant
building cultures of the Himalayan regions of Nepal :
Research report**

Julien Hosta, Philippe Garnier, Yannick Sieffert, Santosh Yadav, Thierry Joffroy, Pawan Shreshta, Salena Sangacche, Olivier Moles, Majid Hajmir

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State of knowledge and identification of research priorities for the
scientific validation of disaster resistant building cultures of the
Himalayan regions of Nepal

Research report



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Glossary

ASF Nepal	Architecture Sans Frontières Nepal
CBS	Central Bureau of Statistics
DUDBC	Department of Urban Development and Building Construction
GMaLI	Grant Management and Local Infrastructure
GoN	Government of Nepal
HRRP	Housing Recovery and Reconstruction Platform
IOE	Institute of Engineering, Tribhuvan University
LBC	Local building culture
NRA	National Reconstruction Authority
NSET	National Society for Earthquake Technology
UK	University of Kathmandu
UNOPS	United Nations Office for Project Service

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Foreword

This document is only a work document.

Its limitations are mainly:

- The difficulty to capture the needs and intentions from the concerned population. The demand from the affected households has not been systematically surveyed nor recorded. We haven't had the opportunity to offer any restitution to the inhabitants neither, nor complete this document with their feedback.
- The "gaps" in the data collected. The author has not been on site. The data mainly collected is mostly "second-hand" data, gather by ASF Nepal team and CRAterre team involved in past reconstruction or housing programmes. Thanks to ASF Nepal previous experiences on site, a lot of data is accessible but it is not completely fitting with the needs of such a research.

We hope that it can participate in highlighting the gaps to fill, and to encourage the reactions of the interested parties.

1. Introduction

Problematic

More than 5 years after the 2015 Gorkha's earthquakes in Nepal, there is still a huge need for addressing the needs of the affected population in the housing and building sectors, which was severely impacted by the events. Most of the activities implemented so far within the Nepalese Housing Reconstruction Programme focused on complete reconstruction, and the largest proportion of HHs enrolled for reconstruction grant. Criteria of eligibility for reconstruction grant have strongly oriented the building systems adopted by the population. Cost efficiency and affordability of current housing reconstruction proposals are very problematic. In most of the cases, the reconstructed houses are smaller than the former ones and do not meet the needs of people in term of spatial usage, needs and practices

On the other hand, the relatively low enrolment for repair and retrofit grant may be due to various reasons:

The complexity of assessment and diagnosis of traditional and non-engineered building system due to the inexperience of experts and lack of technicians mastering structural diagnosis of damaged construction,

The absence of affordable repair and retrofit solutions for the HHs complying with the updated national standards,

And/or the low awareness and knowledge about the repair and retrofit options and costs, including experimental and academic.

In the Himalayan villages of Rasuwa, Gorkha and Dhading districts, and people claim for repair/retrofit support for their damaged houses, in particular for solutions that are suitable to their specific housing patterns, its stone masonry architectures, even the dry one. In the village of Gatlang (Rasuwa) for instance, where ASF Nepal and CRAterre have provided support to the community in the past years, people clearly expressed their will to preserve their old Tamang heritage: an

architecture built out of dry-stone masonry wall combined with wooden structures, wooden carved façades, and black wooden roofs. Gatlang's building culture clearly demonstrate earthquake resistant quality: the experimented use of these elements enabled a good behaviour of the structure and very limited consequences on the life of people. But still there is a need to improve understanding and the behaviour of these houses and their interactions with the built and natural environment to ensure much safer living conditions.

- Lack of knowledge on the behaviour of these vernacular architectures
- Lack of calculation methods, as a consequence it is particularly difficult to repair, or retrofit a house in this context considering at the same time locale practices, means and available resources, and national recommendations and norms.

Seismic retrofit of a structure is the correction of the major weakness in the structure relating to seismic performance. It refers to a process of enhancing the structural capacities such as strength, stiffness, ductility, stability and integrity of a building to mitigate the effect of future earthquakes. The need of seismic retrofitting of building arises under two circumstances: (i) earthquake damaged buildings and (ii) earthquake vulnerable buildings that have not yet experienced severe earthquakes.

*Seismic behaviour of a structure can be enhanced by adopting different retrofitting strategies. The choice of the optimal retrofitting strategy depends on good understanding of the dynamic behaviour of the building, cost of the chosen retrofit strategy and also on the future use of the building.*⁴

Apart from the post-disaster diagnosis bias, it has also to be pointed out that this work is not relevant just after the Gorkha EQ but could be very useful in preparing the future post-disaster reconstruction intervention as well as a more integrated approach towards DRR in Nepal and similar context.

Specific objectives:

- A. To identify and document the earthquake resistant building cultures of the Himalayan regions of Nepal affected during the 2015 earthquakes so that they can be later modelled, characterised, evaluated and validated by relevant scientific communities.
- B. To analyse the typologies and principles of construction applied in the Himalayan regions of Nepal and the appropriate means to rebuild, repair or retrofit housing in the affected areas following the 2015 earthquakes as well as to prevent and mitigate future disasters.

Expected results:

- A first inventory of the "para-disaster" local building cultures with a state of knowledge
- A recommendations report regarding priorities in terms of research, relevance and applicability
- Target audience: research laboratories, organizations involved in reconstruction and DRR in Nepal and in
- An article and a presentation at an international conference to promote the first results of research in "Humanities and Social Sciences" and "Engineering Technical Sciences". In particular, the preliminary validation results of a finite element numerical modelling method, considering the frictional interface between stone masonry, will be presented.

Rational:

- These architectures **are** disaster resistant:
 - Considering statistics on injuries / deaths due to collapse of houses in the studied area
 - Considering other risks: snow storms, high winds, landslides, etc.
- Criteria for studying this particular building system among the building cultures:
 - Previous actions
 - Cooperation with ASF Nepal
 - Lack of documentation
 - Lack of solutions
- Social and cultural demand for repairs and retrofitting: There are 144864 number of damaged houses in 14 districts that are used by the households in risk without repairing possibly because of not having other alternative shelters and couldn't repair the house.⁵
- Understanding the behaviour of some of the elements of this building system could be useful for other building system, including architectures built out of stone in mud mortar masonry
- Focus on a specific typology = realistic scope of this short study
- only a first step in a larger research program

Methodology

1. To do the state of art and knowledge of the research topic/ subject;
To list, document and roughly quantify the building practices and physical/tangible "devices" playing a role in reducing the vulnerability of buildings to EQ in the building cultures of the targeted area of Nepal, in particular dry-stone masonry architectures that may include wood in a specific way, from the data and information collected during field missions or by partners;
2. To define/establish hypotheses about the earthquake / para disaster function of these local building cultures, and their potential and conditions for reuse, repair or evolvement;
3. To identify and establish research priorities based on needs and potential uses and propose the "research pathways" and studies to be pursued to discuss the principles of these building cultures, considering also cost constraints;
4. To develop scientific specifications with identified research partners in Nepal and France as well as at international level;
5. To co-publish, share and disseminate results with/to scientific institutions and organizations involved in post-disaster reconstruction (or DRR), at coordination level with the HRRP (Housing Recovery and Reconstruction Platform) for instance;
6. To discuss the terms of the "roadmap" that the partners could possibly implement for these post-earthquake reconstruction practices under the responsibility of the competent authorities, specifically the NRA (National Reconstruction Authority).

2. Description of local building culture studied: dry stone masonry housing

1.1. Context: Tamang Heritage Trail

According to CBS, most of the drystone masonry houses are built in Rasuwa district, where they represent approximately 25% of the houses. So around 10 000 people of the 42 000 inhabitants are living in this type of houses in the district.⁶

For this reason, we chose to focus on the district and especially on the “Tamang Heritage Trail.

Tamang Heritage Trail (THT) was a program introduced by the Government of Nepal (GoN) as a part of Tourism for Rural Poverty Alleviation Program (TRPAP). This program provides an opportunity to ethnic minorities to exhibit their culture, customs and heritage⁷. THT is located in the Rasuwa district in province#3 which is close to the China boarder. This area is famous among tourist due to the Langtang national park and several trekking routes with beautiful mountains and diversified cultural integrity.

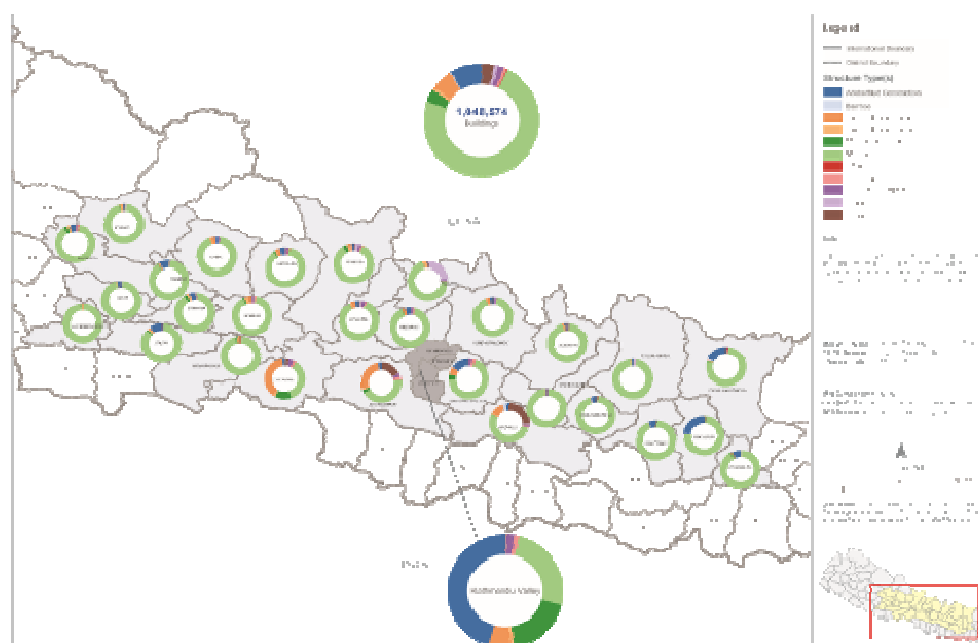


Fig. 1) Nepal: building typology as per CBS. (HRRP)

