THE SECULAR HOUSE

A manual for preservation and seismic improvement of vernacular stone dwellings in Bhutan

POLITECNICO DI TORINO

Corso di Laurea Magistrale in
ARCHITETTURA PER IL PROGETTO SOSTENIBILE

A.A. 2019-2020

Tesi di Laurea Magistrale

THE SECULAR HOUSE

A manual for preservation and seismic improvement of vernacular stone dwellings in Bhutan

Manuela Reitsma

RELATORI

Francesca De Filippi

Roberto Pennacchio

Takayoshi Aoki

Settembre 2020

Abstract ITA

La tesi mira alla ricerca di soluzioni tecnologiche volte al recupero di case rurali in pietra in Bhutan, con l'obiettivo di garantire sicurezza ai loro abitanti contro i terremoti che scuotono l'intera regione.

Il Bhutan è un piccolo paese, situato nella catena himalayana, che avanza in un mondo ormai globalizzato, in bilico tra la spinta modernizzatrice che ha invaso il territorio e l'anima tradizionalista che tiene a galla l'unicità di questa cultura. La grande sfida di questa ricerca, quindi, sta nel trovare soluzioni tecnologiche innovative, rispettando allo stesso tempo la cultura vernacolare architettonica e sociale del contesto rurale bhutanese, così caratteristico da connotare un panorama unico a scala mondiale.

La tesi si svolge nell'ambito un progetto di ricerca internazionale SATREPS "for Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan". Questo studio si rivolge, quindi, a tutti coloro che si troveranno ad affrontare queste tematiche, ma soprattutto si rivolge ai tecnici e agli artigiani locali, ovvero coloro che sono spesso chiamati ad intervenire sul recupero e manutenzione del patrimonio abitativo. Il linguaggio grafico scelto deve essere comprensibile anche a chi non ha particolari conoscenze tecniche, coinvolgendo nella causa ogni singolo abitante del paese. Il lavoro si sviluppa attraverso l'analisi del rischio sismico che minaccia il territorio e successivamente attraverso lo studio dei tratti caratteristici dell'architettura, delle tecnologie costruttive e dei materiali da costruzione tradizionali disponibili localmente. In seguito allo studio e alla rielaborazione di tecniche di intervento consolidate e all'ipotesi di nuovi approcci, si giunge infine alla realizzazione di un manuale di intervento che possa essere d'aiuto nella messa in sicurezza delle case rurali bhutanesi.

Abstract ENG

The thesis aims to find technological solutions for the recovery of rural stone houses in Bhutan, with the purpose of ensuring the safety of their inhabitants against earthquakes, that shake the entire region.

Bhutan is a small country, located in the Himalayas, advancing in a globalized world, poised between the push of modernization that has invaded the territory and the traditionalist soul that keeps the uniqueness of this culture afloat. The great challenge of this research, therefore, lies in finding innovative technological solutions, while respecting the architectural and social vernacular culture of the Bhutanese rural context, so characteristic to connote a unique landscape on a global scale.

The thesis is part of an international research project SATREPS "for Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan". This study is aimed, therefore, to all those who will face these issues, but above all it is addressed to local technicians and craftsmen, that are often called to intervene on the recovery and maintenance of the housing heritage. The graphic language chosen must be understandable even to those who have no particular technical knowledge, involving every single inhabitant of the country. The work is developed through the analysis of the seismic risk that threatens the territory and then through the study of the characteristic features of traditional architecture, construction technologies and traditional building materials available locally. After the study and re-elaboration of common techniques and the hypothesis of new approaches, we finally reach the realization of a manual of intervention, that help in achieving the safety of Bhutanese rural houses.

Introduction

The thesis is part of a collaboration between the CRD-PVS Research Centre and an international research project SATREPS "for Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan", involving the Bhutanese government, a group of Japanese research institutes (Nagoya City University, National Research Institute for Earth Science and Disaster Resilience (NIED), Kyoto University, Kagawa University, Tohoku University, Nihon University) and the Department of Architecture and Design of the Politecnico di Torino.

Bhutan is a small country in the Himalayan mountains. The incredible biodiversity and the rugged morphology have made the country inaccessible: Bhutan was hidden to the world for centuries and the isolation has made the region a unique place. The traditional architecture was preserved for a long time and nowadays is threatened by the modernization process, which is spreading in the country since the opening to the modern world in the '50s. Moreover, the region is subjected to strong earthquakes and rural vernacular architecture is even more vulnerable due to the impoverishment of the constructive knowhow. This thesis aims to develop a retrofitting manual for enhancing stone rural houses' seismic behaviour. Three steps have brought me to the aim: the personal discovery of Bhutan, through readings and conversations with a bhutanese girl, the study of the seismic risk of the country, with reference to architecture, and the research of retrofitting practices. Each step has allowed me to learn more and more about this complex country and about the seismic retrofit issue: the drafting of the manual reflects the several challenges. To simplify the reading, the tesis is divided intro six parts.

The FIRST part gives a brief geographical, historical and social overview of Bhutan, in order to bring out the complexity of the land and society. Bhutan is a rugged region with a mountainous morphology that make movements in the country hard, both for people and ideas. In this scenario, the modernization process brings other urban and social critical aspects. The tension between "modern" and "traditional" is crucial for retrofitting actions. The SECOND part develops a specific feature which brings out even more the complexity of the scenario: the disaster risk. The chapter begins identifying the hazards which affect the country and their impact on buildings and people. A focus on earthquakes is developed. Risk is then defined as the synthesis of three factors: the hazard, the exposure and the vulnerability. The hazard is the probability of occurrence of the natural event. The exposure represents the value of human lives, goods and heritage. Vulnerability concerns the strength of the building. Hazard and exposure are represented with the help of maps, leading to the risky zonation of Bhutan. The vulnerability is the factor which can be prevented by the retrofitting manual application, so it is better analysed in the following chapter. The THIRD part is about traditional architecture. Advantages and weaknesses of typical Bhutanese architecture are bought out in order to define the vulnerability. Firstly, the chapter starts with the design description that brings out historical, religious and social issues, as well as constructive ones. The richness and uniqueness of the traditional buildings are pointed out. The use of local materials, in particular, represents both a vernacular value and a weakness during the earthquakes. So, the issue is better developed in the fourth chapter. The FOURTH part is about construction materials. Traditional and modern materials are analysed, pointing out the local availability and the environmental and social impact, in order to find a compromise between vernacular materials and useful available materials which can be used for the development of the retrofitting actions. After the analysis of the seismic risk of Bhutan, with a specific focus on vulnerability, the thesis moves on drafting the common practices in seismic retrofit. It is the FIFTH part. This chapter is divided into three subchapters: the damages analysis, the common practices list and the selection of these practices, according to the issues developed in the previous chapters (the modernization incursion, the architectural heritage, the seismic risk, the available materials). The SIXTH part is the manual, which is divided in several procedure cards: each card proposes a different action which prevents several damages. The actions proposed comply with the workmanship skills and the tools and materials availability.

For having a better overview on Bhutanese scenario, the thesis must be read entirely. Despite this, each chapter is written so that it can be read separately, according to the reader's interest. Moreover, the bibliography is organized according to three levels, so that it is easy to find the origin of any information: references or numerical data in the text are followed by [author, year] of the original document; each paragraph has a numerical link to the outside column, where the main bibliographical sources are listed; at the end of the thesis the entire bibliography is divided into the six chapters.

Glossary

VERNACULAR ARCHITECTURE

"Vernacular architecture is an architectural style that is designed based on local needs, availability of construction materials and reflecting local traditions. At least originally, vernacular architecture did not use formally-schooled architects, but relied on the design skills and tradition of local builders." [1]

RESILIENCE

"The ability of a substance to return to its usual shape after being bent, stretched, or pressed. In the fields of construction, resilience is the ability to absorb or avoid damage without suffering complete failure." [2]

BHUTAN

"Hidden deep in the folds of the great Himalayan Mountains, Bhutan developed its own civilisation. The population, living in close harmony with nature, evolved a unique identity, derived largely from a rich religious and cultural heritage. The kingdom of Bhutan is a landlocked country bordered to the north by (the Tibetan Autonomous Region of) China and to the south by India. Covering an area of 38,394 km2, Bhutan is located in one of the world's most rugged and fragile mountain ranges. Extreme altitudinal variation ranging from 97 m in the south to over 7,500 m above sea level in the north make Bhutan one of the most ecologically diverse places. To the Bhutanese, their land is known as Druk Yuel: the Land of the Thunder Dragon." [3]

[1] https://www.hisour.com

[2] https://dictionary.cambridge.org
https://en.wikipedia.org

[3] DORJI, Yeshey. 2016. *«Water: securing Bhutan's future.»* Thimphu, Bhutan: Asian Development Bank.

National Environment Commission. 2016. *«National integrated water resources management plan 2016.»* Thimphu, Bhutan.

PENJORE, Thinley. 1999. *«Strengthening housing and urban development division.»* MoC, Urban Development and Housing Division, Thimphu, Bhutan.

Bhutan through the eyes of a bhutanese person

Before beginning the path of discovery of Bhutan, I would like to write down the words of a young Bhutanese woman, an engineer who helped me in the drafting of this thesis, for introducing to the reader this unique country.

1) How long have you lived abroad?

   "It has been almost three years being away from my home country."

2) What is the thing you miss most when you're away from home?

   "The hospitality of the people and social life. Even the food (spicy)."

3) What is the thing you like most about Bhutan?

   "A peaceful, safe and secure place to live in, under the leadership of farsighted kings."

4) If you had to change one thing about Bhutan, what would you change?

   "Hmmmmm, I can't think of anything for now. Bhutan is perfect as it is for me."

5) Can you describe to me a landscape of Bhutan that's clear in your mind?

   "The country is surrounded by beautiful mountains, where some of it has passes and trails which in olden days people used to commute from one village to another. In the present days, people enjoy going hiking and trekking through those trails. The country has beautiful traditional buildings with unique architectural features and each building stories has its specific use. The country is loving and peaceful and we can enjoy beautiful views of rice terraces, pasture lands, community forests and many sacred places."

6) How would you describe local people?

   "People are loving and caring. When we go to new place, the people in that place always welcome us with smile and offer us tea and food without expecting anything in return. We see enthusiasm in their eyes to know more about us and our whereabouts and what we do and so on."

7) Considering your work, what kind of approach do you have to tradition?

   "It has always been challenging as a conservation engineer. The traditional structures/heritage structures are under constant threat due to natural disasters, age of the building and impact of modernization. Safety measures usually comes with implementation of modern technique which cannot be applied due to conservation guidelines. In severe cases, modern technique is proposed and implemented but with approval from higher authorities."

8) Do you think it might be useful that students from other parts of the world take an interest in Bhutan and its problems?

   "It is always important to hear the third person point of view on any matters to improve it. Interest shown by foreign students in Bhutan and its problems is always welcomed and has always been useful. For example, our office (Department of Culture) hosted international competition on cultural landscape in Bhutan in year 2014. Students from various universities namely University College London (UK), University of Tokyo (Japan) and Chulalongkom University (Thailand) took part in it. It was an opportunity to hear innovative proposals from them in strengthening the cultural landscape of Bhutan."

9) If you had to define Bhutan with a word, what word would you use?

   "Did you mean just one word? Happiness."

Thank you.

1

CHAPTER

BHUTAN

"Tradition is not a "canon" that lasts for centuries, and it should not necessarily strive for cultural immobility. Tradition hold the potential to absorb the changes that are vital to the survival of mankind."

MARC DUJARDIN

1 | BHUTAN

The first chapter is a short overview of Bhutan, useful to understand the general aspects that make Bhutan a complex country. The geographical and climatic variety is developed in the first part. The second part is about the population: Bhutan is a rural country with different ethnic groups moving in the region. The last part deals with the modernization process, its impact on Bhutan and its inhabitants.

1.1 THE LAND OF THE THUNDER DRAGON[1]

Bhutan is a small kingdom locked in the Himalayan mountain range. The country has remained hidden for centuries, inaccessible from east, west and north because of the rugged mountain morphology, the dense vegetation and the severe climatic condition.[2] A unique civilisation has lived in that land in harmony with nature, developing its own identity and leaving a religious and cultural heritage. In the last decades something changed: Bhutan has opened its doors to the modern world. The sudden change "from the medieval age into the 21st century" [Penjore, 1999] has brought a rapid urbanization, the cultural impoverishment and a challenge: how to survive in the new modern world, how to achieve an equitable and sustainable development, how to guarantee a good quality of life, without losing the uniqueness of Bhutanese traditions. To understand the complexity of this challenge, let's start from the beginning.

The country is small, with an area of 38.394 km2, the maximum east-west dimension is 300 km and the north-south dimension is about 150 km [BEMP, 2016]. It is bordered to the north by the Tibetan Autonomous Region of China and to the south by India: a small land between two of the biggest countries of the world. High mountain ranges cross the country from north to south, decreasing from the 7.554m Kulha Gangri peak in the north to the 100m hill in the southern region [BEMP, 2016]. The height variation leads Bhutan to have several landscapes and a great biodiversity but, at the same time, these north-to-south mountains represent an obstacle in the east-to-west crossing, generating isolation of communities and inaccessibility of some areas. The road network connects the different valleys; anyhow, lots of rural villages remain isolated from the rest of the country.[3]
From north to south Bhutan is divided into three climatic and geographical areas: the higher Himalayas, the inner Himalayas and the southern foothills. The higher Himalayas is a glaciated mountain arc under perpetual snow, with an alpine climate. This region has a vegetation cover of shrubs and meadows. The inner Himalayas presents large valleys, fast rivers flowing north

[1] (DORJI, 2016)

[2] (KAEWKHUNOK, 2018)

[3] (Bhutan E-RNR Masterplan taskforce BEMP, 2016)

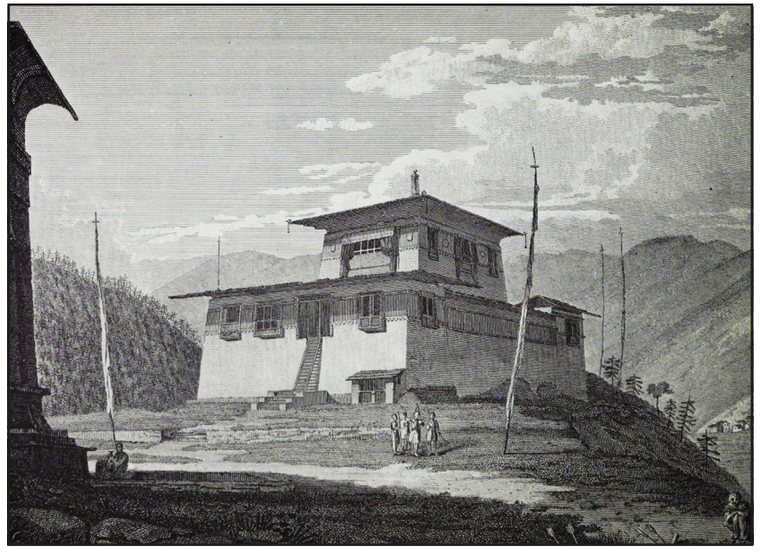
to south, coniferous forests and a cool temperate climate with moderate precipitation. The southern foothills decrease from 1.500 m mountain to the subtropical plain with a hot and humid climate, frequent rainfall and a warm broad-leaf forest.[4] As previously told, Bhutan has a great biodiversity but also a varied land with a small percentage available for human living. In fact, according to the LULC 2016 (Land Use and Land Cover), Bhutan is covered for 71% by forest, 10% by glacier and rocky outcrops, 3% by agriculture and horticulture, 0.19% by settlements [FRMD, 2017]. Moreover, 90% of the land has a slope of more than 25%, making this land subjected to runoff and erosion [NEC, 2016].

Land cover class [5]	Area (%)
Alpine Scrubs	3,39%
Built up	0,19%
Cultivated Agriculture	2,75%
Forests	70,77%
Landslides	0,10%
Meadows	2,51%
Moraines	0,37%
Non Built up	0,02%
Rocky Outcrops	4,15%
Shrubs	9,74%
Snow and Glacier	5,35%
Water Bodies	0,65%

[PICTURE]
(ARIS, 1982)

[4] (National Environment Commission, 2016);
(National Statistic Bureau, 2019)

[5] (Forest Resources Management Division, 2017)



1.2 THE BUTHANESE POPULATION

The geographical conformation of Bhutan, with its high mountains and fast flowing rivers, leads to the isolation of communities. This has made Bhutan a mix of different and unique believes, traditions and culture, despite the small extension of the country. Nomads live in the higher Himalayas, depending on livestock and dryland agriculture along the mountain slopes. These people live under black tents woven from yak hair. The inner Himalayas is inhabited mainly by the Ngalong [Aris, 1994], the dominant group of Bhutan, a Tibetan origin ethnic group. People there live in the fertile valleys, along the rivers: Buddhist influence is reflected in the villages of farmhouses, grown around fortress (Dzong) and temples (Lhakhang). Buddhism is the more practiced religion [NEC,2016]: the respect for nature and the preservation of natural resources is promoted by this culture. A Nepalese origin ethnic group of Hindu faith, instead, resides in the southern regions: they are called the Lhotshampas [Dorji, 2016]. They live in small fertile land surrounded by tropical jungle: the sub-tropical climate and the Hindu origin have led to an architecture pattern different from the Buddhist one.[6]

Agriculture and forestry are the base of Bhutan's economy. In fact, more than 80% of the population still depend on subsistence agriculture and livestock for their livelihoods [Kaewkhunok, 2018]. Despite this, as previously told, only 3% of the land is cultivated. Moreover, the fields are located in the bottom of valleys, exposed to flash floods and land degradation. In the last decades, economy is also driven by hydropower, industrial sector (dolomite and limestone mining, cement, ferroalloys), handcraft and tourism.[7]

[PICTURE]
(ARIS, 1982)

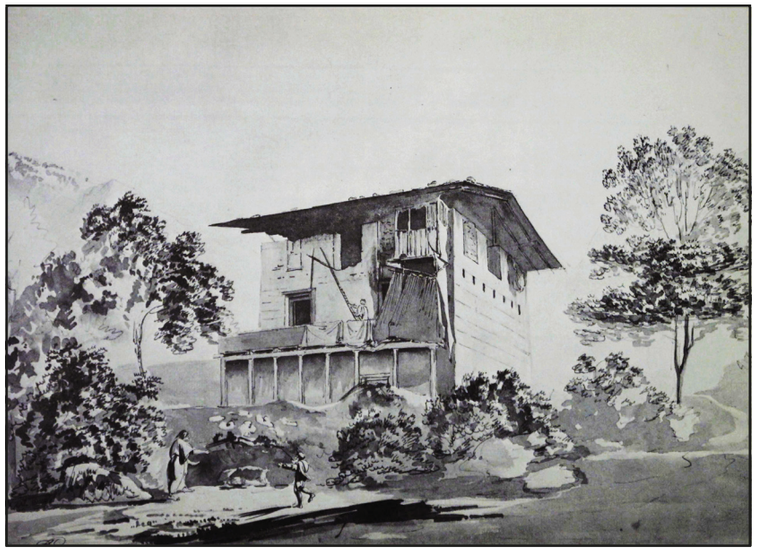
[6] (ARIS, 1994);
(National Environment Commission, 2016)

[7] (DORJI, 2016);
(Forest Resources Management Division, 2017);
(Ministry of Works and Human Settlement, 2008)

	Dzongkhag [8]	Urban people	Rural people
WEST	Samtse	1,4 %	7,3 %
	Haa	0,4 %	1,5 %
	Paro	1,7 %	4,8 %
	Thimphu	15,9 %	3,3 %
	Chhukha	4,9 %	4,6 %
	Gasa	0,2 %	0,3 %
	Punakha	1,0 %	2,9 %
	Wangdue Phodrang	1,4 %	4,4 %
	Dagana	0,6 %	2,8 %
	Tsirang	0,5 %	2,5 %
	Trongsa	0,5 %	2,3 %
	Sarpang	1,8 %	4,5 %
	Bumthang	0,9 %	1,5 %
	Zhemgang	0,5%	1,9 %
	Lhuentse	0,3 %	1,7 %
	Mongar	1,4 %	3,7 %
	Pema Gatshel	1,0 %	2,2 %
	Trashi Yangtse	0,5 %	1,9 %
EAST	Trashigang	1,4 %	4,8 %
	Samdrup Jongkhar	1,7 %	3,1 %
	TOTAL	**38 %**	**62 %**

[PICTURE]
(ARIS, 1982)

[8] (National Statistic Bureau, 2019)



Bhutan is divided in 20 regions called Dzongkhags (subdivided in gewog for a total of 205 gewogs)[9]. People are not evenly distributed in these areas: 44,3% of the population reside in the western regions, the 14% in the central-western, the 14,1% in the central-eastern, the 27,6% in the eastern regions [MoWHS, 2008]. Moreover, urbanization is mainly located in the western regions where 65% of the urban population resides [MoWHS,2008]. In fact, according to the previous tab, eastern regions are inhabited mostly by rural communities, western regions are divided between rural and urban communities. This factor makes the migration in the western urban zone more frequent, improving always more the population in these regions.

Bhutan is a mix of cultures which enhance the uniqueness of the country: the conservation of traditions is crucial. Despite this, the migration in urban areas is growing up and the rapid urbanisation does not allow to have control over the growth of the towns. There is a duality between the uncontrolled towns and the isolated rural villages: both represent a challenge for the conservation of the traditions and, at the same time, the improvement of the quality of life.

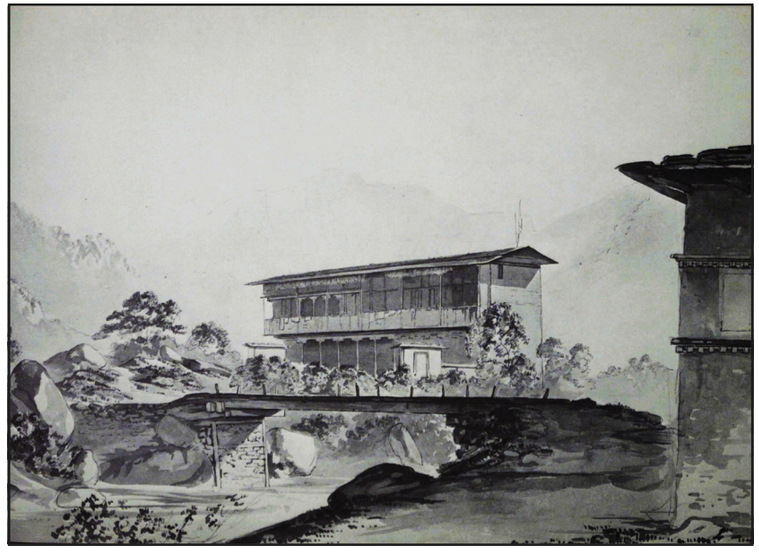
1.3 THE MODERNIZATION PROCESS

According to the "Statistical Yearbook of Bhutan", in 2017, 727.145 people were living in Bhutan: 38% of population were living in urban area [NSB, 2019] and the number is supposed to grow up.

Bhutan for centuries was an isolated place where different communities lived in contact with nature, excluded from the events

[PICTURE]
(ARIS, 1982)

[9] (DORJI, 2016)



which affected other countries. The country was unified as a single state in 1616: a dual system, temporal and spiritual, went on until 1907, when Bhutan became a monarchy. Then, the country chose a self-imposed isolation. Only in 1950, the king Jigme Dorji Wangchuck opened up the country to the world and introduced an inclusive modern economic development, based on the Gross National Happiness concept [10]:

"promotion of equitable and sustainable socioeconomic development, preservation and promotion of cultural values, conservation of the natural environment, good governance".
[BEMP, 2016]

In 1961 the development programme started: the "Five Years Plans" were formulated every five years in order to modernize the old institution and to improve the communication with the outside world: construction of roads, improvement of education and health facilities, enhancement of agricultural production, promotion of national identity and sustainable development were planned and nowadays the programme is still going on.[11]

Unfortunately, the consequence of modernization was the growth of population, which led to several critical aspects. As previously told, the agriculture is limited to a small area, due to the difficulties of farming on slopes. So, the educated younger generation starts migrating to urban areas, leading to a decline of the agriculture workforce and the rapid and uncontrolled urbanization. It is estimated that 13% of the population resides in Thimphu alone [NEC, 2016]. Moreover, it was observed that the urbanization is leading to a forest cover decrease and the "Land Use and Land Cover" of the country will change over the years.

[PICTURE]
(ARIS, 1982)

[10] (ARIS, 1994);
(KAEWKHUNOK, 2018);
(WEBB, 2004)

[11] (AKIKO, 2003)

The rapidity of urbanization brought problems in the towns too: inadequate infrastructure, water storage, pollution, waste generation, land degradation have impact on the environment.[12]
The modernization leads to the impoverishment of traditions and culture, so the preservation of the Bhutanese heritage and identity has become a crucial aim for the government: the new development approach must coexist with the Buddhist beliefs and values, the country must act "as custodian of a distinctive and unique culture" [RGoB, 1999].

In conclusion, Bhutan is a unique country with a great biodiversity. The mountainous morphology leaves a little space for human life: agricultural and build up lands are a small percentage of the total country. Moreover, connections between villages are difficult, leading to isolation and inaccessibility. Those issues, during the centuries, resulted in different ethnic groups: a rich cultural heritage characterizes the country. Climatic conditions are diversified too, according to the variety of landscapes. A short overview on Bhutan quickly brings out the cultural and morphological complexity of the country. Modernization caused the rapid urbanization: this uncontrolled process brought benefits but at the cost of cultural values' impoverishment, disparities increase and environment degradation. The national identity must be preserved, but the conservation is hampered by both the isolation of the villages and the uncontrolled growth of the towns. So, morphological, cultural and social variety is surely a treasure but also a complicated challenge.

[PICTURE]
(ARIS, 1982)

[12] (Ministry of Works and Human Settlement, 2008);
(National Environment Commission, 2016);
(UGYEN, 2015)

2
CHAPTER

RISK

"Earthquakes are a special category of hazards in that most human losses are due to failure of human-made structures – buildings, dams, lifelines, and so on. Therefore, in principle, with sufficient resources for research, development, education, followed by necessary investments in hazard reduction, earthquakes are a hazard that are within our power to respond to. We can reduce their threat over time as much as we want to. We can learn where not to build and how to build so that failure of structures will not occur."

DR. FRANK PRESS

2 | RISK

The second chapter is divided into three parts. The first one is about the fragility of Bhutan: the country is subjected to many natural hazards that affect people lives. The second part talks specifically about the earthquake and its effects. Then the earthquake's impact on Bhutan in 2009 is analysed. The third part finally is about risk: the meaning of this word, the factors involved and a mapping of Bhutan risk.

2.1 A FRAGILE LAND

Bhutan is a mountainous country located in the Himalayan mountain range. Bhutan is characterized by a natural diversity due to the extreme altitudinal variation. This variation leads to different climatic zonation. The diversity of Bhutan makes it a unique place in the world, but the country is also prone to multiple natural hazards: earthquakes, glacial lake outburst floods, windstorms, floodings, landslides, forest fires, pests and diseases. The results are damages to buildings and infrastructures and loss of lives.

The uniqueness of Bhutan has a double face: on one side an extraordinary small country with a big diversity, on the other side a fragile land with dramatic implications.

Earthquake
Himalayan mountains are one of the most seismically active zones in the world. Several earthquakes shook Bhutan in the past decades, causing building failure.[1]

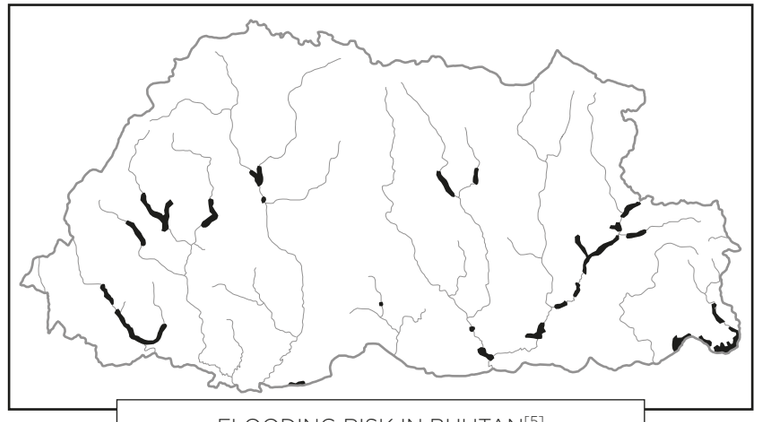
Year	Magnitude	Location	Losses [2]
2003	5.5	Paro	Few landslides along highways, minor damages in buildings (Paro, Haa and Thimphu)
2006	5.8	Dewathang	Around 126 houses suffered minor damages
2009	6.1	Mongar	12 live lost, 4950 households damaged, 117 schools, over 800 cultural heritage buildings
2011	6.9	Sikkim area	1 life lost and 14 injuries, 6977 rural homes damaged, 36 schools, 22 hospitals, 286 heritage sites, monasteries

[1] (Department of Disaster Management, s.d.)

[2] (YESHEY, 2015)

Flash floods
Flash floods are local floods of great volume in a shot period. They could be caused by cyclones, heavy rains, GLOFs. It is a seasonal hazard, increased by climate change. The most affected areas are southern and eastern Bhutan.[3]

Year	Origin	Affected area	Losses [4]
1994	burst of Lugye Tsho	Punakha-wangdue valley	21 lives lost, 91 households affected, 12 houses damaged, 5 water mills washed away, 816 acres of dry land, 965 of wetland affected, 4 bridges washed away, 1 temple in Tsojug damaged
2000	heavy rains	Phuentsholing, Pasakha	49 lives lost, damages to factory infrastructure
2004	heavy rains	6 eastern dzongkhags	9 lives lost, 29 houses completely washed away, 26 houses collapsed and 107 houses partially damaged, 161 acres of wetland and 503 of dry land washed away
May 2009	cyclone Aila	17 districts	12 lives lost, estimated damages losses of Nu. 719 million
June 2013	heavy rains	5 villages in Punakha	Over 14 acres of agricultural land filled with debris



FLOODING RISK IN BHUTAN[5]

[3] (Department of Disaster Management, s.d.)

[4] (YESHEY, 2015)

[5] (National Environment Commission, 2016)

Windstorm
Strong wind affects the country seasonally. Rural houses are the most involved: the traditional timber roof is prone to damages caused by wind.[6]

Year	Affected areas	Losses [7]
April 2011	17 dzongkhags	2424 rural homes roof damaged, 77 lhakhangs, 57 schools
March 2012	Zhemgang, Wangdue, Punakha, Haa	221 rural homes roof damaged, 10 lhakhangs, 4 schools
July 2013	Sarpang	4 homes roof
Sept. 2013	Zhemgang	22 rural homes roof and 100 acres of maize field
Dec. 2013	13 Dzongkhags	1012 rural homes roof, 12 schools, 58 cultural heritage sites
March 2014	Dagana, Mongar, S/Jongkhar, Sarpang, Trashigang, Zhemgang	102 rural homes roof, 2 schools, 4 lhakhangs
May 2014	Samtse	106 homes
April 2015	9 Dzongkhags	792 houses, 92 cultural and public infrastructure, 3 people injured

GLOF
The rising temperature is responsible of glacier retreat in Bhutan. This process leads to the formation of glacial lakes. The quick increase of water volume in the lakes is the cause of GLOF (= Glacial Lake Outburst Flood) that is the release of big amount of water from the lake to the valley. The Department of Geology and Mines lists 2674 glacial lakes (562 are associated with glaciers).[8]

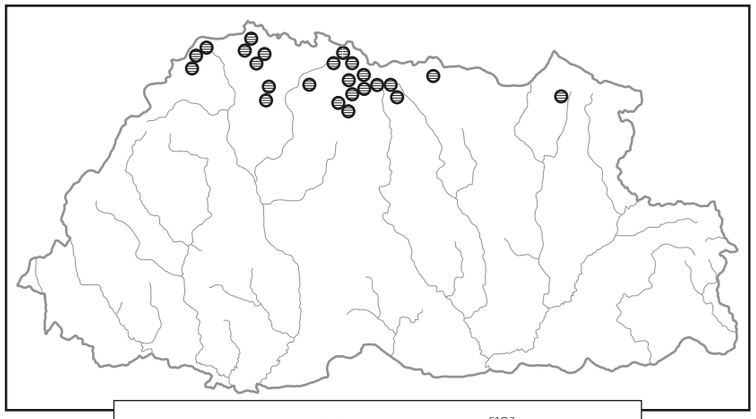
Year	Affected lake	Losses [9]
1994	Luggye Tsho (in Lunana)	massive damages downstream in the Punakha-Wangdue valleys and claimed 21 lives

[6] (Department of Disaster Management, s.d.)

[7] (YESHEY, 2015)

[8] (Department of Disaster Management, s.d.)

[9] (YESHEY, 2015)



GLOF RISK IN BHUTAN[10]

Landslides
Landslides are caused by intense rainfalls on fragile slopes or by tremors of an earthquake. The most prone areas are the eastern and southern foothill where slopes are steep and rocks are fractured. Infrastructure are more susceptible than buildings.[11]

Year	Origin	Affected area	Losses [12]
2000	seasonal monsoon	12 dzongkhags	Phuentsholing – Thimphu highway severely disrupted by numerous major landslides, highways and roads between and within districts blocked
Aug. 2002	burst of sliding mud	Tsirang highway	Loss of 2 pre-primary school children
April 2005	heavy rains	Palamphu, Mongar-Lhuentse highway	2 buried alive, 1 injured
July 2006	n/a	Bemsisi, Thimphu	7150.9 square meters of wetland affected
Sept. 2011	2011 Sikkim earthquake	Haa	Loss of one life due to landslides

[10] (National Environment Commission, 2016)

[11] (Department of Disaster Management, s.d.)

[12] (YESHEY, 2015)

Forest fires
Fires cause losses to the biodiversity and belongings of rural communities. Losses are often difficult to measure.[13]

District	N° cases	Losses (in acres) [14]
Bumthang	4	62
Chukhha	10	94.5
Dagana	5	339.5
Gasa	1	50
Haa	4	1359.9
Lhuentse	32	14849.3
Mongar	35	12620.49
Paro	8	1091.8
Punakha	9	1858.9
Pemagatshel	3	-
S/Jongkhar	5	-
Sarpang	7	2710
Samtse	15	1668.18
Trashigang	29	15309.69
Trashiyangtse	18	1893.07
Thimphu	64	5675.02
Tsirang	1	-
Trongsa	4	640.2
Wangdue	26	31078.45
Zhemgang	13	1295.67

Pest and disease
In the past, epidemic diseases affected Bhutan. Contacts with the outside world lead to porous borders and exchange of products and people, enhancing the risk of infections of future pandemic.[15]

Human contribution
Bhutan is a fragile land exposed to natural hazards, but human behaviour is the cause that converts hazards into a disaster risk.

Several items take place in the one I call “human contribution”. The primary factor is the lack of awareness: in Bhutan, mostly in rural areas, people don’t know anything about risk, human

[13] (Department of Disaster Management, s.d.)

[14] (YESHEY, 2015)

[15] (Department of Disaster Management, s.d.)

contribution and solutions, they don't know that simple actions can save their house and their life. Construction practices, rapid urbanization, environmental degradation are other items to take in consideration. Surely, the geographical morphology of Bhutan doesn't help in the overview of risk, but making people aware about the complexity behind the disaster is the first step.

LACK OF AWARENESS [16]

UNSAFE CONSTRUCTION PRACTICES [17]

Vernacular architecture passed down verbally for centuries. In the last decades traditions have lost some good practices and nowadays traditional safe construction practices are lacking. So, the current construction technique has limitations which make vernacular houses more susceptible to hazardous events like earthquakes. New good practices need to be reintroduced in the building process: this knowledge must be spread among rural people, that build their own houses with the help of other villages' inhabitants.

UNPLANNED URBANIZATION [18]

In the last decades Bhutan has passed through a modernization process that change drastically the face of the country. Urban area became bigger and people started move from the countryside to the town, making the town even bigger. Population density grew up and then the exposure to hazard. Towns grew even in red-zone areas, without control or planning. The building codes in urban area is nowadays insufficient to face the hazards and their consequence. The absence of trained workmen is the main factor of the unplanned construction.

FRAGILE ROAD NETWORK [19]

Rural settlements are spread out over the country. Mountainous terrain makes them isolated and sometimes very far from other villages. A road network connects quite all these settlements but, during an emergency, these fragile roads could be inaccessible, leaving people without communication or help for lot of time. On one hand there is an unplanned urbanization, on the other hand the isolation of rural villages and their inaccessibility.

ENVIRONMENTAL DEGRADATION [20]

Environment conservation is crucial for the risk reduction. The growth of towns, with the construction of buildings, roads and infrastructures, led to the exploitation of land and natural resources: mines and quarries have been opened, deforestation has increased, mountains have been cut by roads, causing degradation and denudation of hills and then landslides and flash floods. Human development is making land more and more fragile and new conservative interventions are required for stopping this process.

[16] [17] [18] [19] [20] (Department of Disaster Management, s.d.)

Disaster management

In order to prevent and reduce hazards effects and to respond properly during the emergency situations, a national strategy has been developed: the Disaster Risk Management Strategy (DRMS). The strategy was part of the Disaster Management Act of Bhutan 2013 and it is in line with Sendai Framework for Disaster Risk Reduction 2015-2030, a global agreement to prevent and reduce disaster risk.

The Sendai Framework four pillars which guide the DRMS are:

1. Improving understanding of disaster risk
2.Strengthening risk governance system
3.Investing in Disaster Risk Reduction (DRR) for resilience
4.Strengthening disaster management capabilities

From these actions, the DRMS has formulated some principles on which developing the whole strategy:

1. Strengthening Resilience and Sustainability
2.Whole-society approach
3.Protecting Indigenous Knowledge and Cultural Heritage
4.Coherence and coordination
5.Considering other cross-cutting issue

The Bhutanese strategy looks at the risk reduction approach with a holistic view: the whole community is involved for having safer places, working together, looking at the future without losing the vernacular soul of the country.[21]

2.2 WHAT IS AN EARTHQUAKE?

In the 20th century (specifically between 1900 and 1976) the number of people killed by natural disaster around the world was estimated to be more than 2.66 million due to earthquake, 1.29 million due to flood and 0.43 million due to cyclone [Arya, 2000]. Earthquakes are still one of the deadliest natural hazards in a lot of countries. Every year, all around the world, the earthquakes large enough to be noticed without instrument are estimated to be about 50000, 100 of which may potentially produce substantial damages [Bolt, 2020]. The more affected countries are the developing ones: in the last two decades they collect the 96% of fatalities [Sathiparan, 2015]. In the 20th century (1900-1999) 75% of fatalities were estimated to be caused by collapse of buildings [Sathiparan, 2015]: the bad construction in developing country could be a reason why percentages are so high there. Moreover, rural areas in these countries have little knowledge about earthquakes and sometimes are also difficult to reach in emergency situations. For a long time, natural disasters were faced only as post-disaster emergency response, but

[21] (Department of Disaster Management, 2013)

it's very important that these tasks could be part of a long-term national development planning. Disaster mitigation could take place with public awareness, education and training, and then building construction improvement, land use zonation, financial support and so on.[22]

But to begin with, what is an earthquake? Which are the causes of the ground motion?
The Earth's crust consists of 6 big plates and some smaller moving in relation to one another (tectonic theory). The friction at the edges of these plates produced energy that is stored in the rocks over a period of time. When the resulting stresses exceed the strength of the rocks, this energy is suddenly released, causing the production of seismic waves and then the ground motion. Other causes of earthquakes could be volcanic eruption or artificial induction like excavation of mines. The movement of the seismic waves in the ground can have varied effects. The first one people notice is the ground motion: this effect is responsible of building failure when the structure is too stiff and is not able to shake. But earthquakes are also responsible of ground changes like liquefaction of sandy ground, landslides, mudflow. Volcanic explosion could be a cause but also an effect. Moreover, if the epicentre (the surface point vertically above the inner point of the earthquake's generation) is in the oceans, earthquakes may lead to a tsunami.[23]

And Bhutan?
As mentioned above, Bhutan is part of the Himalayan region. 50 million years ago the collision of the Indian plate and the Eurasian plate started, leading to the raising of the Himalayan mountain range. This process is still going on and the pushing action of the plates is the cause of the high seismic activity of the region. The Himalayan is one of the most active zones in the world, even if it is now apparently quiescent for large scale earthquakes. Unfortunately, in Bhutan no records of past earthquakes intensities were taken but the last events have marked the country.[24]

The most damaging disaster that affected Bhutan in the last times was the earthquake of September 21, 2009. The epicentre was in Mongar dzongkhag: the earthquake affected all the eastern region of Bhutan. The magnitude (the measure that describes the strength of the earthquake) of 6.1 leads to several problems: 12 people died and 47 injured, 4614 households have been affected in 12 dzongkhags, 7290 people were left without adequate shelter. Infrastructure and institution registered damages too: 91 schools, 25 health centres and hospitals, 281 monasteries, 485 stupas (places of meditation), 7 Dzongs and 50 government office [RGoB, 2009].
The response was immediate: it was a collaboration between Bhutan and international agencies.

- The Royal Bhutan Army (RBA) was employed for immediate assistance: a rapid assessment of damages was done, and basic services were provided to people.

- The Lhengye Zhungtshog (the Bhutanese Cabinet) provided the families with temporary shelter material, medical assistance and cash grants.

- The Armed Forces and the school students constructed the temporary shelter.

- UNICEF distributed emergency family kit and blankets.

- The Department of Disaster Management (DDM) collected the situation updates in all 20 Dzongkhags, providing then the news to each agency.

- The UN in collaboration with the World Bank assembled a Joint Rapid Assessment team with the purpose of guarantee the recovery priorities visiting the villages in two of the most affected dzongkhags, Mongar and Trashigang: an outline of early recovery and reconstruction program was done. A package of livelihood assistance, consisting of grants for agriculture, livestock maintenance and income generating activities, was required. New structures of bamboo, wood and CGI sheet were planned, with a lifespan of at least two years, waiting for repair and reconstruction of buildings.

The reconstruction program was based on a "build back better" approach: seismic-resistant feature should be included in new buildings. Moreover, the reconstruction should be an owner-driven reconstruction. Building materials were provided to affected families and a training was conducted, in order to ensure the resilient features incorporation.

From the Joint Rapid Assessment team mission, some observations came up:
- the deterioration of the craftsmanship skills for building in stone and wood was one of the most important reason that has led to building collapse.
- the erosion of the community process of construction, based on cooperation and mutual help, has led to an individual construction effort with consequence on construction quality.

So, the solution requires the involvement of people in order to guarantee instruction, awareness and skills. It's impossible to avoid the natural phenomena, earthquakes will always occur, but knowledge may help in having a good respond, in order to preserve building and guarantee safety for the future.[25]

[22] (ARYA, 2000); (BHATTACHARYA, 2014)

[23] (BOLT, 2020); (BHATTACHARYA, 2014); (PAUDYAL, 2010)

[24] (Ministry of Works and Human Settlement, 2017)

[25] (Department of Disaster Management, 2009); (The Royal Government of Bhutan, 2009)

2.3 WHAT IS THE RISK?

Risk is an index, established *"analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend"* [UNISDR 2009][26]. So, risk measures the relation between three items in a specific zone: hazard, vulnerability, exposure.

ABSOLUTE RISK = HAZARD x VULNERABILITY x EXPOSURE

The hazard is the probability of occurrence of the natural event in a period of time in a specific area. The hazard analysis is about the study of past earthquakes, the frequency in time, the ground's properties of the zone. The ground shaking motion is estimated leading to a hazard map as result.

The exposure represents a measure of people and things affected by a potential earthquake in a specific area: it considers the number of human lives, the number of building and their value, the cultural heritage and the potential function of each place, the resources and goods of that specific area. The same earthquake with the same magnitude has a different impact if it happens in an urban centre or in an uninhabited area, so the exposure influences the risk. The exposure analysis could lead to a demographic map and a use of land map.

The vulnerability measures the strength of structures and buildings: it is the susceptibility of that buildings to be damaged and collapse because of a seismic event. The vulnerability depends on geometrical, structural and constructive features. It's possible to analyse the vulnerability of each single building providing then an index.[27]

It's difficult to represent the vulnerability on a map of the whole country, it is necessary to have an index for each building. So later, there are represented only the seismic map and the demographic map: the first one represents the HAZARD distribution in Bhutan, the second one represents partially the EXPOSURE of the country, according to the demographic distribution in the regions (the demography is also representative of number of buildings, but not of quality and heritage value). The overlapping of these two maps shows partially the earthquake absolute risk of Bhutan: it is not complete, but it is a more detailed step.

A focus on VULNERABILITY is developed later, within the traditional architecture analysis. In this thesis, vulnerability is the most considered feature because is the one subjected to the resilient retrofitting action. Anyway, it's possible to assume the intervention at country scale for the HAZARD mitigation: earthquakes could not be avoided but the environmental safeguard may help in minimizing some effects like landslides and ground failure. Instead, it's more difficult to assume the intervention on EXPOSURE feature. Imaging people moving from a hazardous place to a safer one is not so easy: a safer place doesn't mean a liveable one. In fact, Bhutan is a mountain country and villages are located in the valleys where people can build and grow farms. Instead, having less towns, and so people concentration reduced, in a small country with a growing population is also quite difficult. In conclusion, saving vernacular architecture, also considering the research field of the thesis, is more easily achieved by reducing the vulnerability.

Conclusions

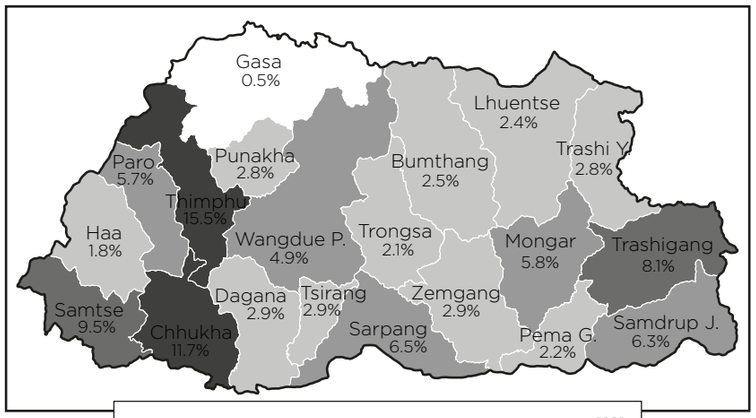
Bhutan is a fragile land: the country is affected by several natural hazards like earthquakes. Moreover, the human contribution, like the unplanned urbanization, makes the risk higher. Nevertheless, the country's reaction to natural disaster, like the earthquake in 2009, and the development of disaster management strategies in the last years, underline the interest of Government about going beyond the difficulties and looking for feasible solutions, in respect of traditions.

The risk represents a crucial aspect in the overview of Bhutan complexity: the next maps show the risk distribution on the country, bringing out the areas more affected.

[26] in (Ministry of Works and Human Settlement, 2017)

[27] (CORRADI, 2018); (FLORIO, 2010); (Ministry of Works and Human Settlement, 2017)

SEISMIC HAZARD IN BHUTAN[28]



DEMOGRAPHIC DISTRIBUTION IN BHUTAN[29]

RISK IN BHUTAN

[28] (Indian Institute of Technology ITT, 2009)

[29] (Ministry of Works and Human Settlement, 2008)

The maps

Seismic hazard level: color range

- Low hazard
- Moderate hazard
- High hazard
- Very High hazard

This thesis is focused on stone masonry houses, located in the central-eastern and eastern regions. According to the hazard map, the central-eastern region is one of the less hazardous area and the eastern region is one of the riskier. In accordance with the demography map, instead, population is more concentrated in western region; the reason of that is a complicate combination of different factors:

1. Bhutan has a mountainous morphology that make villages construction limited to the valleys: a central big mountain range cross the country from north to south, making the area difficult to be inhabited (*look at chapter 1*);
2. The protected forest areas and agriculture lands are mostly located in the central and eastern regions: this also make the western area more inhabited (*look at chapter 4*);
3. Urbanization is concentrated in western region, following points 1 and 2 above: the moving of population from rural areas to urban ones, due to the modernization process (*look at chapter 1*), means that people migrate from east to west, making western region more and more inhabited that eastern one.

As previously told the exposure can be reduced imagining people moving from a risky place to a safer one, and it happens when people migrate in western region that is a little bit safer. But, as previously told, this process is not so easy: Bhutanese people still depend on agriculture, so eastern region is inhabited by rural communities which are more isolated and buildings are less regulated, making them more vulnerable. Moreover, people in western area are partially concentrated in towns where exposition is increased.

The third map, generated by the overlap of the hazard and demography maps, shows a more detailed risk zonation, pointing out the more hazardous areas of Bhutan, the darker ones. These areas are ideally the first where starting with retrofitting actions. The vulnerability analysis, in the next chapter, will bring out the common weaknesses of the traditional houses, achieving an overview of the absolute risk of the country.

CHAPTER 3

ARCHITECTURE

“Bhutanese villages built along the sides of the mountains look over terraced rice fields and fast-flowing rivers, their isolation emphasised by the wild terrain and the absence of vehicles. In autumn, their roofs are covered with red chillies laid out to dry in the sunshine. The typical village contains several residential buildings, a Lhakhang (or village temple), perhaps some small shops and a bar, all arranged in an arbitrary fashion. Around the Lhakhang there are prayer wheels, and in strategic places about the village there are tall poles for the prayer flag. Each time the wheel turns or the flag flaps in the wind, a prayer is given to the gods.”

DAVID NOCK

3 | ARCHITECTURE

This chapter is developed in three parts. The first one gives an overview of the role of the housing architecture in Bhutan, taking in exam its relevance and how modernization affected it. The second part is a more specific description of the traditional house through its principal elements. The third part is a collection of pro and cons of vernacular architecture: a list of considerations leads to some reflection about the balance between past and future.

3.1 A SECULAR TREASURE

The ancient culture of Bhutanese people found expression in the traditional architecture, that reflects the concept of simplicity of Bhutanese life in a peaceful landscape of mountains and valleys. Bhutan is crossed by high mountain ranges, which cut the country from north to south; flat land is scarce and is located in the valleys, at the base of mountain slopes, where fields and settlements develop along the rivers. Villages of farmhouses grown around the temple (Lhakhang) or near a fortress (Dzong). Isolated farmhouses are also common, depending on the availability of arable land. [1]

High value is given to vernacular housing architecture (Yue Chim), that includes three different typologies, depending on construction materials. Traditionally, material distinction is influenced by local material availability, by climatic condition and by functional and spiritual demarcation of spaces. The most common typologies are rammed earth and stone masonry buildings. Rammed earth walls enclose the ground floor of dwellings in the Western part of Bhutan, solid rubble stone walls in the Central and Eastern parts. In these regions, upper floors walls’ structures are composed of timber frames, ekra infill (woven bamboo with mud plaster) and timber windows. At the top, the timber roof encloses the typical house. Houses appear like light structures floating above a massive basement. In the Southern hot region, bamboo is used for building construction: this third category is less common and diverge a little from the others.[2]

Stone rural houses construction, the focus of this thesis, is influenced by the dominant historical architecture of the Dzong, fortified monasteries constructed between 1594 and 1651, which nowadays still conserve a strong identity and religious value. The massive whitewashed masonry walls rise from the landscape. The rectangular basement of the main temple is totally closed, except for the entrance door. The second masonry level is characterized by some timber windows. The third level is

[1] (HELLIWELL, 2003); (JENTSCH, 2017); (Ministry of Works and Human Settlement, 2014)

[2] (CHUKI, 2017); (JENTSCH, 2017); (NOCK, 1995)

a continuous light timber structure with traditional trefoil windows. This level is highly decorated with carving and paint. The upper level is the overhanging timber roof, which fly above the massive building, loading above a solid timber structure. A red painted band below the roof is typical of religious building. The main temple is then surrounded by smaller religious buildings. The strength of this compound evokes eternity and unit with nature.[3]

Stone farmhouses follow construction principles similar to this building. The house is spacious and takes advances by natural factors, as natural light and wind. Like the Dzong, the traditional house is divided in different vertical levels. The ground floor, as mentioned above, is a rubble stone masonry floor. Traditionally, this floor is used as animals shelter and storage space. Bhutan is periodically subjected to heavy rain and the ground floor is easily inundated during monsoon periods, making it unsuitable for living spaces. The external wood staircase leads to the first floor. This floor is the family living space, with a large kitchen, some private rooms and a holy space, including an altar and a prayer room. The level is characterized by a light timber structure (rabsel) which takes the place of stone walls. Big decorated windows allow light to enter inside. Another stair leads to the upper level, the attic. The space below the roof, the attic, is a well-ventilated space, used for drying the summer's harvest. The low sloped roof lies above timber trusses and encloses the house as the last layer. The roof is traditionally closed by timber shingles, held in place by stones. Levels are divided inside by timber floors with mud layers above. The building is the result of a good carpentry work, based on an interlocking system, the "nailless architecture".[4]
The vernacular architecture reflects the identity of the country, its culture and believes. The cowshed at the ground floor and the attic for drying the harvest reflect the Bhutan agrarian society. Buddhism plays a significant role in Bhutanese architecture. For example, the buildings' rectilinear forms evoke the Buddhist concept of purity, focus and determination. Elevation represents higher value of mind: the altar is located in the highest level of the house. Colours of the exterior façade are limited to white, mud colour or stone natural aspect for having a harmoniously connection with the nature, that is source of inspiration in Bhutanese architecture and in people's lives.[5]

Despite its historical and cultural relevance, traditional architecture is threatened by the incursion of industrialization and modernization in the country. Until now, these processes hit urban areas of Bhutan: a new categorization divides Bhutanese architecture in urban and rural buildings. But, in urban areas, there is the effort of not losing traditions at all: design and details are re-proposed with modern materials, but this approach often results in a poor-quality construction. Introduction of concrete replaces the local materials, and the effort to reproduce traditional appearance turns into a failure. Moreover, modernization replaces sliding shutters with glass and bring electricity in the houses, making houses more comfortable but bringing also changes. Modernization leads to the growing of towns and to the migration from rural areas. New urban settlements cover large parts of valleys, replacing rural villages, showing a lack of organization in urban spaces distribution. Growth of population in towns leads to the impoverishment of tradition: for example, the attic, traditionally used as a drying and storage area, is converted into habitable rooms.[6]
The modernization process is proper of urban areas, but some changes reach rural villages too. As mentioned above, a traditional roof structure is covered by timber shingles held down by stones. This type of construction requires ordinary maintenance due to the short lifespan of the shingles. Moreover, wood is susceptible to fire. So, it's common to find corrugated iron sheets replacing the timber shingles. The harmony with nature is affected: the sunshine reflection causes glare and the visual setting is disturbed. Some authors argue that the new sheets should at least be painted, in order to minimize the damage and conserve the colour palette inspired by nature.[7]

In order to prevent the loss of traditional architecture some building rules are adopted. Constructive tradition has been passed down verbally over the century, so the Department of Urban Development and Housing develops a "guideline on traditional architecture of Bhutan", which is the present-day interpretation of age-old traditions. New rules are then set down: limitations in height, roof pitches and use of attic in order to prevent the improper use as habitable rooms; limitations in painting for avoiding the fake imitation of architectural features; incentives in conforming with the guidelines and so on. Rural rules are more restrictive about the dimensions of the buildings, the use of local materials, the preservation of traditional features like doors and windows, rabsel in the topmost floor, roof structure, and so on. Reinforced Concrete (RC) are highly discouraged in rural areas.[8]

These rules act to control the modernization process. But not only the traditional appearance is changing, the workmanship approach too. Traditionally, rural villages rise on the basis of the mutual help of village community: if one family has to build its own home, the whole community will help them, under the guidance of skilled craftsmen. There is no planning from architects or engineers, just a majority of unskilled labours working with a few experts whom skills resulted from experience. Making the construction of a single farmhouse a community matter evokes a strong sense of belonging and the houses themselves will always evoke a self-preservation sense. The result is a high-quality construction. The head-carpenter (zopön) is the person who ensure traditions passing down and ideological values continu-

[3] (HELLIWELL, 2003);
(NOCK, 1995)

[4] (CHUKI, 2017);
(HELLIWELL, 2003);
(NOCK, 1995);
(SABOO, 2016)

[5] (CHUKI, 2017);
(SABOO, 2016)

[6] (Department of Urban Development and Housing, 1993);
(HELLIWELL, 2003);
(SABOO, 2016)

[7] (HELLIWELL, 2003);
(NOCK, 1995);
(SABOO, 2016)

[8] (Department of Urban Development and Housing, 2002);
(Department of Urban Development and Housing, 1993);
(Ministry of Works and Human Settlement, 2013)

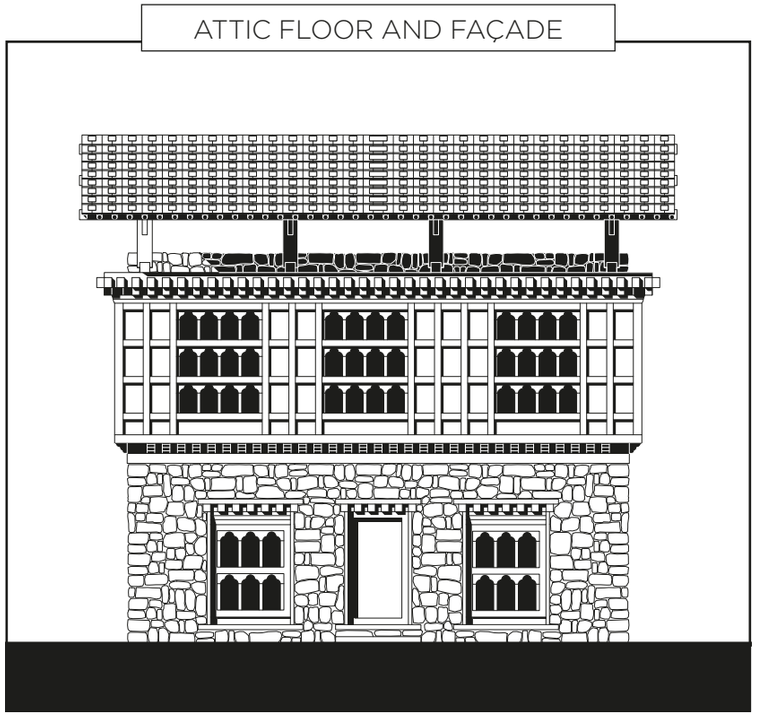
ity. Buildings are not the result of individual creativity but the architectural synthesis of spiritual, practical and cultural features. This kind of experience is obtained by a period of work under the guidance of the most highly qualified zopön, the Zorik Lapön. The recruitment of the carpenters takes place during the renovation periods of dzongs and lhakhangs. This training system allows the uniformity in country's building traditions and, sometimes, the introduction of new concepts in villages farmhouses' construction. The zopön training and the mutual help practice cannot be applied in the modern urban context. Architects and engineers design the new RCC buildings. Until recently, their training takes place in foreign countries, most of the time in India. The new building construction follows the Indian building codes and often requires Indian workers. Moreover, new construction materials are not always available in Bhutan: steel, bricks, glazing, aluminium and synthetic materials are imported. The mutual help system is replaced by a "professional trade" with foreign construction companies.[9]

Bhutanese architecture has ancient origins. It is believed that the oldest building dates back to the 7th century [Chuki, 2017]. Architecture is a material transposition of social beliefs and coexists with the agricultural and natural landscape. Moreover, architecture, as result of cooperation, evokes in people a sense of belonging. For centuries, the country's isolation has allowed traditions to be passed down and preserved, but the opening to modernization has brought changes. Change may be positive for the community, but it needs to be controlled. An uncontrolled development may have unfortunate effects and Bhutan may lose a secular treasure.

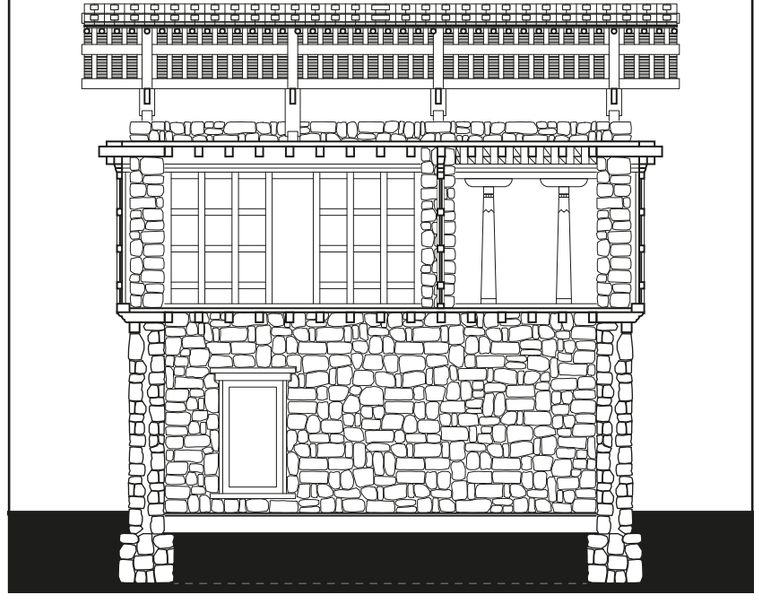
3.2 TRADITIONAL HOUSES

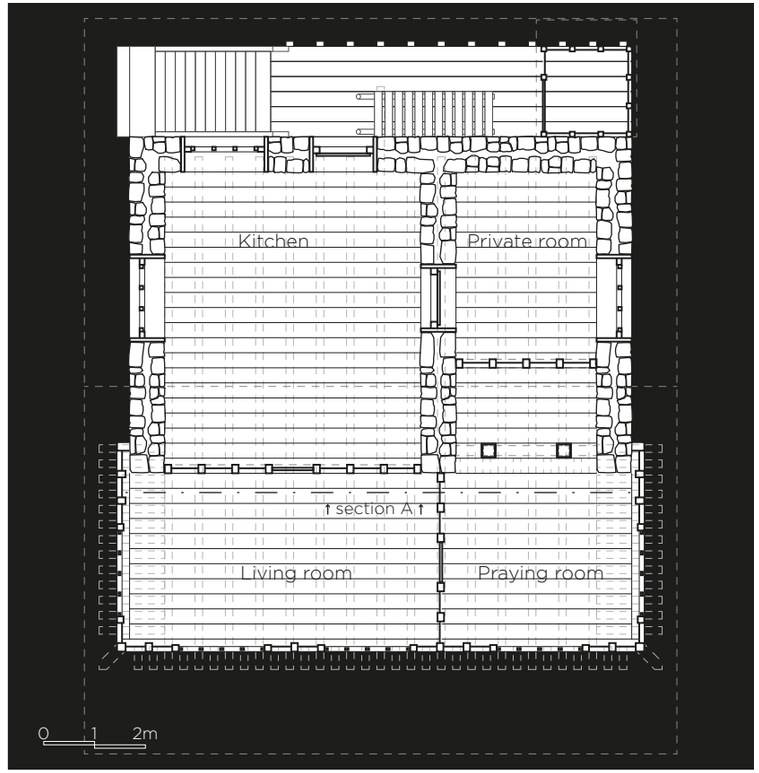
As previously told, the traditional rural house in the central and eastern regions of Bhutan is a stone masonry house with a wood structure at the second level (the rabsel) and a wooden roof. In the following pictures, a type house is represented. The three floors (attic, first and ground floor) show the vertical distribution: the attic, used for drying the harvest, is accessible from small wooden stairs; the external staircase also allows the access to the first floor, where stone walls and light timber frames divided the space between living and holy space; the ground floor, used for storage, is entirely enclosed by stone masonry walls. The sections and façade show the proportions and connections between stone and wood elements, the floor layer structure, the windows and doors appearance, the rabsel modularity. Then, a more detailed description of each typical element is developed with an axonometric drawing: the specific naming of each part shows the importance of every detail in the vernacular Bhutanese architecture.

[9] (ARIS, 1994); (DUJARDIN, 2000); (JENTSCH, 2017); (LANG, 2013)

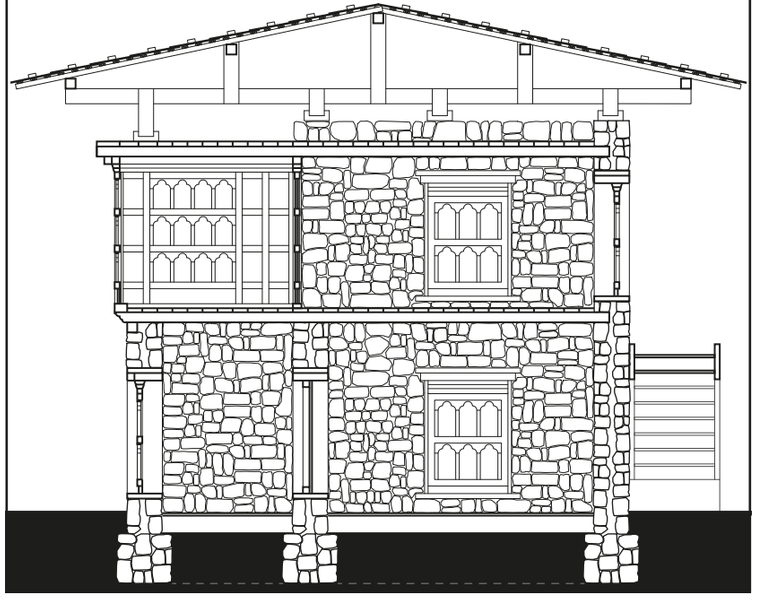


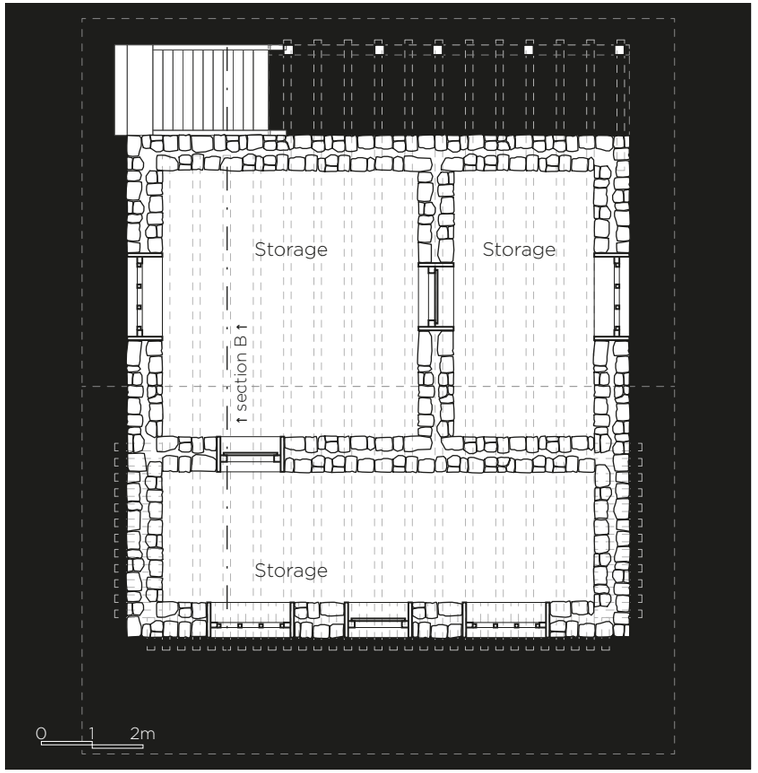
FIRST FLOOR AND SECTION A



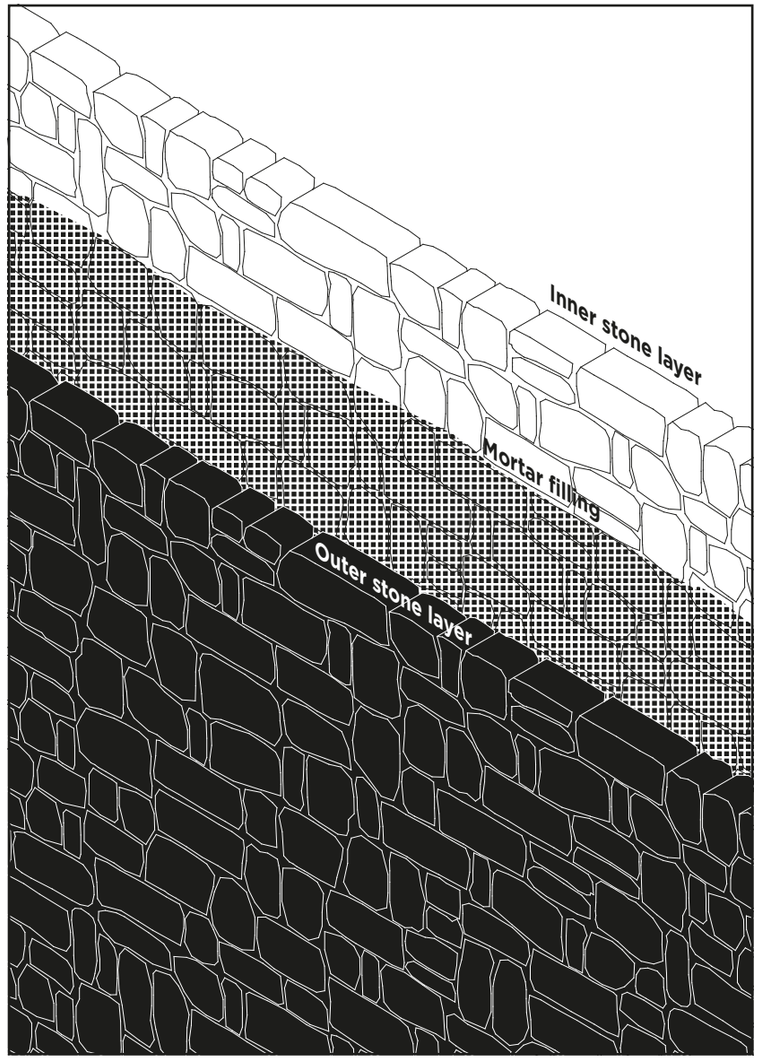


GROUND FLOOR AND SECTION B





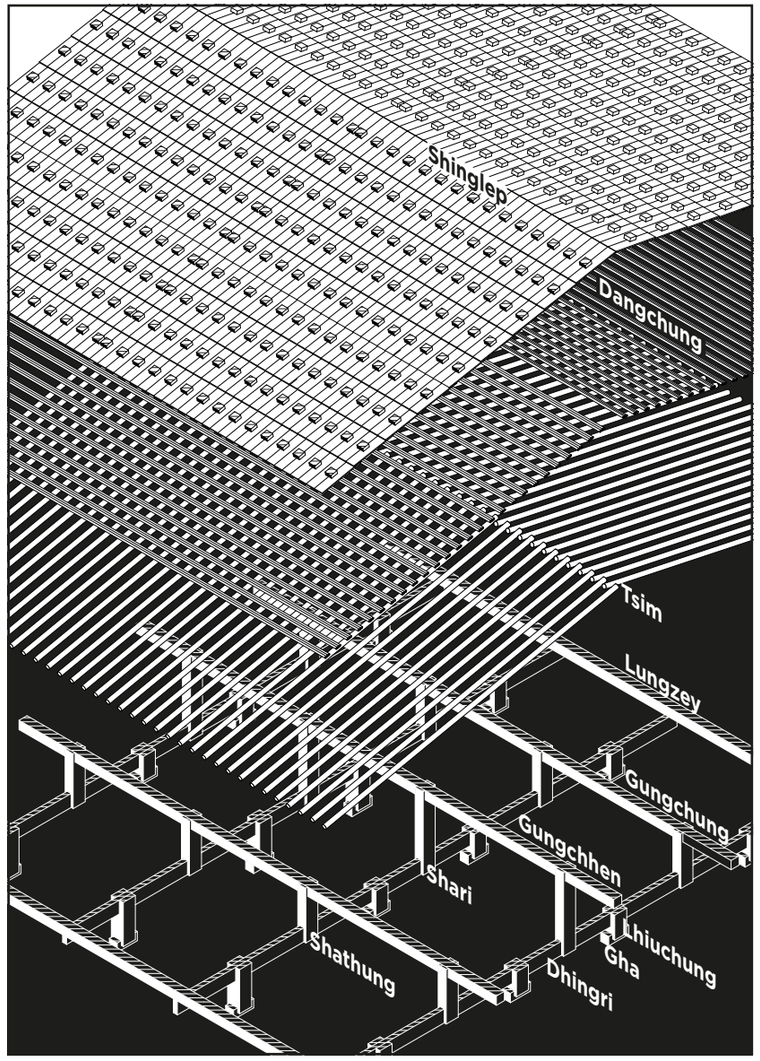
THE WALL



Mostly, walls of central-eastern regions of Bhutan are made of irregular stones, collected by the inhabitants themselves. Usually, stones in the walls are unshaped stones, joined by a mud mortar. Walls consist of two outer stone layers and a rubble and mortar infill. The wall's layers are poorly connected. Corners of walls present poor connection too.[10]

[10] (CHIDIAC, s.d.); (ORTEGA, 2017)