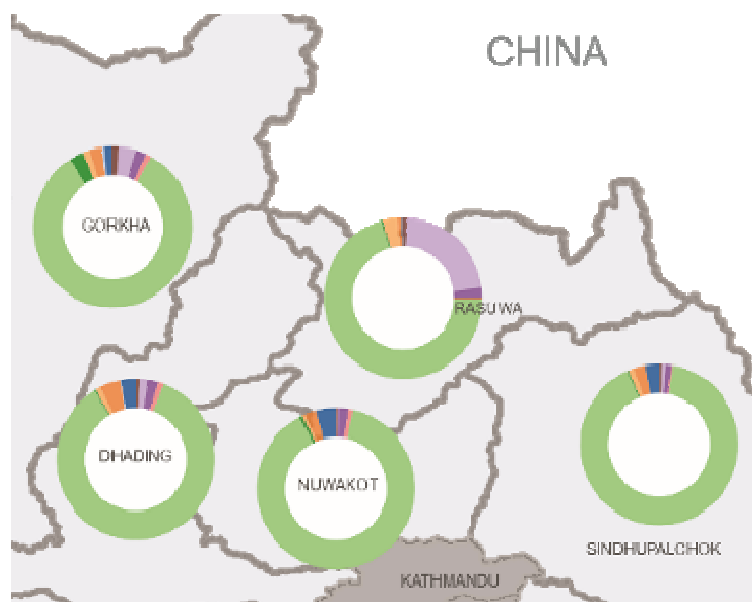


Fig. 2) Focus on Rasuwa district

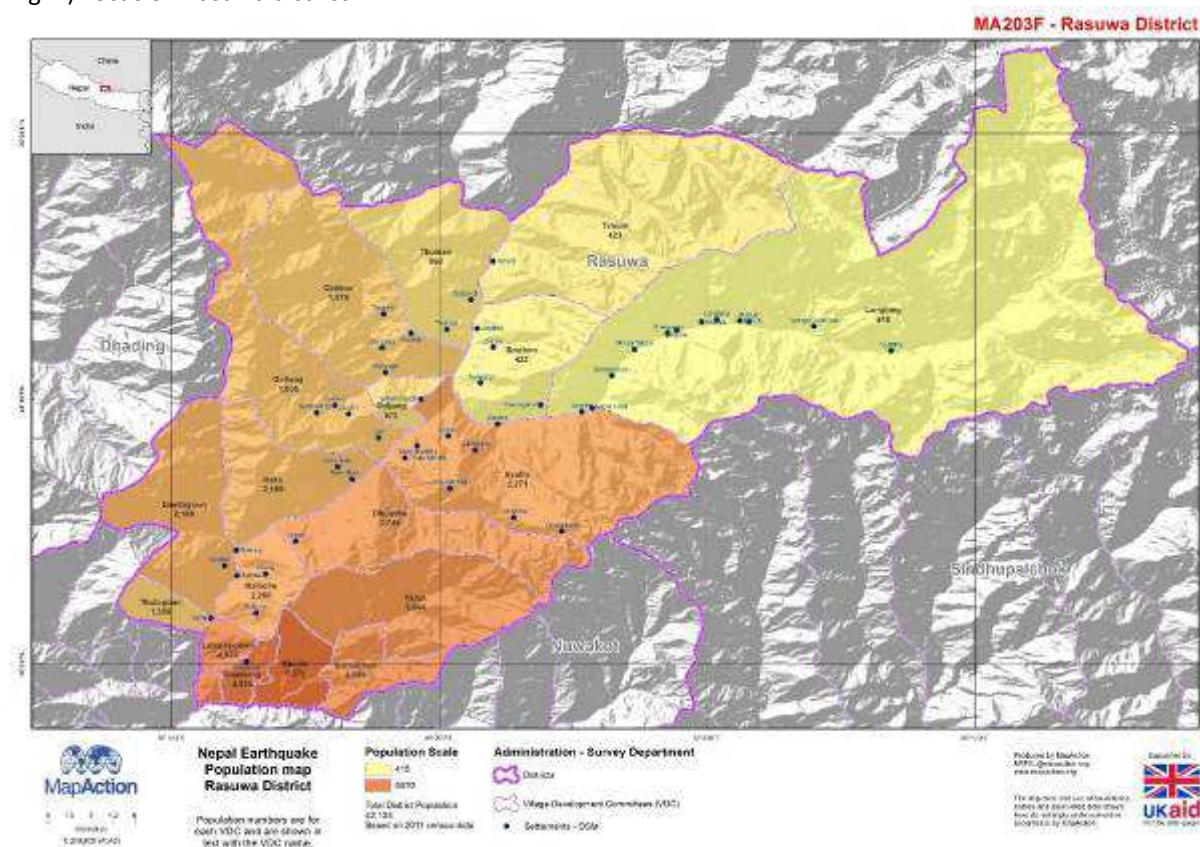


Fig.3) Population map of Rasuwa District, including in the considered region. (Map action)

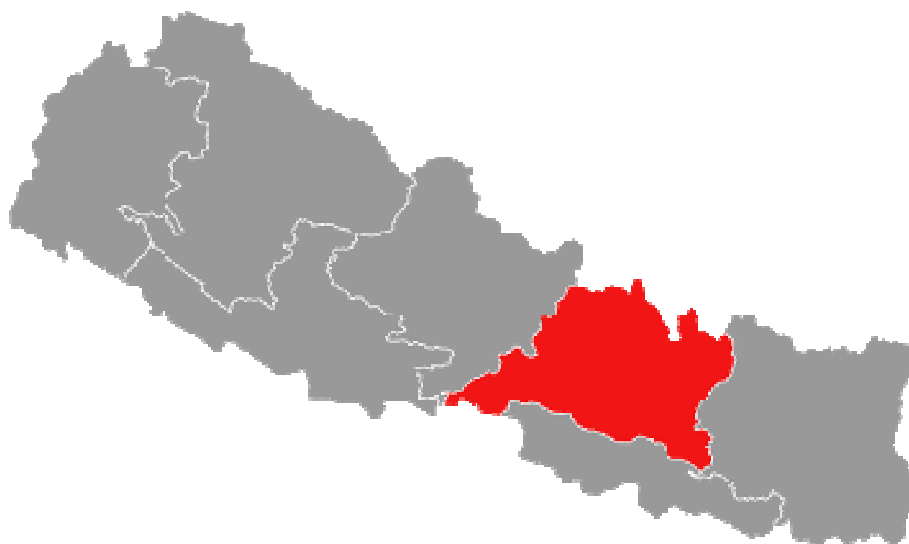


Fig. 4) Location of Province #3, Nepal. (Wikipedia)



Fig. 5) Location of Rasuwa district. Source Map of Province #3. (Wikipedia)

Local risks

- Earthquakes
- Strong winds: March and April are regarded as a strong windy month; as it blows from north-east to south.
- Landslides
- Heavy snow falls
- Low temperatures
- Heavy rains (monsoon)

1.2. Site: focus on the example of Gatlang⁸:

Geography:

- Gatlang is a small village in the northern side of Rasuwa district of Nepal. It lies at about 2200m from sea level and at almost 150 km distance from Kathmandu (only 50 km as the crow flies). At the Interfluve Trisuli-Ankhu Khola.
- The territory of the village occupies the entire upper valley of the Bemdang Khola River. The slopes of the left bank of the Bamdang Khola are SE, S, SW oriented, often higher than 40°, unsuitable for agriculture, difficult to access to the herds. The slopes of the right bank, oriented NW, N and NE, have slopes less than 30° and have therefore been terraced at the bottom.
- This slope is divided into 3 cultivation levels.

Natural Environment

- The upper part of the village territory (North) is covered with oak forest, rhododendron and pine forest up to 3600. Upper the territory is covered with lawn and heathland.
- There is a community forest of pine trees from where people get wood for different livelihood propose.
- Due to high rocky hill, there is very thin layer of organic soil so most of the land is barren.

Accessibility:

- Though it is connected through a gravelled road (with 17 km of poorly gravelled road), there is still lack of public transportation facility. The existing road can be only operated for eight months in a year and it is normally closed for four months during rainy season due to heavy landslides.

Settlement implantation:

- The village comprises of nine wards, of which six forms the centrally clustered village.
- The density of the housing implantation can be explained by the influence of production system. The village is indeed settled at the limit of 2 cultivation levels, though off-centre of the 3rd cultivation level.
- The inclination of the slope is relatively small (around 10°) on a large area.

Number and Size of households

- The clustered village counts about 400 households.

Facilities and infrastructure:

- The basic infrastructure such as drinking water, sanitation and waste water management and primary health are still not easily accessible among the community.

Population:

- Tamang is the main ethnic group represented in Gatlang along with Bishwokarma (Dalit caste). They all speak Tamang Language.

Livelihood activities:

- Agriculture is the main source of livelihood in Gatlang. The major crops grown include maize, finger millet, barley, buckwheat, potato, beans, black lentils, and vegetables.
- Some villagers grow apples, peaches, and plums as well. Overall, the main exports are potatoes, beans, and livestock.
- The average agricultural land holding is a little over an acre, and villagers still practices *parma*, a culture that relates to the reciprocal exchange of labour.

NB: The household food production is barely sufficient for six months.

- Animal husbandry – mostly chauris (yak and cow hybrids), goats, and sheep – is another major livelihood option for the people. Those who raise animals also sell livestock to local traders who transport the animals to Kathmandu/Trishuli during the festival seasons.
- Beside farm-related activities, women are engaged in weaving and preparing wool for those households that produce radi and pakhi, homemade caps and bags.
- A few people are also engaged in the tourism industry, as Gatlang is a major destination on the Tamang Heritage Trail. Women are getting the main respondent regarding tourism.
- Additionally, older villagers and youths who can identify non-timber forest products are engaged in the collection and trade of medicinal plants.
- More recently, the youth have become involved in trade and commerce, as the trade route between China and Nepal has become more functional.
- Another important source of income for the locals is the shares that have been issued by the Chilime Hydropower Company.
- Labour migration for foreign employment is emerging as an attractive livelihood strategy in Gatlang.
- The major push factor for this labour migration is poverty. Environmental stressors – rainfall variability, increase in temperature, decrease in snowfall duration and intensity, increase in wind speed and duration, thunderbolt, landslides have resulted in low agricultural productivity, hereby triggering migration⁹.

1.3. Characteristics of Vernacular architecture of the considered zone

The building culture observed in Gatlang is represented in a larger region so called “Tamang Heritage Trail, is localised in Province #3, in the district of Rasuwa, including the VDCs of Gatlang, Chilime, Goljung, Syafru & Langtang.

The following characteristics are based on the documentation gather mainly on vernacular architecture in Gatlang (which is better documented) & vernacular architecture of villages of the Langtang Valley.

Settlement implantation:



Fig.6) Top view of the village of Gatlang after 2015 EQ. (Source ASF Nepal report)

Main typologies:

- Single units: the house is isolated from other constructions.
- Row houses: the houses share a common wall.
 - Row houses parallel to the level lines
 - Row houses in the slope. In this case the level differences of the roofs induce extra complexity in connexion of the adjacent units

NB: In Gatlang, all row houses are settled in the slope (with probably 1-2 exceptions).¹⁰



Fig.7) Row houses in Langtang Valley after the avalanches due to the 2015 Gorkha EQ.



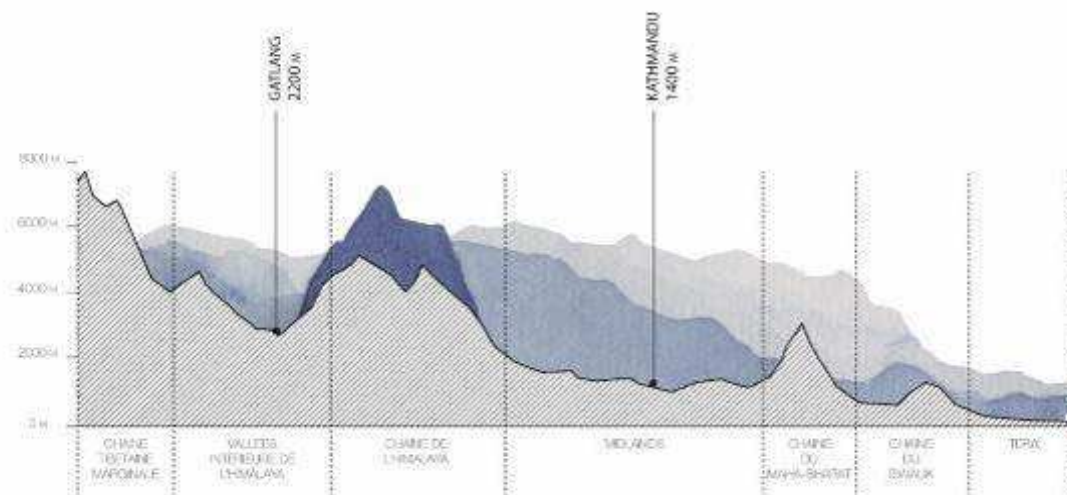
Fig.8) Row houses in Gatlang before Gorkha EQ

Orientation:

Generally, the houses face east to obtain enough solar heat during the day, which reduces humidity in the house and provides some thermal comfort.

Another hypothesis: the orientation is related to people believes, such as the “Vastu Shastra”. This traditional Indian system of architecture incorporates traditional Hindu and in some cases Buddhist beliefs. In this system:

- The east direction is given the first position;
- Veranda should be on east or north side;



- The main entrance should be on north, northeast or east but never southeast northwest or southwest;
- There should be no obstacles for air or light in front of the entrance which might answer why they have open space in front of their houses

Fig. 9) Location of Gatlang on a N/S section of Nepal. (source: Remy Buscot PFE)

Space arrangement

- Ground Floor: single room with open façade, used for shed of cattle.
- First floor: habitation. Kitchen is inside the house. Larger families' houses have a veranda.
- Attic: small attic, generally used for storage of goods and seasonal foods like potato, beans.