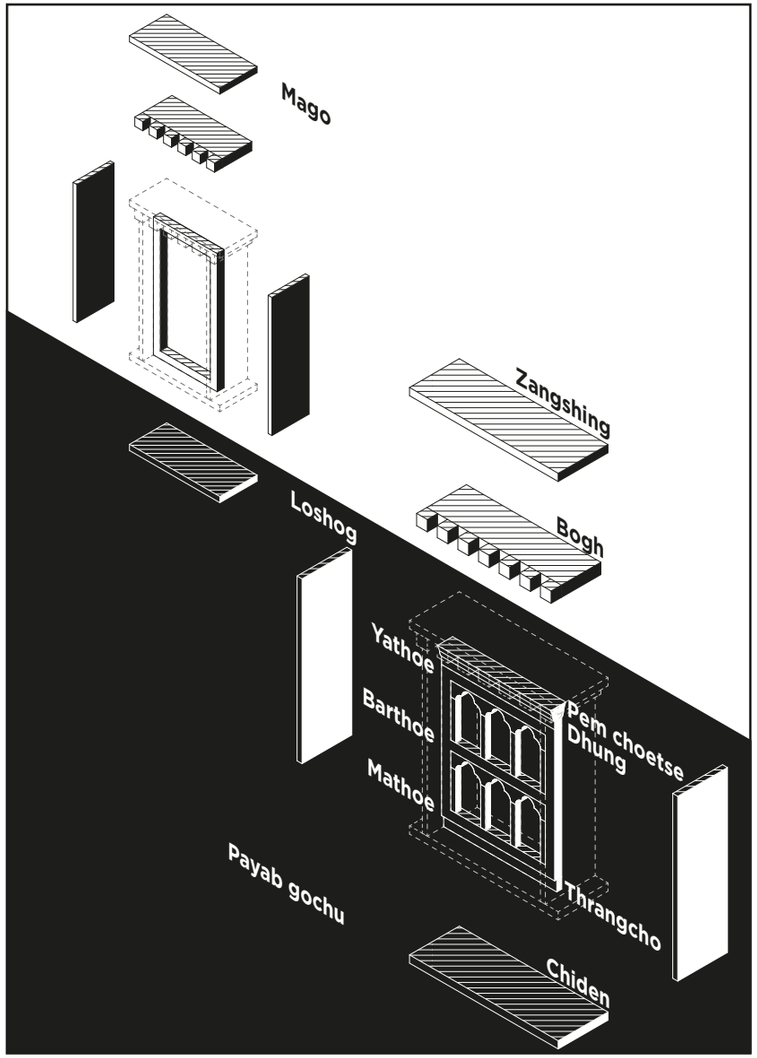
THE ROOF



The simple gable roof is the most common in the vernacular housing architecture. The structure is constructed without nails and simply rests on the topmost floor: it's not integral to the whole system. The timber structure is the set of different elements: bottom-up, the first member (Gha and Lhiuchung) support the principal truss (Dhingri). Above, timber posts rest on the truss: the central post (Shari) supports a central roof ridge (Gungchhen) and the lateral posts (Shanthung) support the under purlins (Gungchung). The upper rafters (Tsim) support timber battens (Dangchung) which support timber shingles (Shinglep). Shingles are held in place by stones.[11]

[11] (LANG, 2013); (Ministry of Works and Human Settlement, 2014)

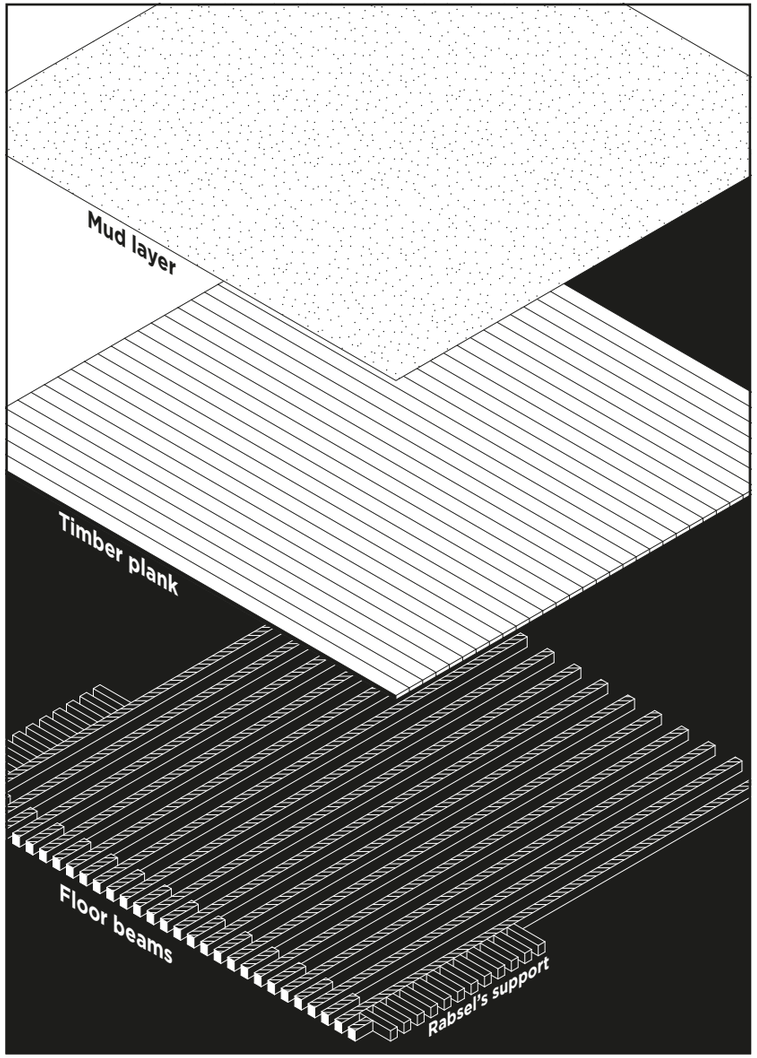
THE WINDOW AND THE DOOR



The traditional windows (Payab Gochu) is enclosed by a first layer of timber boards on the four sides, protecting the windows to the stone walls: the laterals boards (Loshog), the lower (Chiden) and the upper lintel (Zangshing). Below the lintel, the second layer is a cornice (Bogh) which can be single or double. This layer is located up to other three levels (Choetse, Pem and Dhung). Below, the window frame is composed of three horizontal levels (Yathoe, Barthoe, Mathoe). The traditional main entrance door (Mago) has similar levels to the window. These levels have the same dimensions of the windows in order to create a harmonious façade.[12]

[12] (Ministry of Works and Human Settlement, 2014)

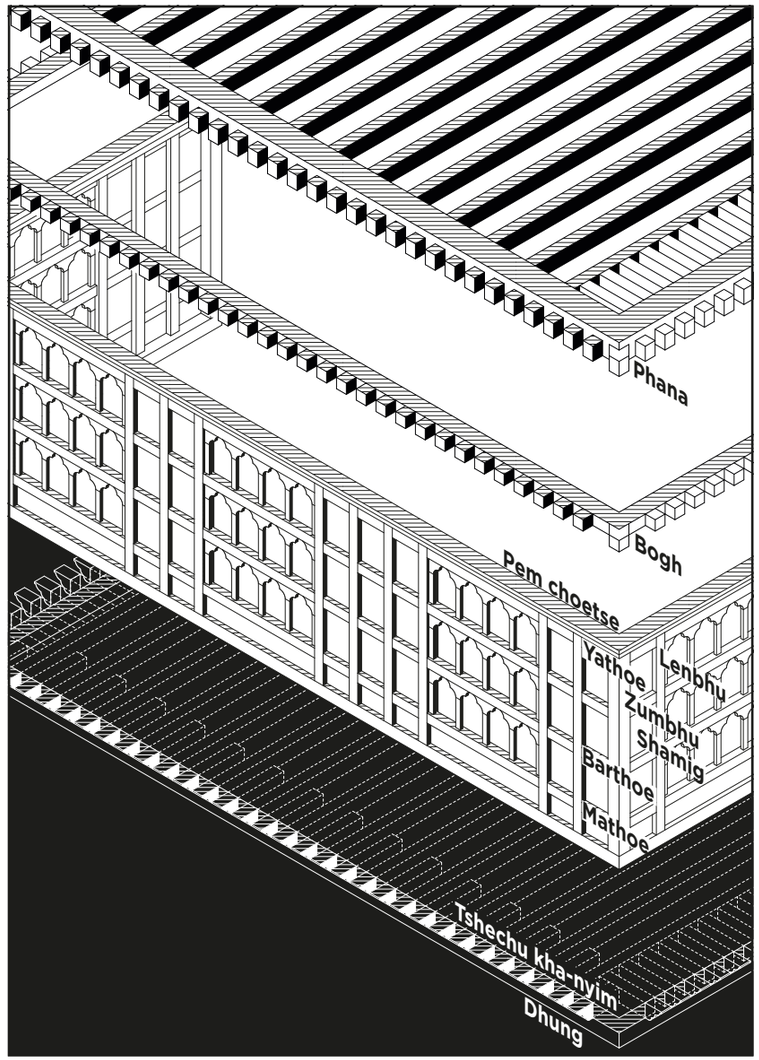
THE FLOOR



Traditionally, houses have simple timber floors. The floor is divided in three layers: the timber beams, covering the entire length of the house, the timber plank and sometimes the mud layer. Beams are not assured to the walls, they are simply trapped by the stones. This joint is a very vulnerable part, due to the poorness of the connection. Some beams cross the entire section of the wall in order to support external elements, like the stair block or the base of the rabsel, or as decorative elements, in the upper part of the rabsel. Timber plank rests on the beams without use of nails.[13]

[13] (LANG, 2013)

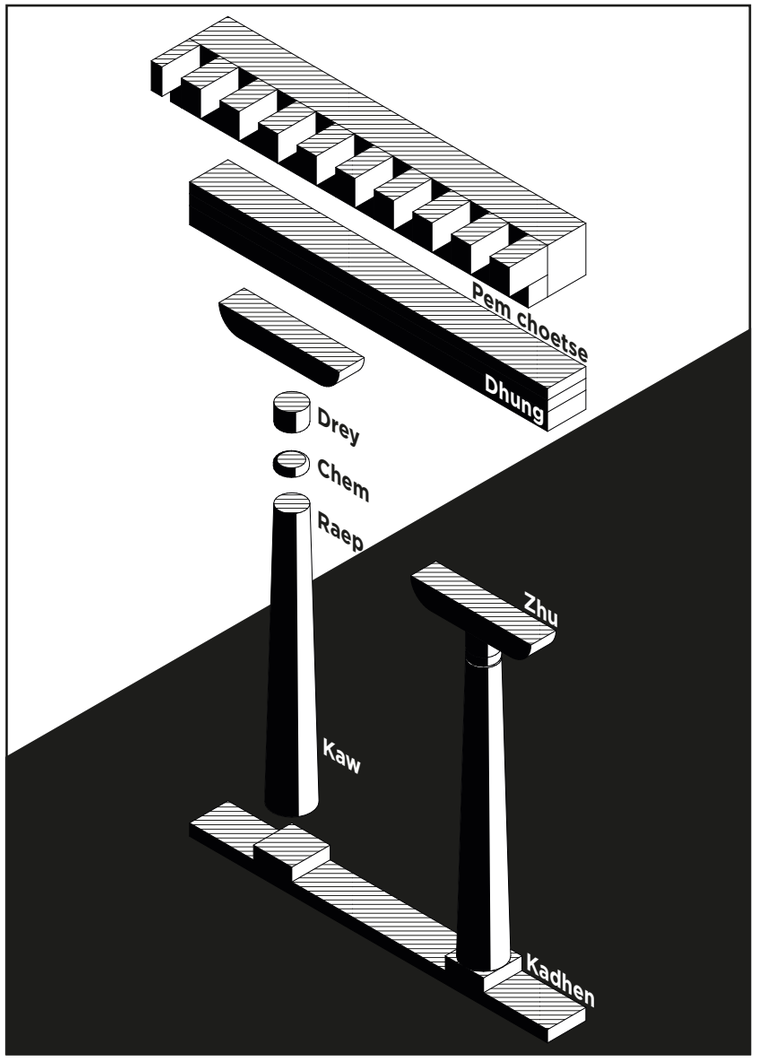
THE RABSEL



The Rabsel is a timber frame structure located in the second floor of the house. Vertical members (Lenbhu and Zumbhu) and horizontal members (Budhen, Mathoe and Yathoe) are assembled with windows and panels. These panels may be made of timber (Soma) or bamboo and mud plaster (Shamig). The frame lays on the floor's beams extensions (Tshechu kha-nyim) which are supported by a lintel member (Dhung) embedded in the wall. The Rabsel is cantilevered about 15cm beyond the stone structural walls. All the frame members are interlocked without nails.[14]

[14] (JENTSCH, 2017); (Ministry of Works and Human Settlement, 2014)

THE KACHEN AND THE ZHU



These two elements are the column and the capital placed in the altar room of the house. They are made of timber, fashioned out by carpenters, joined together during installation. The Kachen is divided in three parts: the tapering body (Kaw), shoulder (Raep) and head (Drey). These parts are separated by a neck of carved beads (Chem or Threngwa). The Kachen lays on a single stone square base (Kadhen). The Zhu is placed on the top of the Kachen. It is a timber bracket that support the beam above (Dhung). In rural house Kachen and Zhu are the simple ones, without intricate carvings and paintings.[15]

[15] (Ministry of Works and Human Settlement, 2014)

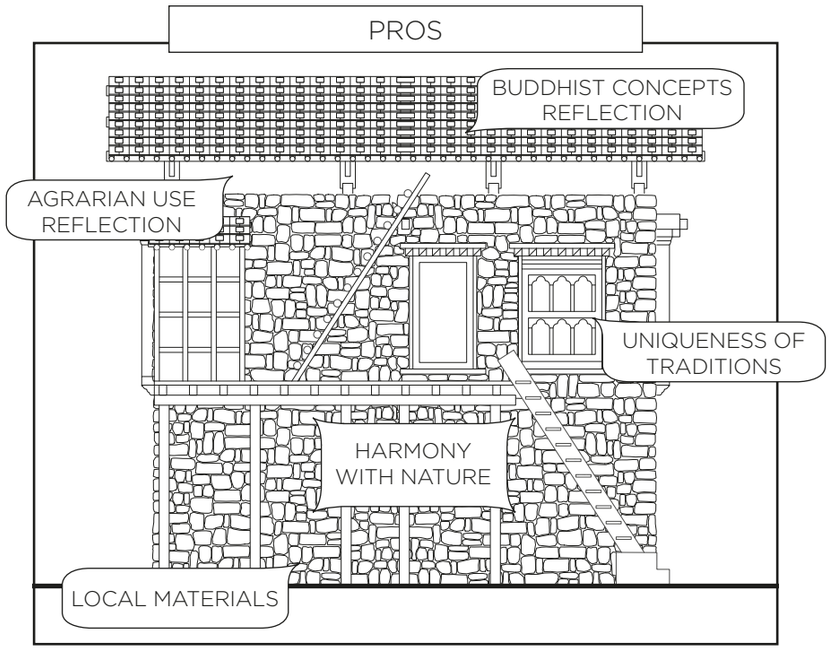
3.3 STRENGTH AND VULNERABILITY

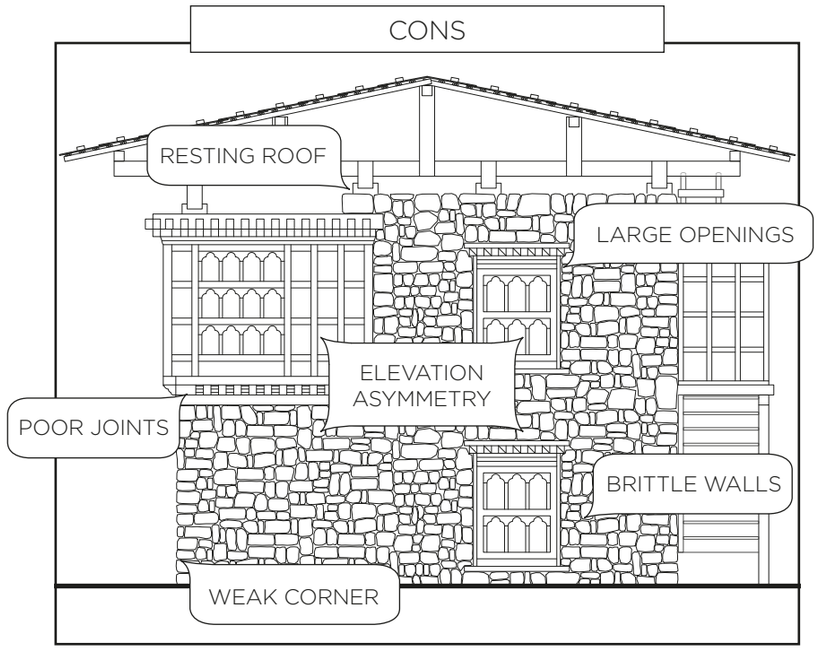
The Bhutanese architecture, as previously told, reflects the people's lives: the agrarian society is represented in the storages and in the attic, the Buddhist influence is reflected in building's elevation and distribution, the rural limitations are pointed out by the use of local materials. The strong connection of people lives with nature is also reflected in the harmonious architecture. Centuries of isolation and peace have made Bhutanese architecture a unique treasure that must be preserved.

All the traditional aspects represent the strength of building and they cannot be ignored. Despite this, during a post disaster mission, the deterioration of the craftsmanship skills and the erosion of the community process of construction, based on cooperation and mutual help, were observed. The unproper construction makes the building vulnerable.

Vulnerability is the susceptibility of the buildings to be damaged and collapse because of a seismic event: it depends on geometrical, structural and constructive features. For example, the plan or elevation asymmetry creates more difficulty for the house to act as a uniform monolithic box. Connections between elements in traditional Bhutanese houses are a very vulnerable part. Roof rests upon the topmost floor: the absence of joints makes the roof and the walls moving as different elements during seismic events, improving the vulnerability. At the same way, the floor is not connected to the walls: the beams are only trapped by the stones. The wall itself is vulnerable: the heavy structure of unshaped stones and mud mortar has a brittle behaviour during the earthquake. Moreover, the two external stone layers are not connected and the inner infill is weak: the stone leaves, subjected to a tensile stress, are prone to collapse during the earthquake. The large openings weaken the wall too. At the same way, the connection between different walls is absent: the corner is very vulnerable during the seismic events.

The poor quality of materials is another cause of building's weakness. In fact, as the unproper construction, also the use of bad quality materials decreases the building's resistance. In the following chapter, construction materials will be analysed, pointing out the local availability and the environmental impact, in order to find a compromise between vernacular materials and useful materials which can be used without losing the strength that makes Bhutanese architecture so unique.





CHAPTER

4

MATERIALS

“Even before the advent of modernization in 1961, the country consisted of self reliant and self subsistent communities, possessing well defined community based rules and institutions to facilitate the use of common resources.”

PLANNING COMMISSION

4 | MATERIALS

The chapter is divided into four parts. The first one is about the process that leads Bhutan to a mayor need of construction materials, and the general availability of resources in the country. The second part talks about the availability of raw materials from mines and quarries. The third part, instead, is about the availability of forest products. The last part is the conclusion of the chapter: pros and cons of materials are compared, in order to draw out the critical aspects behind every choice.

4.1 AVAILABILITY

In the last decades, the modernization process in Bhutan has led to an economic growth. The increasing sector of hydropower production has supported the establishment of new industries and the development of infrastructure: roads and bridges, urban infrastructure and building other hydro-electric power projects. The inner growth has promoted the industrialization also for exports. The energy increase leads to the economic enhancement and vice versa. The increasing development of infrastructure and the rapid urbanization of the last decades have resulted in a higher demand of construction materials.[1]

The construction materials are used in different locations depending on the local availability. Traditional local materials (stone, wood, earth) build up the vernacular architecture, typic of rural areas: rammed earth or rubble stone masonry houses with timber roofs and floors are part of the non-engineered construction. In urban areas, instead, the modern architecture is divided into multi-storeyed reinforced concrete construction, dressed stone masonry buildings, cement stabilized earthen block or concrete blocks buildings: traditional materials and new ones (steel and concrete) work together. The distinction between rural and urban areas is due to the geomorphology of Bhutan: high mountain ranges cross the country from north to south, making transport of materials, technology and workmanship very hard. The road network is not appropriate enough for the spread of modernization in the whole country: the development is focused in urban and accessible areas. From the traditions’ point of view, this limitation to the urban areas is not a negative aspect. In fact, the use of modern materials has led to the impoverishment of traditions in urban architecture: for example, the typical façades are only painted or carved on the modern ones. Moreover, urbanization and material consumption are causes of environmental degradation. Vernacular Bhutanese buildings, using low energy construction method and natural local resources, responding to the climatic conditions with a spe-

[1] (Department of Industry, 2009)

cific design, are an example of sustainable architecture. Modern buildings don't respect the traditional methods and the effect is reflected on the environment.[2] Despite this, "modern" material could be good allies in seismic retrofit actions. So, is it possible to bring these materials in rural areas? Is it possible to use them in a sustainable way, without losing the traditional values? Moreover, we talk about local material but what does it means? Where do construction materials, traditional and modern ones, come from? For sure, new materials are only partially produced in Bhutan: big steel elements, for example, are imported from India, included specialized workers. This kind of resources is not affordable for rural communities, whose houses are the subject of this thesis. So, which is the real availability of construction materials?

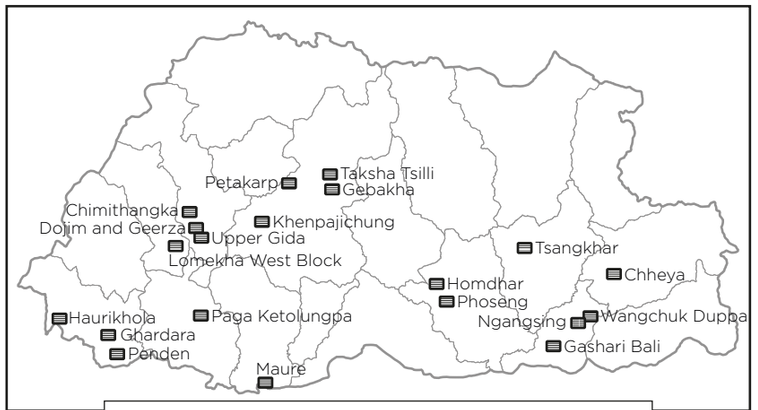
According to the information found in literature, construction materials taken in exam are stone, concrete, steel, wood and bamboo. Other materials are not considered because of the lack of information. Rammed earth is commonly used but it is not considered in this thesis because it doesn't appear in traditional stone houses. The country has a big reserve of stone quarries. Large limestone deposits are spread in southern Bhutan and some small cement plants make the country self-sufficient in production of cement. Forests cover 72% of the total area of Bhutan and there are huge wood reserves and expert artisans. Steel, as previously told, is mostly imported, but there is a huge demand for steel bars and the interest in developing internal industries [DoI, 2009]. In the next part the previous questions will find a more detailed answer.

4.2 MINES AND QUARRIES

Literature doesn't give the actual number and location of mines and quarries. In the period from 2008 to 2012, 33 mines and 48 quarries were leased or operating [RAA, 2014]. In 2013, the Final Mines Feasibility Studies estimated 62,427 million MT (metric tons) of limestone minable reserve spread in the southern-western part of Bhutan and 100,83 million MT of stone quarries deposit spread in all the country [RAA, 2014]. In 2015, 26 stone quarries and 22 mineral mines were under operation. The distribution of mines was 42% in western (mostly Thimphu, Wangdue Phodrang, Paro), 35% in southern (mostly Samtse) and 19% in eastern region (mostly Pema Gatshel). Minerals in Bhutan are limestone, talc, gypsum, quartzite, granite, marble, dolomite, coal and iron ore [A-CC, 2016]. In 2018, 1.344.038 MT of limestone, 3.730.975 MT of stones and 37.843 MT of iron ore were produced in Bhutan [NSB, 2019]. For sure, currently, a good reserve of limestone and dolomite is available in Bhutan: these minerals are raw materials for concrete and mortar in construction industry [DoI, 2018].

[2] (Department of Industry, 2009); (The Engineering Adaptation and Risk Reduction Division, 2013); (Ministry of Works and Human Settlement, 2017)

	Name of quarries / mines (*) [3]	Dzongkhag
WEST ↓	Haurikhola Stone Quarry	Samtse
	Ghardara Stone Quarry	Samtse
	Penden Limestone Mine	Samtse
	Lomekha West Block Stone Quarry	Paro
	Chimithangka Stone Quarry	Thimphu
	Dojim and Geerza Stone Quarry	Thimphu
	Upper Gida Stone Quarry	Thimphu
	Paga Ketolungpa Stone Quarry	Chhukha
	Maure Iron Ore	Dagana
	Khenpajichung Stone Quary	Wangdue Phodrang
	Petakarp Stone Quarry	Wangdue Phodrang
	Taksha Tsilli Stone Quarry	Wangdue Phodrang
	Gebakha Stone Quarry	Wangdue Phodrang
	Homdhar Stone Quarry	Zemgang
	Phoseng Stone Quarry	Zemgang
	Tsangkhar Stone Quarry	Mongar
	Gashari Bali Stone Quarry	Pema Gatshel
	Ngangsing Stone Quarry	Pema Gatshel
EAST ↑	Wangchuk Duppa Stone Quarry	Pema Gatshel
	Chheya Stone Quarry	Trashigang



LOCATION OF QUARRIES AND MINES (**)[4]

(*) In the tab, there are the quarries surely leased at this moment. It doesn't exclude that there are more quarries and mine operating or available.

(**) In the map, the location of quarries and mine is approximate, but shows the overview of available materials and their distribution in the country.

[3] (Royal Audit Authority, 2014)

[4] (National Council of Bhutan, 2013)

Industry

In 1970s the mining activity started. At the beginning the government enterprises managed this sector but, gradually, the sector was privatized, and now private agencies mostly manage the mining activities, except for some mines controlled by government enterprises. Nowadays, a new process is going on: the nationalization. The government started acquiring privately owned enterprises in order to bring the sector under the government's development policy. Minerals are non-renewable materials and are limited in nature. Because of that, the mining activities should be carried out according to the policy of intergenerational equity of Bhutan government. The administration and management of country's mineral resources is operated by the Department of Geology and Mines (DGM), but every Bhutanese has the responsibility to take care of the natural resources. [5]

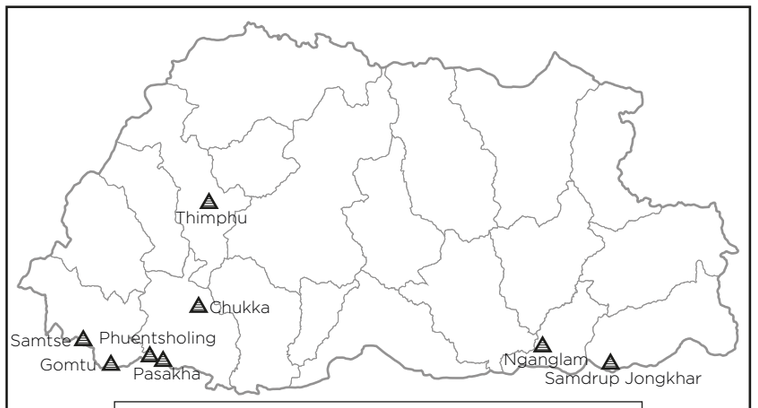
Nowadays, the factories are mainly located in the western region of Bhutan. The 90% of the construction materials produced remains in the country, the 10% is exported to India [RAA, 2014].

	Dzongkhag [6]	Mineral based industries (2019)
WEST	Samtse	49
	Haa	4
	Paro	26
	Thimphu	35
	Chhukha	27
	Gasa	1
	Punakha	3
	Wangdue Phodrang	24
	Dagana	12
	Tsirang	5
	Trongsa	7
	Sarpang	26
	Bumthang	11
	Zhemgang	5
	Lhuentse	1
	Mongar	13
	Pema Gatshel	19
EAST	Trashi Yangtse	4
	Trashigang	9
	Samdrup Jongkhar	29

[5] (Royal Audit Authority, 2014)

[6] (National Statistic Bureau, 2019)

	Name of industries (***) [7]	Dzongkhag
CEMENT	Bhutan Carbide and Chemicals	Chukka
	Druk Cement Co.	Phuentsholing
	Dungsum Cement Corporation	Nganglam
	Lhaki Cement	Gomtu
	Penden Cement Authority	Gomtu
	Yangzom Cement Industry	Samtse
	Singye Stone and Sand Factory	Thimphu
IRON AND STEEL	Bhutan Ferro Alloy	Pasakha
	Bhutan Steel Industries	Chukka
	Dorji Metal Fabrications	Thimphu
	Druk Iron & Steel	Phuentsholing
	Druk Wang Alloys	Phuentsholing
	Lakhi Steel & rolling mills	Phuentsholing
	SD Eastern Bhutan Ferro Silicon	Samdrup Jongkhar
	Ugen Ferro Alloys	Phuentsholing



LOCATION OF INDUSTRIES [8]

The presence of leased quarries and industries makes it possible to verify the existence of the inner process of extraction and manufacturing of construction materials derived from minerals. In particular, the quarried stones are available in the whole country, even if rural communities use unshaped stoned found by themselves for the house construction. In addition, Bhutan is

(***) The tab shows the most important industries, not the total number.

[7] (Department of Industry, 2009); (Department of Renewable Energy, 2012); (Royal Audit Authority, 2014)

[8] (Department of Industry, 2009); (Department of Renewable Energy, 2012); (Royal Audit Authority, 2014)

supposed to be self-sufficient in cement production but the poor documentation about limestone mines makes suppose that the use of cement is not so common, maybe it is concentrated only in the biggest towns. Moreover, industries are mainly located in the south of the country, near the boundary with India, maybe because of the flat land: distribution of materials in the whole country could be difficult, especially in the remote villages.

Impact

The exploitation of mines and quarries has increased over the years. This activity has got a positive effect on socio-economic development of Bhutan but, at the same time, has a negative impact on communities and the natural environment. Mines and quarries are a source of national income and generate employment. Moreover, communities living near mines and quarries are assisted with social initiatives like donations and support for instruction, health and religion, or like drinking water and irrigation water supply. Specific supports help communities to survive and preserve traditions and culture. Nevertheless, communities don't appreciate the coming of a mine: sometimes it represents the displacement of the community or more often unavailable donations for the people in order to preserve their support. The human balance is affected. Moreover, nature balance is affected too. Construction of roads, exploration drilling, discharge to water and air affect the natural ecosystem and then the quality of life. Rivers' water has been revealed to be more turbid in downstream areas in presence of mines and quarries and the impact could be worst during monsoon. Dust from stone crushing or trucks move is exposed to air and affect the surrounding area: a long period exposure could be a problem for people health. Vegetation is also affected: the mining activity requires the removal of plants. Even if the restoration of the land after the end of the activity is mandatory, natural ecosystem are difficult to be reconstituted. In order to ensure the environmental restoration at the end of mining or quarrying activity the Environmental Restoration Bond (ERB) payment is collected annually proportionally to the annual production.[9]

Mines and quarries have positive and negative impacts: the natural balance needs to be preserved complying with environmental requirements, and the communities' wellness has to be guaranteed. The privatisation of mines could represent a problem for the application of the government's development policy of intergenerational equity: this factor has to be taken into account.

4.3 FOREST PRODUCTS

The National Forest Policy of Bhutan identifies the forest as a "land with trees spanning more than 0,5 ha with trees higher than 5 m and a canopy cover of more than 10%" [MoAF, 2011]. According to that, 71% of the total country land is under forest cover [NSB, 2019].

Bhutan is mainly an agrarian country: the subsistence farming system is based both on agricultural land and forest. In fact, rural villages livelihood depends on forest products: wood, fuel, fodder, leaf litter for animal bedding and as organic manure, water, mushroom and edible fens. Moreover, forests are used for cattle grazing and wild animal hunting. 79% of Bhutanese is forest-dependent [Webb, 2004]. That leads to the development of a conservative approach on forest resources and, at the same time, to an aware and sustainable extraction of products.[10]

Historically, even before the modernization process of 1960s, there was a forest management institution, which provided rules to the self-subsistent communities for using common resources. Those rules were applied according to the proximity and accessibility of the forest by villagers: far from villages, forests were not regulated, and the religious believes of deities residing in natural elements were enough for respecting and conserving them. Nowadays, nothing has changed: a formal regulation of those areas doesn't exist and local religion is still important in forest preservation in rural areas.[11]

In 1952 a forest unit was created, according to the balanced approach between conservation of environment and sustainable utilization of forest resources (now called "Middle Path" approach). In 1961 the unit was upgraded to the Department of Forestry and Park Services (DoFPS). In 1969 the Bhutan Forest Act stated the nationalization of forest: the forest outside of private tenure was managed by the central government authority according to the "Middle Path" approach. In 1995 the Forest and Nature Conservation Act limited the extraction of products by local people: forest is required to remain at least 60% of the total country area. Moreover, the act encouraged people to grow forest on own private land.[12] So, nowadays, the Department of Forestry and Park Service acts in order to obtain the maximum benefits to society and the minimum negative impact on environment:

1. Ensuring the preservation of 60% of forest
2. Managing forest, biodiversity and water resources through a sustainable way
3. Facilitating the development of industries based on forest products[13]

The department is assisted by regional centres. The department preservation action found expression in the 11th Five Year Plan (2013-2018): the Renewal Natural Resources (RNR) sector is introduced in the Plan in order to preserve forest, animal and plants. So, the natural resources conservation takes part in the

[9] (National Council of Bhutan, 2013)

[10] (Forest Resource Management Division, 2014); (WEBB, 2004)

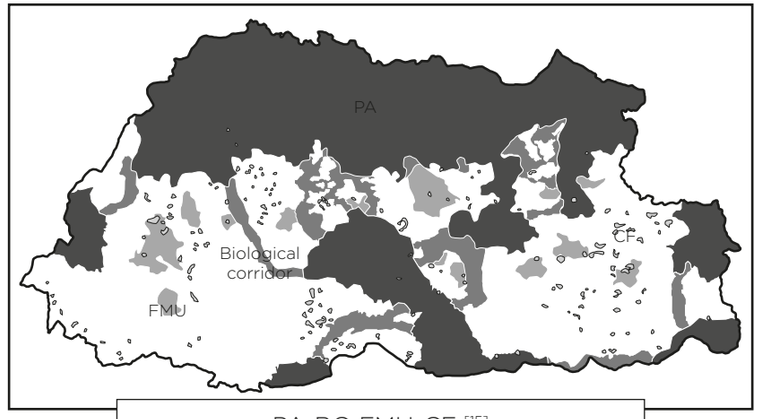
[11] (WEBB, 2004)

[12] (WEBB, 2004)

[13] (Department of Forests and Park Services, 2017)

pursuit of Gross National Happiness. Instead, the department developing action takes place with the Forest Resourced Potential Assessment (FRPA) which states the forest that can be sustainably managed.[14]
Currently, the department is not the only institution managing Bhutan's forests areas. Other institutions are:

- PROTECTED AREAS (PA) network which includes national parks, wildlife sanctuaries, strict nature reserve, biological corridors and the royal botanical park (51,44% of the country) [DoFPS, 2019].
- COMMUNITY FOREST (CF) which is a participatory program where inhabitants are involved in the forest management process (2,3% of the country) [DoFPS, 2019]. CFs are "rural communities able to meet the majority of their timber demands from their own community forests and derive economic benefits from the sustainable management of their forests through sale of forest products and services" [SFD, 2010]. CFs are crucial for generating rural income and opportunities. Following a people-centred approach, the aim is a sustainable future which includes poverty reduction and improvement of resilience to climate change.
- FOREST MANAGEMENT UNITS (FMU) subjected to a scientific management of the forest (5,03% of the country) [DoFPS, 2019]. FMUs are responsible for commercial timber extraction [FRMD,2014].
- NON-WOOD FOREST PRODUCT (NWFP) GROUPS which work with different species.
- PRIVATE FOREST.



PA-BC-FMU-CF [15]

Moreover, the DoFPS is not directly responsible for the wood harvesting. In 1979 the Logging Division was set up. In 1984 it became the Bhutan Logging Corporation and in 2007 the Natural Resources Development Corporation Limited (NRDCL), which is, currently, the most important enterprise supplier of commercial timber, sand and stone, covering 80% of the total forestry activities in the country [WB, 2019]. The NRDCL has a government mandate for its activities and is responsible for the management plans of FMUs and CFs. Logging activities in FMUs are done by the NRDCL, in the CFs by the community.[16]

Forest use
TIMBER
As previously told, forest cover 71% of total country land, of which 45,9% is broadleaf, 13,5% mixed conifer, 6% fir, 2,6% chir pine and 2,6% blue pine [WB, 2019].

In 2018, NRDCL has extracted 119.739 m^3 from FMUs and other areas. Moreover, the department has extracted 15.209 m^3 of timber and 11.894 m^3 of firewood at commercial rate, and 72.296 m^3 of timber and 35.473 m^3 of firewood at subsidized rate [DoFPS, 2019]. In fact, the timber logging has to comply with both commercial timber supply and subsidized timber supply for rural inhabitants. They may receive timber at discounted price for the construction or renovation of rural houses, and an amount of fuelwood depending on the accessibility to electricity.[17]

Despite the amount of potential timber reserve of the country, only 5% of it is under commercial management. Moreover, 3% of the total is used by CFs and 7% is used by rural householder for subsistence. So approximately 15% of Bhutan's forests is used [WB, 2019].

Dzongkhags (*) [18]	N. FMU	Allowable cut m^3/year
Haa	3	20.466
Paro	2	13.866
Thimphu	2	7.470
Chhukha	1	4.131
Wangdue Phodrang	2	17.300
Trongsa	1	1.100
Bumthang	3	32.220
Zhemgang	1	2.100
Lhuentse	1	4.577
Mongar	2	12.800
Trashi Yangtse	1	4.215
Trashigang	1	2.708

(*) The tab shows the timber available for cutting, not the total timber really harvested.

[14] (Bhutan E-RNR Masterplan taskforce BEMP, 2016);
(Forest Resource Management Division, 2014)

[15] (Department of Forests and Park Services, 2018)

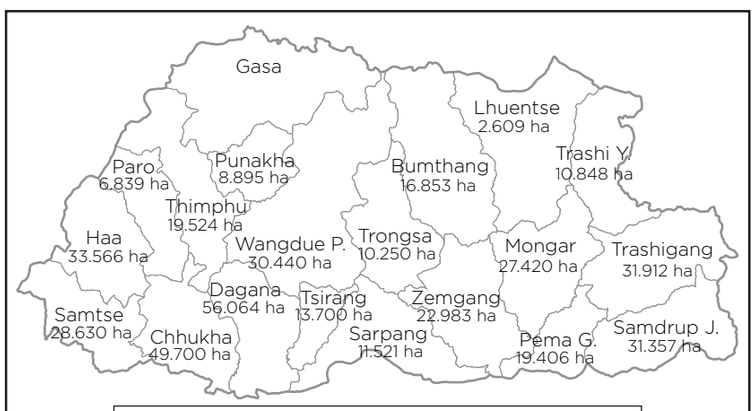
[16] (The World Bank, 2019)

[17] (Forest Resource Management Division, 2014);
(The World Bank, 2019)

[18] (Renewable Natural Resources Statistics Division, 2018)

Protected Areas [19]	Supply of timber m^3 (2018)
Bumdeling Wildlife Sanctuary	2.125,82
Jomotshangkha Wildlife Sanctuary	3.919,75
Jigme Singye Wangchuck National Park	1.011,56
Jigme Khesar Strict Nature Reserve	328,49
Jigme Dorji National Park	7.221,56
Phrumsengla National Park	7.151,52
Phibsoo Wildlife Sanctuary	855,74
Royal Manas National Park	708,29
Sakteng Wildlife Sanctuary	6.065,26
Wangchuck Centennial National Park	3.026,54
Biological corridors	-

According to the FRPA, the potential production area within protected area, with a slope <35° (better for harvesting) is 11,79% of total country area. The logging of protected area is not for commercial aim, but for helping the area itself and for inner distribution. Outside the PA, the potential production area with slope <35° is 11,27% of total area, available for commercial forest management [FRDM, 2014]. The use of these areas, however, would mean also the investment for developing connection roads and access. Moreover, it is reported that the improvement of equipment which is old and frequently breakdown, and a good planning in FMUs would improve the harvest volume of timber. In the following map, it is represented the distribution of Potential Forest Production Areas outside the protected areas. [20]



POTENTIAL PRODUCTION AREAS [21]

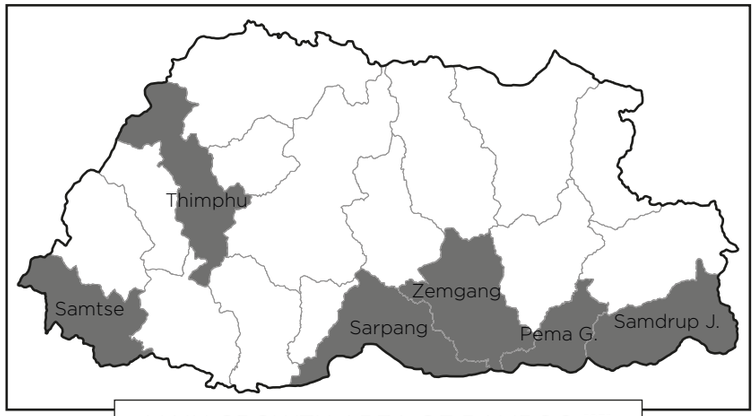
[19] (National Statistic Bureau, 2019); (Renewable Natural Resources Statistics Division, 2018)

[20] (Forest Resource Management Division, 2014); (The World Bank, 2019)

[21] (Forest Resource Management Division, 2014)

BAMBOO

Bamboo is a Non-Wood Forest Product (NWFP). In Bhutan, about 42% of population use bamboo for different purpose [Tobgay, 2008]. Bamboo grows naturally in the country: there are 31 different species for sure. It's possible that other species exist. Bamboo in rural villages is commonly used for production of daily household items, fences, ropes, mats for roofing, or as edible supplement. The use of bamboo as construction material is not common and limited to the southern region of the country. Otherwise, it is used in minor element like the rabsel panels (ekra). Bamboo resources in forest is currently more than sufficient according to local needs. Moreover, people use to grow own bamboo plantation for easier extraction and for the wind and soil erosion control.[22]



MAIN GROWTH AREA OF BAMBOO [23]

FACTORIES

Wood based industry could be of different type: sawmill, furniture unit, particle board factory, plywood factory, fibre mill, wood lamination, wood joinery, block board, handcraft unit, and so on. Sawmill is the mainly industry, for the process from logs to sawn timber. The number of sawmills increased over the years. [24]

	Dzongkhag [25]	Forest based industries (2019)	Sawmills
WEST ↓	Samtse	24	3
	Haa	49	24
	Paro	151	24
	Thimphu	152	18
	Chhukha	58	12

[22] (Department of Human Settlement, 2013); (DORJI, 2018); (FRITH, 2015)

[23] (Department of Human Settlement, 2013)

[24] (Department of Forest and Park Services, 2017); (Department of Forest and Park Services, 2018)

[25] (Department of Forest and Park Services, 2018); (National Statistic Bureau, 2019)

	Dzongkhag	Forest based industries (2019)	Sawmills
WEST	Gasa	1	-
	Punakha	21	-
	Wangdue Phodrang	34	10
	Dagana	12	-
	Tsirang	18	2
	Trongsa	13	1
	Sarpang	54	6
	Bumthang	71	20
	Zhemgang	34	2
	Lhuentse	14	1
	Mongar	51	5
	Pema Gatshel	28	1
	Trashi Yangtse	104	1
EAST	Trashigang	45	4
	Samdrup Jongkhar	44	4

IMPORT AND EXPORT

Bhutan's Forest and Nature Conservation Rules 2017 states: "export of timber in either log form, sawn timber form or as firewood is banned" [WB, 2019]. Preservation of forest within the only inner distribution is a crucial key. However, export is permitted when timber is unsold in the country.

Instead, processed wood and bamboo are respectively the 31% and 8% of the wood-based import item [WB, 2019]. In fact, despite the large wood availability, the increase of raw materials prices in Bhutan and the high transportation costs make the inner production not competitive: the supply of products from neighbouring countries results convenient.

Exported products [26]	Exit point	Quantity
Timber	Phuentsholing	24,28 m^3
Used timber	Phuentsholing	1 truckload
Limestone	Phuentsholing	188,18 MT
Ply board	Phuentsholing	360 pieces
Stone chips	Phuentsholing	12 MT
Ply wood	Gelephu	8861 pieces
Semi-finished wood	Gelephu	15,42 m^3
Stone aggregates	Gelephu	1115 truckloads

[26] (Department of Forest and Park Services, 2017)

Imported products [27]	Enter point	Quantity
Bamboo	Phuentsholing	299924 pieces
Bamboo chips	Phuentsholing	80415 MT
Bamboo chips	Phuentsholing	216 m^3
Bamboo mats	Phuentsholing	2930 rolls
Limestone	Phuentsholing	15,79 MT
Timber	Phuentsholing	5,05 m^3
Bamboo	Gelephu	29475 pieces
Bamboo mats	Gelephu	264 rolls
Stone	Samdrupjongkhar	3 truckloads
Timber	Samdrupjongkhar	66,17 m^3
Large bamboo	Samdrupjongkhar	10966 pieces

Impact

The presence of forest has a positive impact on the land and economy. Trees' rots carry out erosion control, preventing landslides and improving safety in transport sector. Forest also controls the sedimentation process generating benefits for the energy sector. Moreover, forest products are part of people's nutrition and the uniqueness of flora and fauna are a treasure both for inhabitants and for enhancing tourism too. The Bhutan's attention on forest preservation is due to several matters, which are crucial for balancing human life and environment.[28]

Despite this, forests are subjected to several disturbance factors. Wood harvesting is itself a disturbance factor: it's crucial to manage the logging process in a sustainable way, in order to guarantee the forest preservation. Forest fires are the main cause of forest degradation and are mainly located in the central and eastern Bhutan, due to the pine and oak forest susceptibility [WB, 2019]. The cause may be natural or may derive from man-made activities. In 2018, 39 fires affected the country [DoFPS, 2019]. Urbanization and infrastructure development are also cause of forest cover decrease. Another disturbance factor is the cattle grazing, which affects the regeneration of forest, compacting the soil and reducing the germination potential. Human and natural disturbance affects forests: human negative impact needs to be limited according to the idea of preservation. Moreover, natural building materials, particularly bamboo, have a negative impact on local people: they aspire to live in concrete houses, associating them with safety and long-life span of the house. Bamboo particularly is subjected to a negative attitude due to the lack of knowledge and skills about bamboo construction.[29]

[27] (Department of Forest and Park Services, 2017)

[28] (The World Bank, 2019)

[29] (Department of Forest and Park Services, 2018); (DORJI, 2018); (FRITH, 2015)

4.4 CONCLUSIONS

	STONE	CONCRETE	STEEL	WOOD	BAMBOO
AVAILABILITY IN THE COUNTRY	Stone quarries are available in the whole country	Limestone mines are located in the south of the country	One Iron ore mine is located in the south. Limited information	High availability of wood in the whole country	Bamboo is available in the south-east of the country
PRESENCE OF INDUSTRIES	Limited information	Industries in the south of the country	Industries in the south of the country	Industries in the whole country	Limited information
RURAL PEOPLE SKILLS	Construction of traditional houses	No skills	No skills	Construction of traditional houses	Production of daily household items
IMPACT ON TRADITIONS	Traditional material commonly used	Huge use impacts the appearance and the building process	Huge use impacts the appearance and the building process	Traditional material commonly used	Possible substitute of wood
IMPACT ON ENVIRONMENT	Mines activities affect people health and water quality. Natural restoration is difficult	Mines activities affect people health and water quality. Natural restoration is difficult	Mines activities affect people health and water quality. Natural restoration is difficult	Uncontrolled exploitation of forest affects natural balance	Uncontrolled exploitation of forest affects natural balance

In conclusion, there is not the “right” material: everyone presents opportunities and critical aspects.
STONE is locally available, traditionally used in rural houses construction, but the quarry activities impact the environment: a controlled program of extraction is required and good-construction practices must be spread in the country. Moreover, as previously told, rural houses are not built with quarried stones, but with unshaped ones found by people. The quarried stone quality is better than other ones so quarried stones should be sold to rural communities at affordable prices.
WOOD is locally available. Moreover, the forest conservation programs prevent the uncontrolled exploitation, but raw materials and transport cost too much at present, maybe as consequence of the conservation programs themselves. New programs could solve also this problem in order to avoid importation of wood. Affordable sales programs for rural communities already exist.
STEEL big elements are not locally available. There is a lack of information about this material, but the presence of industries and the more frequent demand in urban areas maybe will lead to the development of the sector: at the moment it is reasonable to think that there is an inner production of small elements. Unfortunately, the production is located in the south of the country so transport to the remote villages in the east regions could be tricky.
CONCRETE seems to be locally available, but its huge use leads easily to a loss of traditional architectural features. As the production of steel elements, concrete production is located in the south of the country. Moreover, the mines impact on environment, like stone quarries and iron mines, requires a program for a sustainable extraction. The lack of skills for the use of concrete in the rural houses’ construction must be solved with the education of the communities.
BAMBOO is commonly used for smaller daily items. Cultivation of bamboo is easy and the structural behaviour is good. The main problem is the people’s attitude: spreading awareness and knowledge about the good quality of bamboo could lead to the introduction of bamboo in the traditional house construction.

Construction materials represent a crucial aspect of architecture vulnerability: good quality materials can change the seismic response of traditional buildings. In order to reduce the vulnerability, according to the previous analysis, preventive actions will include the use of quarried stones, a big amount of wood, the introduction of small steel elements, the limitation of concrete to the use of cement mortar, a little use of bamboo.

5

CHAPTER

PLAN OF ACTION

"The vision attempts to strike a balance between development and environment, modernization and tradition, values and technology, immediate and long term, individuals and the society, and realism and aspirations."

PLANNING COMMISSION

5 | PLAN OF ACTION

The chapter is divided into four parts. The first one is about damages that frequently affect Bhutanese architecture: a complete overview of causes and effects is developed. The second part is a collection of common practices extracted by the literature: interventions on architecture are listed and explained. The third part is a critic selection of those practices: the systematization of the various aspects developed in the entire thesis (risk, architectural, material, damaging factors) leads to a collection of concepts useful for the retrofit. The last part is the development of the manual of intervention.

5.1 DAMAGE PATTERNS

Bhutan is a fragile country: it's subjected to natural extraordinary hazards that damage architecture and change people's life deeply. The most common hazards are earthquakes and windstorms, which provoke serious damages to buildings and, sometimes, loss of human lives. Moreover, buildings are subjected to the effect of ordinary attacks by moisture, vegetation, weather and aging. These lead to a weakness of construction material and then of the structure itself.

But what is the cause of these damages? Men design and build in a well-known environment: studies and science have allowed us to highlight the most seismic areas, to measure the lifespan of materials, to have the overview of critic aspects in traditional architecture. So, the point is to build in the best possible way in this environment. The cause of the damages should be sought in the construction errors: correcting these errors helps to reduce the vulnerability, mitigate damages and make the building more resistant.

In the following tab the specific constructive causes of each damage are listed. At the end, human factors are collected as general categories that enhance construction damages: they are the use of poor-quality materials, improper construction practices, the use of unskilled workmanship, the total absence of maintenance. The last one is quite relevant: Bhutanese people are not aware that maintenance can save their lives, it's seen like an unnecessary cost.

Awareness of people is the starting point: instruction and practice can lately lead to a better-quality construction and save lives.

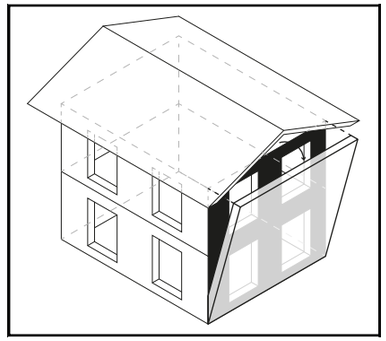
Tab of damages

	EXTERNAL FORCES	CAUSES	A.E.*	EFFECTS	SUB-EFFECTS
Extraordinary causes	Earthquake	Lack of connections	B	Out-of-plane collapse	
		Poor tensile strength of masonry	B	In-plane cracks	
		Poor connection of masonry layers	B	Delamination	
		Lack of connections	B	Loss of structural integrity	
		Wall collapse, lack of connections	B	Roof/floor collapse	
	Windstorm	Lack of connections	R	Blown off failure	
		Lack of connections	R	Panel failure	
		Large spacing between purlins	R	Peeling failure	
		Purlins protrude too much	R	Roof overhang failure	
		Inadequate size, lack of connections	R	Support failure	
Ordinary causes	Load	Accident	S	Chipping	Decrease building quality
		Overloading	S	Cracking	
	Weather	Lack of protection (roof coverage)	S W	Erosion by rain and wind Weathering of wood	Increase moisture effects Increase biological attack
	Biological attack	Inherent weakness, lack of cleaning	S S W W	Erosion by fungus acid Dislocation by plant roots Rots by fungi Weakening by insects attack	Decrease building quality Increase moisture effects
	Moisture	Inherent porosity Lack of protection (infiltration) Lack of drainage	S S S S S	Efflorescence/subflorescence Exfoliation/delamination Crumbling Rising damp deterioration Cracking	Decrease building quality Increase biological attack
Human factor	→	Poor quality of materials Improper construction Unskilled workmanship Absence of maintenance	→		Increase seismic damages Increase windstorm damages Increase time effects Increase weather effects Increase moisture effects Increase biological attack

(*) A.E. =
Affected Elements

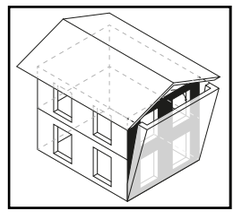
B= whole Building
R= Roof
S= Stone masonry
W= Wood elements

Extraordinaty causes | EARTHQUAKE



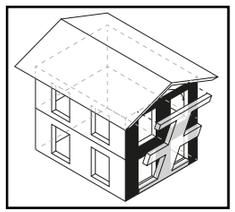
Out-of-plane collapse [1], vertical overturning

It's the collapse of a big portion of the wall. It's caused by the poor wall-to-wall, wall-to-floor and wall-to-roof connections. Each part vibrates on its own: the floor pushing action against the wall and the roof motion make the wall move away from the rest plane.



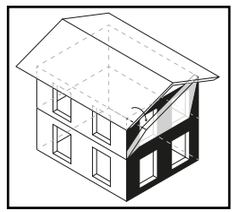
Overturning with 1-2 side wings

Sufficient connection with edge



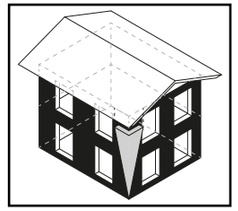
Vertical strip overturning

Poor connection across the openings



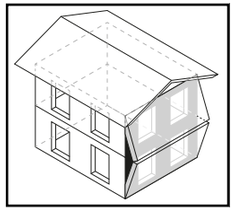
Partial overturning

Uneven connection at the edge, poor quality of masonry



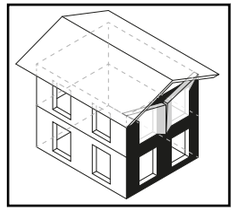
Corner failure

The two walls involved are well connected, poor quality of masonry



Vertical arch

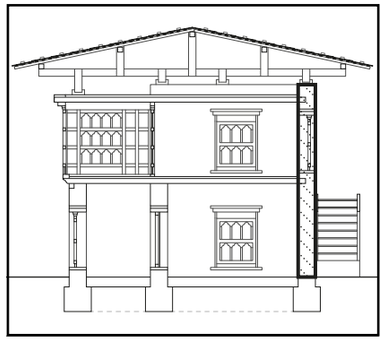
Wall connected only with the top floor



Horizontal arch

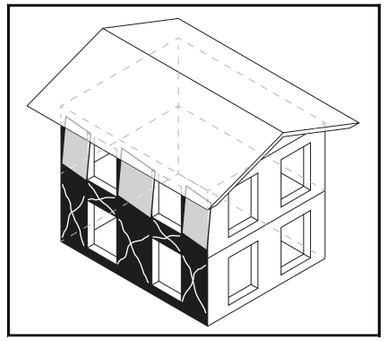
Wall connected with lateral ones, poor quality of masonry

There are more type of collapse depending on strength of connection between elements: a sufficient connection at the edge of the walls and no wall-to-floor/roof connection lead to the overturning with one or two side wings, no connections at the edge of the walls and a poor wall fabric lead to the partial overturning, and so on.



[1] (BHATTACHARYA, 2014); (BOTHARA, 2011); (D'AYALA, 2002); (FLORIO, 2010); (Ministry of Works and Human Settlement. 2014); (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2017); (SATHIPARAN, 2015)

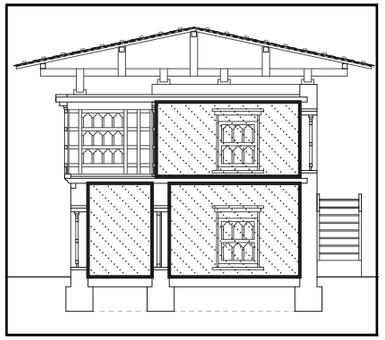
Extraordinaty causes | EARTHQUAKE

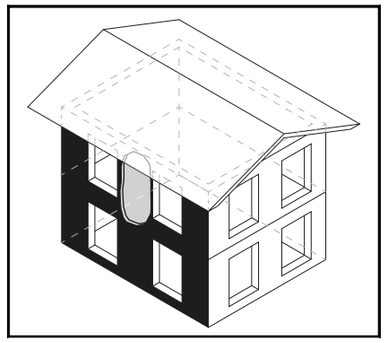


In-plane cracks [2]

The walls parallel to the earthquake shaking direction are subjected to in-plane lateral loads. These loads induce the rocking of piers, or, more of the time, diagonal X-shaped cracks when tensile forces exceed the masonry tensile strength.

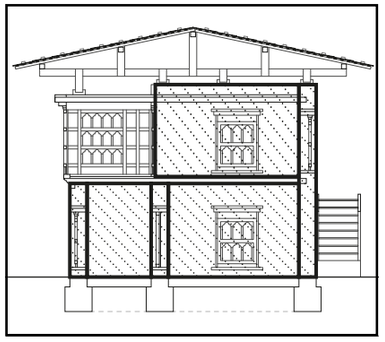
The poor tensile strength of the masonry is the primary cause of these kinds of damage. The tensile strength depends on the length and thickness of the walls, the presence of openings and discontinuities, the use of irregular stones and weak mortar, the absence of reinforcement.





Delamination [3]

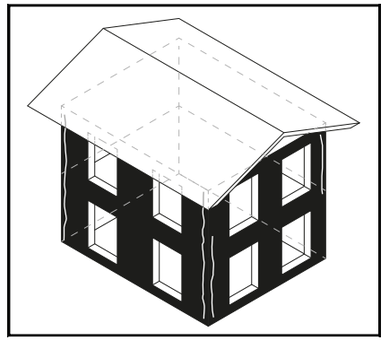
The Bhutanese wall is usually built with two exterior leaves of large stones and a rubble infill with small stones and mud mortar.
Delamination occurs when one of the wall leaf collapse, due to the reduction of frictional forces between stones and the increase of internal forces pushing outward. The cause is the poor quality of the masonry: the use of irregular shaped stones, the absence of through-stones or others joints between the two stone layers, the weak rubble infill between the leaves. Delamination usually occurs on the upper portion of the wall.



[2] (BHATTACHARYA, 2014); (BOTHARA, 2011); (FLORIO, 2010); (Ministry of Works and Human Settlement. 2014); (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2017); (SATHIPARAN, 2015)

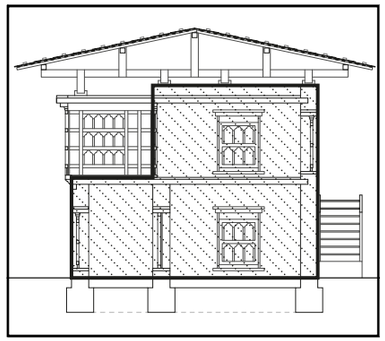
[3] (BHATTACHARYA, 2014); (BOTHARA, 2011); (Ministry of Works and Human Settlement. 2014); (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2017)

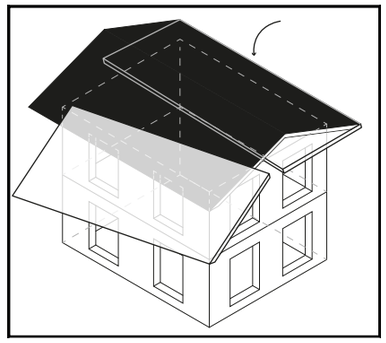
Extraordinaty causes | EARTHQUAKE



Loss of structural integrity [4]

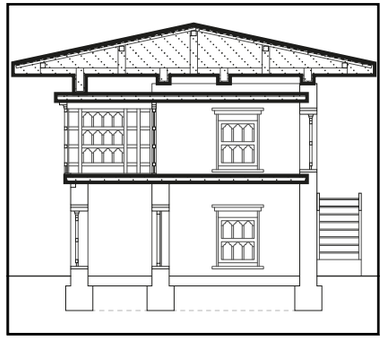
The integrity of the structure depends on how well the elements are tied together. The building must work like a monolithic box. Loss of structural integrity means the failure of connections and damages at intersections, that are vulnerable due to the tensile and shear forces developed during the earthquake. These damages are vertical cracks and, sometimes, separation of the walls. The cause is the weakness of connections between walls. It's also caused by the pushing action of floors against walls, that is due to a lack of connection. The loss of integrity may lead to an out-of-plane wall collapse.





Floor/roof collapse [5]

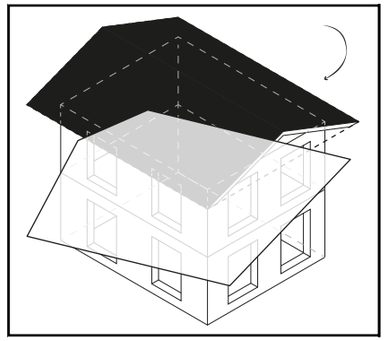
The floor or roof collapse is the failure of these timber structures. Stone walls and timber structures, which are not well connected, vibrate differently during an earthquake, pushing each other in different directions. The roof may collapse because of the support wall collapse, or for the failure of the structure itself. The floor may collapse because of the expulsion of the beams from the support wall, causing the collapse of the building. The pushing action of the floor on the walls may lead to an out-of-plane collapse. The cause of these failures is the lack of connection between floors and roof with the walls.



[4] (BOTHARA, 2011); (Ministry of Works and Human Settlement. 2014); (SATHIPARAN, 2015)

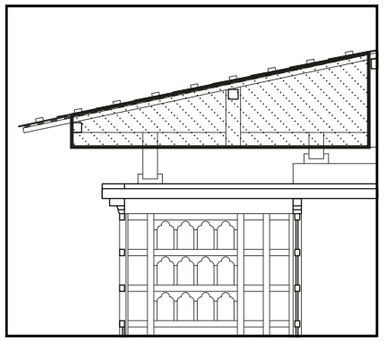
[5] (BOTHARA, 2011); (Ministry of Works and Human Settlement. 2017); (SATHIPARAN, 2015)

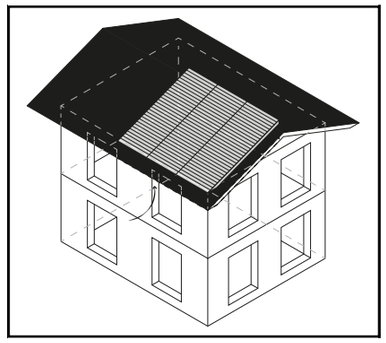
Extraordinaty causes | WINDSTORM



Blown off failure [6]

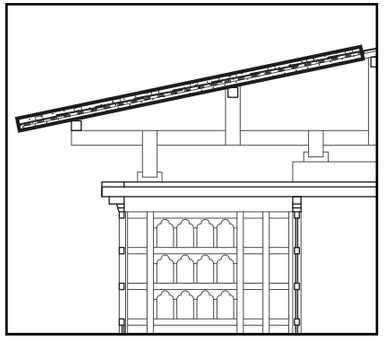
The Bhutanese roof is a timber structure joint without nails, simply resting on the topmost floor.
Various damages affect the roof. Blown off failure takes place when more than 50% of the trusses are lifted up. The cause is the absence of connection between tie beam, truss and the wall. Different layers of the roof are affected by wind causing a big damage that must be prevented connecting the elements together. Junctions must be strengthened in order to avoid the roof failure and damages to people.





Panel failure [7]

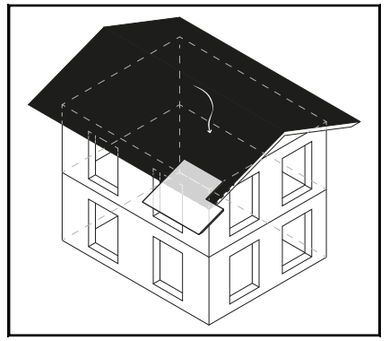
The panel failure occurs when a portion of the roof (panel = shingles/CGI sheets + purlins + reapers) blown off.
The damage involves the upper portion of the roof. The failure takes place due to inadequate connection of the elements to the truss system, the lower layers are better connected. The undersized reapers and purlins are another cause of collapse. Bigger elements and good connections among all the roof structure must be achieved.



[6] (Ministry of Works and Human Settlement. 2016)

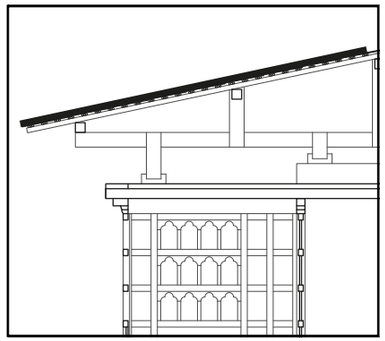
[7] (Ministry of Works and Human Settlement. 2016)

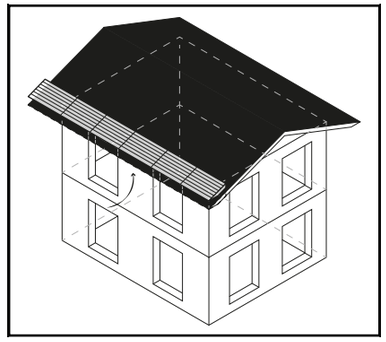
Extraordinaty causes | WINDSTORM



Peeling failure [8]

The failure is classified as peeling when the whole or part of roof coverings (shingles/CGI sheets) is peeled off. The truss system remains undamaged. So, the failure involves only the upper layer of the roof. The failure is caused by the lack of connection of the covering with purlins. Moreover, large spaces between purlins result in large wind pressured surface area. Connection between traditional wood shingles, held in place by stones, and purlins is very complicated, the connection with a CGI sheet is easier.

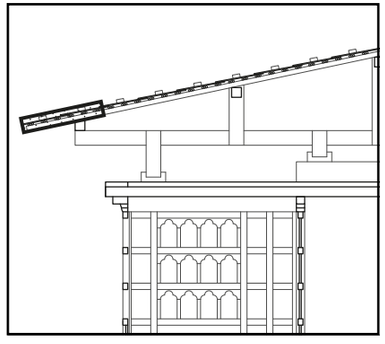




Roof overhang failure [9]

The overhang is the protraction of purlins and reapers over the truss support. The roof overhang failure takes place when the overhang is excessive: there is a big surface area subjected to the wind pressure action.

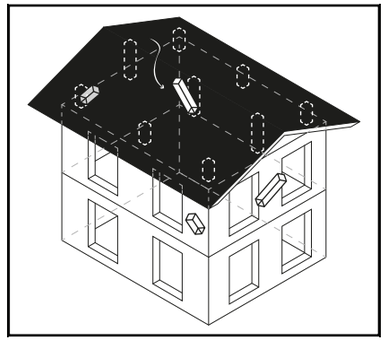
Overhangs are crucial for the protection of the lower walls from rain, so the solution must take this fact in consideration, enhancing the connection between existing elements and making new connections between the overhangs and the building structure.



[8] (Ministry of Works and Human Settlement. 2016)

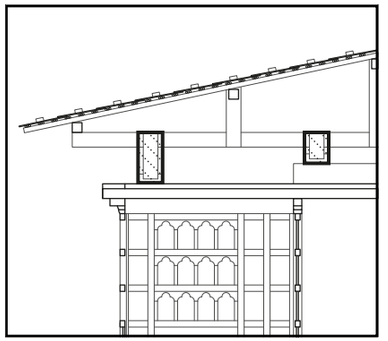
[9] (Ministry of Works and Human Settlement. 2016)

Extraordinaty causes | WINDSTORM



Support failure [10]

The failure is classified as support failure when the whole or part of the roof is damaged because of the failure of vertical support (called Lhiu-chung). The lower layer of the roof is affected and the whole structure is undermined. The damage is due to the undersized supports or to the lack of connection of the support with the roof floor.
Bigger supports and good connections between all layers of the roof must be achieved in order to avoid big damages and people injuries.



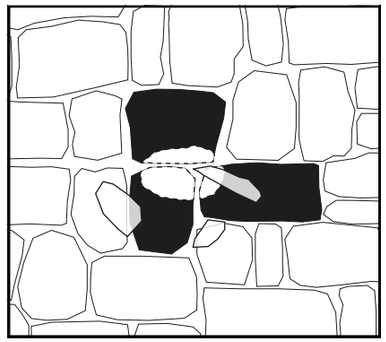
Extraordinary causes | CONCLUSION

The earthquake vulnerability is primary due to the presence of elements with different materials, which have different seismic reaction. All these elements are not connected, so everything moves alone in different directions. The aim is the join of these separated parts in order to create a “monolithic box” with a unique re-action to the earthquake.
Intervention on masonry quality is quite difficult but a “monolithic box” behaviour and a good management of the load path can help in this direction.
In Bhutan the masonry corner is a very vulnerable junction.
Moreover, literature never explains how the rabsel influences the behaviour of the building: it’s a timber unconnected element so it moves apart from stone masonry, affecting it. It’s important to understand how these two elements can be joined.

Windstorms in Bhutan affect the roof of the building. The roof structure is simply lying on the topmost floor and inner elements are assembled without nails. Strengthen the roof and anchor it to the house is a solution.

[10] (Ministry of Works and Human Settlement. 2016)

Ordinary causes | LOADS AND WEATHER

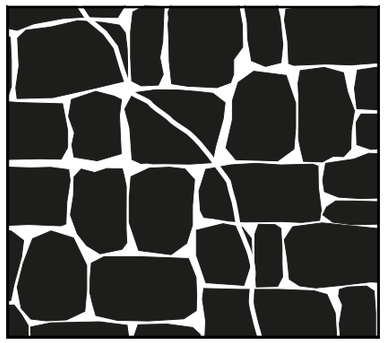


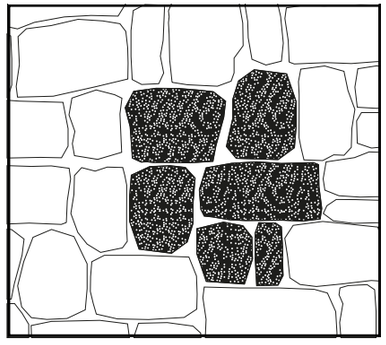
Chipping [11]

Small or large pieces of stone detached from the masonry are called chipping damage. They are due to accident, caused by percussion. The loss of a single piece is not a problem for the masonry, but the loss of more pieces during time may weaken the masonry.

Cracking [12]

Cracks are fissures from 1mm upwards. They are due to structural problems such as overloading of the masonry or foundation failure. The repair of the crack is not sufficient, it is necessary to act on the cause by better distributing the loads and, when possible, by intervening on the foundation.



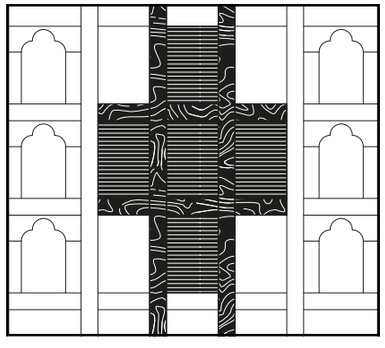


Erosion by rain and wind [13]

The erosion is the tendency of masonry to dissolve. It's due to rain and wind action. This process could affect the quality and durability of the masonry.

Weathering of wood [14]

Drying-wetting action, exposure to light, freezing, are part of the weathering process of wood. It is a superficial damage and doesn't cause structural problem, but it makes wood more susceptible to biological attack. Weathering process can damage ekra elements too.



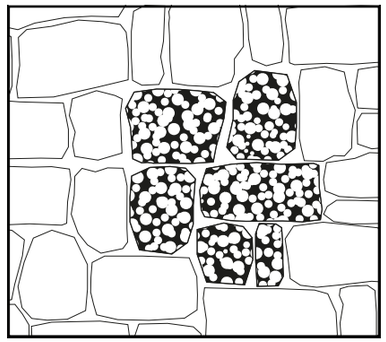
[11] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[12] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[13] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[14] (MINDESS, 2007)

Ordinary causes | BIOLOGICAL ATTACK

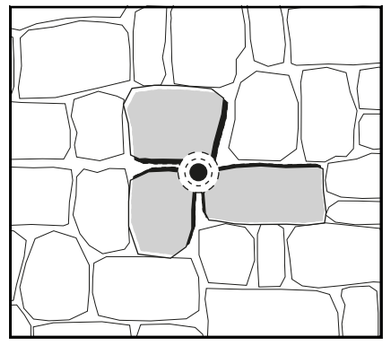


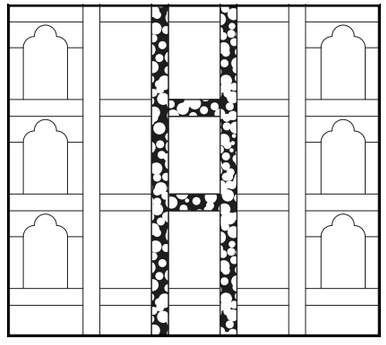
Erosion by fungus acid [15]

Fungi can lead to superficial damage secreting small amount of acid. They don't cause structural problem, but an excessive growth may indicate presence of moisture in the masonry. The same is for other biological growths such as mosses and algal growth.

Dislocation by plant roots [16]

Plants on the masonry can cause damage with their roots penetrating joints and cracks. Roots could lead to dislocation of stone blocks and afterwards to water penetration and, eventually, to structural problems.



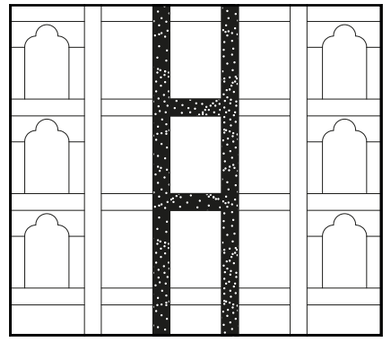


Rots by fungi [17]

Rots is the consequence of fungi action on the wood. Fungi attack the molecular composition of the wood, leading to the loss of strength. Fungi growth is due to the moisture in the wood.
Mould has no effects on wood but could be a problem for human health.

Weakening by insects [18]

The excavation of tunnels through the wood by insects' colonies weakens the structure. Moisture in the wood and presence of rot make the material more susceptible to insect attack, leading to wood decay.