Dimensions

- Average size of house 39'x26'
- Average Room size: 17'7" x 26 x 24'1" & 17'8" x 24'1"
- Average Height of room varies from 6'-7'

Lifespan of constructions

- Some of the houses are more than 100 years old

Building Process & maintenance

- Normally it takes one month to complete the construction.
- Maintenance of a building used to be done annually, especially in festivals.
- All wood is unseasoned but the house-owner circulate smoke regularly

Load bearing system

- Key components of load bearing structures are: dry stone masonry wall and timber beam-column system.
- Houses have a dual gravity load-bearing structure: wooden beams and in the interior (and front side) and dry-stone masonry for the exterior.
- The load from the floor is solely carried by wooden columns. Floor beams are not resting on the wall: they are independent and only supported by wooden columns.
- Initially people construct the wall and then the other superstructure consisting in vertical posts, beams, and joists.

Walls

- the load bearing masonry walls are made out of dry-stone masonry (maybe due to the scarcity of soil for construction)
- trapezoidal shape of the wall is common, but rectangular shape is also observed
- average thickness of the wall: average 2'
- Gable wall: dry stone masonry with no openings
- Weak connection of walls observed
- the first floor is between 8' and 10' high

Foundation / plinth

- The depth foundation is generally shallow because of the hard rock underneath the soil
- But the width of the foundation is very large: 4' or more;
- No continuous foundation all around the building: front side is open (punctual foundation);
- No plinth differentiation

Vertical post, beam and joist

- Beams and joists do not rest on wall of the building.
- They are connected with vertical post raised from the floor.
- Vertical post lies 6"-12" away from the corner/wall.
- There is no nailing on the connection.
- The size of beam and joist are almost same (6" x 6") with 3' to 4' c/c spacing.
- The height of vertical post (attic level) are 3' to 4' located only on centre of the building (which supports the purlin)
- Height of post on ground floor and 1st floor: 6'

Floor/Slab

- Generally flooring is made out of wooden planks (1st floor & attic).

Partition walls:

- light partition (i.e. wooden planks) internal wall

Opening

- Ground is open (no doors nor windows).
- Front façade of first floor consist of carved door and window.
- All openings are on front side of the building (Winds blows from north-east to south so there is no opening on that surface of the building).
- Size of door: - 2.5'-3' x 5.5'-6'
- Size of window: - 2' x 3' and 3' x 4'

Roofing

- Double pitch roof (the pitch of the roof is relatively flat because wooden planks rest on the wooden purlins without any external connections).
- wooden Purlins, rafter and post
- No eaves board and strut
- Purlin resting on wall
- Wooden planks (*panglen*) roofing (rotated every year)
- No nailing on wooden planks so that it can be rotated easily
- Big stone or timber above planks for the support.

Finishes

- Inside: Mud plaster or wood cladding (living space)
- Outside: dry stone masonry



Fig.10) main façade of a house in Gatlang before Gorkha Earthquakes (source : ASF Nepal)

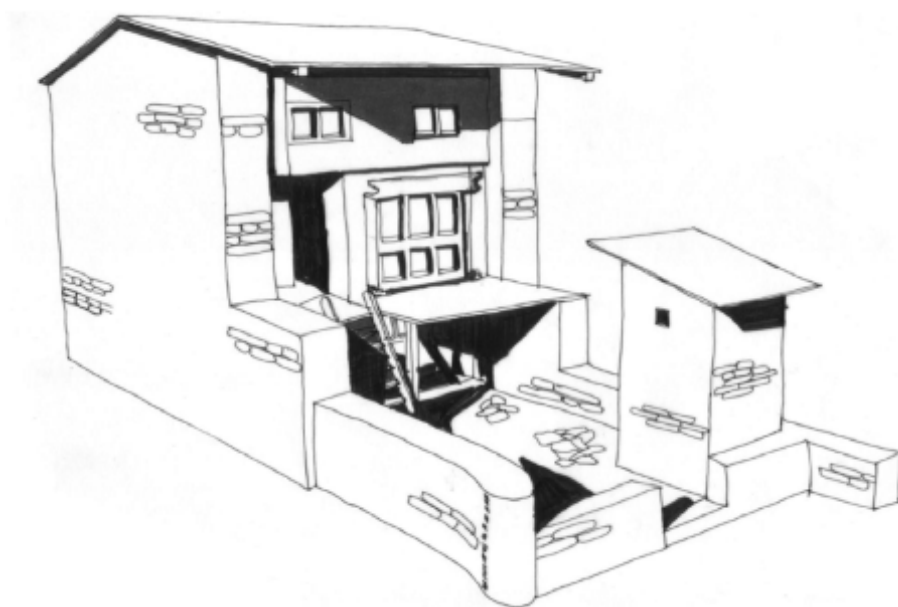


Fig. 11) House unite in Gatlang, in Final Report on Healthy Home Project, Rasuwa. (source ASF Nepal)

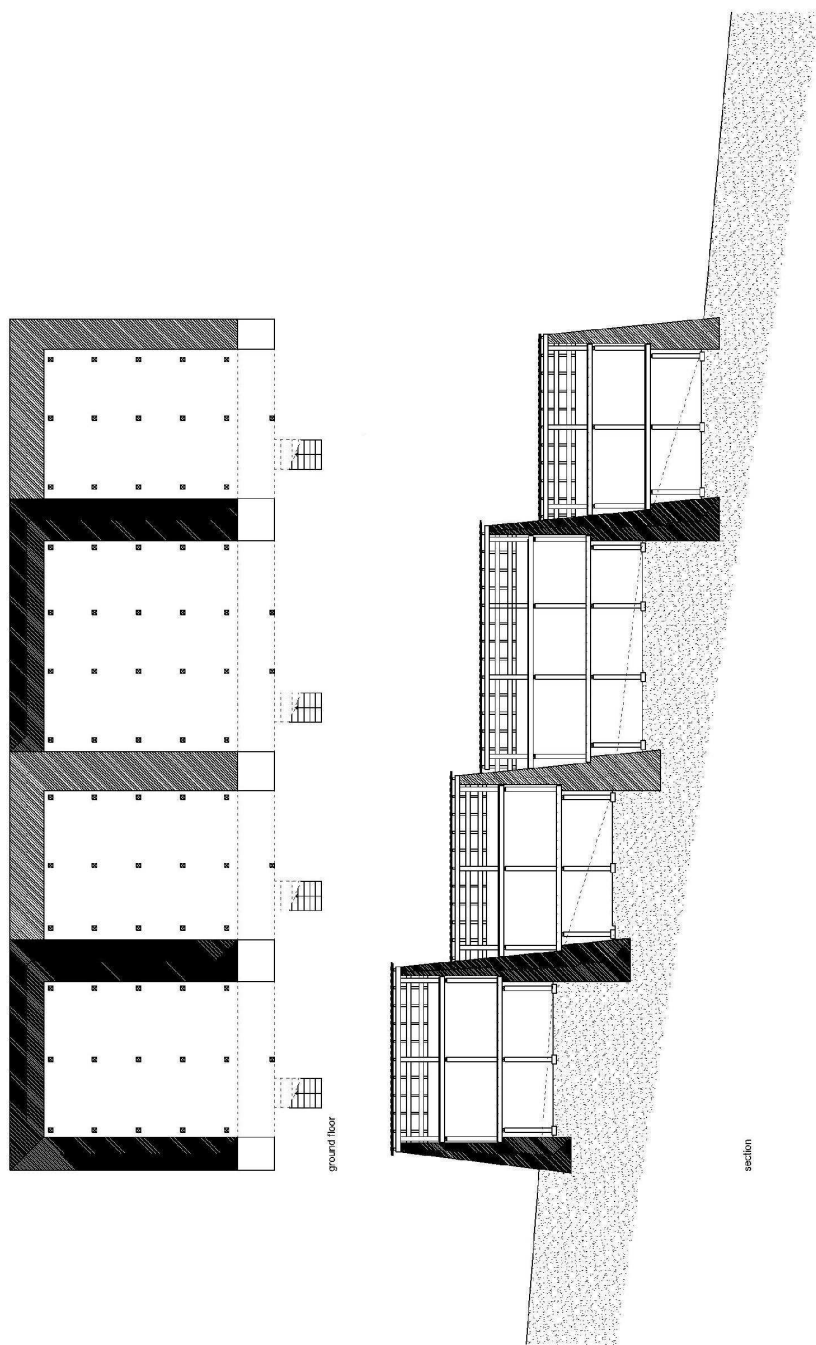


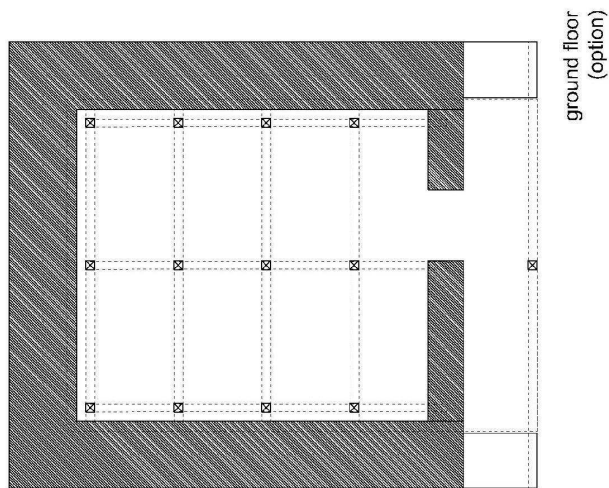
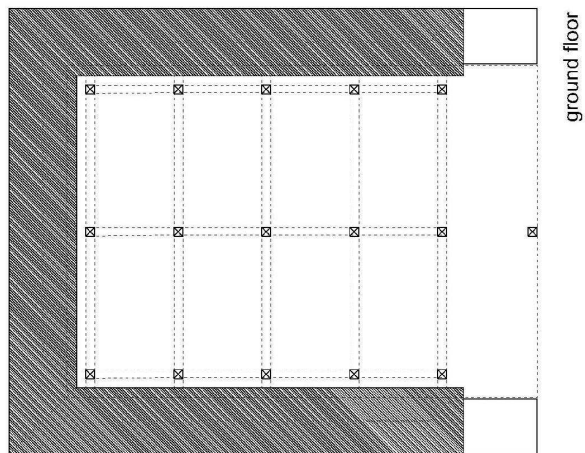