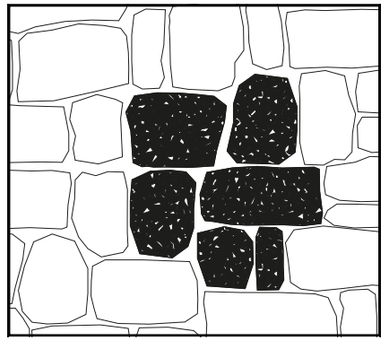
[15] (EKLUND, 2013); (Prof. GIANNATTASIO, 2013-2014)

[16] (EKLUND, 2013); (Prof. GIANNATTASIO, 2013-2014)

[17] (MINDESS, 2007)

[18] (JENKINS, s.d.); (MINDESS, 2007)

Ordinary causes | MOISTURE

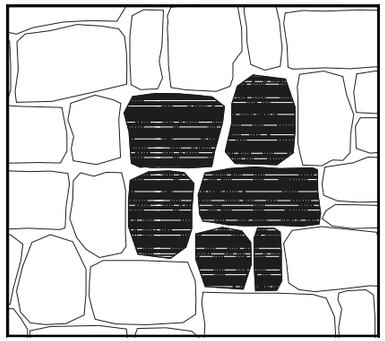


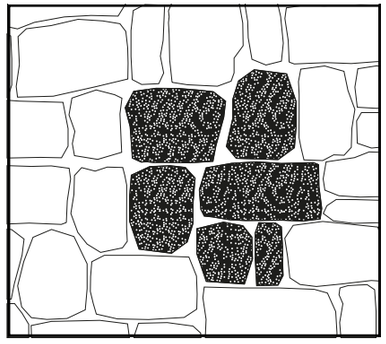
Efflorescence [19]

Efflorescence is the accumulation of soluble salt on the stone surface. Efflorescence itself may not be a problem but the water inside the masonry could lead to serious damages. Subflorescence is the accumulation of salt under the stone surface. It could lead to delamination.

Exfoliation/delamination [20]

Exfoliation or delamination occur when the surface of the stone flaks off into thin layers. The cause is the expansion and contraction of trapped moisture inside the stone. This process could affect the quality and durability of the masonry.



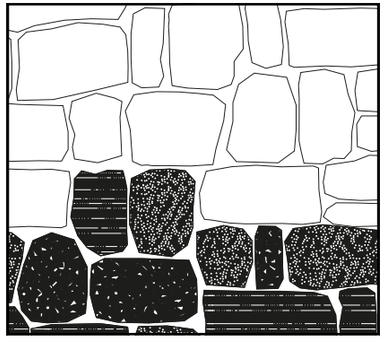


Crumbling [21]

It is the tendency of masonry to dissolve. It could be due to the inherent weakness of the stone or may be caused by external factor such as salt and moisture inside the masonry. This process could affect the quality and durability of the masonry.

Rising damp deterioration [22]

The rising damp is the suction of groundwater into the basal part of the masonry. It could lead to efflorescence and subflorescence, exfoliation and delamination, crumbling, and then to the weakening of the masonry. The rising damp is due to a lack of ground drainage.



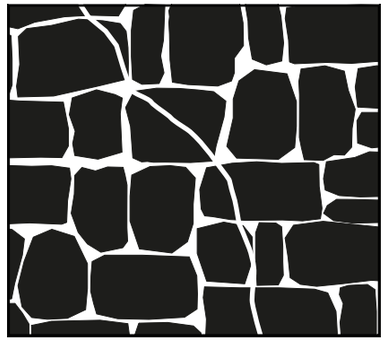
[19] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[20] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[21] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

[22] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

Ordinary causes | MOISTURE



Cracking [23]

Cracks are fissures caused by moisture retention and mortar shrinkage. Small cracks may not be serious, wider crack may become dangerous.
Small cracks can be repaired, but it is always better to protect the masonry from infiltration and rising damp.

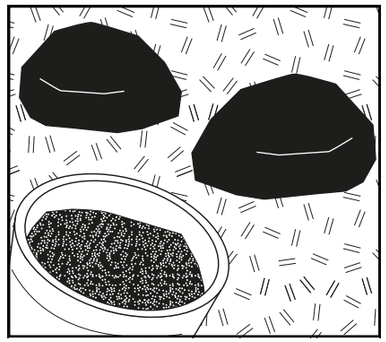
Ordinary causes | CONCLUSION

Building materials are subjected to ordinary attacks. Stone and wood decay gradually, leading to a weakening of the building in the whole. The solution for these “ordinary problems” is an ordinary maintenance. As told previously, maintenance is not an usual practice of Bhutanese people, but it should be.
Often replacing damaged elements, ensuring a good ventilation in order to avoid moisture, protecting wood by rain is enough. Other times it’s more complicated: moisture and cracks can lead to more serious problems. In these cases, a specific structural analysis is necessary to understand the damages and their causes. The specificity of each case makes it more difficult to map out general guidelines of intervention.

Maintenance, in conclusion, is a crucial practice and most of the times can save the building and the people living inside. Maintenance is not a preventive intervention as the one against extraordinary causes, but a posteriori intervention that do not allow damages get worse.

[23] (GRIMMER, 1984); (Prof. GIANNATTASIO, 2013-2014)

Human factor

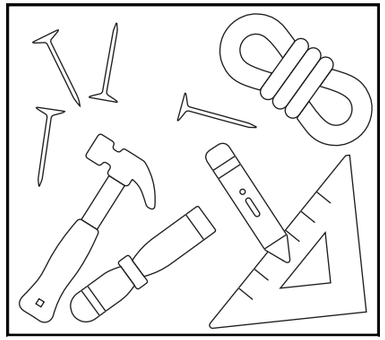


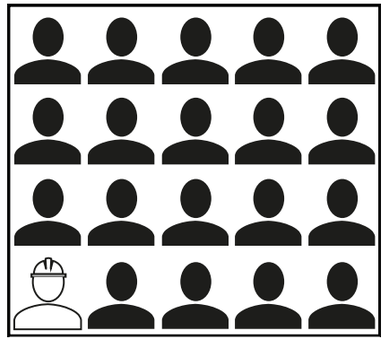
Poor quality of materials

· Weak mortar
· Irregular shaped stone
· Ekra wall system

Improper construction

· Absence of connection
· Use of elementary tools
· The wrong design configuration



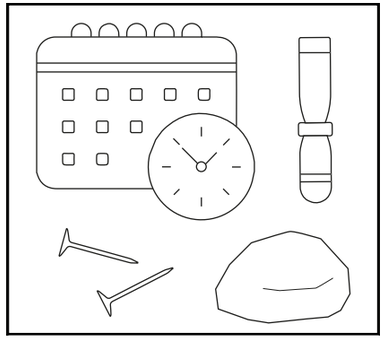


Unskilled workmanship

· Prevalence of unskilled workers
· “Skills” obtained by practice

Absence of maintenance

· No ordinary maintenance for costs
· No awareness of maintenance benefits



Human factor | CONCLUSION

Human factor is difficult to improve. In rural areas, Bhutanese constructor are usually unskilled inhabitants that work together to build up their houses. They follow the traditional practices passed down by one generation to another. Sometimes they work under the supervision of one master constructor, that is considered “skilled” for his period of practice in a dzong construction site. Their tools are often simple hammers and chisels and materials are the ones they can find by themselves. Maintenance, as told previously, is not considered.

In this scenario, awareness is the base of improvement. People instruction and training can lead to a better-quality construction. Some helps by government can make the difference: providing good quarried stone at cheaper price, likely about wood provision, and the supply of shared construction tools are some options. Construction manuals are other useful options for spreading knowledge and easy practices to improve building design and structural strength.

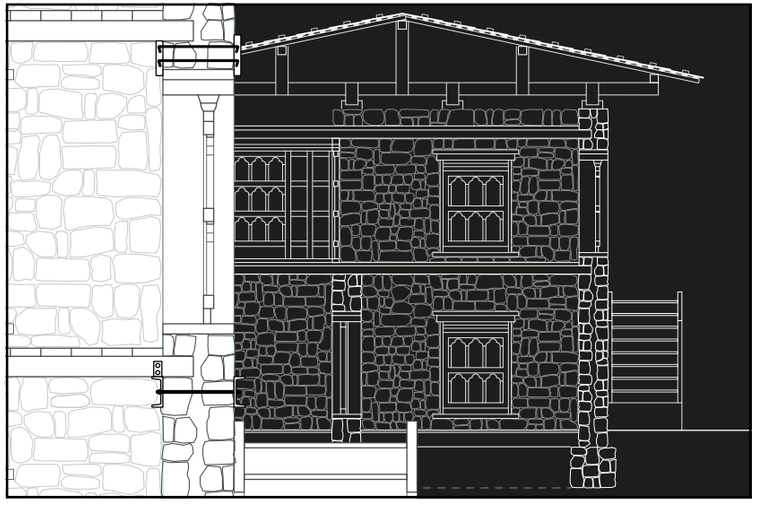
5.2 COMMON SEISMIC PRACTICES

Literature provides some common practices useful for an anti-seismic retrofit or a masonry quality improvement. These practices are listed in the following part. The failure mechanism solved, the architectural elements involved, and the material required are pointed out. These practices often require skilled workmanship or professional tools, or maybe impact to much the traditional aspect of the house, or sometimes require construction materials that need to be imported. So, it’s important to analyse these interventions in order to understand the basic concept and later re-propose it in other feasible practices. This part is also useful to understand which elements are not considered in the common retrofit interventions.
Below, only the preventive actions are developed, the ordinary maintenance is developed directly in the manual.

Practices are divided into five categories:

- CONNECTION BETWEEN STRUCTURAL ELEMENTS
- STABILIZING STRUCTURAL ELEMENTS
- ALLOWING PARTIAL COLLAPSE OF STRUCTURAL ELEMENTS
- COUNTERACTING HORIZONTAL LOADS
- DESIGN IMPROVEMENT

Connections between structural elements | **RING BEAMS**



The ring beam is a wood horizontal structure located in the wall thickness that allows the loads to be distributed evenly over the wall structure and improve the connection between orthogonal walls. It's composed of two longitudinal beams joined together with transversal elements. In existing buildings this practice would require the demolition of part of the wall. In order to avoid that, the ring beam is composed of two elements located at the wall inner and outer surfaces (steel elements or reinforced mortar bandages) which are connected by through-wall anchor. The ring beam system is continuous around the entire building and could be located at different levels to have a better seismic response: plinth, lintel and eaves levels.

FAILURE MECHANISM SOLVED

- ■ In-plane cracks
- ■ Delamination
- ☐ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

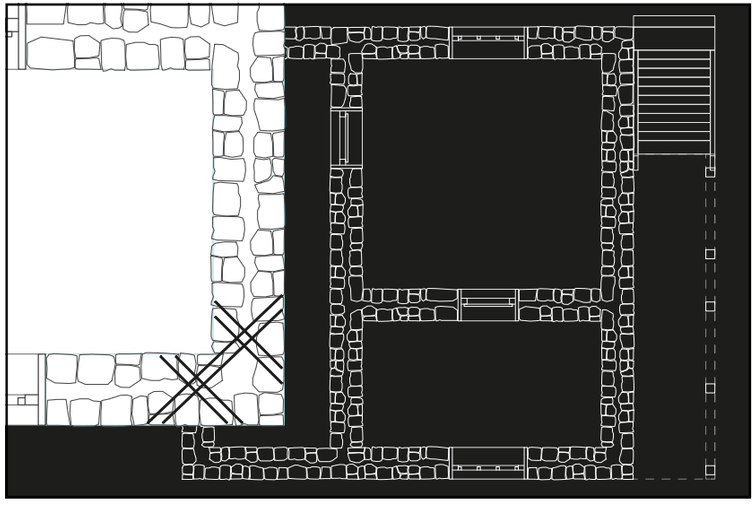
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ☐ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ☐ Others

(ARYA, 2014); (ARYA, 2010); (BOTHARA, 2011); (Ministry of Works and Human Settlement. 2017); (Ministry of Works and Human Settlement. 2010); (ORTEGA, 2018); (ORTEGA, 2017)

Connections between structural elements | **WALL-TO-WALL**



The wall-to-wall connections are ensured by reinforced perforations at corners, at T-shaped wall intersection or at X-shaped wall intersection. Steel bars are embedded in cement mortar in order to achieve a monolithic behaviour. The bars are located at different levels and some are inclined to the vertical axis.

An alternative solution is the use of fiberglass rods embedded in epoxy, but this is a very expensive solution.

It's possible to have timber corner braces having the same function, but their application requires the demolition of part of the wall.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

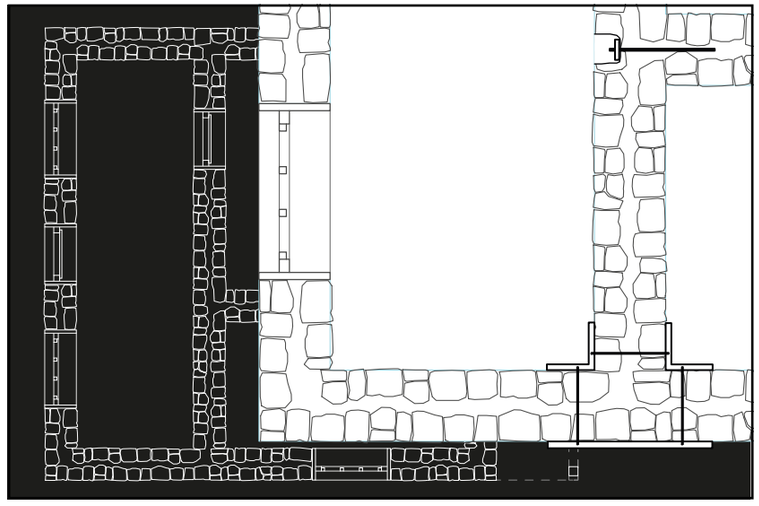
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ☐ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ■ Others

(ARYA, 2014); (ARYA, 2010); (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2018); (ORTEGA, 2017)

Connections between structural elements | **WALL-TO-WALL**



The wall-to-wall connections are ensured by L-shaped mortar overlay or by post-tensioned anchor.
L-shaped mortar overlay is a corner exterior reinforcement: two layers at the wall inner and outer surfaces are joined by crossed anchors embedded in concrete filled holes. The mortar overlay is reinforced by a welded wire mesh.

The post-tensioned anchor is a steel element located at corners or at T-shaped wall intersection. The post-tensioned treatment or the bar ensure a stronger connection. A grout layer covers the exterior steel plate and preserve the exterior appearance of the wall.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

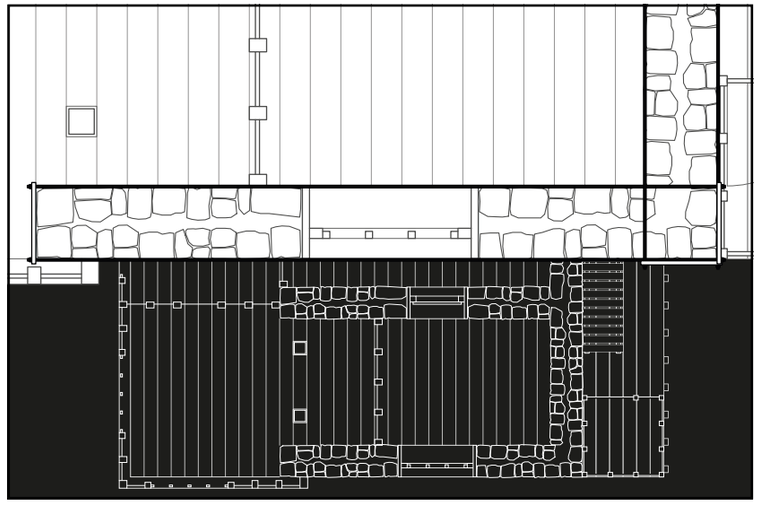
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ☐ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ☐ Others

(BOTHARA, 2011); (Ministry of Works and Human Settlement. 2014)

Connections between structural elements | **TIES**



Ties are an easily implement in existing structures. Ties connect orthogonal masonry walls: the aim is to hold together different structural elements in order to improve the monolithic box behaviour of the building. If not well connected, they could produce counterproductive stress concentration.

They are placed at the floor and roof levels, fastened at the end with steel anchor plates. Ties could be placed vertically at the corner and between openings too.

Ties could be either steel ties with steel anchor plates or timber ties with timber wedges.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

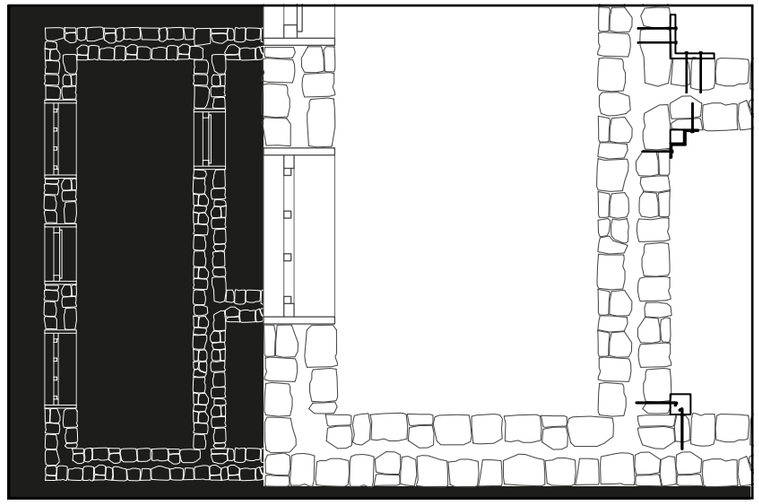
- ■ Walls
- ■ Floor
- ☐ Roof
- ■ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ■ Wood
- ☐ Bamboo
- ■ Steel
- ☐ Concrete
- ☐ Others

(BOTHARA, 2011); (LUTMAN, s.d.) (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2018); (ORTEGA, 2017)

Stabilizing structural elements | **CONFINEMENT**



Confinement strategy is the use of columns fixed at all corners in order to stabilize structural elements. These columns run all through the building height.

Reinforced tie columns confine the building walls at all intersection. Confinement can be obtained by use of timber reinforcement too: the wooden post is fixed to the wall with metal strap and nails. Another confinement way is the application of two orthogonal planks that are joined together by nails and are anchored to the seismic bands and to the wall.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

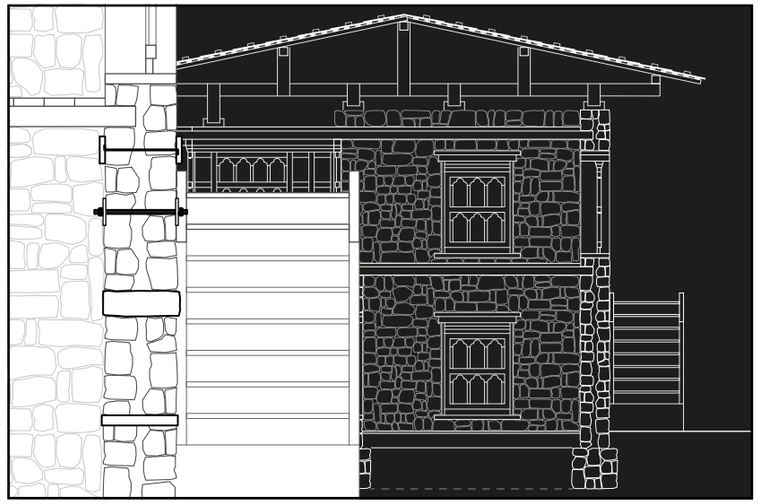
- ■ Walls
- ■ Floor
- ■ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ■ Wood
- ■ Bamboo
- ■ Steel
- ■ Concrete
- ☐ Others

(BHATTACHARYA, 2014);
(Ministry of Works and Human Settlement. 2010)

Stabilizing structural elements | **BONDING ELEMENTS**



Transversal bonding elements are placed inside the walls to improve shear behaviour. This strategy imposes the creation of a hole in the wall, removing stones without disturbing the others, and the consequent filling of that with concrete or anti-shrinkage mortar.

The transversal element could be a natural through-stone, a steel bar, a stainless-steel bar or a timber element.

The exposed surfaces of the elements must be protected by cement or sand plaster coating, in particular the steel ones.

FAILURE MECHANISM SOLVED

- ■ In-plane cracks
- ■ Delamination
- ☐ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

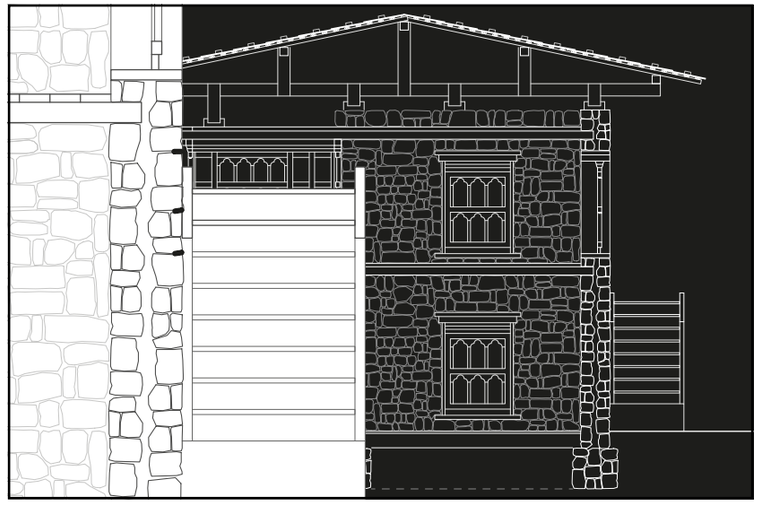
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ■ Stone
- ■ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ☐ Others

(BOTHARA, 2011);
(LUTMAN, s.d.);
(Ministry of Works and Human Settlement. 2017);
(ORTEGA, 2018);
(ORTEGA, 2017)

Stabilizing structural elements | **DEEP RE-POINTING**



Deep re-pointing is applied in order to prevent damages caused by weakening over time. A re-pointing is a simple one when the mortar joints is partially replaced with better quality mortar. This action is called reinforced deep re-pointing when the replacement is preceded by the insertion of reinforced rods or strips inside the joints.

The rods are made of steel or fibre reinforced polymer and are placed on both sides of the wall.

The reinforcement increases the ductility of the walls.

FAILURE MECHANISM SOLVED

- ■ In-plane cracks
- ■ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

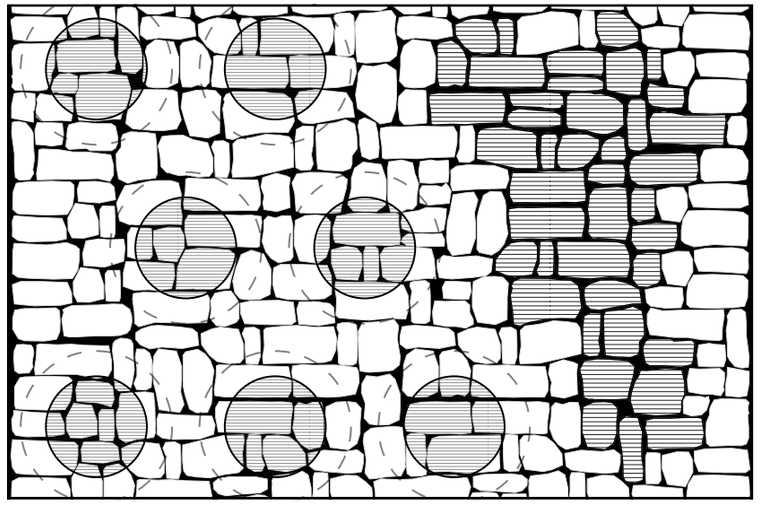
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ☐ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ■ Others

(BHATTACHARYA, 2014);
(LUTMAN, s.d.);
(Ministry of Works and Human Settlement. 2017);
(SATHIPARAN, 2015)

Stabilizing structural elements | **RESTORATION OF WALLS**



These strategies are applied to restore the structural characteristics of the stone walls.

The first one, the grout injection, restores the walls with diffuse lesions filling the inner voids.

The second one, unstitch and stitch, replaces part of the masonry. This is more complicated due to the removal of stones and the introduction of new elements that have to cooperate with the old part. The connection between old stones and new ones must be strong.

FAILURE MECHANISM SOLVED

- ■ In-plane cracks
- ■ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

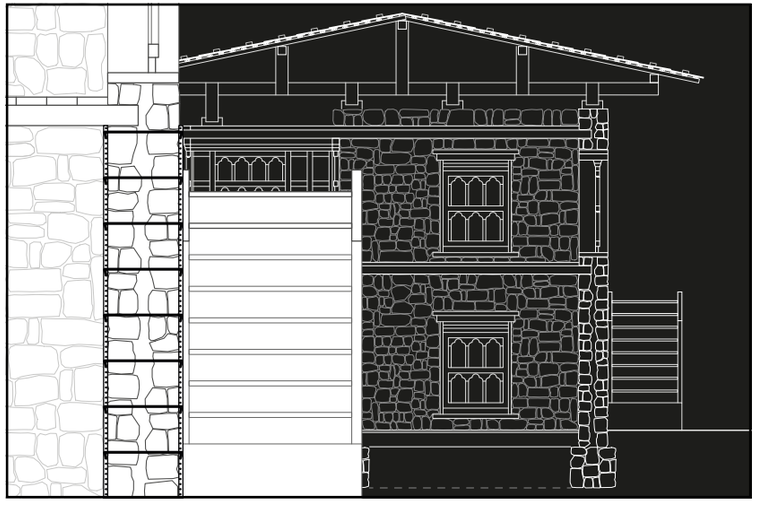
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ■ Stone
- ☐ Wood
- ☐ Bamboo
- ☐ Steel
- ■ Concrete
- ☐ Others

(BHATTACHARYA, 2014);
(BOTHARA, 2011);
(LUTMAN, s.d.);
(Ministry of Works and Human Settlement. 2017);
(SATHIPARAN, 2015)

Stabilizing structural elements | **NEAR-SURFACE**



The walls are strengthened with near-surface mounted reinforcement technique.
The reinforcement could be a concrete jacket: steel meshes anchored to both faces of the wall, joined together with through elements, and cement mortar on the top.
Another solution is a seismic wallpaper: glass fibre-reinforced polymer reinforcement bonded on the wall using epoxy resin. Other is a mesh reinforcement: steel cage, polymer mesh, PP-band mesh, bamboo mesh. Meshes achieve a stress distribution allowing cracking without loosing integrity: ductility and energy dissipation capacity increase, disintegrated elements are hold together, collapse is avoided.

FAILURE MECHANISM SOLVED

- ■ In-plane cracks
- ■ Delamination
- ☐ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

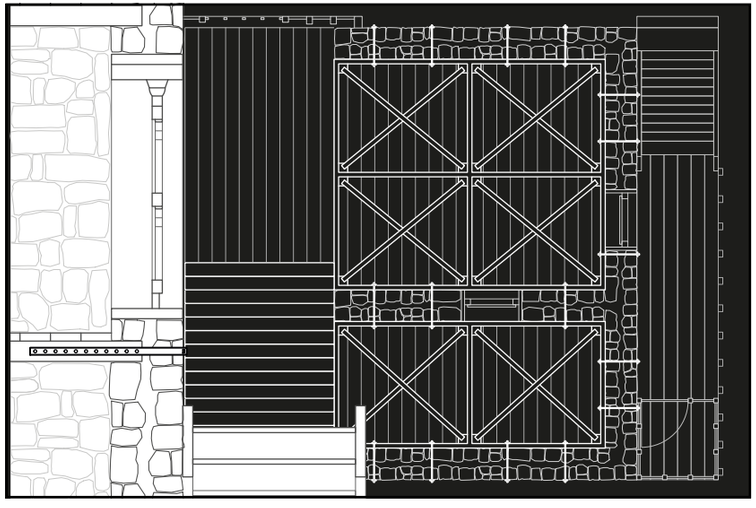
- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ☐ Wood
- ■ Bamboo
- ■ Steel
- ■ Concrete
- ■ Others

(BHATTACHARYA, 2014);
(BOTHARA, 2011);
(Ministry of Works and Human Settlement. 2017);
(SATHIPARAN, 2015)

Stabilizing structural elements | **FLOOR STIFFENING**



The in-plane floor stiffening strategies promote a reinforcement of the floor and its connection with the walls.
Floor is reinforced with a timber plank that lays perpendicular to the existing floor. The two layers are nailed together. Another way is a RC topping upon the existing floor. The new layer has to be well joined with walls and the old layer.
Diagonal bracings are another strategy: timber or steel bracing are located underneath the existing floor.

The steel straps connect the stone walls to the timber floor.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ■ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

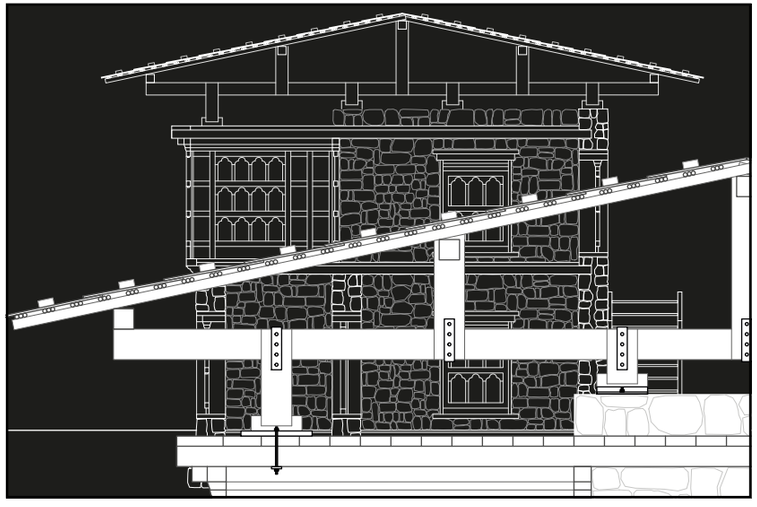
- ■ Walls
- ■ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ■ Wood
- ☐ Bamboo
- ■ Steel
- ■ Concrete
- ☐ Others

(BOTHARA, 2011);
(LUTMAN, s.d.);
(Ministry of Works and Human Settlement. 2017);
(ORTEGA, 2017)

Stabilizing structural elements | **ROOF STRENGTHENING**



The roof structure is assembled by the dove-tail technique without use of nails. The structure is so reinforced with metal gussets joining together wooden elements.
Moreover, the roof is simply resting on the topmost floor. Metal straps secure the connection between wall and roof structure. A wooden plank, ghadhen, if necessary is placed below the structure for levelling and transferring load from above to the topmost floor.
The roof overhangs prevent the walls from the heavy rain: overhangs are strengthened by increasing the number of outriggers.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ☐ Loss of structural integrity
- ■ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

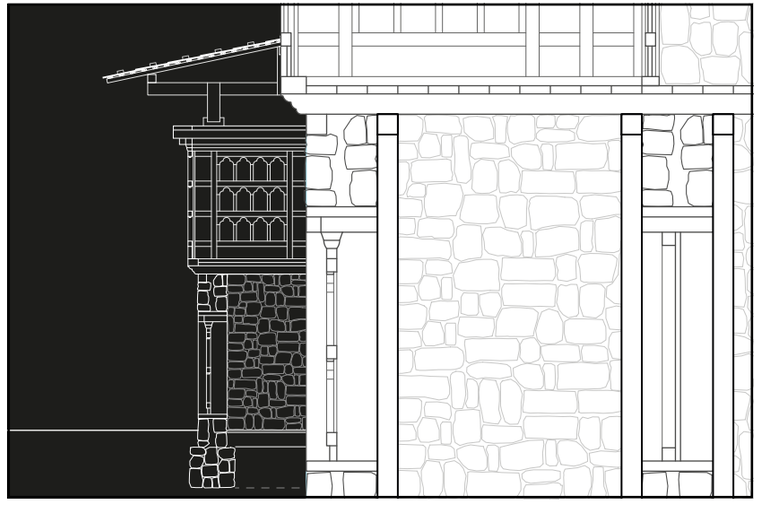
- ☐ Walls
- ☐ Floor
- ■ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ■ Wood
- ☐ Bamboo
- ■ Steel
- ☐ Concrete
- ☐ Others

(Ministry of Works and Human Settlement. 2016)

Allowing partial collapse of structural elements | **REDUNDANCY**



Redundancy of structural elements is achieved by the construction of a timber skeleton inside the primary structure: timber structural columns and beams are located inside the house in order to support the building. The failure of some structural elements doesn't mean the collapse of the building.

This is a temporary solution: the part of structure collapsed must be repaired later. Anyway, this strategy saves lives during the earthquake.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ☐ Out-of-plane collapse
- ☐ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

- ☐ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ☐ Stone
- ■ Wood
- ☐ Bamboo
- ☐ Steel
- ☐ Concrete
- ☐ Others

(ORTEGA, 2017)

Counteracting horizontal loads | **NEW STONE WALLS**

New stone walls are constructed in order to counteracting horizontal loads. New walls are located in one or both directions. A different solution is the construction of buttresses. Another one is increasing the wall thickness, increasing the resisting area.

These strategies require attention on the connection between new walls and original ones: if they are not properly connected, the effect is reduced or null. Connections could be achieved with steel elements embedded in cement mortar.
Moreover, it could be useful constructing new foundation beneath the new walls.

FAILURE MECHANISM SOLVED

- ☐ In-plane cracks
- ☐ Delamination
- ☐ Floor collapse
- ■ Out-of-plane collapse
- ■ Loss of structural integrity
- ☐ Roof collapse

ARCHITECTURAL ELEMENTS INVOLVED

- ■ Walls
- ☐ Floor
- ☐ Roof
- ☐ Openings
- ☐ Rabsel

CONSTRUCTION MATERIALS REQUIRED

- ■ Stone
- ☐ Wood
- ☐ Bamboo
- ■ Steel
- ☐ Concrete
- ☐ Others

(BOTHARA, 2011); (LUTMAN, s.d.); (Ministry of Works and Human Settlement. 2017); (ORTEGA, 2018); (ORTEGA, 2017)

Design improvement | **FIVE DESIGN ASPECTS**

Even if design aspects are proper of a new building construction, understanding how design choices may improve seismic response could be useful for the retrofitting strategies too.
Symmetry, regularity, separation of blocks, simplicity and enclosed area are the five aspects that have to be considered.

Symmetry in plan, elevations and location of openings is preferable because asymmetrical building corners are stressed more during an earthquake. Small openings should be located as far as possible between themselves and from corners.

Regularity in plan means simple rectangular shapes: shapes with projections are more affected. Moreover, regularity means a proportion length-width of 3:1.

When the length of the block is bigger than three times its width, it's useful to have more blocks separated by a 3-4 cm gap for avoiding damages between blocks. The span between walls should be a maximum of 5m.

Simplicity is an ornamental approach: large cornices, projections, facial stones are seismically dangerous. Avoiding unnecessary ornamentation is the better solution.

A small building enclosed with high-quality connections acts like a monolithic box. This is the more desirable seismic response. For stone buildings with mud mortar, the box should be of one storey, with a wall height of 3m.

(ARYA, 2014); (ARYA, 2010); (Ministry of Works and Human Settlement. 2014)

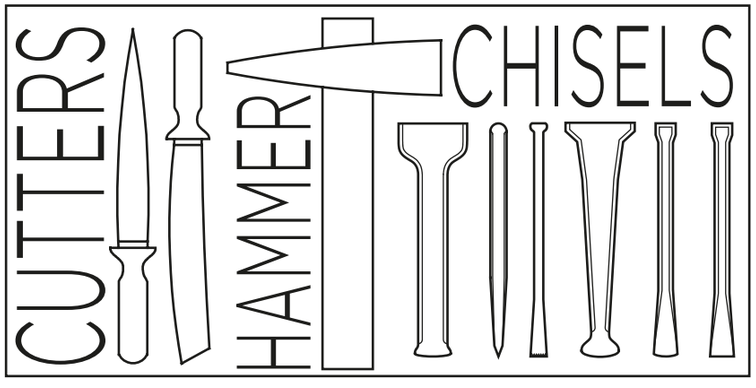
5.3 SELECTION OF SEISMIC PRACTICES

Bhutan is a complex and fragile land. The varied geomorphological aspect makes the country a unique conjunction of cultures and traditions: the opening to modernization puts everything at risk. At the same time, the natural hazards affect people every year: the traditional architecture is subjected to damages and failure and people's life changes drastically. The balance between modernization and traditional practices, new skills and old tools, local materials and modern ones, traditions' preservation and constructive improvement is the main aim of future actions.

Considering...

1. The limited skills of builders. As previously told, in the rural areas, inhabitants work together for the houses' construction: they are unskilled people led by a skilled person whom ability come from experience and not from education. Skills are then limited to the traditional practices involved in the house construction, passed down verbally from one builder to another.

2. The basic tools. In rural area, inhabitants haven't got specialized modern equipment: people usually work with basic tools like hammer and chisel. Buying modern tools is, generally, too expensive for farmers and then the practices involved in construction are limited by the tools they usually use.



3. The available materials. Vernacular houses in eastern Bhutan are built with stone and timber: these are the local available materials. Moreover, Bhutan has an internal concrete production and a small production of metal elements; the biggest steel elements are imported. Nevertheless, the skilled builders in rural areas are used to work with local and traditional materials; the use of modern materials means the involvement of specialized workmanship or the instruction of local people. Bamboo is also available in Bhutan, but people often use it only for daily items.

4. The architectural heritage. The preservation of the traditional architecture is crucial in retrofitting projects: rural houses are the reflection of people's believes and the result of inhabitants' efforts. The uniqueness of architectural features is due to the ancient origin and the transposition of Bhutanese culture in buildings: it must be protected.

...the common practices previously introduced need to be evaluated according to these four considerations.

Ring beam
This could be a good solution in Bhutanese context. A timber external ring could easily surround the house. The joint of the ring with the stone wall could be a problem because of the difficulty of making a hole in the 70 cm wall with only hammer and chisel: a metal junction passing through the entire thickness of the wall would be more resistant but some different solution could help in having a similar effect avoiding the long hole.