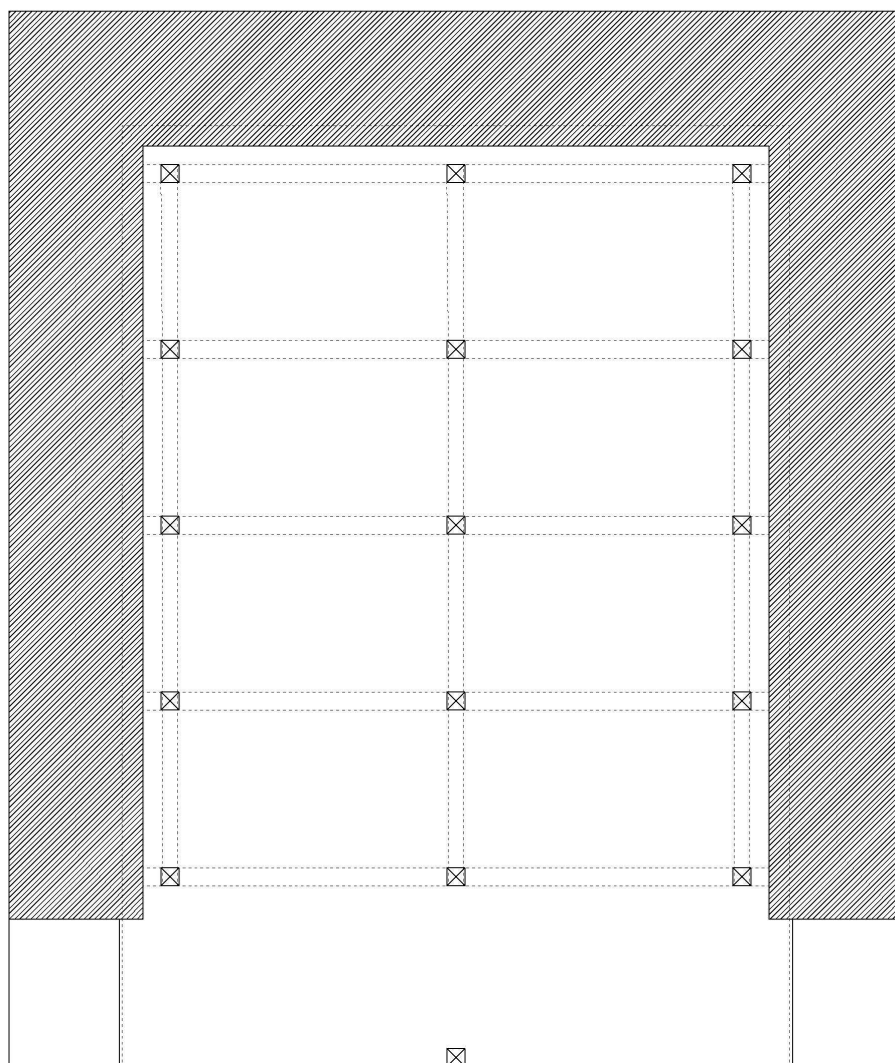
Fig. 12) Row of houses / Plan & section

GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry CRAterre J. Hosta	Row houses_plan			échelle 1:200	format A4	date 01.04.2020
						



GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry	Row houses_plan	échelle 1:100	format A4	date 01.04.2020	5m
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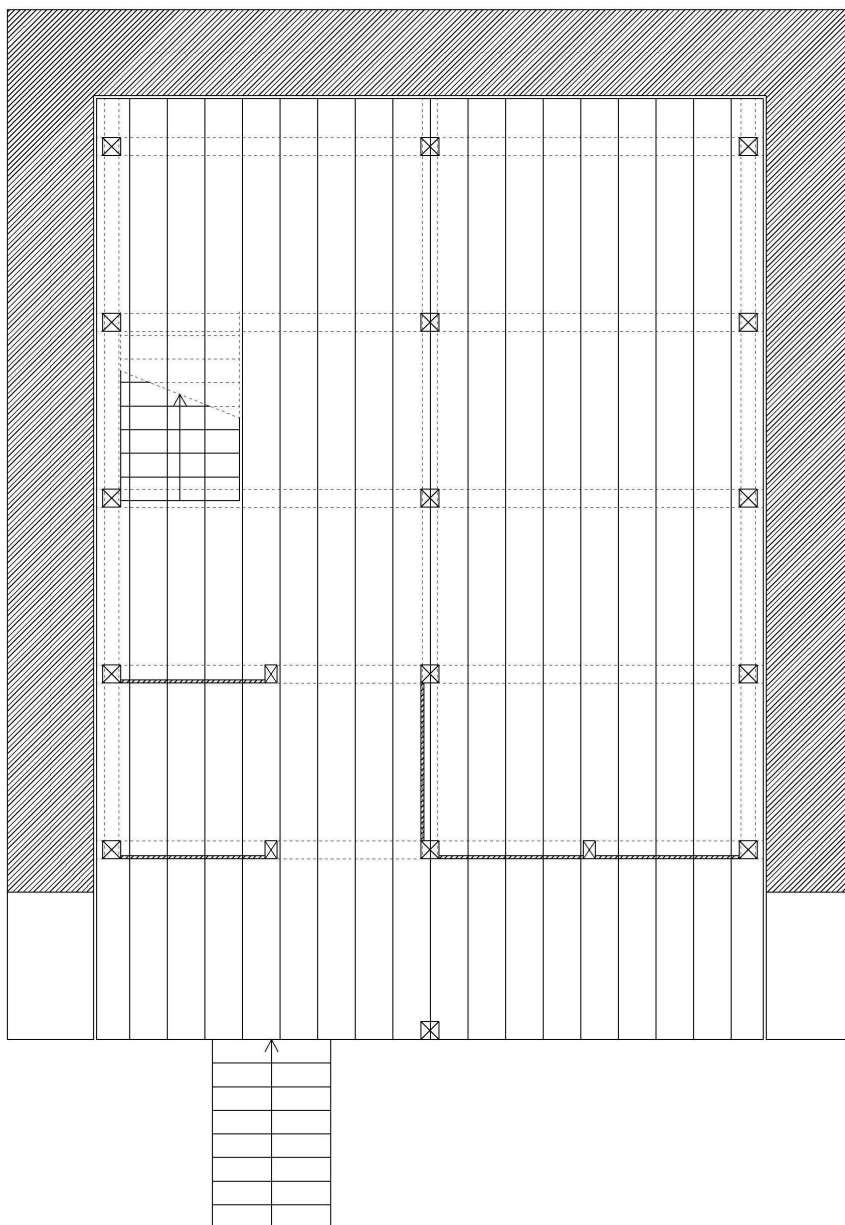
Fig. 13) Variants of house unit / Ground floor Plan



ground floor

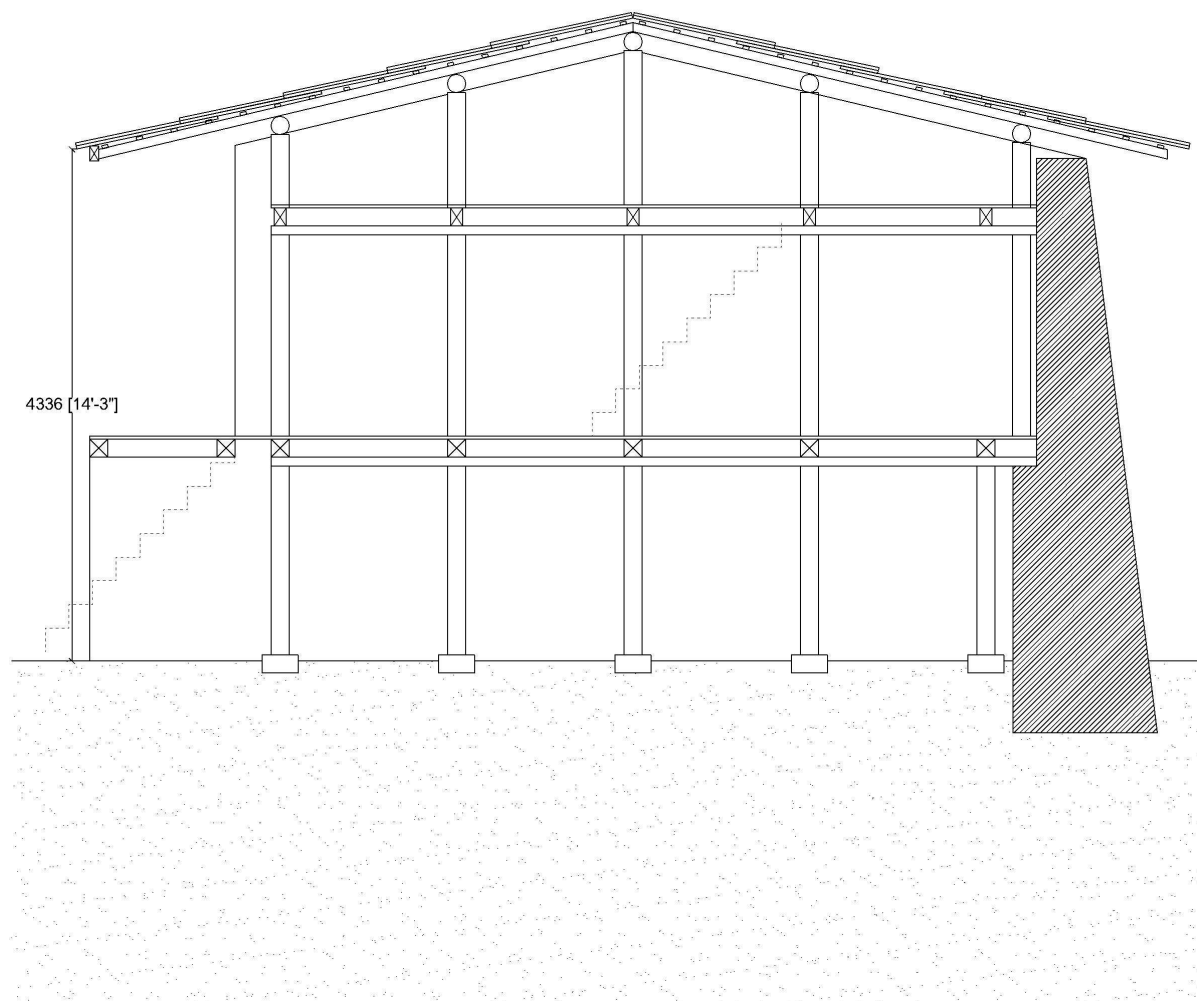
GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry		plan_ Ground floor	échelle 1:150	format A4	date 01.04.2020	
CRAterre J.Hosta	<input type="text"/> <input type="text"/>					

Fig.14) Sample of house unit / Ground floor



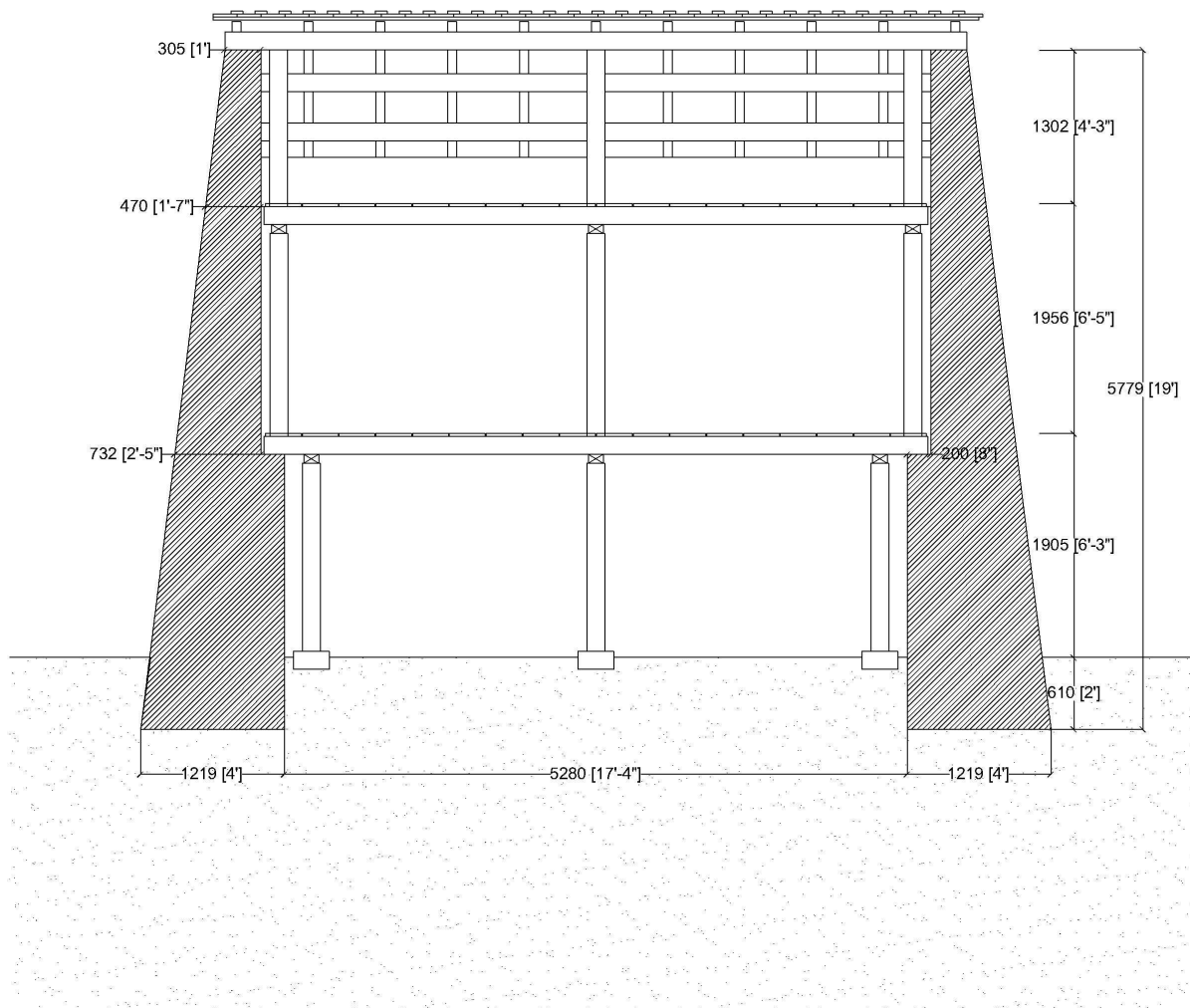
GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry		plan_ first floor	échelle 1:150	format A4	date 01.04.2020	
CRAterre J.Hosta	<input type="checkbox"/> <input type="checkbox"/>					

Fig. 15) Sample of house unit / First floor



GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry		section BB'	échelle 1:50	format A4	date 01.04.2020
CRAterre J.Hosta	<input type="checkbox"/> <input type="checkbox"/>	0 0.5 1 2.5m			

Fig. 16) Sample of house unit / Section.



GATLANG VERNACULAR HOUSE TYPE 1 Existing drawings - dry stone Masonry		section BB'	échelle 1:50	format A4	date 01.04.2020
CRAtterre J.Hosta	<input type="checkbox"/> <input type="checkbox"/>	0 0.5 1 2.5m			

Fig. 17) Sample of house unit / Section.

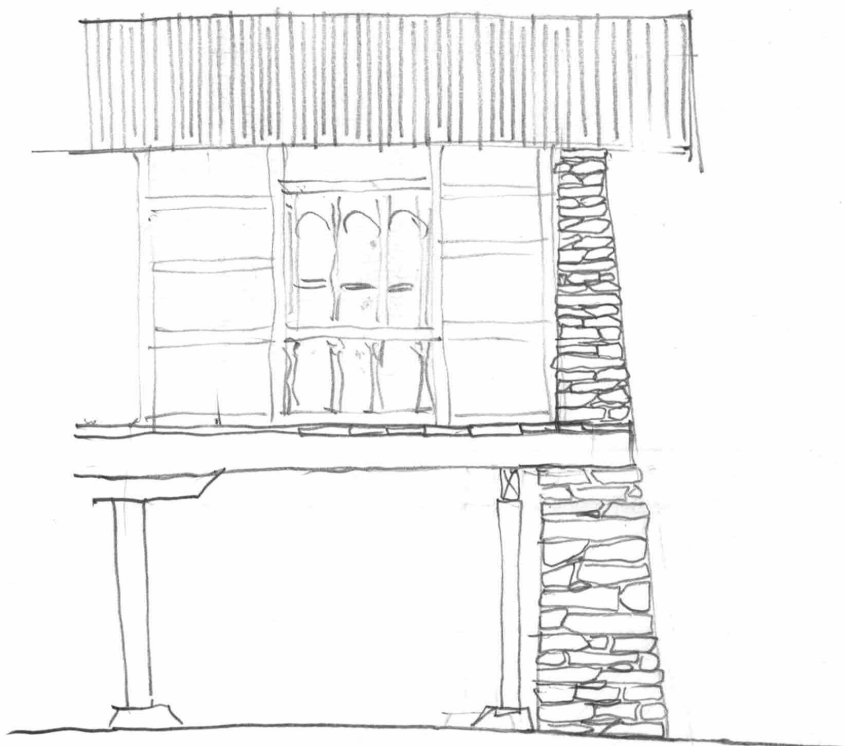


Fig. 18) Sample of house unit / Front view.

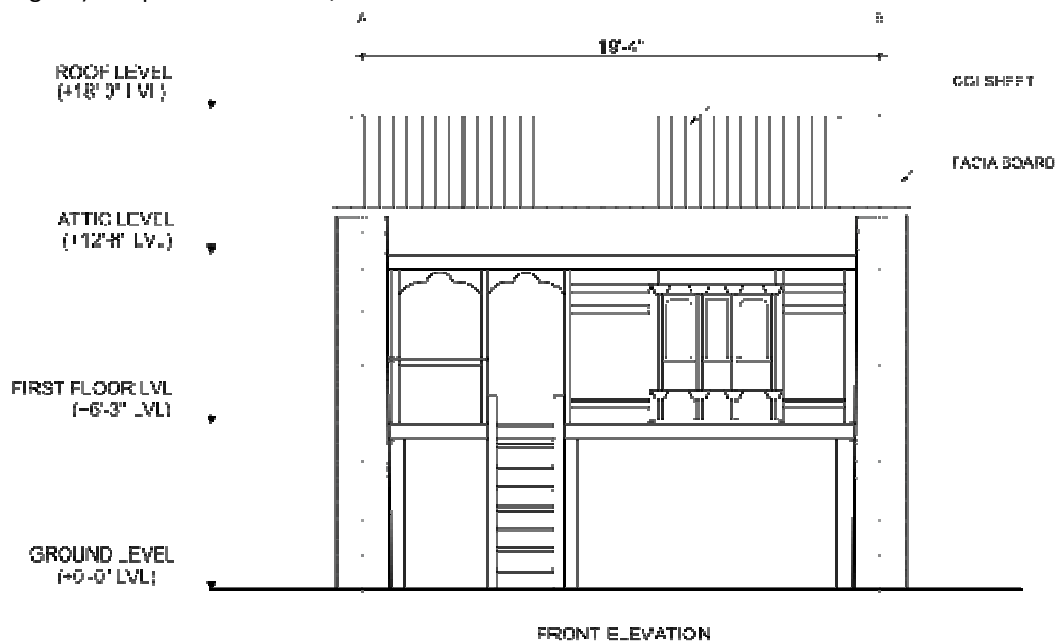


Fig. 19) Sample of house unit / Front elevation. (Build change)

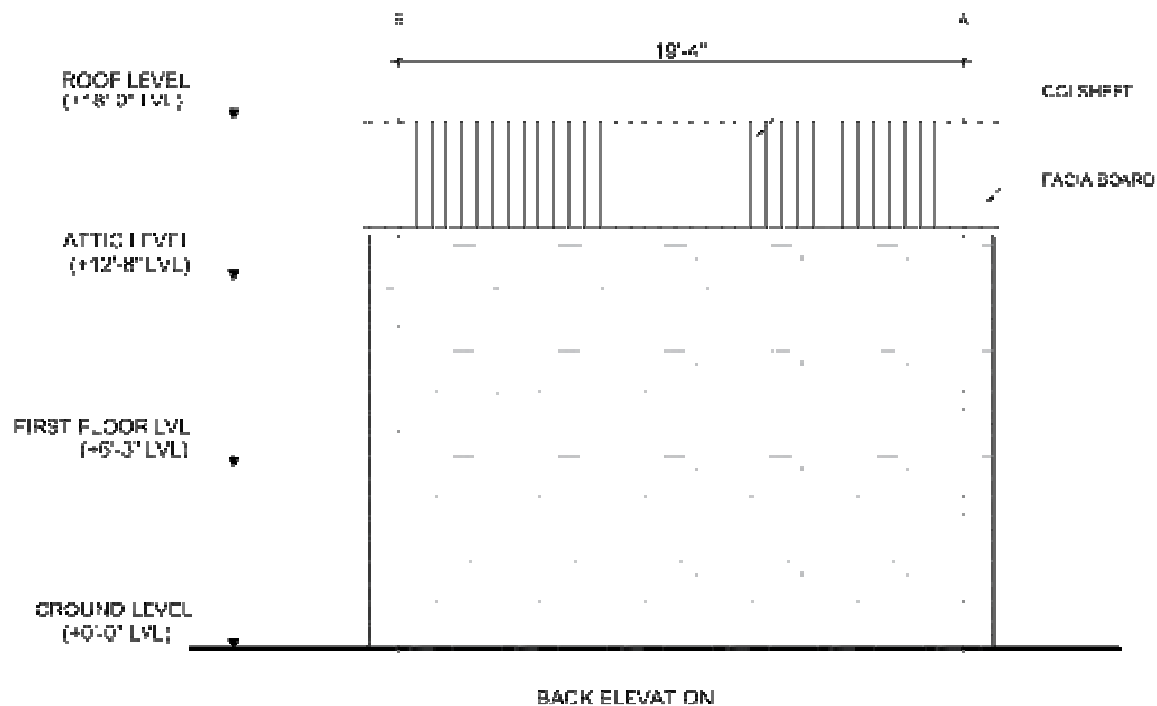


Fig. 20) Sample of house unit / Back elevation. (Build change)

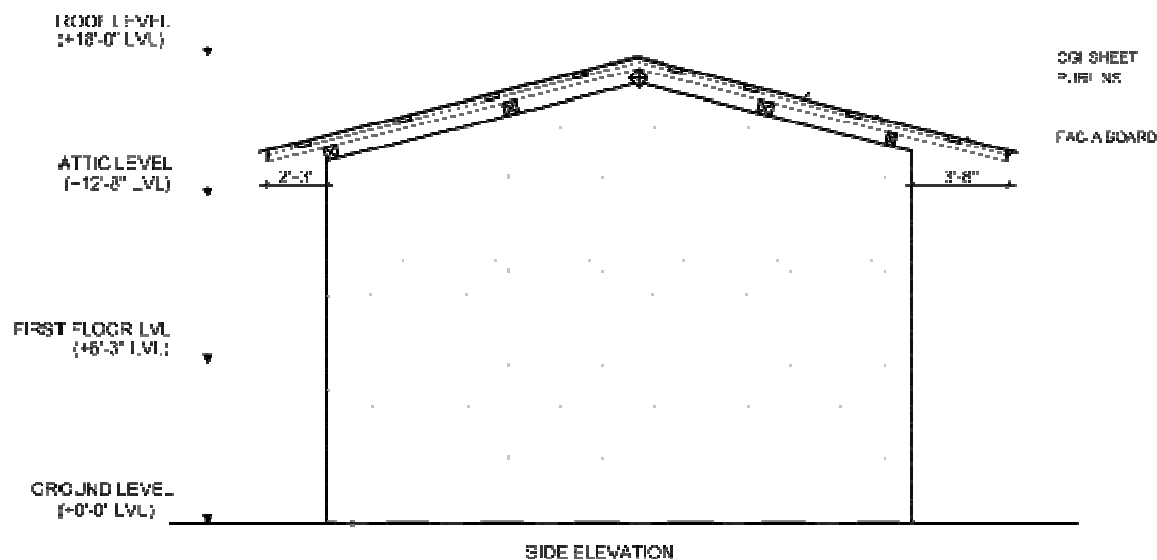


Fig. 21) Sample of house unit / Side elevation. (Build change)

3. Identified practices and physical or constructive devices involved in reducing the vulnerability of buildings to seismic risk - primarily

1.1. Settlement level

1.1.1. Row houses:

- peripheral L-shaped dry-stone masonry walls + wooden structure

Hypotheses: the series of units stand together, habitation units at the end of the rows have specific details and specific behaviour during a seismic event (need to characterize them)

1.2. Building level

1.2.1. 2 disconnected structures: peripheral walls and internal wooden structure

- Freestanding dry-stone masonry wall on 3 sides
- Wooden structure and wood cladding on the front façade connected with a wooden structure (posts and beams) supporting the floors and roof.

>see “sample of research catalogue”

1.2.2. Composite structure of the envelope: wooden façade and masonry walls.

Hypotheses:

1. [technique] Masonry walls and wooden structure walls work together. Dry-stone masonry walls and wooden façade have a similar stiffness.