Wall-to-wall
The wall-to-wall connections require holes passing through the wall thickness or even more difficult holes like in the corner wall-to-wall connection. This kind of intervention is too difficult considering the basic tools and the unskilled builders. Moreover, for having a successful action, the use of steel and concrete is crucial. At the end, the effect doesn't balance the difficulty of the work. But, how to protect the fragile corner in another way?

Ties
Ties present some troubles: again, the difficulty in making the holes and the use of steel ties, but this time the process of realization is not so difficult. The effect is good so it could be useful to preserve the idea behind the ties and to think in a new work with the same concept of pull elements together, maybe through a floor revision or with ropes.

Confinement
This solution could be easily realized and could improve the seismic resistance of the house. It could be made of timber or bamboo and basic tools would be enough for the work. Anyway, it would be better to have other options working together with the confinement one: the confinement alone could be insufficient to resist.

Bonding elements
The introduction of bonding elements in the masonry is crucial for having a monolithic wall and preventing the delamination. The main problem is the realization of the hole: it's necessary to work accurately for removing the stones from the two leaves of the wall and introducing a new element. It could be a long and difficult work for an unskilled person without experience.

Deep re-pointing
The replacement of mortar joints is an easy action that increase the ductility of the masonry. The use of cement mortar may be envisaged. The action is useless if the wall presents a weak inner mortar between the two leaves of stones: in this case a restoration of the wall is crucial.

Restoration of walls
A grout injection needs a mechanical pump that push mortar inside the two leaves of stone with a certain pression. With the basic tools in rural areas it is not possible to do this kind of work. The unstitch and stitch practice could be a good solution for the introduction of new mortar and new stone; new through-stones could be introduced too. As previously told, it could be a long and difficult work for an unskilled person without experience.

Near-surface
This practice results in a new façade of concrete: it's a good solution for reaching the monolithic box behaviour of the house but it's a strong impact action that deletes completely the traditional aspects of the vernacular houses. Moreover, it requires modern materials and a specialized workmanship working with specific tools.

Floor stiffening
The overlapping of new timber elements above the original floor is a feasible action but the connection with the walls could be more difficult. Making holes in walls, in order to have through passing joints, has always the same problem but different solutions with a similar result can be taken in consideration. The floor stiffening is crucial for the monolithic box behaviour of the house so it's worth working on it.

Roof strengthening
The strengthening of the roof timber elements is easy: the use of metal joints and ropes has a good result and it's feasible. The connection between the roof and the walls is more complicated: it needs to be strong and resist to windstorm action. The cooperation of different new elements could succeed with this purpose.

Redundancy
This is a temporary solution but could be feasible and useful. The introduction of the inner skeleton is not resolutive but it's cheap and safes lives. Moreover, the concept of redundancy could be transposed as redundancy of practices preventing the same damage: if one of the practices fails, there is another one acting for the same purpose.

New stone walls
The building of new walls in order to counteract seismic forces could be a feasible practice. The more difficult part is the joint with the old wall. Moreover, the feasibility depends on the dimension of the new walls: big walls could change to much the exterior aspect of the house and, in a village pattern, to have space enough between the houses could be complicated; for smaller walls there are less problems.

Practices		Selection of practices
Ring beam	-	The ring idea must be adapted to Bhutan houses
Wall-to-wall	-	It is not considered, but the corner must be protected in another way
Ties	-	The concept of 'pull elements together' can be repurposed according to houses' needs
Confinement	-	It is not enough alone, it needs to be part of a bigger strategy
Bonding elements	-	The practice is good but requires time and experience
Deep re-pointing	-	It is not enough alone, it needs to be part of a bigger strategy
Restoration of walls	-	The practice is good but requires time and experience
Near surface	-	It is not considered
Floor stiffening	-	The practice must be adapted to Bhutan houses
Roof strengthening	-	The practice must be adapted to Bhutan houses
Redundancy	-	The practice and the concept of redundancy may be used
New stone walls	-	The practice may be used but there are some limits in the application

In conclusion, literature provides common practices but it's impossible to apply them directly in Bhutan: they need to be adapted or, at the worst, excluded. The tab offers a starting point for the development and understanding of the manual, which provides practices achievable in Bhutanese scenario, according to the local workmanship, tools, materials and tradition preservation.

6
CHAPTER

MANUAL

"The future cannot be what it brings to us, it must be how we want it to be. Visioning is a means of determining our own future."

PLANNING COMMISSION

6 | MANUAL

The last chapter is the manual of prevention and repair of damages which affect Bhutanese traditional stone rural houses. The chapter is divided into two parts: the first one is the introduction which explains the layout of the manual itself and gives some beginning knowledges for starting. The second part is the development of the actions which enhance the structural strength, the house quality and the building resilience.

6.1 PRIOR KNOWLEDGE

The manual is a construction tool for the rural population, the aim is to propose specific actions useful for the prevention or repair of typical damages which affect typical rural houses in Bhutan. The manual has been developed after analysing various issues of this complicated country. Bhutan is a unique land with old strong traditions, rooted in a small population. But, at the same time, it is a fragile land: isolated and inaccessible villages are subjected to natural hazards. Nowadays, the country is divided between traditions and modernization: a new balance is required. Earthquakes shake the land and rural houses require to be improved: the manual aims to help inhabitants with actions balanced between the respect of old believes and the introduction of the resilience concept, according to the ability of local workmanship and the availability of local materials.

In this first part of the manual, the beginning knowledges are given to the population for the correct reading of the actions' procedure cards and for the proper use of the basic tools. The actions are proposed according to the available tools and, as previously told, with respect to workers' skills and available materials.

All the actions are collected in a tab that introduces the second part of the manual. In the previous chapter, damages in traditional houses in Bhutan have been catalogued according to three macro causes: extraordinary causes, ordinary causes and human factor. The manual's actions are then catalogued according to the prevention of the same three macro causes: extraordinary causes, like earthquake, and ordinary causes, like moisture, are faced by practical constructive actions, explained through procedure cards; human factor requires a different approach. The human factor's micro causes are the use of poor-quality materials in the construction of the houses, the improper construction by inhabitants, the prevalence of unskilled workmanship and the absence of maintenance. For facing them, knowledge and awareness must be spread in the country.

For starting | PRIOR KNOWLEDGE

HOW TO READ THE MANUAL

The manual includes four procedure cards of damage prevention, three cards of damages repair and three cards of cause prevention. Damage prevention means acting on the weaknesses of the building (in this case, on the connection between structural elements) in order to prevent future damages due to extraordinary causes like earthquake and windstorm. Each procedure card consists in a first part collecting a small description of the action, the number of skilled and unskilled workers required, a list of materials and tools needed, the most complicated steps to take care about. The second part describes the procedure for a correct execution and the last part shows the building elements to be careful with. The damage repair cards explain the reparation of damages due to common ordinary causes. For preventing these damages, the cause prevention cards show how to act at the source of the problem, stopping moisture, rainwater and biological attacks before they happen. The damages repair and cause prevention cards are shorter than the damages prevention cards: the first and second part are the same, the last part is unnecessary.

The card must be read from the beginning to the end without skipping parts. The “be careful” section, in the first part, must be checked at the end of each step. In case of doubt about the use of any tool, look at the “beginning knowledge”. Each procedure card can be used alone, without reading the other cards and the order of lecture of different cards is not mandatory. Despite this, in the procedure card there are links to other actions, in order to have the best overview of possible combinations between actions and make the house safer and safer. The beginning tab may help in the preliminary choice of the action, according to the common damages which could change from one case to another, for example depending on the seismic risk variation in the country.

Be careful in using the manual: be sure to understand the procedures, use the correct tools, ask for help to skilled person every time it’s possible, be sure to have good-quality materials, remind that prevention is better than repair, and ordinary maintenance is a good preventive action, take care of your home.

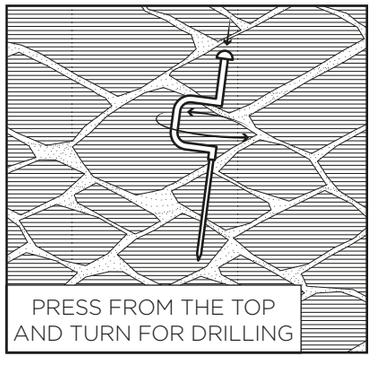
The “human factor” part describes general aspects to take into account, but it is not a practical hand work useful for inhabitants: it is a lecture for being aware that good materials and tools, and skilled workers make a difference in the house safety. Knowledge and awareness are the foundation of a good manual.

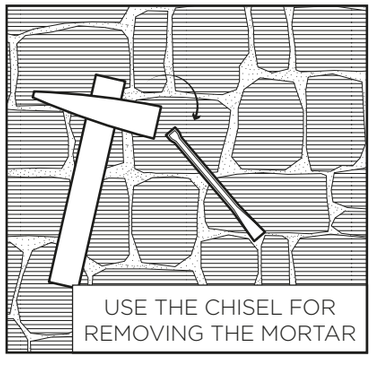
For starting | PRIOR KNOWLEDGE

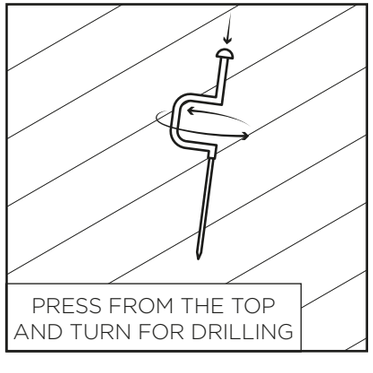
HOW TO USE HAND DRILL AND CHISEL

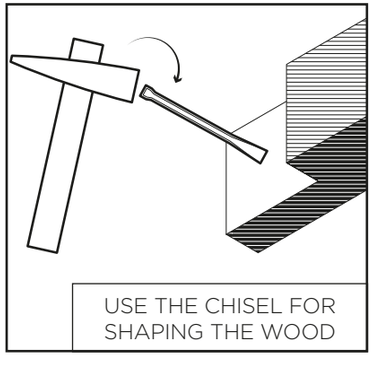
For drilling the stones and the wooden element a hand drill can be used. Push down the upper part with a stone or with the body and turn the handle to start. Steel drill bits are used. Drilling a stone is a longer work than drilling the wood: other solutions are preferred, otherwise, work with patience! Drilling the stone requires possibly a skilled man: holes must be precise and don’t have to disturb the entire wall. A hole in the stone can be made with hammer and chisel too, but this kind of work disturb mostly the other stones. The hole must be 1 mm smaller than the screw.

Hammer and chisel can be used for removing the old mortar and facilitate the removal of stones during a work on the wall leaf. Percussion must be careful, not too strong for avoiding wall damages. Hammer and chisel are used for shaping the timber elements, according to the traditional arts of Bhutan. These tools have to be managed by a skilled person for the more difficult works.







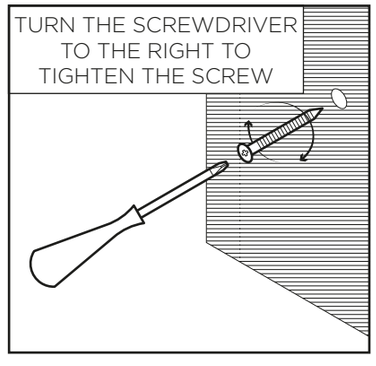


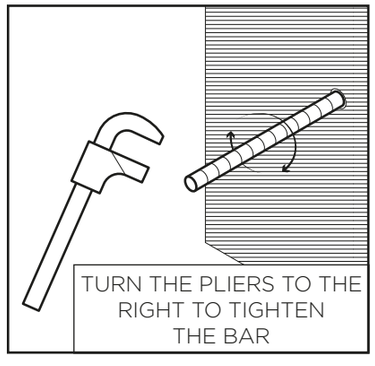
For starting | PRIOR KNOWLEDGE

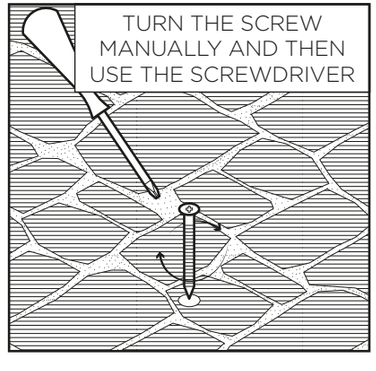
HOW TO USE SCREWDRIVER AND PLIER

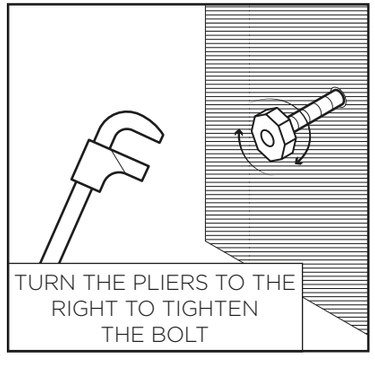
The tip of the screwdriver must coincide with the head of the screw for a good performance. The threaded screw is tightened to the wood plank: the screw has a better grip on the wood than nails. The screw is tightened in the stone too: the hole is filled with cement mortar and the screw must be tightened for having a better grip between the thread and the mortar. At the beginning the screw can be tightened manually, at the end with the help of the screwdriver.

The threaded steel bar is placed in the wood with the help of the plier: the bar does not have a head like screws, so the screwdriver is useless. The plier grabs firmly the bar and help the tightening process. The plier is also used for tightening bolts. Bolts are used for fastening the bars and the plier guaranties a strong closure.









For starting | PRIOR KNOWLEDGE

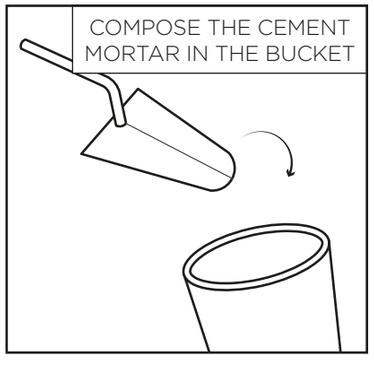
HOW TO USE TROWEL AND BOTTLE WITH SPOUT

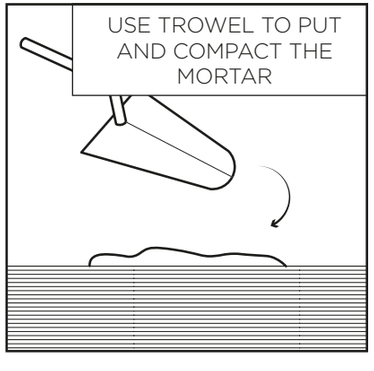
Stones in the wall are joined by mortar. The cement mortar is stronger than the mud mortar usually used in rural villages in Bhutan. For preparing the cement mortar, take:

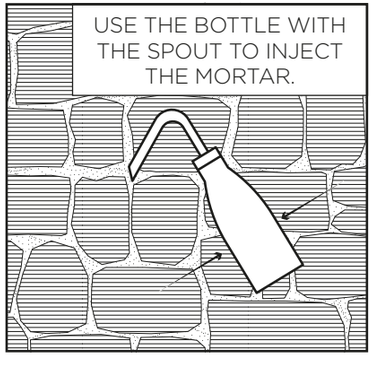
- 1 part of cement
- 1 part of water
- 4 part of sand

Mix the cement and the sand together, then stir the water. All the material must come into contact with the water. Stir with the trowel until the mixture remains soft and lump-free. When the cement mortar is ready, lay it in the bigger cavities with the trowel.

To inject the mortar into small cracks or into small cavities left over during the laying of the stone, the trowel is useless. So, firstly, fill a bottle with spout of mortar, then close the bottle and squeeze out small amounts of mortar. The spout guarantees a localized injection of mortar.







6.2 ACTIONS

	GENERAL ACTION	FIELD OF ACTION	ACTION	PREVENTED DAMAGES
Extraordinary causes	Damages prevention	Wall to wall connection	The exoskeleton	out-of-plane loss of structural integrity in-plane delamination
		Wall to floor connection	The timber plank	floor collapse out-of-plane loss of structural integrity
		Wall to roof connection	The upper joints	roof collapse windstorm effects
		Wall's leaf to wall's leaf connection	The bonding stones	in-plane delamination loss of structural integrity out-of-plane
Ordinary causes	Damages repair	Stone walls damages	The cracks	shallow cracks
		Stone walls damages	The unstitch-stitch	chipping erosion exfoliation/delamination crumbling
		Timber beam damages	The replacement	rots by fungi weakening by insect attack
	Causes prevention	Non-draining ground	The ground	rising damp deterioration
		Water path	The bamboo slope	erosion by rain and wind weathering of wood
		Stone and wood elements	The cleaning	erosion by fungus acid dislocation by plant roots rods by fungi weakening by insect attack erosion by rain and wind weathering of wood
Human factor	Knowledge	Poor quality of materials	Supply of quarried stone	house quality construction
		Poor construction	Supply of tools and manuals	
		Unskilled workmanship	Workers education	
	Awareness	Absence of maintenance	Informing people	

Damages prevention

Extraordinary causes | DAMAGES PREVENTION

THE EXOSKELETON

WALL TO WALL CONNECTION

Prevention

Out-of-plane collapse
Loss of structural integrity
In-plane cracks
Delamination

The exoskeleton is a timber and steel external structure: each corner of the house is covered by a frame of timber boards joined together with metal plates and connected to the walls by screws. The corner reinforcements are joined with metal tie rods, if they are available. The new exoskeleton enhances the wall-to-wall connection and secures the fragile corners: the house then acts more like a monolithic box, improving the wall resistance to the in-plane cracks and to the delamination.

WORKERS: ■ Skilled - n. 2 ■ Unskilled - n. 2
(skilled workers role: to install the tie rods)

TIME: ☐ Short ☐ Medium ■ Long

MATERIALS: wood plank, steel “L” shaped plates, cement mortar, steel screws and bolts, steel tie rods

TOOLS: chisel, hammer, hand drill, screwdriver, plier, trowel, bottle with spout, brush

BE CAREFUL:

⚠ Be careful in drilling the timber boards at the same position of the metal plates holes

⚠ Be careful in drilling the stone at the same position of the timber plank holes

⚠ Holes must be drilled with care and precision: it is better referring to a skilled workman

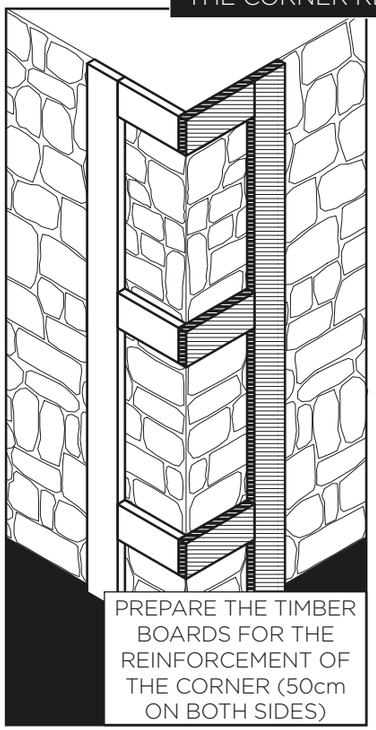
⚠ Use good quality cement mortar

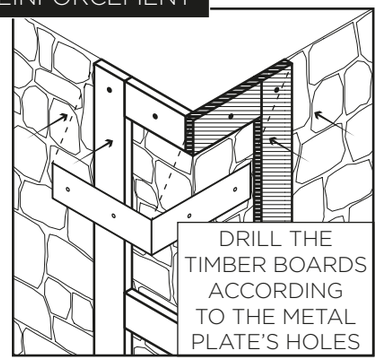
⚠ Clean timber element (look at “The cleaning”)

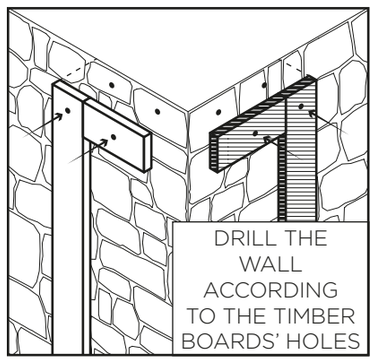
⚠ The rabsel is not involved in the exoskeleton action

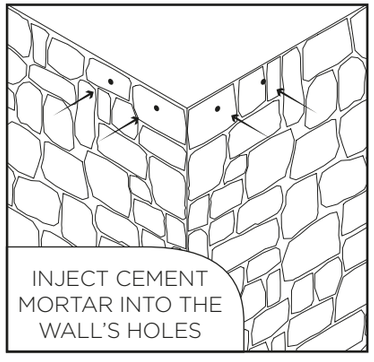
⚠ The tie rods need to be placed on the four sides

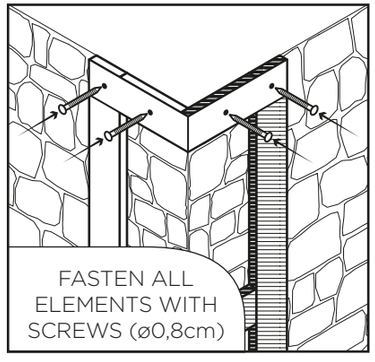
THE CORNER REINFORCEMENT

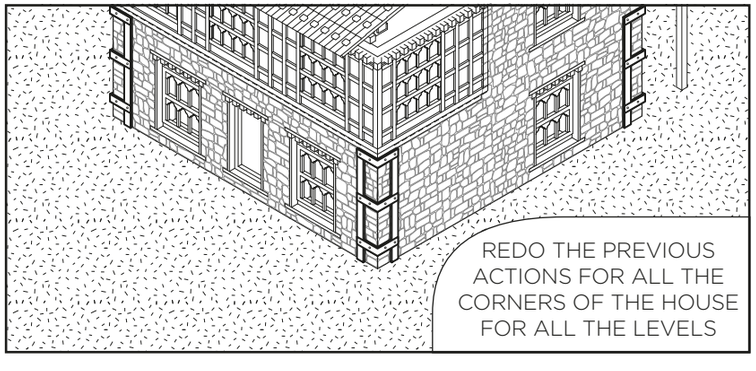




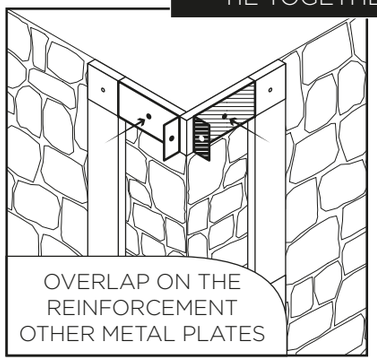


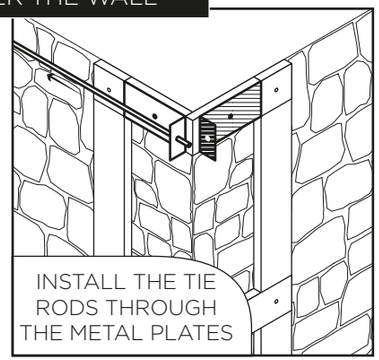


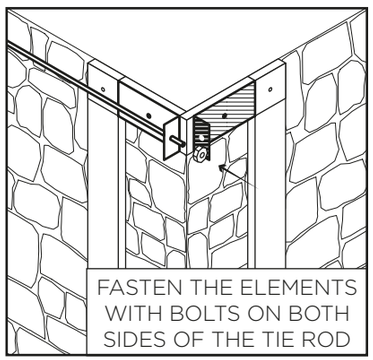


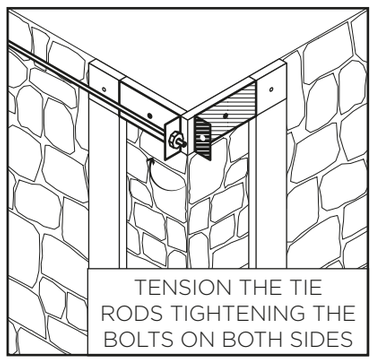


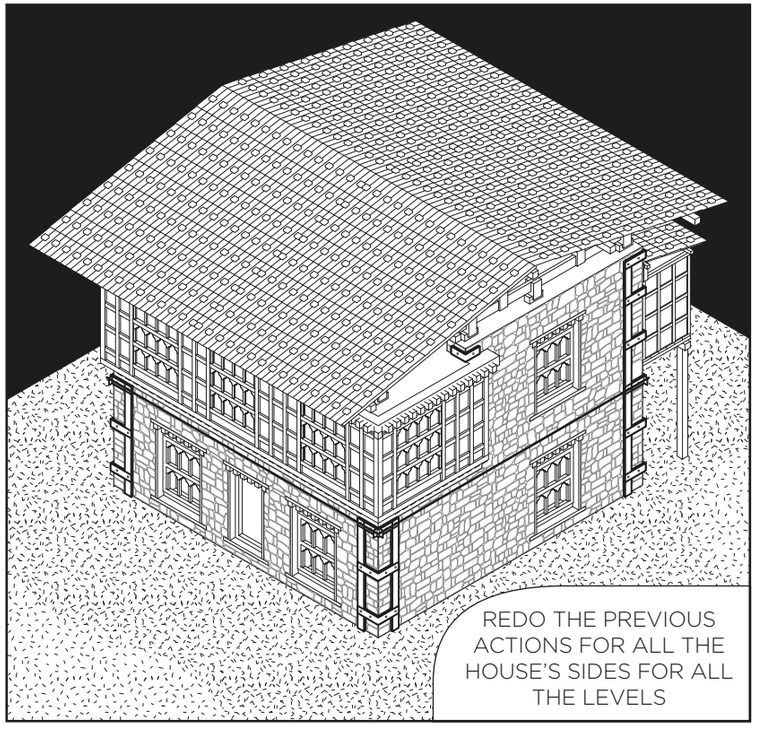
TIE TOGETHER THE WALL

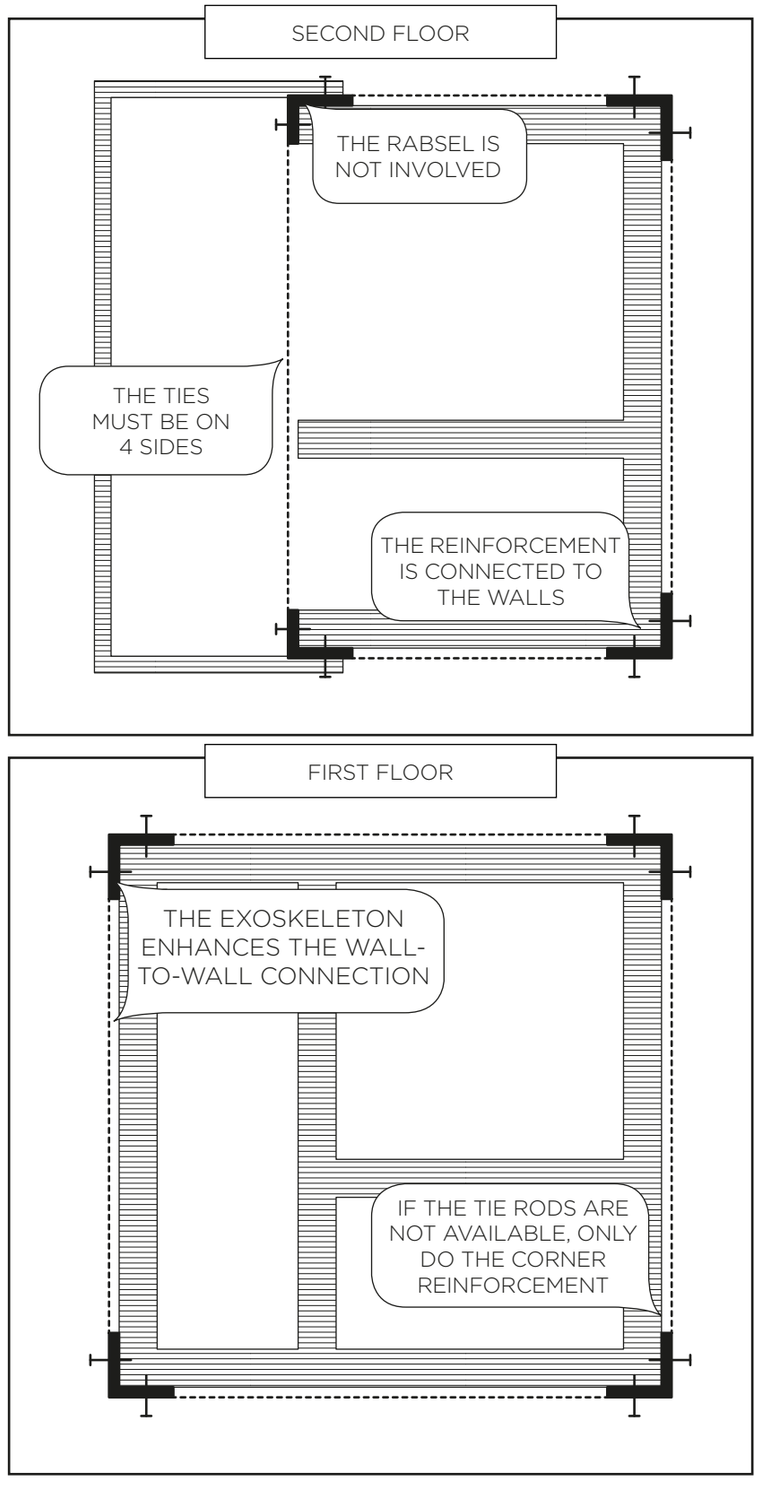












Extraordinary causes | DAMAGES PREVENTION

THE TIMBER PLANK

WALL TO FLOOR CONNECTION

Prevention

Out-of-plane collapse
Loss of structural integrity
Floor collapse

The plank is a timber layer above the existent floor. The traditional floor is composed of timber planks laying above timber beams, trapped at the ends in the stone walls. This connection is strengthened by steel bars which anchor the beams to the wall. The new layer lays above the old planks: the larger dimension is perpendicular to the one of the old planks. All the layers are fastened together and with the walls. The stiffening of the floor and its connection with the wall prevent both floor damages and wall ones.

WORKERS: ■ Skilled - n. 1 ■ Unskilled - n. 2
(skilled worker role: to supervise the beam anchoring)

TIME: ☐ Short ☐ Medium ■ Long

MATERIALS: threaded steel bars, steel rectangulare plates, cement mortar, wood planks, steel screws and bolts, steel “L” and “C” shaped plates

TOOLS: chisel, hammer, hand drill, screwdriver, plier, trowel, bottle with spout, brush

BE CAREFUL:

⚠ Use scaffoldings to assure stability during the work

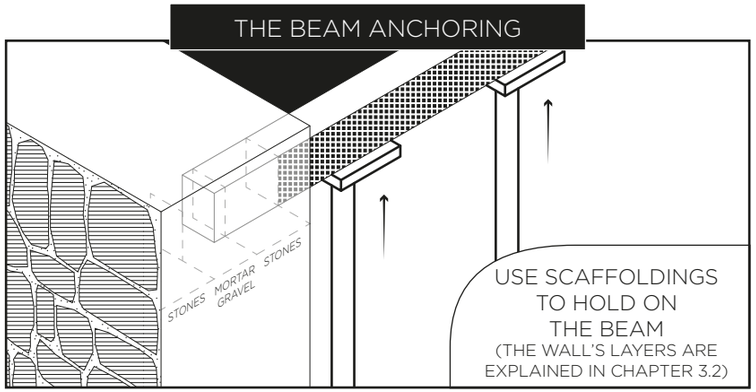
⚠ Work manually during the removal of stones, clean and fill with good quality cement mortar (look at “*The un-stitch-stitch*”)

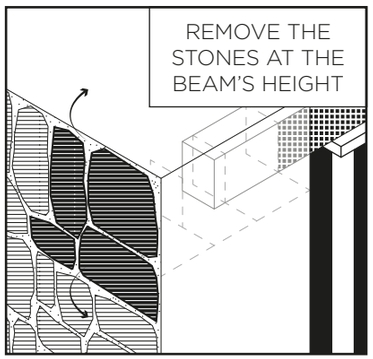
⚠ Be careful in drilling the stone wall and the timber floor at the same position of the metal plates holes

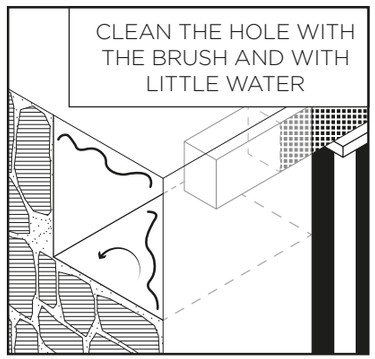
⚠ Holes must be drilled with care and precision: join together the beam, the old planks and the new planks

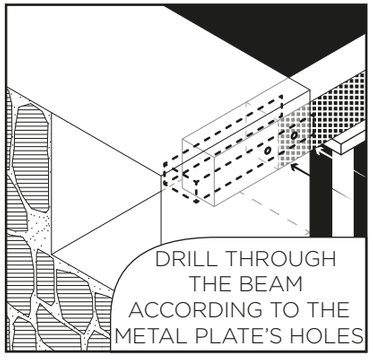
⚠ Clean timber element (look at “*The cleaning*”)

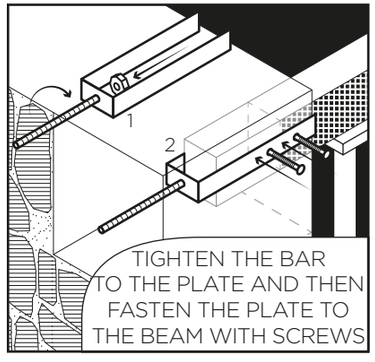
⚠ Connect the roof to the floor (look at “*The upper joints*”)

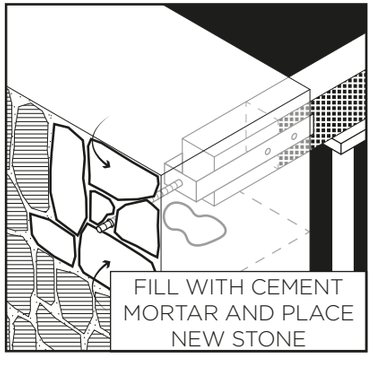

THE BEAM ANCHORING
STONES
MORTAR
GRAVEL
STONES
USE SCAFFOLDINGS TO HOLD ON THE BEAM
(THE WALL'S LAYERS ARE EXPLAINED IN CHAPTER 3.2)