1.3. Elements level

1.3.1. Drystone masonry walls

- Trapezoidal section wall, with wide base and adapted slenderness (1:4,5)
- Freestanding walls
- Inside plasters
- Inside wood cladding

Hypotheses:

1. [technique] The shape of the wall is reducing the risk of collapse during a seismic event
2. [technique] Inside plasters have a role in reducing risks of stone displacement / fall during a seismic event
3. [practice] Suitable spacing for placing of through stone which helps in enhancing out-of-plane resistance of the wall

1.3.2. Wooden structure: Flexible links between elements

- Posts are only standing on a stone without strong anchorage
- Posts and beams are not tied but there is a large surface of contact that allows horizontal displacement

Hypotheses:

1. [technique] During a seismic event energy dissipation at every node is high, wooden elements can move but within a “mastered” range, low risk of breaking of posts and beams.
2. [practices] After the event, wooden structure can be easily repaired (and elements reused)

1.3.3. Wooden roof

- Heavy roof

Hypotheses: load of wooden structure and wooden planks on top of the masonry walls is participating with the general behaviour of the wall, better than a light roof structure covered with CGI.

1.4. Material level

- Wood elements are exposed to smoke: wooden planks smoked on both sides Stone: walls are built out of dry-stone masonry, using flat stones including very large stones (up to 150cm)

Hypotheses:

1. [technique] high seismic energy dissipation thanks to friction between stones¹¹
“There is evidence to suggest (reference NSET shake table tests) that dry stone construction performs better in an earthquake than mud mortar stone construction due to greater friction between stones which reduces the transference of ground forces up the wall. In some cases, mud is used after construction to fill the air gaps in the walls, but this is not structural.¹²”
2. [Practices] Smoke protects wood elements for decay, improves the lifespan of these elements

4. Observations on damages after Gorkha's EQ (2015)

The following observations are based on field reports and pictures.

No systematic data has been collected. Some of the pictures studied have been taken months after the major EQs, during CRATERre Field missions (October 2017, January -February 2018), and shared by ASF Nepal.

The main damages observed are:

- Stone masonry walls distortion
- Partial collapse of drystone masonry walls, mostly on gable walls
- Displacement of timber, up to partial collapse of wooden structure
- Partial collapse of wooden roofing

The following table, vulnerability assessment has been prepared by ASF Nepal.

The major objectives of the assessment are the identification of vulnerability factors of local structures and evaluation of structural deficiencies and damages of existing buildings during the recent earthquake. The assessment is based on the visual observation of the buildings and Checklists of the seismic vulnerability based on FEMA 310 with some modification. The result of the vulnerability assessment of 100 buildings is presented in tabular form. Most of the buildings belong to this category.¹³

NB: This assessment should be cross-checked



Fig. 22) Damages on gables walls on a row of Houses. Gatlang (CRAterre)



Fig. 23) Stone masonry wall distortion. Gatlang (ASF Nepal)



Fig. 24) Partial collapse of gable wall. Gatlang (ASF Nepal)



Fig. 25) Partial collapse of wall / standing wooden structure inside. Gatlang (ASF Nepal)

vulnerability factors		Increasing Vulnerability of the Building by different vulnerability factors					Remarks
		High	Medium	Low	N/A	Not Known	
Geometry	Shape regularity			x			Shapes are almost square but lack partition wall.
	L:B ratio			x			L/B ration is not a problem but long wall without partition wall cause several problems
	Storey height		x				The first floor with dry stone masonry have almost 8- 10 ft. height may cause some problems
	Building Height	x					Dry stone masonry wall more than 15' height may cause serious problem in strong quake
	Roof	x					No proper connection and supported by stones from above increase vulnerability
Slenderness Ratio	Length/ Thickness			x			Since thickness of walls are around 2' so slenderness is not so problem
	Height/ Thickness			x			
Building System	Load Path		x				Load path is not continuous in wooden structures.
	Adjacent Buildings	x					Buildings are connected by common walls; failure in a building may cause ripple effect.
	Masonry units		x				Fall down of stones during lateral movement are strong possible since wall is dry stone masonry
	Masonry joints				x		
	Cracks in infill walls			x			No distinct cracks are seen because of lack of use mortar but movement of stone can be seen.
	Gable wall	x					Heavy weight dry stone gable wall without and bands or protection is vulnerable to fall during shaking.

vulnerability factors		Increasing Vulnerability of the Building by different vulnerability factors					Remarks
		High	Medium	Low	N/A	Not known	
	Wall Deformation	x					Possibility of Buckling or toppling of wall due to no cross wall to support. No tie between walls
Plan irregularities	Torsion		x				Lack of wall in front façade increase chance of torsion as asymmetrical wall system
	Diaphragm continuity	x					Especially wooden frame system
Vertical irregularities	Weak Storey		x				Drastically change in number of wooden posts from Ground floor to First floor causes some problems.
	Soft storey		x				Opening in Front façade of Ground floor where as covering by wooden plank in first floor make some soft storey effect.
	Mass irregularity	x					No wall at all at front façade.
	Vertical geometric irregularity			x			
	Vertical discontinuities		x				
Diaphragm Connection	Plan irregularities	x					
	Timber connection		x				No problems in the connection between timber members but connection in timber in roof is not good
Geologic site	Area History				x		
	Liquefaction			x			
	Slope Failure			x			
	Slope of Ground			x			
Others	Non-Structural Components			x			

Fig. 26) Vulnerability assessment report

5. Local response after Gorkha's EQ

Some houses have been repaired, without grant, but the result is not always as safe as the previous state of the building. This can be explained by:

- A need to repair fast, without any financial support
- Loss of know-how
- Repairs considered as a temporary stage

But still many houses are still to repair. People have built a small house compliant with GoN policies in the front yard.

- Some houses have been dismantled and replaced by new houses
- People are “returning” to their damaged house due to the need of adapted spaces for their livelihood activities, habits, etc.

NB: In those 2 cases, there is no (or low) consideration of the existing buildings around, which constitute a risk for future EQs or storms.



Fig.27) New house under construction beside an existing house in a row. (CRAterre)



Fig. 28) partially repaired house, showing evidence of vulnerability, see gable wall (CRAterre)



Fig. 29) partially repaired house, with addition of retrofitting component, see gable wall (CRAterre)

6. Applied methods for repairs and retrofitting of rural houses after Gorkha's EQ (at country level)

In the brief description of repair and retrofitting method and comparative matrix proposed below, we considered different options. The option of restoring the damaged houses back to their pre-earthquake state by observing the good practices and technical option is described in this document. Indeed, there are field evidences that:

- damages on people are very low
- quality of repairs after the EQ is uneven and should be improved

The main organization involved in retrofitting in Nepal after Gorkha's EQ have adopted the following solutions¹⁴ (with very few applications on drystone masonry walls):

- (A) GI wire mesh splint-bandage with GI wire jacketing (concrete plaster): NSET ("Baliyo Ghar")
- (B) RC Splint-Bandage with GI wire Mesh Jacketing: Build Change ("Strong back") and UNDP

Other retrofitting options have been applied at smaller scale such as:

- (C) Insertion of RC shear bands: CRAterre /ASF Nepal (On-site training in Gatlang, dry stone masonry)

And the following option could also be considered:

- (D) Wooden splint-bandage (+ gabion)
- (E) Wall jacketing using PP mesh and mud plaster
- (F) Addition of cross walls and buttresses
- (G) Vertical nylon straps

NB: All of these repairs and or retrofitting options have not been applied to the dry-stone masonry houses described in the previous chapter. But they could be considered as possible option to improve the behaviour of these houses in future EQ and other hazards.

1.1. Wall jacketing method (A)

Gabion wire or Geomesh (+ plasters) can be used to prevent the local failure of stone walls applied on one side or both sides of the walls. The mesh is anchored to the wall and then plastered with cement mortar. The mortar joint in a masonry structure is weak in tensile and flexural strength, thus, by application of wall jacketing, one improve the tensile and flexural resistance of the building and improve the integrity of the masonry components.

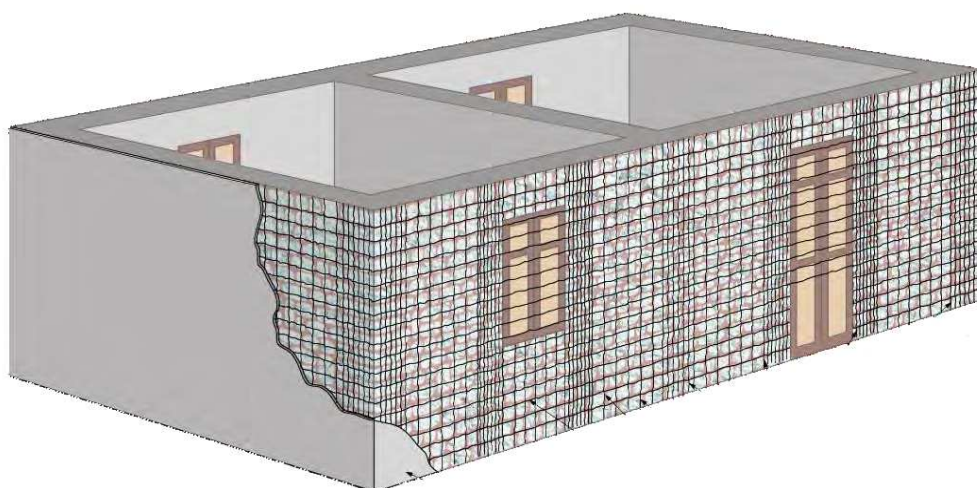


Fig. 30) Schematic drawing of Wall jacketing ¹⁵

1.2. RC splint-bandage with GI wire jacketing (B)

The RC splint bandage helps to prevent global failure of the structure whereas GI wire jacketing applied on the remaining portion helps in preventing local failure. During the application, RC splint bandage is applied around the opening, corner and T-junction to improve the resistance towards seismic loading. The GI wire is properly anchored to the wall for its effectiveness.



Fig. 31) Gatlang, retrofitted house using “strong back” approach¹⁶



Fig. 32) Gatlang, retrofitted house using “strong back” approach¹⁷

1.3. Insertion of seismic bands or shear bands (C)

The seismic band is a particular member that is used for providing seismic resistance to the low strength masonry structures at different horizontal level using various material: timber, bamboo or concrete. Such band could be continuous at plinth, lintel, and roof level and discontinuous at the opening location such as sill and stitch band. The proper application of such band helps to prevent chances of out-of-plane, in-plane and corner separation failure. The shear band at roof level also help in proper connection of roof with the wall and provide support during the seismic action (S. Yadav, 2017)

The following technic is not applicable in retrofitting since the bands are inserted in between masonry layers. But applicable for heavy repairs, with complete or partial dismantling of the dry-stone masonry walls.



Fig. 33) Repairs and reconstruction of gable wall (confined) in Gatlang, ASF Nepal /CRAterre 2017



Fig. 34) Repairs and reconstruction of gable wall (confined) in Gatlang, ASF Nepal /CRAterre 2017

1.4. Wooden splint-bandage (D)

Timber in Splint and Bandage Method of Retrofitting consists in adding a timber structure on both side of the walls. The main attention need to be paid for the connection between horizontal and vertical wooden posts. Such bandage can help to confine the wall and prevent global failure.