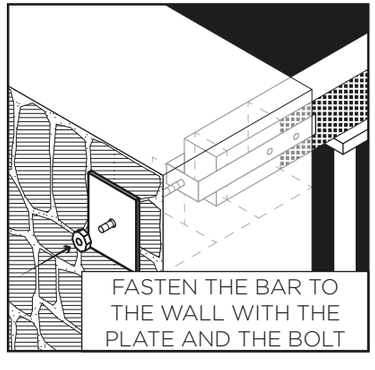

REMOVE THE STONES AT THE BEAM'S HEIGHT

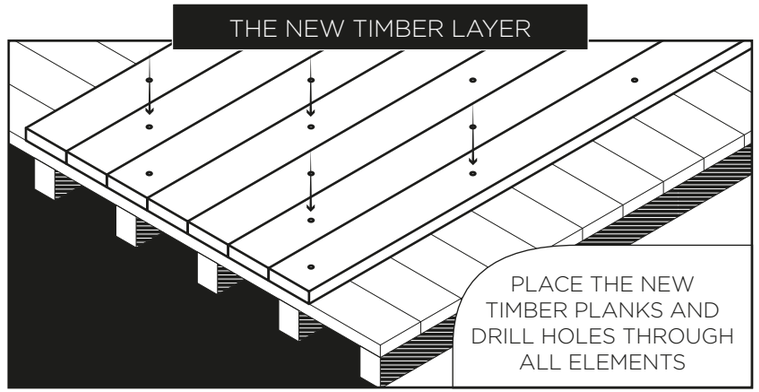

CLEAN THE HOLE WITH THE BRUSH AND WITH LITTLE WATER

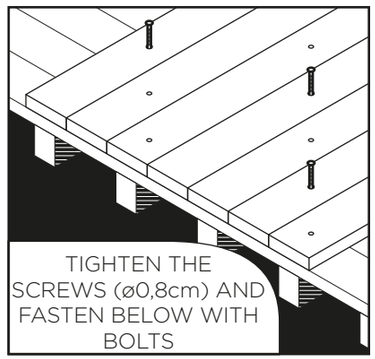

DRILL THROUGH THE BEAM ACCORDING TO THE METAL PLATE'S HOLES

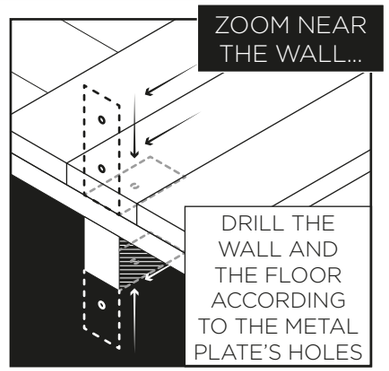

1
2
TIGHTEN THE BAR TO THE PLATE AND THEN FASTEN THE PLATE TO THE BEAM WITH SCREWS

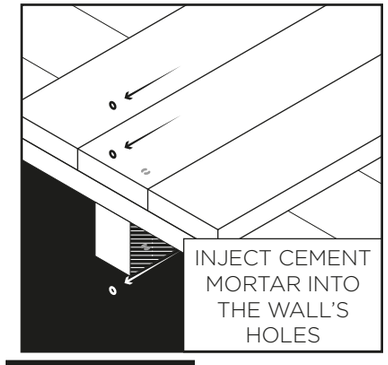

FILL WITH CEMENT MORTAR AND PLACE NEW STONE

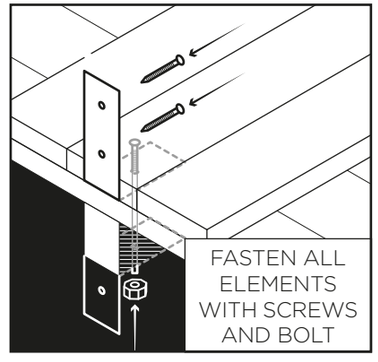

FASTEN THE BAR TO THE WALL WITH THE PLATE AND THE BOLT

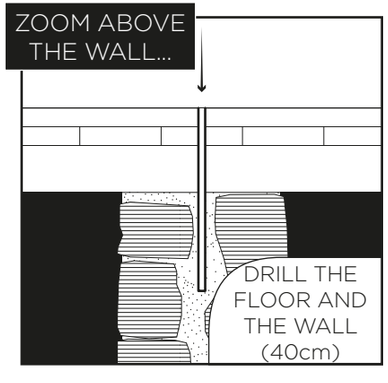

THE NEW TIMBER LAYER
PLACE THE NEW TIMBER PLANKS AND DRILL HOLES THROUGH ALL ELEMENTS

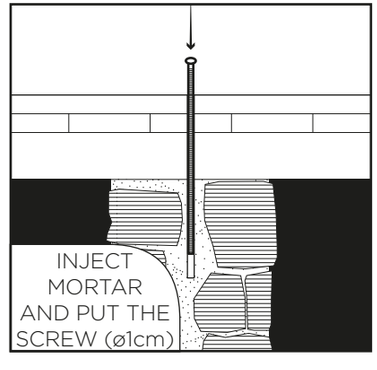

TIGHTEN THE SCREWS (ø0,8cm) AND FASTEN BELOW WITH BOLTS

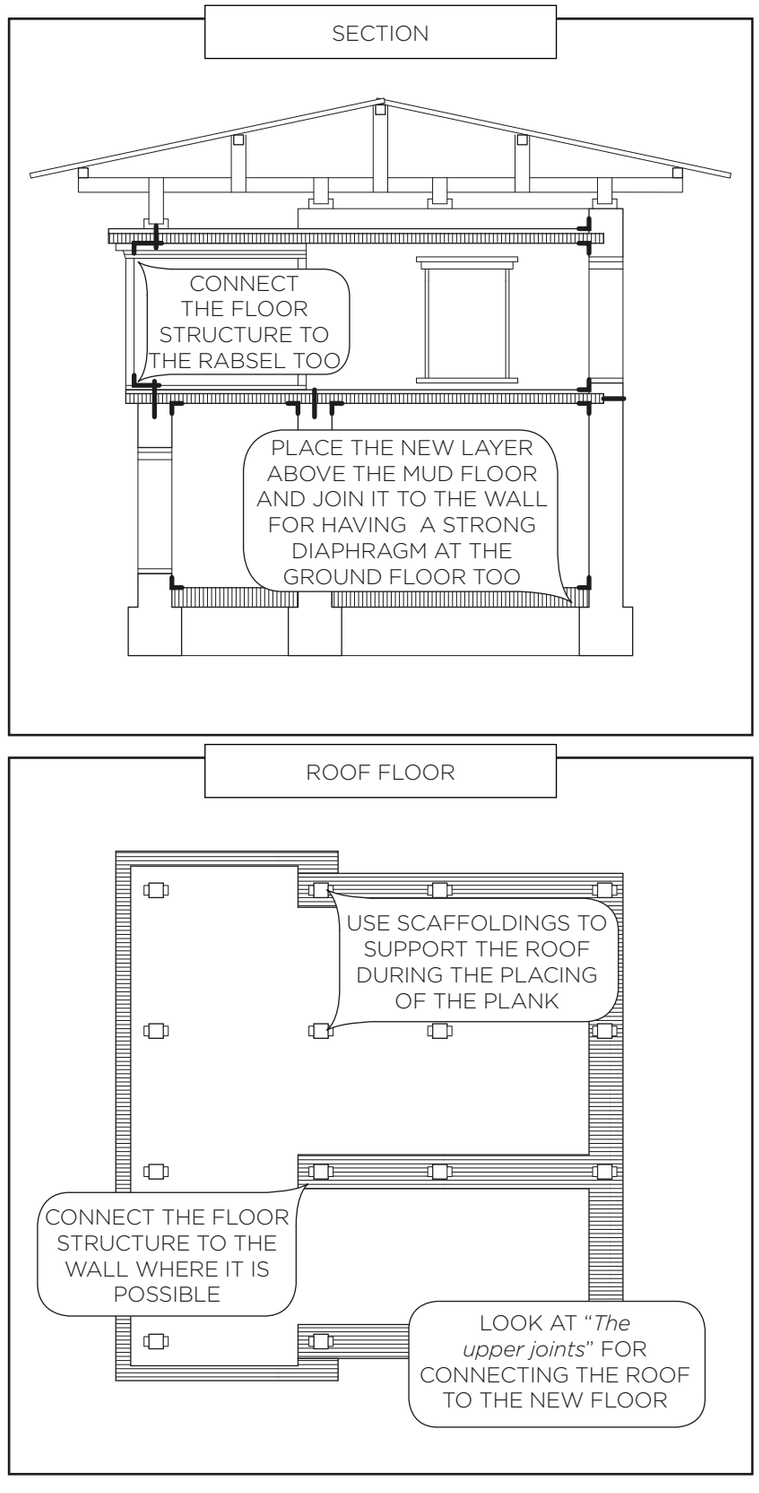

ZOOM NEAR THE WALL...
DRILL THE WALL AND THE FLOOR ACCORDING TO THE METAL PLATE'S HOLES


INJECT CEMENT MORTAR INTO THE WALL'S HOLES


FASTEN ALL ELEMENTS WITH SCREWS AND BOLT


ZOOM ABOVE THE WALL...
DRILL THE FLOOR AND THE WALL (40cm)


INJECT MORTAR AND PUT THE SCREW (ø1cm)



Extraordinary causes | DAMAGES PREVENTION

THE UPPER JOINTS

WALL TO ROOF CONNECTION

Prevention
- Blown off failure
- Panel failure
- Peeling failure
- Roof overhang failure
- Support failure

The joints are metal elements and ropes connecting each roof parts together. Bhutan's traditional roof has timber elements resting on the ones below, the total structure rests on the top-most floor or on the walls. These elements need to have strong connection with each other and with the floor/walls in order to avoid damages caused by windstorms. For enhancing the action, where it is possible, the roof could be connected with the ground through ropes and cement blocks.

WORKERS: ■ Skilled - n. 1 ■ Unskilled - n. 1
(skilled worker role: to supervise the support connections)

TIME: ☐ Short ☐ Medium ■ Long

MATERIALS: threaded steel bars, steel screws and bolts, steel "L" shaped plates, cement mortar, bamboo poles, ropes, steel rings

TOOLS: hand drill, screwdriver, plier, shovel, bottle with spout

BE CAREFUL:

⚠ Holes must be drilled with care and precision

⚠ Be careful in drilling the stone wall and the timber floor at the same position of the metal plates holes

⚠ Ropes need to be periodically checked and replaced in case of failure

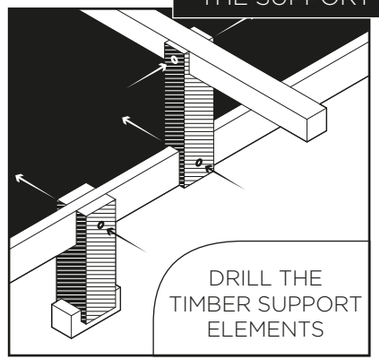
⚠ Clean timber element (look at "*The cleaning*")

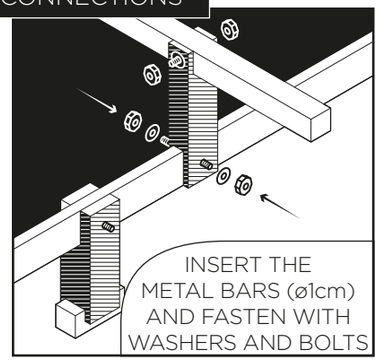
⚠ Use good quality cement mortar

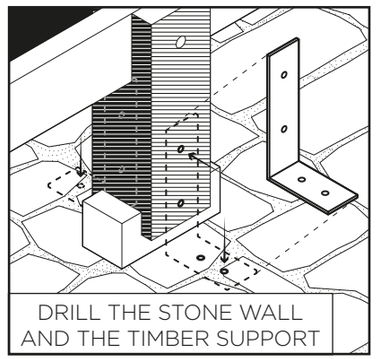
⚠ Shingles are not joined to the other parts: check them periodically and replaced in case of failure

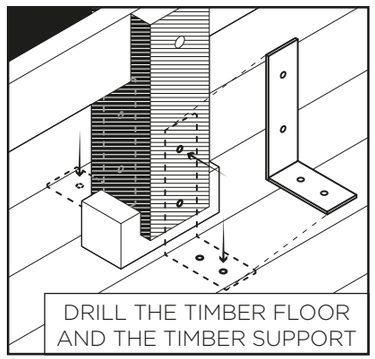
⚠ Connect the roof to the floor (look at "*The timber plank*")

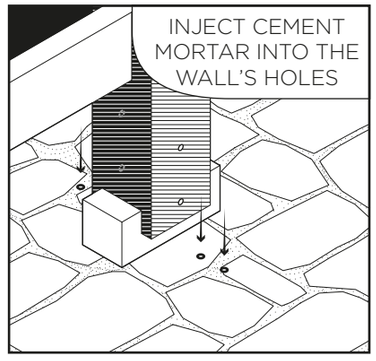
THE SUPPORT CONNECTIONS

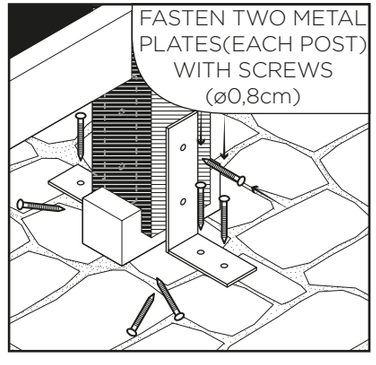


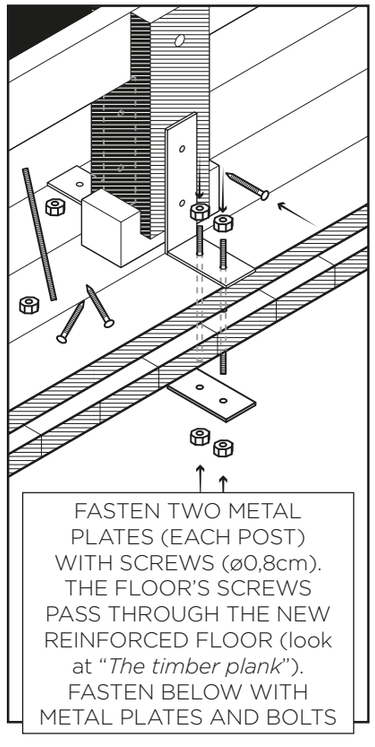




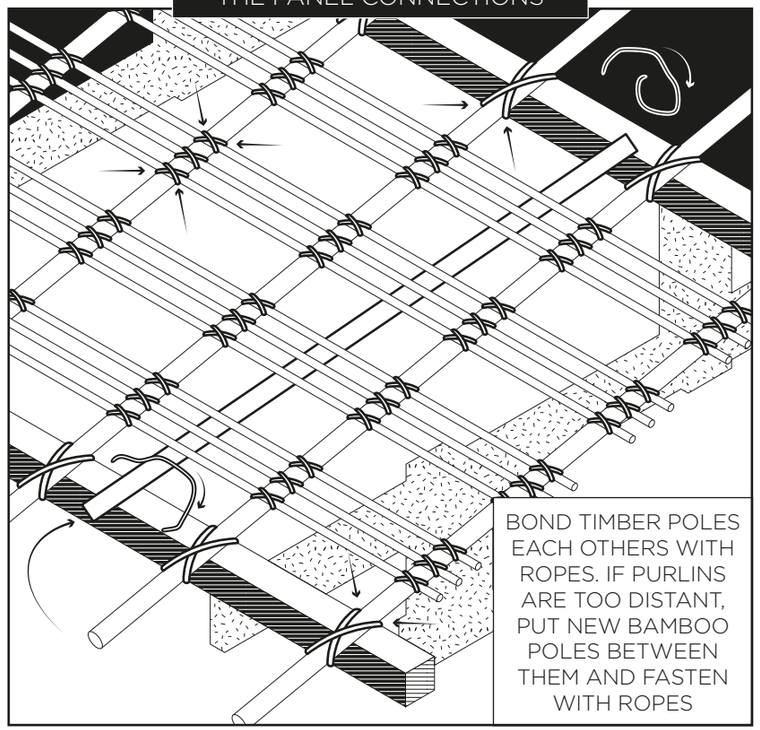




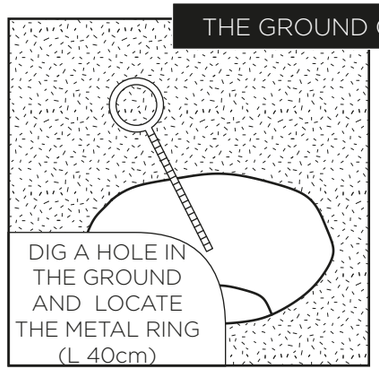


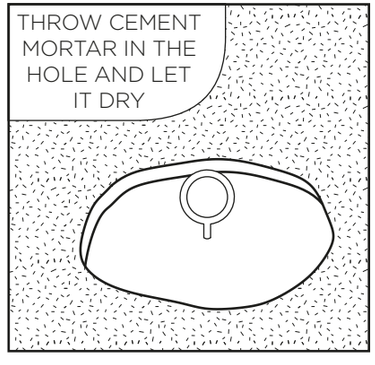


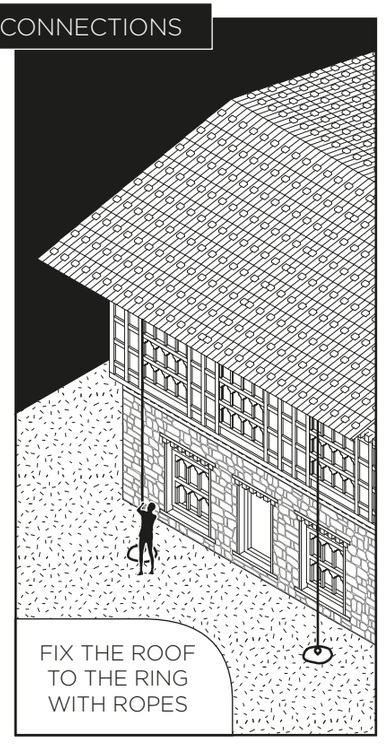
THE PANEL CONNECTIONS

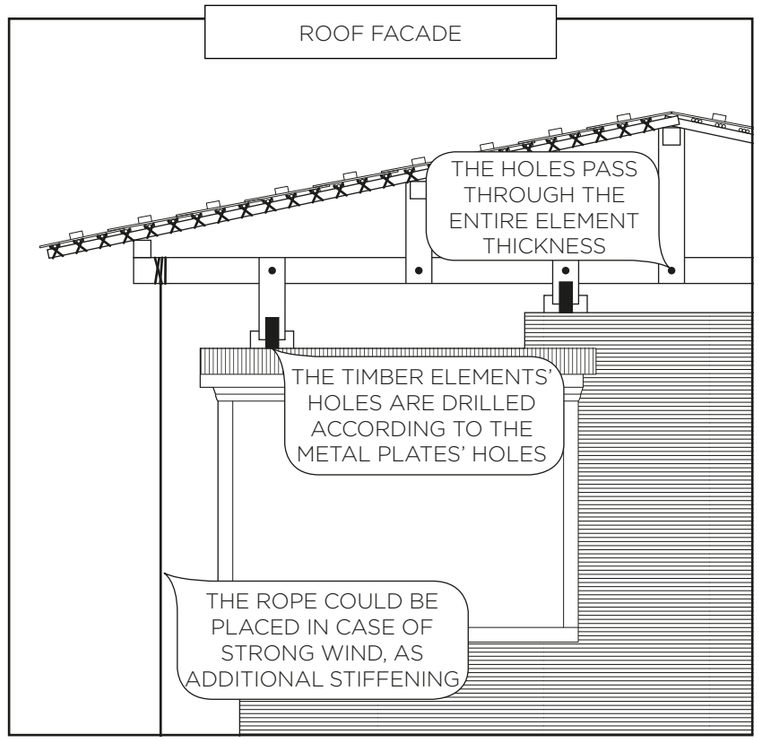


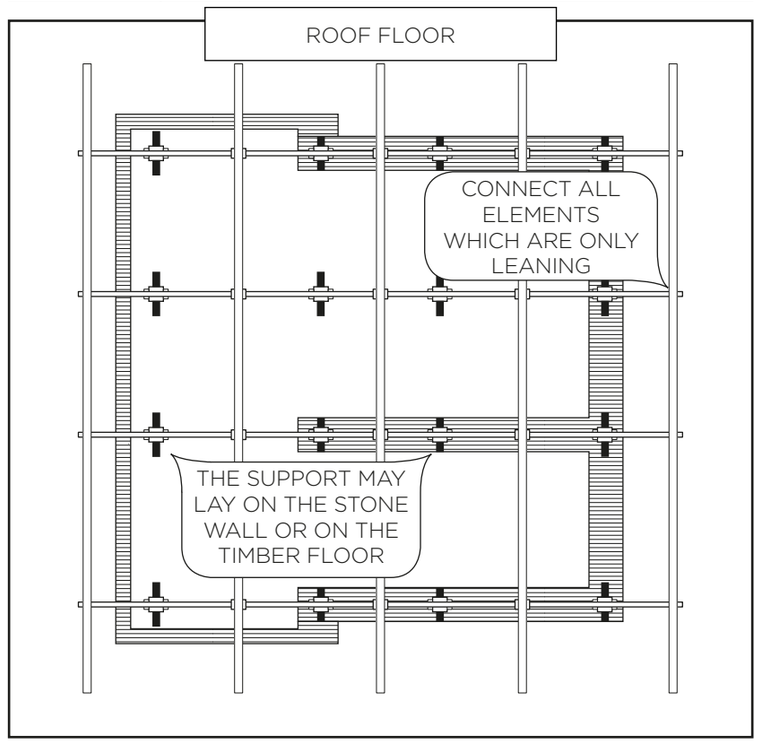
THE GROUND CONNECTIONS











Extraordinary causes | DAMAGES PREVENTION

THE BONDING STONES

WALL'S LEAF TO LEAF CONNECTION

Prevention

Out-of-plane collapse
Loss of structural integrity
In-plane cracks
Delamination

The wall is made of two stone layers with an inner mortar and gravel layer. The bonding stone is a natural stone passing through the whole thickness of the wall. This new stone must be joined to the old stones with cement mortar. The connection of the two external layers prevent the delamination of one leaf and improve the monolithic behaviour of the wall, avoiding other wall's damages.

WORKERS: ☐ Skilled ■ Unskilled - n. 2

TIME: ☐ Short ☐ Medium ■ Long

MATERIALS: cement mortar, natural stones

TOOLS: chisel, hammer, brush, trowel, bottle with spout

BE CAREFUL:

⚠ Use scaffoldings and props to assure stability during the work

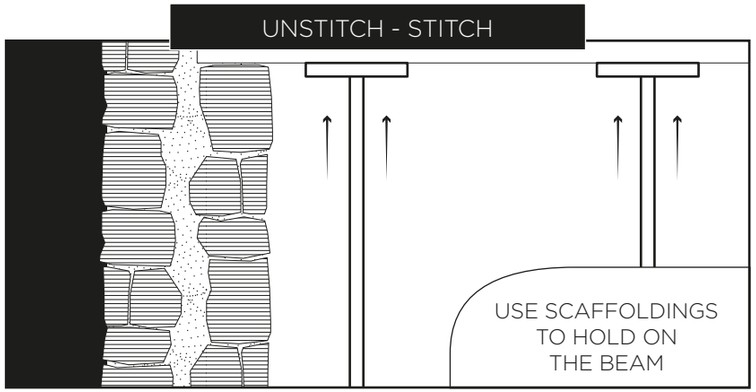
⚠ Always clean the inner void and fill with good quality cement mortar

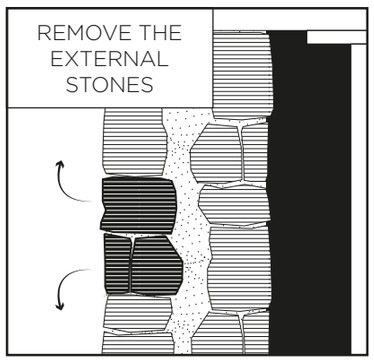
⚠ Use good quality cement mortar to assure connection with the older stones

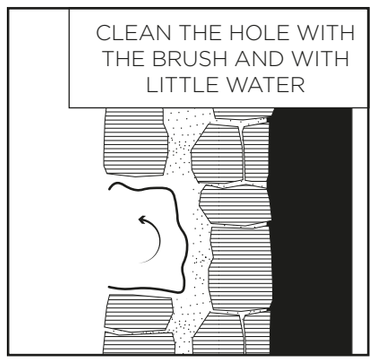
⚠ Work on a small area at the time, and then wait some weeks before proceeding with surrounding areas

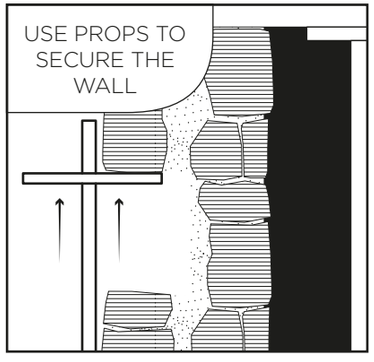
⚠ Work manually: pay attention not to damage the wall

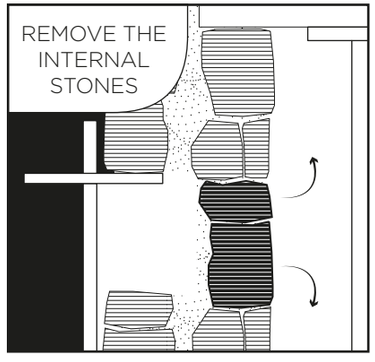
⚠ Place natural stones large as the wall thickness as through stones

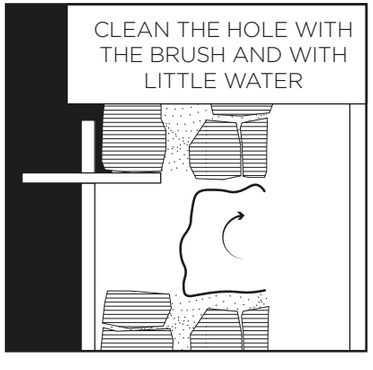

UNSTITCH - STITCH
USE SCAFFOLDINGS TO HOLD ON THE BEAM

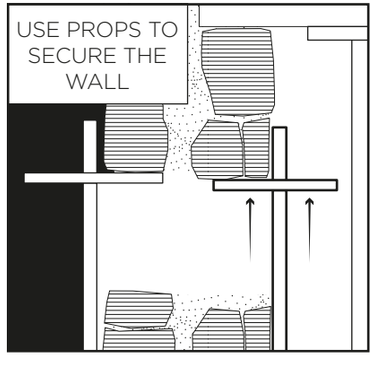

REMOVE THE EXTERNAL STONES

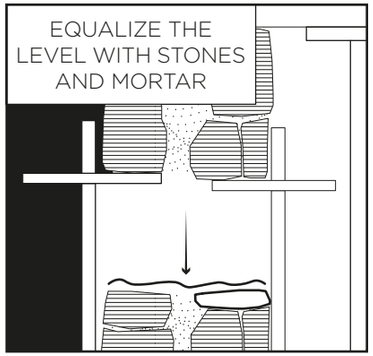

CLEAN THE HOLE WITH THE BRUSH AND WITH LITTLE WATER

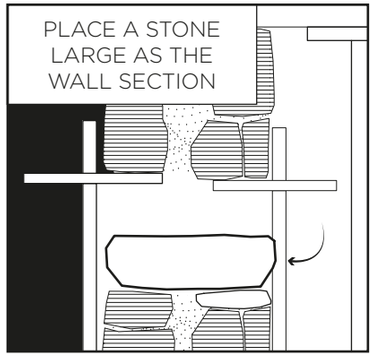

USE PROPS TO SECURE THE WALL

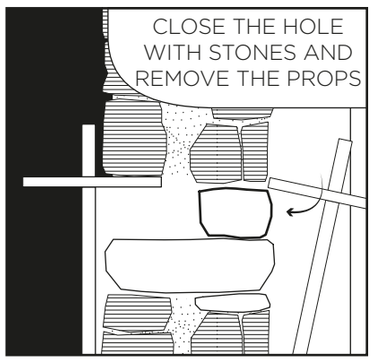

REMOVE THE INTERNAL STONES

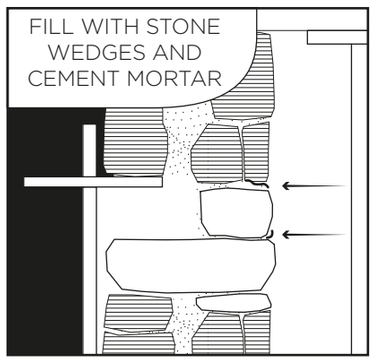

CLEAN THE HOLE WITH THE BRUSH AND WITH LITTLE WATER

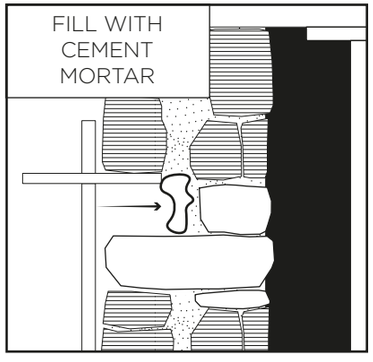

USE PROPS TO SECURE THE WALL

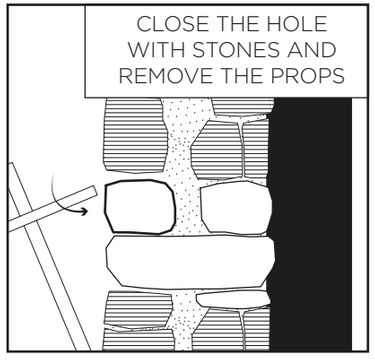

EQUALIZE THE LEVEL WITH STONES AND MORTAR

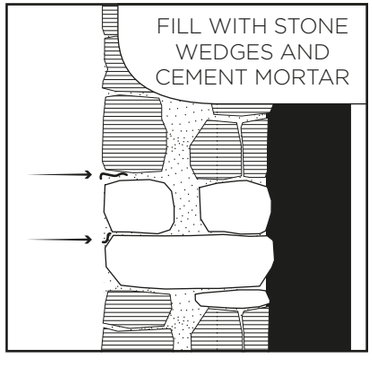

PLACE A STONE LARGE AS THE WALL SECTION

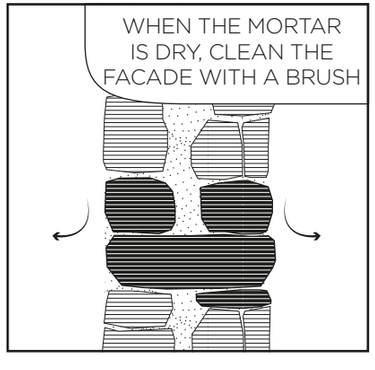

CLOSE THE HOLE WITH STONES AND REMOVE THE PROPS

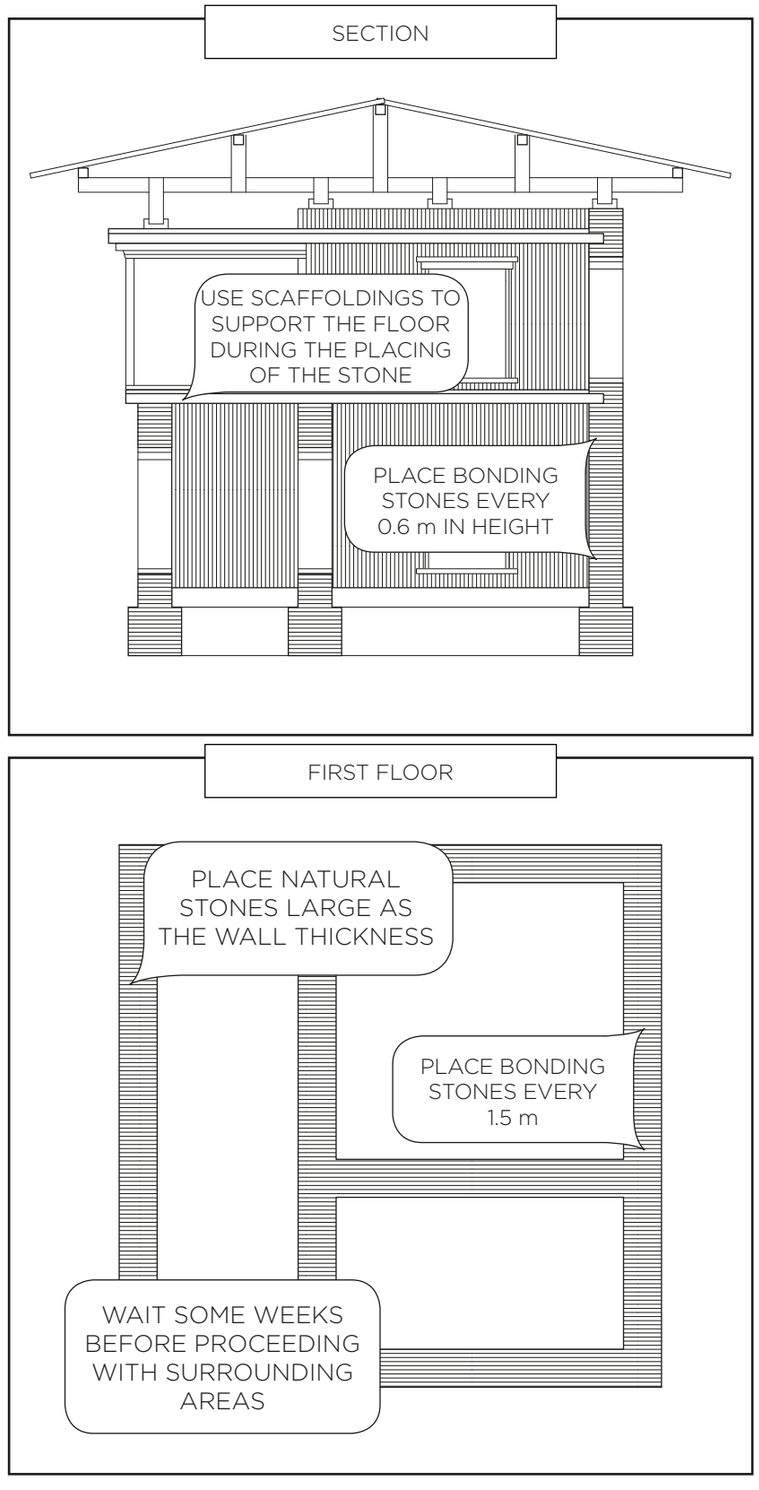

FILL WITH STONE WEDGES AND CEMENT MORTAR


FILL WITH CEMENT MORTAR


CLOSE THE HOLE WITH STONES AND REMOVE THE PROPS


FILL WITH STONE WEDGES AND CEMENT MORTAR


WHEN THE MORTAR IS DRY, CLEAN THE FACADE WITH A BRUSH



ORDINARY CAUSES

Damages repair

THE CRACKS

THE UNSTITCH-STITCH

THE REPLACEMENT

Causes prevention

THE GROUND

THE BAMBOO SLOPE

THE CLEANING

Ordinary causes | DAMAGES REPAIR

THE CRACKS

STONE WALLS DAMAGES

Prevention

Shallow crack

Shallow cracks (<2cm deep) or small holes may be fixed cleaning the damaged portion and filling it with new cement mortar. Deeper cracks cannot be fixed in the same way: the reconstruction of the wall's leaves is required. In these cases, the cause of the crack must be identified: moisture in the wall must be prevented, concentrated loads must be avoided, foundation problems must be carried on by a specialized worker. For earthquake in-plane cracks see "Extraordinary causes | Damages prevention".

WORKERS: ■ Skilled - n. 1 ■ Unskilled - n. 1
(skilled worker role: to evaluate the type of crack)

TIME: ■ Short ☐ Medium ☐ Long

MATERIALS: cement mortar

TOOLS: chisel, hammer, brush, bottle with spout

BE CAREFUL:

⚠ Measure it: it is possible to act just if the crack is limited to the superficial mortar (10mm width), for bigger cracks refer to a specialized person

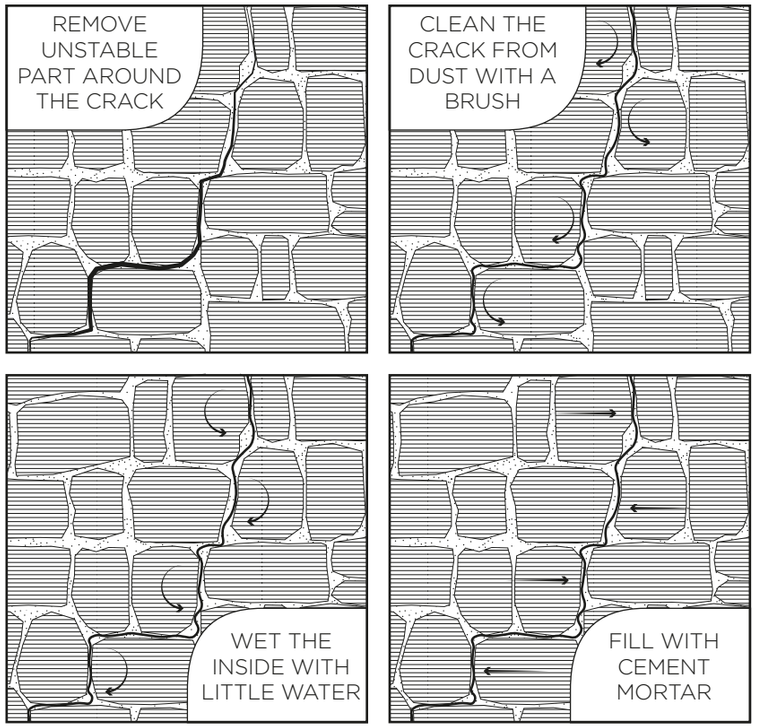
⚠ Check for possible presence of other cracks in the wall: more and deeper they are, more dangerous is the problem

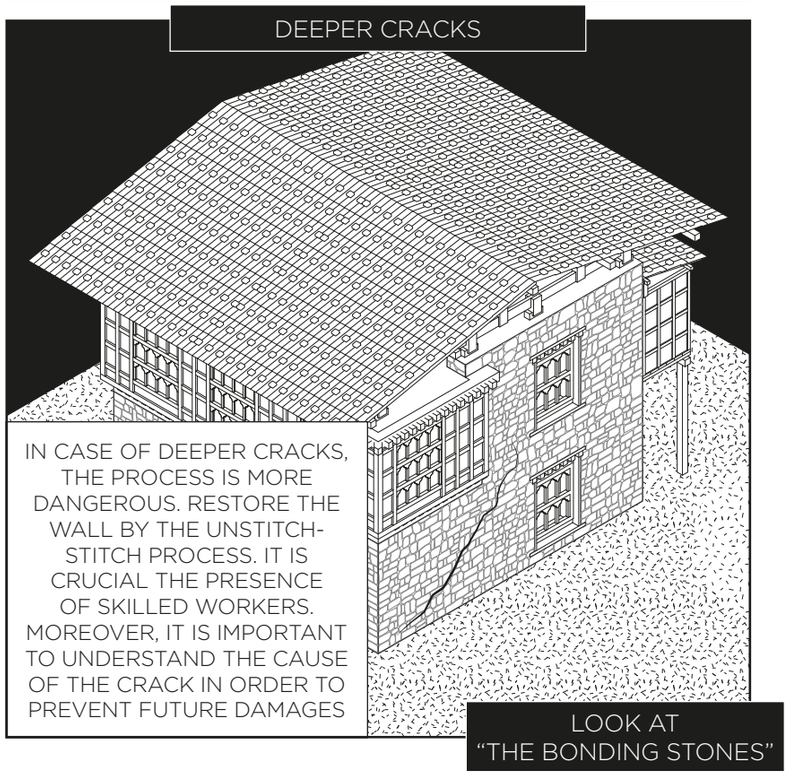
⚠ Monitor the possible size variation: if it grows, the crack may get worse

⚠ Identify the cause of the crack

⚠ Check for possible other problems generated by the crack

⚠ If it is possible, always refer to a specialized person





Ordinary causes | DAMAGES REPAIR

THE UNSTITCH-STITCH

STONE WALLS DAMAGES

Prevention

Chipping
Erosion
Exfoliation
Crumbling

Moisture, weather and accidents may damage the stones: superficial damages don't represent a serious problem for the wall but, sometimes, a developing damage affects the stability of the wall and the stones need to be replaced. Smaller stones are easier to be removed, bigger ones require more attention. Moreover, it's crucial to identify the cause and prevent it in order to avoid possible future problems. Monitoring periodically the stone wall's health is mandatory.