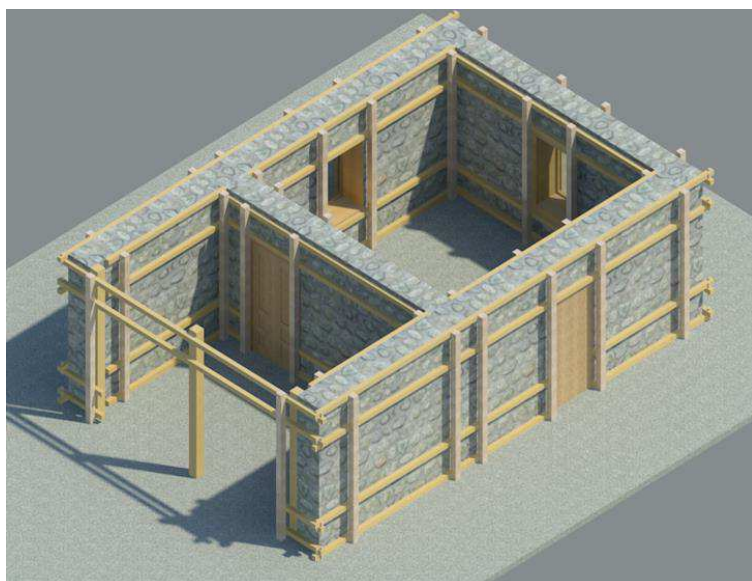


Fig. 35) Retrofitting scheme using timber 18
Variant: Wall jacketing + wooden bandage (+ gabion)



Fig. 36) Retrofitted wall sample with built-in wooden bandages with wooden posts combined with gabion wire jacketing¹⁹

1.5. Wall jacketing using PP mesh and mud plaster (E)

Polypropylene meshing uses common polypropylene packaging straps (pp-bands) to form a mesh which is used to encase masonry walls, preventing both collapse and the escape of debris during earthquakes. PP-bands are used for packaging all over the world and are therefore cheap and readily available while the retrofitting technique itself is simple enough to be suitable for local builders. PP meshing has been applied in Nepal, Pakistan and more recently in China. This method is most readily applicable in terms of low-cost upgrading of traditional structures to limit damage caused by normal earthquakes and give occupants a good chance of escape in a once-in-a-lifetime large earthquake.

To protect the Polypropylene from UV rays, mud plaster is used on the outside, providing adequate cover to ensure the durability of the material.²⁰



Fig. 37) NSET, Implementation of PP band method of retrofitting in Kathmandu Valley²¹

1.6. Addition of cross walls and buttress (F)

Description:

Addition of buttresses and / or cross walls can improve the behaviour of dry-stone masonry walls. This option should be considered mostly for building with unsupported walls of length larger than 12 times the average thickness of the wall.²²

This might not be the case for common constructions observed). This option could be particularly appropriate for end-of-row houses, most exposed in case of EQ.

NB: The connection of such elements with existing walls is a key element.

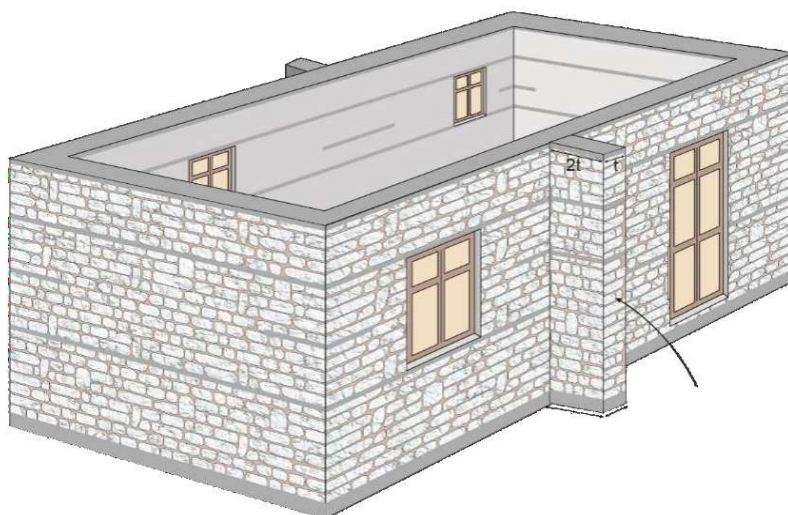


Fig. 38) Buttresses (outer face of wall)²³

1.7. Vertical nylon straps (G)

Description:

The use of nylon rods and straps in case of masonry structures helps to increase the ductility of the wall and also prevent out-of-plane failure.²⁴ The pre-tensioning of the straps is not required, however it should be tightened in order to eliminate slippage. This runs on both exterior and interior wall surface.

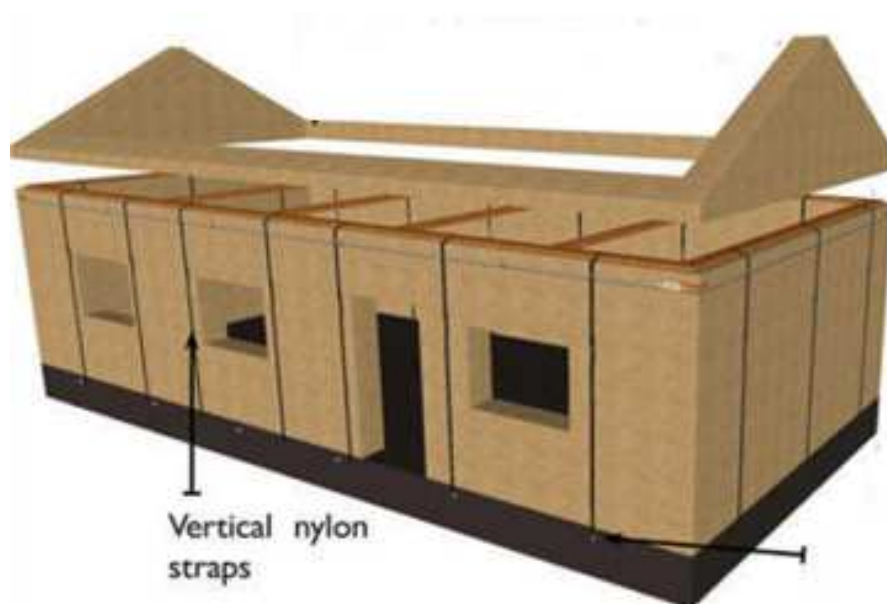


Fig. 39) Nylon straps on low strength masonry building (Michiels)

7. Comparative analysis of the different repair & retrofitting methods, applied to the case of drystone masonry house (presented typology)

In this table, the different repair and retrofitting methods presented are analysed not only regarding their technical characteristics, but also regarding the social, economic and environmental aspects so as cultural and concerning governance.

This table does not cover all the different technics that could be used. Combinations of technics, for example combination of addition of wooden seismic/shear bands and gabion have also been tested²⁵, and could be considered a good option.

When comparing the different methods, it is necessary to consider constructions with the same stress effects: type of damage and same site effects in particular.

It is interesting to note that the choice of location, architecture and technical details result from the consideration of other risks and the management of runoff water in particular.

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		LBC	#A	#B	#C					
#	Criteria	Repairs to pre-EQ state	GI wire mesh splint-bandage with GI wire jacketing	RC splint-bandage with GI wire jacketing	Insertion of shear bands	SOCIA	ENVIR	ECON	CULT	GOVE
1	compliant with national policies	no	yes	Yes (validated model)	Yes?					•
2	Behaviour in case of EQ	Good: FE	Good: minimize local disintegration of masonry material and enhance tensile and flexural strength of structure.	Medium: Difficult in proper connection on reinforcement bar with the wall	Good. Behaviour depend on the materials used for the shear band and connection typology of shear band (Yadav et al 2018)	•				
3	Behaviour in case of storms	FE	good	good	good	•				
4	Resistance to fire	medium	Good	Good	Better for RC shear band	•				
5	Affordability	FE, if possible, reuse of most materials	Medium to expensive	expensive	Low (bamboo) to Medium (soft wood) and high (hard wood /concrete) ²⁶			•		
6	Cost of local material in global cost of repair and retrofitting	Low if possible, reuse of material	Low	Low	Medium (RC shear band) to high (wooden or bamboo shear band)			•		
7	Cost of imported / industrial materials in global cost of repair and retrofitting	Low	high	high	medium			•		
8	life span of materials	depend on quality of wood	Depend of quality of RC elements (exposed to frost) Reinforcement element are also subjected to rusting due to lack of proper concrete cover space	Depend of quality of RC elements (exposed to frost). Reinforcement element are also subjected to rusting due to lack of proper concrete cover space	Depend of quality of RC elements (exposed to frost). Reinforcement element are also subjected to rusting if lack of proper concrete cover space Timber and bamboo treatment necessary		•	•		
9	Based on existing know-how?	yes	no	no	no				•	

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		LBC	#A	#B	#C					
10	Potential participation of family / neighbours /community	Medium (helpers for dry stone masonry)	medium	medium	Medium (helpers for dry stone masonry)	•			•	
11	Available skilled labour	yes	No	No	No	•			•	
12	Can be replicated without external support?	yes	no	no	no					•
13	Work duration (per house)	Medium	Medium	Medium	medium			•		
14	Period of construction	All year long	Only in Frost free period	Only in Frost free period Frost free period	Only in Frost free period Frost free period				•	
15	Availability of materials (transport?)	Possible reuse of materials? NB: difficult to provide new elements out of hard wood	Low	Low	High if reuse of materials. Medium for RC shear band		•			
16	Labour intensive	High	Low	Medium	Medium	•				
17	Adapted to repairs (heavy)	yes	yes	yes	yes			•		
18	Adapted to consolidation (no need for partial reconstruction)	Yes	Yes	Yes	no			•		
19	possible extensions	Yes FE	Not applicable?	Not applicable?	yes				•	
20	suitable for subsequent repairs/ maintenance (after hazards)	yes	Possible to dismantle / disassemble and reuse part of the materials?	Possible to dismantle / disassemble and reuse part of the materials?	yes			•		
21	Possible reuse of materials	yes	No	No	yes		•	•		
22	Impact on Aesthetic	Respect identity of the built environment	Introduction of new finishes (cement plasters)	Introduction of new finishes (cement plasters)	Low impact				•	

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		LBC	#A	#B	#C					
23	Impact on thermo-hydric comfort	air-permeable walls (cold) solar gain on wooden façade preserved	Airtight walls: less heat losses, but risks of pathologies due to humidity /inner smoke	Airtight walls: less heat losses, but risks of pathologies due to humidity /inner smoke	air-permeable walls (cold) solar gain on wooden façade preserved				•	
24	Impact on livelihood activities	No change	Access for animal on ground floor?	Access for animal on ground floor?	Non-change			•	•	
25	Impact on local environment	Medium: Pressure on wood stock if reuse of wooden element is not possible	Medium: more imported industrial materials (cement, iron)	Medium: more imported industrial materials (cement, iron)	Medium: Pressure on wood stock if reuse of wooden element is not possible. & need for imported materials for RC shear band		•			
26	Impact on global environment	Low	Medium	Medium	Low		•			


 Identified weakness

Fig. 40) Matrix comparing different repair options for dry stone architecture in the Himalayan regions of Nepal: main options applied

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		#D	#E	#F	#G					
#	Criteria	Wooden splint-bandage (+ gabion)	Wall jacketing using PP mesh and mud plaster	Addition of cross walls and buttresses	Nylon vertical straps	SOCIAL	ENVIRONMENTAL	ECONOMIC	CULTURAL	GOVERNANCE
1	compliant with national policies	Yes?	Yes	Yes	Yes					•
2	Behaviour in case of EQ	Better with gabion There is always a chance of local failure of material in between the bands. In such cases either closely spaced splints and bandages have to be used or the unreinforced wall panels need to be confined.	Increasing the structural ductility and energy dissipation capacities. Expected to prevent or delay the collapse, thus, increasing the rates of survival.	Help to reduce the out-of-plane moment in the wall preventing it from complete failure Should be applied in addition to other measures to increase the tensile and ductility of the structure	As vertical straps run on the both surface of wall, it can be helpful for providing confinement up to some extent and help to prevent collapse of wall in out-of-plane direction	•				
3	Behaviour in case of storms	To be completed	To be completed	To be completed	To be completed	•				
4	Resistance to fire	Wooden elements require fire protection	Good	Good	NB. Straps require fire protection	•				
5	Affordability	Low: due to the amount of timber required	Medium to high: cheaper than wire mesh and cement plaster	high	Cost could be medium to high depending up on the availability of the material			•		
6	Cost of local material in global cost of repair and retrofitting	High if local wood is used. Can be mitigated by the reuse of salvaged material	Low: check availability of sand / mud / fibres	high	low			•		

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		#D	#E	#F	#G					
7	Cost of imported / industrial materials in global cost of repair and retrofitting	High due to the cost of metal wire + rust protection	Low (PP mesh)	low	medium			•		
8	life span of materials	Low: Wooden element exposed to climate	No data	high	NB. Straps should be protected from UV / fire / etc.		•	•		
9	Based on existing know-how?	no	no	yes	no				•	
10	Potential participation of family / neighbours /community	medium	High (mud plasters)	yes	Easy to apply and required few tools	•			•	
11	Available skilled labour	Medium (wooden construction)	Yes (plasters)	yes	No	•			•	
12	Can be replicated without external support?	difficult	difficult	yes	No					•
13	Work duration (per house)	Medium	low	medium	Low			•		
14	Period of construction	All year long	Frost free period	All year long	All year long				•	
15	Availability of materials (transport?)	Medium (need to import wire gabion)	Medium (need to import PP mesh)	High (but depend on connection detail)	Medium (need to import nylon straps)		•			
16	Labour intensive	Medium	yes	yes	no	•				
17	Adapted to repairs (heavy)	Yes	yes	yes	yes				•	
18	Adapted to consolidation (no need for partial reconstruction)	yes	yes	yes	yes				•	

		REPAIR & RETROFITTING OPTIONS				Sustainability indicators				
		#D	#E	#F	#G					
19	possible extensions	yes	Yes	yes	Yes?				•	
20	suitable for subsequent repairs/ maintenance (after hazards)	Reversible / easy to follow up the need for repairs	Yes	yes	Yes?				•	
21	Possible reuse of materials	yes	YES	yes	Yes?		•	•		
22	Impact on Aesthetic	Aesthetic compatible with the local architecture since timber and other wooden elements are part of the commonly used elements	loss of the dry-stone wall appearance since the walls have to be plastered	Low impact	loss of the dry-stone wall appearance since the walls have to be plastered				•	
23	Impact on thermo-hydric comfort	Can be combined with inner wood cladding	Better: vapour / permeable airtight walls	low	low				•	
24	Impact on livelihood activities	No data	Impact on tourism appeal?	low	low			•	•	
25	Impact on local environment	Medium: Need to check or improve wood availability locally	Introduction of new material + Production of Solid wastes (PP)	low	Introduction of new material + Production of Solid wastes (nylon)		•			
26	Impact on global environment	medium	Medium (PP = petroleum derivative)	low	medium		•			


 Identified weakness

Fig. 41) Matrix comparing different repair options for dry stone architecture in the Himalayan regions of Nepal: additional options

Prepared by Julien Hosta_AE&CC /CRAterre-ENSAG

05 octobre 2020

8. Conclusions

The two main objectives of this research are:

1. To identify and document the earthquake resistant building cultures of the Himalayan regions of Nepal affected during the 2015 earthquakes so that they can be later modelled, characterised, evaluated and validated by relevant scientific communities.
2. To analyse the typologies and principles of construction applied in the Himalayan regions of Nepal and the appropriate means to rebuild, repair or retrofit housing in the affected areas following the 2015 earthquakes as well as to prevent and mitigate future disasters.

Considering the objective 1

First findings:

- There are field evidences that the settlements and houses documented here are disaster resistant since the damages recorded after 2015 Ghorka's EQ on the inhabitants is relatively low. These architectures respond to the main objective of a disaster resistant architecture: saving people lives. And they fit with most of the constraints people are dealing with locally, including social, environmental, economic & cultural aspects so as the governance.

Questions remaining:

In order to complete this research, there is a need to gather more data to better understand these architectures and better identify how to support the inhabitants in improving them (see "major missing information").

- Statistics on the damages (injuries / death) due to 2015 Ghorka's EQ
- Update on the situation nowadays of the inhabitants of the considered area
- Updated data on the capacities of the HHs and construction costs
- Updated data on the difficulties faced and solutions applied by the population for repair and retrofitting of their habitat, including

Next steps:

The gaps identified could be addressed and completed carrying field activities:

- Community based assessment on LBC
 - Sharing this first findings with the inhabitants and other local stakeholders
 - Preparing survey forms to fill the identified gap (see annexe 1)
 - Organizing joint assessment to gather complementary data on the house and settlement problematics today, including scaling up the assessment to a wider region.
- Post-disaster diagnosis preparedness
 - Training local professional to post disaster diagnosis adapted to stone masonry construction (and other non-engineered building systems).
 - Organizing Joint assessment to put into practice this specific diagnosis

Considering the objective 2

First findings:

- Supporting the population in repairing their houses so that they are at least as safe as they were before 2015 would be a necessary contribution to DRR. There are field evidences that local building culture ensure a globally safe behaviour of the constructions. But it is observed that recently built or repaired houses do not count with the main technical features and practices
- The addition of extra features such as buttresses could be a good option to consider too, depending on the geometry of the houses considered and their localisation in the built environment.
- Of course, other option could be explored in parallel or in a second step

Questions remaining:

How to make stone masonry and vernacular architecture more acceptable for the users (inhabitants of these regions) and fit with the national policies?

What should be the criteria for the acceptance of this building systems? And how to balance them? How to reach a consensus, and validate the meaning and importance of criteria such as those used in this study or of the Nepalese organisations, for instance NSET: Technical Reliability / Economic affordability / Local Availability of Material / Cultural acceptability / Sustainability and environmentally friendly.

Next steps

- There is a need to deal with the main barriers in order to validate repair and retrofit designs adapted to housing specifics and inhabitants' capacities: Experiments on first identified options (See annexe 2: research catalogue)
- But also to develop strategies with the local population to ensure access to quality local materials, in particular quality wood, since this resource is becoming scarce. This should include community forest management, support to local sawmills, etc.
- And to sensitize the population on the advantages of applying simple and affordable repair and retrofitting solutions, in order to make the homes safer:
- Research on repair and retrofitting should not only focus on technical aspects related to seismic vulnerability of the structures but also aim to identify and better understand all of the factors that influence the choices of the affected population in the recovery process.

Annexe 1: Preliminary list of missing information for complementary research

A more complete context analysis would allow to better evaluate the feasibility of the different repair and retrofitting strategies.

The methodology developed and adopted by CRAterre and research partners²⁷ could be continued, namely to develop the investigation on the following themes:

Local Building Culture assessment:

The data collected relate to housing typologies and construction characteristics. A detailed survey on housing typologies and construction characteristics is still needed as the available drawings and descriptions are still incomplete or not convergent.

The main identified gaps concern the following topics:

Context:

- Socio-economic profile: need to have an updated data base

Site

- Settlement implantation: updated data on clustered and scattered housing
- Proportions of houses settle in rows or isolated units
- Number and size of households
- Stakeholders in the area

Building process:

- Organization of building activities
- Roles in building activities
- Periods of construction

Maintenance

- Frequency of maintenance activities
- Frequency of repair activities

Skills for construction

Construction cost

- Main d'oeuvre
- Material cost
- transportation

Coping strategies

Post EQ diagnosis

- statistics on injuries / deaths due to collapse of houses in the studied area
- Statistics on the damaged houses (possible repairs), destroyed, dismantled houses (for reuse of materials? Reuse of space?)
- technical assessment of the main damages on the houses, considering:
 - housing typologies
 - Localisation: site effects, place in the rows, etc.

- Assessment on Reconstruction / repairs:
 - Statistics on proportion of households who have rebuilt/ repaired their house in the past 5 years?
 - Data on economic means, access to grants
 - Statistics on proportion of different options applied.

- Survey on the social demand
 - updated needs (financial, technical, administrative, etc.) and intentions of the inhabitants regarding their housing situation
 - What are the main challenges faced by the Hhs (regarding health, land tenure, etc.)

Annexe 2: Sample of research catalogue

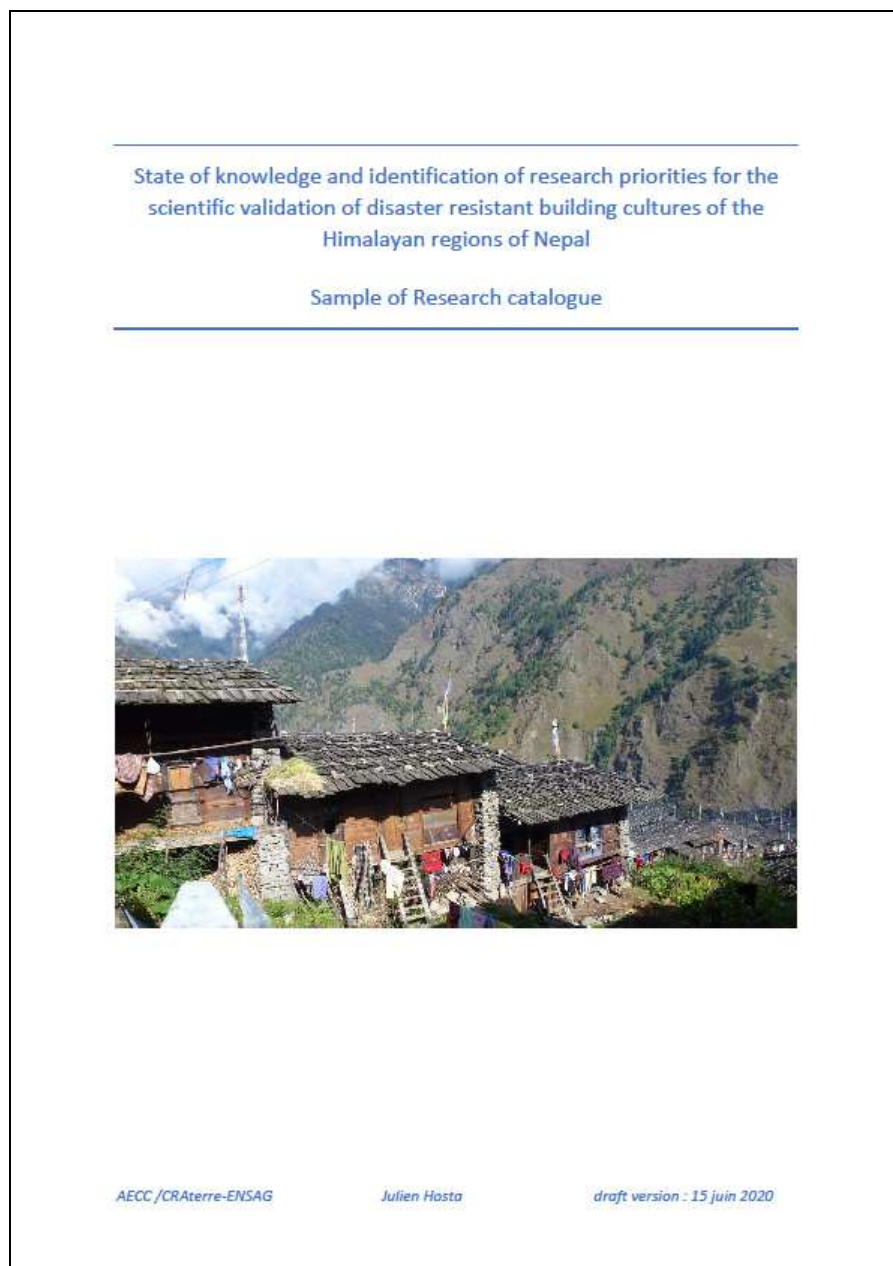


Fig.42) Preview of the annexe, shared as an additional document

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²⁵ See Ming Wang, · Kai Liu, · Ramesh Guragain, · Hima Shrestha, · Xiaowei Ma (2018). Shake table tests on the two-storey dry-joint stone masonry structures reinforced with timber laces and steel wires

²⁶ For details refer to cost analysis in reconstruction housing in Nepal taking mechanical aspect of traditional cultural construction, Yadav et al 2018 (In particular Figure 3. 12 Comparison of Different material used as shear band)

²⁷ See for instance Caimi Caimi, A., 2015. *Assessing local building cultures for resilience development*, and the work developed within the research project on shelter self-recovery :<https://self-recovery.org/>