WORKERS: ☐ Skilled ■ Unskilled - n. 2

TIME: ☐ Short ■ Medium ☐ Long

MATERIALS: cement mortar, natural stones

TOOLS: chisel, hammer, brush, trowel, bottle with spout

BE CAREFUL:

⚠ Work on one side at the time

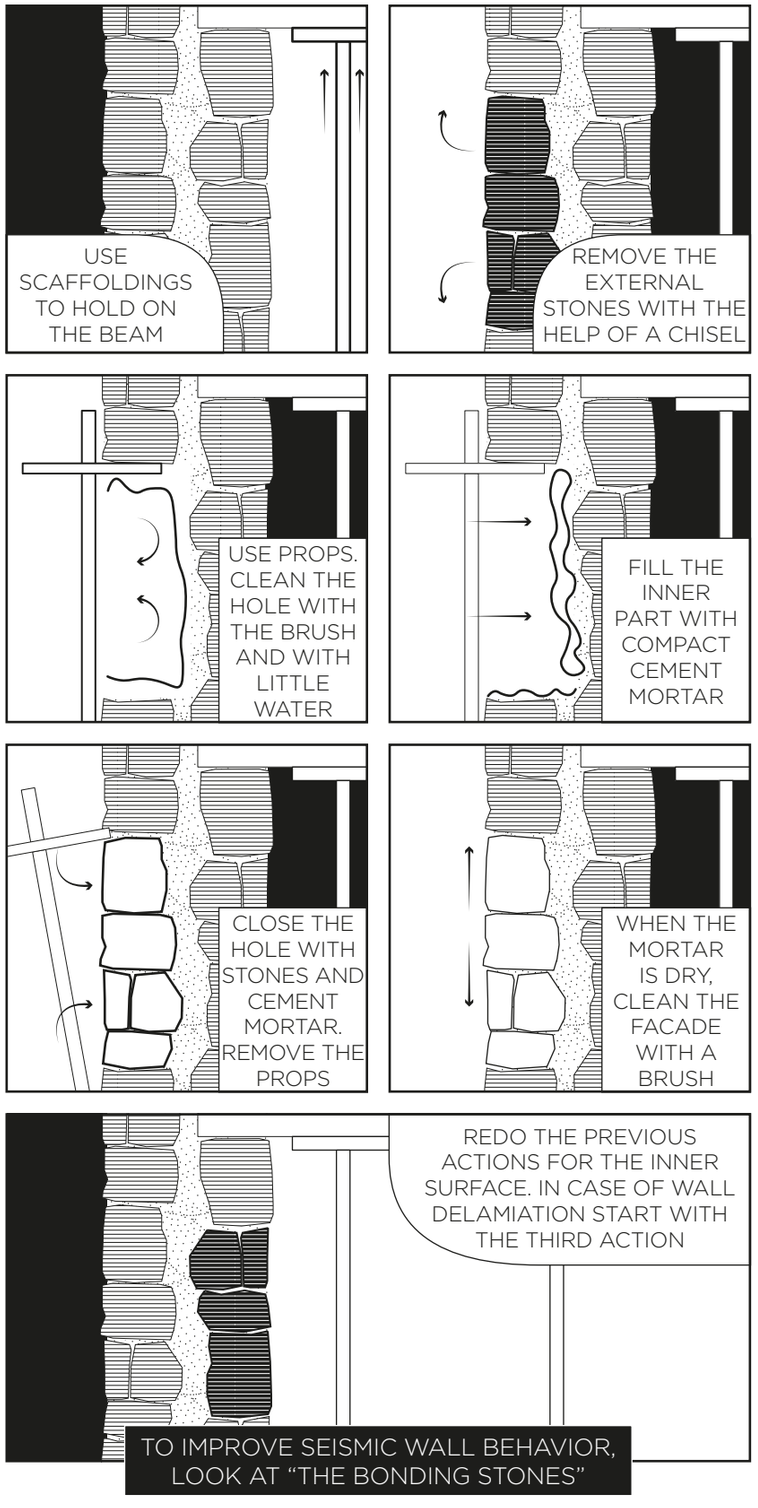
⚠ Use scaffoldings and props to assure stability during the work

⚠ Always clean the inner void and fill with good quality cement mortar

⚠ Use good quality cement mortar to assure connection with the older stones

⚠ Work on a small area at the time, and then wait some weeks before proceeding with surrounding areas

⚠ Work manually: pay attention not to damage other part of the wall



Ordinary causes | DAMAGES REPAIR

THE REPLACEMENT

TIMBER BEAM DAMAGES

Prevention

Rots by fungi
Weakening by insects attack

Wood elements are subjected to fungi and insects attack: the weakened parts need to be removed. The beam head is one of the more susceptible part. The work requires the replacement of the rotten part with a new one made of the same timber, for having the same behaviour along the whole beam. A reinforcement helps in having a stronger connection between the old and the new parts.

WORKERS: ■ Skilled - n. 1 ■ Unskilled - n. 1
(skilled worker role: to supervise the installation of the metal bands)

TIME: ☐ Short ■ Medium ☐ Long

MATERIALS: timber shaped beam, timber planks, threaded steel bars, steel bolts, cement mortar, natural stones

TOOLS: chisel, hammer, handsaw, hand drill, screwdriver, plier, trowel, bottle with spout

BE CAREFUL:

⚠ Use the same timber of the older beam

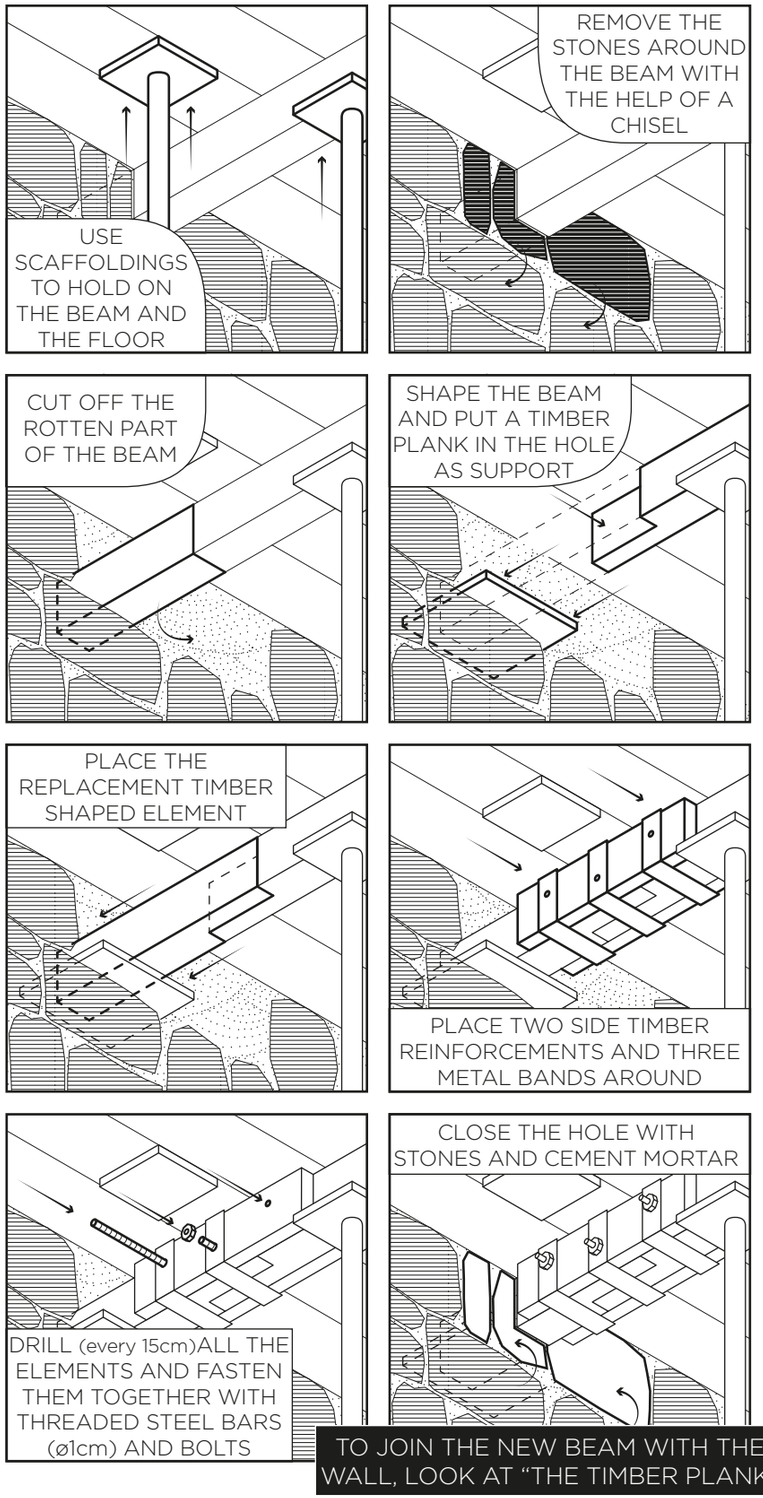
⚠ Work manually for removing the stones: take care not to damage the wall

⚠ For the wall reconstruction, look at *"Unstitch-stich"*

⚠ The timber drilling and connection need to be accurate: it is better referring to a skilled workman

⚠ Monitor the beam and wall situation for some weeks after the work: any damage connected to the work must be shown to a skilled workman

⚠ Connect the new beam to the wall (look at "*The timber plank*")



Ordinary causes | CAUSES PREVENTION

THE GROUND

NON-DRAINING GROUND

Prevention

Rising damp deterioration

A non-draining ground is the cause of water accumulation at the base of the stone walls. The raising damp deterioration affects the quality and durability of the wall. For draining the ground, a layer of gravel lead water to the lower layer of river clay, used in order to bring water far from walls and foundation. The water path control is crucial for preventing damages to the building. The ground drainage could be done in other ways: crucial is the concept of bringing the water far from the house.

WORKERS: ☐ Skilled ■ Unskilled - n. 2

TIME: ■ Short ☐ Medium ☐ Long

MATERIALS: river clay, different sized gravel

TOOLS: shovel, rammer

BE CAREFUL:

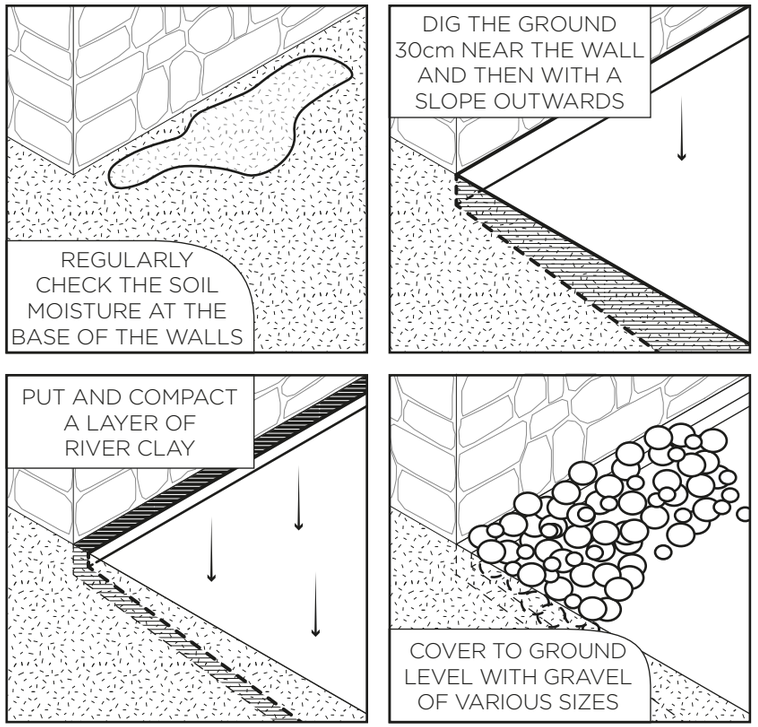
⚠ Check the presence of water before acting and verify that it is not due to other causes (underground aquifers, roots of large plants)

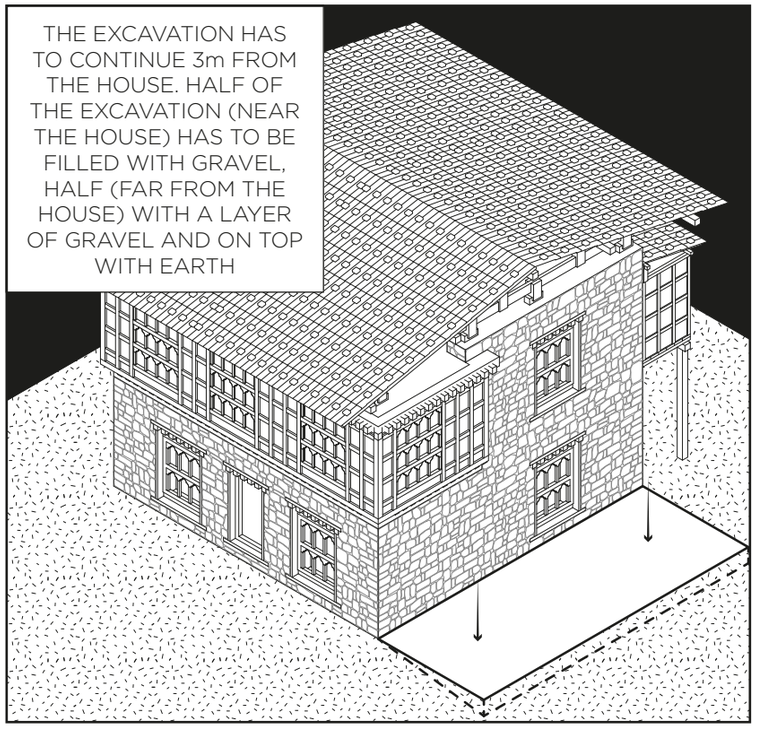
⚠ Do not affect the wall or the foundation during the dig of the ground

⚠ Create a constant slope sufficient to allow the water to flow away and avoid accumulations

⚠ Put a thick layer of clay to be sure not having infiltration

⚠ Check the functioning of the clay by pouring water before covering with gravel





Ordinary causes | CAUSES PREVENTION

THE BAMBOO SLOPE

WATER PATH

Prevention

Erosion by rain and wind
Weathering of wood

The overhanging typical roof protects the walls from rain. If the roof has only two pitches, two facades will be more exposed. The bamboo slope is an additional layer that covers the uncovered facades. A timber structure is joined to the existent one and is covered by a bamboo mat finely woven. The rainwater flows above the mat and fall on the ground, far from the façade. A draining ground is crucial for a better water path control.

WORKERS: ☐ Skilled ■ Unskilled - n. 3

TIME: ■ Short ☐ Medium ☐ Long

MATERIALS: timber beams, bamboo poles, ropes, bamboo mat, steel screws, steel plates

TOOLS: hand drill, screwdriver

BE CAREFUL:

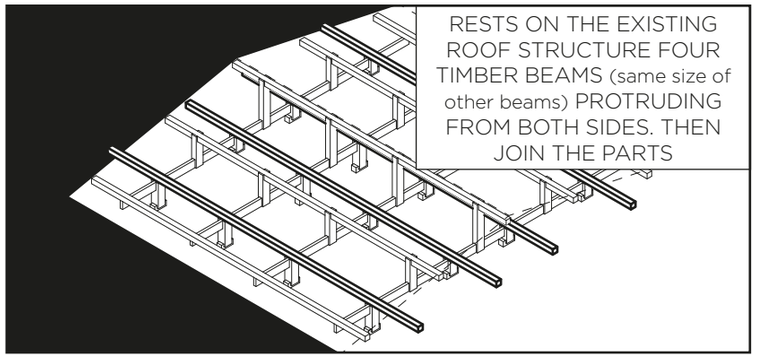
⚠ Protect the timber element with paint of linseed oil (look at *"The cleaning"*)

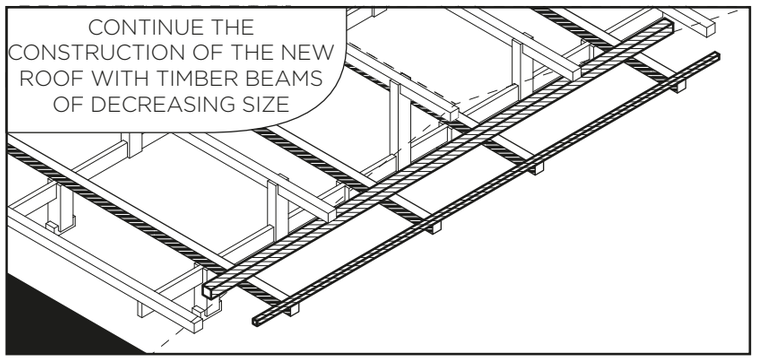
⚠ Join correctly the new timber beams together and with the old part (look at *"The upper joints"*)

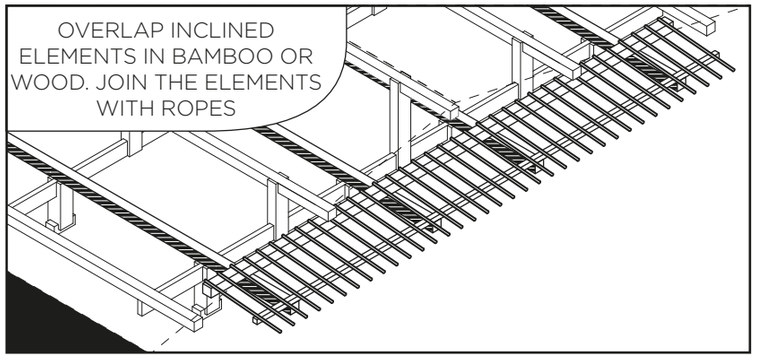
⚠ The new structure could be done entirely with bamboo but it's important to have knowledge enough about bamboo construction

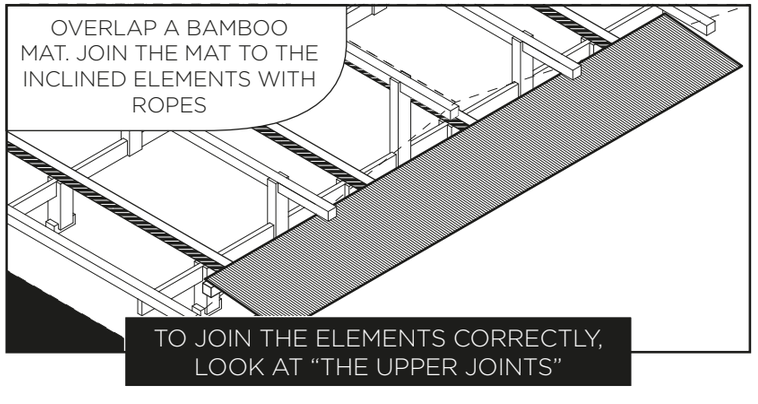
⚠ The bamboo mat needs to be checked and cleaned ordinarily for avoiding the bamboo decay

⚠ The slope must be sufficient to allow the water to flow down









Ordinary causes | CAUSES PREVENTION

THE CLEANING

STONE AND WOOD ELEMENTS

Prevention

Erosion by fungus acid
Dislocation by plant roots
Rots by fungi
Weakening by insects attack
Weathering of wood

A constant maintenance of the house is crucial for preserve stone and wood elements. Cleaning these parts with brushes and water, covering them with paint or other oily substances prevent the insect and fungi attack. Small actions like these could be useful for the prevention of bigger problems, which would require more difficult actions. Moreover, the presence of fungi and insects is due to the presence of moisture: removing the moisture is a crucial action.

WORKERS: ☐ Skilled ■ Unskilled - n. 1

TIME: ■ Short ☐ Medium ☐ Long

MATERIALS: paint, linseed oil

TOOLS: brush, paintbrush

BE CAREFUL:

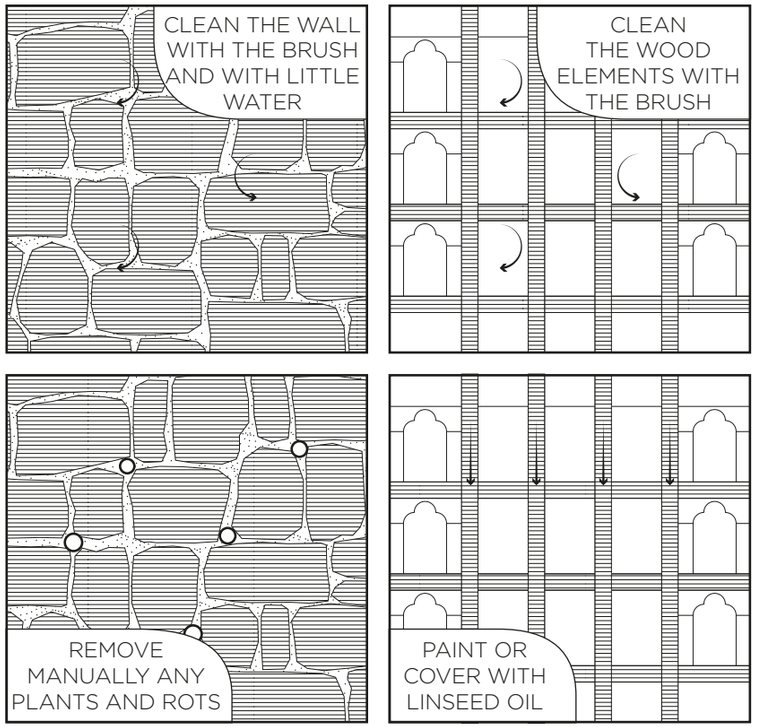
⚠ Cleaning constantly the house walls and wood parts: one time is not sufficient

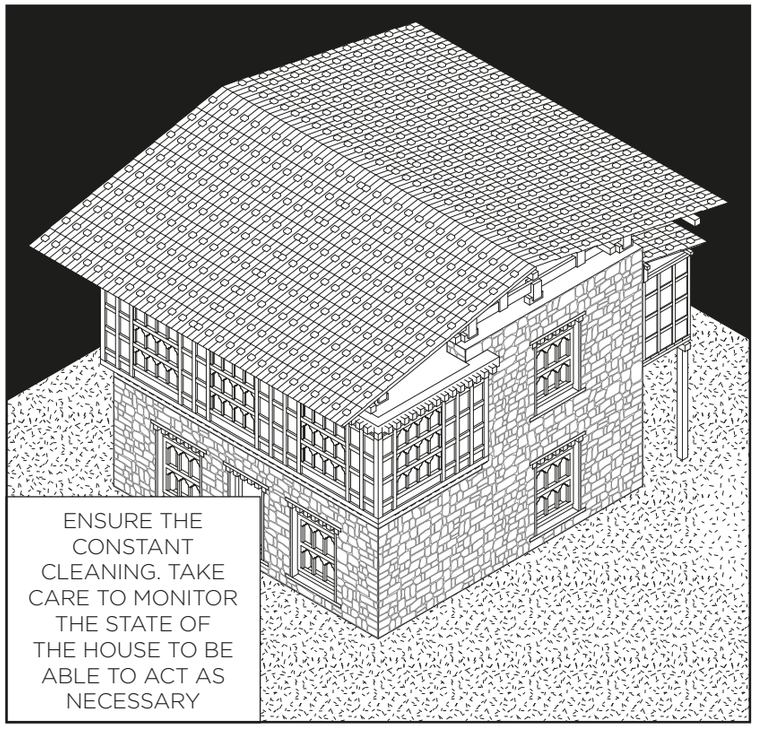
⚠ Check the presence of moisture and avoid its accumulation (look at *"The ground"* and *"The bamboo slope"*)

⚠ Guarantee ventilation across the inner rooms for preventing moisture inside the house

⚠ Fill possible holes in the wall with cement mortar for preventing infiltration

⚠ Take care not to damage the wall during the small plant removal





HUMAN FACTOR

Knowledge

SUPPLY OF QUARRIED STONE

SUPPLY OF TOOLS AND MANUALS

WORKERS EDUCATION

Awareness

INFORMING PEOPLE

Human factor | KNOWLEDGE

SUPPLY OF QUARRIED STONE

The government nowadays provides wood to rural community at discounted price for the construction and renovation of rural houses: the same action could be suggested for quarried stone supply. Rural communities use stones they can find by themselves for the buildings, quarried stones are mostly used in urban area: the supply of good-quality stones or other materials like cement mortar at discounted price could be crucial for a better-quality house.

SUPPLY OF TOOLS AND MANUALS

The supply of modern tools may help too: rural communities work with basic hand tools like chisels and cutters; the provision of modern electrical tools may improve the quality of the work and reduce the execution time. Manuals could be useful in the explanation of the construction processes, underlining the design and technical problems which must be avoided. Manuals may explain the proper use of new tools too.

WORKERS EDUCATION

The rural communities built together the houses of the village: unskilled inhabitants are led by one master constructor in the construction process. The master has increased his skills with experience: traditions are passed down, but it is more difficult to introduce modern construction models in vernacular buildings. Education of master constructors could help in the introduction of new practices that provide greater security for buildings.

Human factor | AWARENESS

INFORMING PEOPLE

Awareness is crucial for preventing human factor: informing people about risk and damages prevention, about the importance of the ordinary maintenance in the life cycle of the house, about resilience, is vital. Moreover, awareness gathers a larger user base than knowledge. A small group of persons is interested by the know-how spread: the educated workmanship which deals with traditional house construction with good materials and proper tools. But awareness includes all the Bhutanese, passing a concept: the importance of every single person in making homes safe.

Conclusion

Bhutan is a country in the Himalayan region. It remained closed to the world for centuries, developing its own civilisation. Unfortunately, the uniqueness of the architectural heritage is affected by natural hazards, such as earthquakes. In order to preserve this uniqueness, the thesis aims to develop a retrofitting manual for enhancing traditional stone rural houses. The discovery of Bhutan (through its believes, population, architecture and through its vulnerability, exposition to hazard, fragility) and the study of common retrofitting practices have led to the aim. The complexity of the work lies in the duality of tensions, internal to the country, which represent a challenge: the isolation of rural villages and the uncontrolled growth of towns, the strength of local believes and the opening to the globalized world, the uniqueness of the biodiversity and the fragility of the land, the heritage value of vernacular architecture and the need of new technology, the preservation of traditional houses and the modernization process of new buildings. These dual tensions made it complicated to realize the manual: it represents the balance between the respect of old believes and the introduction of the resilience concept, helping inhabitants to improve their houses with actions that reflect the ability of local workmanship and the availability of local materials.

Bibliography

1 | BHUTAN

AKIKO, Ueda. 2003. *«Culture and modernisation: from the perspectives of young people in Bhutan.»* Thimphu, Bhutan: Centre for Bhutan Studies.

ARIS, Michael. 1982. *«Views of Medieval Bhutan: the diary and drawings of Samuel Davis 1783.»* London: Serindia publications.

ARIS, Michael, e Michael HUTT. 1994. *«Bhutan: aspects of culture and development.»* Vol. 5, Kiscadale Asia Research Series. Gartmore, Scotland, UK: Kiscadale.

Bhutan E-RNR Masterplan taskforce (BEMP). 2016. *«Bhutan E-RNR Masterplan.»* Thimphu, Bhutan.

Department of Industries. 2009. *«Detailed feasibility report on construction materials.»* Thimphu, Bhutan.

DORJI, Yeshey. 2016. *«Water: securing Bhutan's future.»* Thimphu, Bhutan: Asian Development Bank.

Forest Resources Management Division. 2017. *«Land Use and Land Cover of Bhutan 2016: maps and statistics.»* Thimphu, Bhutan.

KAEWKHUNOK, Suppawit. 2018. «The commodification of culture: Bhutan's tourism in globalisation contex.» *Thammasat Review* 21 (1): 152-164.

Ministry of Works and Human Settlement. 2008. *«Bhutan national urbanization strategy.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2016. «National report.» *The 3rd UN conference on housing and sustainable urban development.* Royal Government of Bhutan.

National Council of Bhutan. 2013. *«Socio-economic and environmental impact assessment of mining and quarrying activities in Bhutan.»* Thimphu, Bhutan.

National Environment Commission. 2016. *«National integrated water resources management plan 2016.»* Thimphu, Bhutan.

National Statistic Bureau. 2019. *«Statistical yearbook of Bhutan 2019.»* Thimphu, Bhutan.

PENJORE, Thinley. 1999. *«Strengthening housing and urban development division.»* MoC, Urban Development and Housing Division, Thimphu, Bhutan.

Planning Commission. 1999. *«Bhutan 2020: a vision for peace, prosperity and happiness.»* Thimphu, Bhutan: Royal Government of Bhutan.

UGYEN, Yangchen, Thinley UGYEN, e Wallentin GUDRUN. 2015. *«Land use land cover changes in Bhutan: 2000-2013.»* Thimphu, Bhutan.

WALCOTT, Susan M. 2011. «One of a kind: Bhutan and the modernity challenge.» *National Identities* (Taylor & Francis) 13 (3): 253-265.

WEBB, Edward L., e Lam DORJI. 2004. *«The evolution of forest-related institutions in Bhutan.»* Asian Institute of Technology.

2 | RISK

ARYA, Anand S. 2000. «Non-engineered construction in developing countries - an approach toward earthquake risk preduction.» *12th World Conference on Earthquake Engineering*, paper 2824. Auckland, New Zealand.

BHATTACHARYA, Subhamoy, Sanket NAYAK, e Sekhar Chandra DUTTA. 2014. «A critical review of retrofitting methods for unreinforced masonry structures.» *International Journal of Disaster Risk Reduction* (Elsevier) 7: 51-67.

BOLT, Bruce A. 2020. *«Earthquake.»* Encyclopædia Britannica. https://www.britannica.com/science/earthquake-geology.

CORRADI, Emilia, e Andrea GRITTI. 2018. «Il patrimonio delle comunità resilienti. Mappe e codici nell'Italia dei terremoti.» *Techne* 15: 81-91.

Department of Disaster Management. s.d. *«Bhutan: Disaster Risk Management Status Review.»* Thimphu, Bhutan.

Department of Disaster Management. 2013. *«Disaster risk management strategy: "Safe, Resilient and Happy Bhutan".»* Thimphu, Bhutan.

Department of Disaster Management. 2009. *«National recovery and re-construction plan "Building back better".»* Thimphu, Bhutan.

FLORIO, Gilda. 2010. *«Vulnerability of historical masonry buildings under exceptional actions.»* PhD Thesis, Università degli Studi di Napoli Federico II. Napoli, Italy.

Forest Resources Management Division. 2017. *«Land Use and Land Cover of Bhutan 2016: maps and statistics.»* Thimphu, Bhutan.

Indian Institute of Technology ITT. 2009. *«Bhutan: seismic hazard risk map.»* Rourkee.

MANFREDI, Gaetano, e Iunio IERVOLINO. 2010. «Prospettive e traguardi per la sicurezza delle costruzioni in zona sismica.» *Archi: rivista svizzera di architettura, ingegneria e urbanistica* 2: 59-61.

Ministry of Works and Human Settlement. 2008. *«Bhutan national urbanization strategy.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2017. *«Retrofitting manual for load bearing structures.»* Thimphu, Bhutan.

National Environment Commission. 2016. *«National integrated water resources management plan 2016.»* Thimphu, Bhutan.

PAUDYAL, Harihar, e Ananta PANTHI. 2010. «Seismic vulnerability in the Himalayan region.» *The Himalayan Physics* 1 (1): 14-17.

SATHIPARAN, Navaratnarajah. 2015. «Mesh type seismic retrofitting for masonry structures: critical issues and possible strategies.» *European Journal of Environmental and Civil Engineering* (Taylor & Francis) 19 (9): 1136-1154.

SENO, Silvio. 2010. «La natura dei terremoti: come nasce un terremoto.» *Archi: rivista svizzera di architettura, ingegneria e urbanistica* 2: 50-53.

The Royal Government of Bhutan. 2011. *«Joint rapid assessment for Recovery, Reconstruction and Risk Reduction.»* Bhutan.

The Royal Government of Bhutan. 2009. *«Joint rapid assessment for Recovery, Reconstruction and Risk Reduction.»* Bhutan.

YESHEY, Lotay. 2015. *«Bhutan disaster management.»* Asian Disaster Reduction Center, Bhutan.

ZANINI, Cristina. 2010. «Costruzioni e sisma nella Svizzera italiana.» *Archi: rivista svizzera di architettura, ingegneria e urbanistica* 2: 54-58.

3 | ARCHITECTURE

ARIS, Michael, e Michael HUTT. 1994. *«Bhutan: aspects of culture and development.»* Vol. 5, Kiscadale Asia Research Series. Gartmore, Scotland, UK: Kiscadale.

ARYA, Anand S, Teddy BOEN, e Yuji ISHIYAMA. 2014. *«Guidelines for earthquake resistant non-engineered construction.»* IAEE, UNESCO, IISEE.

CHIDIAC, S.E. s.d. *«Seismic guidelines for stone-masonry components and structures.»* Ontario, Canada.

CHUKI, Sonam, Raju SARKAR, e Ritesh KURAR. 2017. «A review on traditional architecture house in buddhist culture.» *American Journal of Civil Engineering and Architecture* 5 (3): 113-123.

Department of Urban Development and Housing. 2002. *«Bhutan building rules.»* Thimphu, Bhutan.

Department of Urban Development and Housing. 1993. *«Traditional architecture guidelines.»* Thimphu, Bhutan.

DUJARDIN, Marc. 2000. «From Living to Propelling Monument: the Monastery-Fortress (dzong) as Vehicle of Cultural Transfer in Contemporary Bhutan.» *Journal of Bhutan Studies* 2 (2): 151-181.

HELLIWELL, Bo, e Kim SMITH. 2003. «View from Bhutan.» *The Architectural Review* 214 (1278): 24-25.

JENTSCH, Mark F., Christoph KULLE, Tobias BODE, Toni PAUER, Andrea OSBURG, Karma NAMGYEL, Karma EUTHRA, Jamyang DUKJEY, e Karma TENZIN. 2017. «Field study of the building physics properties of common building types in the Inner Himalayan valleys of Bhutan.» *Energy for Sustainable Development* 38: 48-66.

Korakit Lawsakool. 2017. «Bhutanese Traditional house in Thimphu, Bhutan.» *Wisdom to the future*. Khon Kaen University, Khon Kaen, Thailand.

LANG, Dominik H., Yogendra SINGH, e Karma NAMGYEL. 2013. «Building Classification Scheme for Bhutan.» *EQRisk project report*, n. 13-006. Kjeller, Roorkee, Thimphu.

Ministry of Works and Human Settlement. 2014. *«Bhutanese architecture guidelines.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2017. *«Retrofitting manual for load bearing structures.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2013. *«Rural construction rules.»* Thimphu, Bhutan.

NOCK, David. 1995. «The architecture of Bhutan.» *The Architectural Review* 198 (1186): 78-80.

ORTEGA, Javier, Graça VASCONCELOS, Hugo RODRIGUES, Mariana CORREIA, e Paulo B. LOURENCO. 2017. «Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: a litarature review.» *Journal of Cultural Heritage* 27: 181-196.

RODGERS, J.E., B.J. LIZUNDIA, S. YANGDHEN, Y. LOTAY, A. HORTACSU, e K.D. TSHERING. 2014. «Postearthquake safety evaluation procedures for Bhutan buildings.» *Tenth U.S. National Conference on Earthquake Engineering*. Alaska.

SABOO, Nupur Saran. 2016. «Guiding the change in transforming townscapes of Bhutan.» *International Journal of Environmental Studies* 73 (4): 541-562.

4 | MATERIALS

Anti-Corruption Commission of Bhutan. 2016. *«Improving business environment: the case of the mining industry in Bhutan.»* Thimphu, Bhutan.

Bhutan E-RNR Masterplan taskforce (BEMP). 2016. *«Bhutan E-RNR Masterplan.»* Thimphu, Bhutan.

Department of Forest and Park Services. 2017. *«Forest and nature conservation rules and regulations of Bhutan.»* Thimphu,

Bhutan: Ministry of Agriculture and Forest.

Department of Forests and Park Services. 2017. *«Forest facts and figures 2016.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

Department of Forests and Park Services. 2018. *«Forest facts and figures 2017.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

Department of Forests and Park Services. 2019. *«Forest facts and figures 2018.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

Department of Forests and Park Services. 2018. *«National forest inventory report: stocktaking nation's forest resources.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

Department of Human Settlement. 2013. *«Guidelines for planning and development of human settlements in urban and rural areas of Bhutan to minimise environmental impacts.»* Thimphu, Bhutan: Ministry of Works and Human Settlement.

Department of Industry. 2009. *«Detailed feasibility report on construction materials.»* Thimphu, Bhutan.

Department of Industry. 2018. *«Detailed feasibility study on industrial linkages and cluster (mineral based industry).»* Thimphu, Bhutan: Ministry of Economic Affairs.

Department of Renewable Energy. 2012. *«Bhutan energy efficiency baseline study: final report.»* Thimphu, Bhutan: Ministry of Economic Affairs.

DORJI, Chhimi, e Phuntsho NAMGYEL. 2018. *«Bhutan bamboo baseline and situational analysis study for promoting integrated bamboo based enterprise development among SAARC countries.»* Thimphu, Bhutan: Tarayana Centre for Social Research and Development.

Forest Resource Management Division. 2014. *«Forest resources potential assessment of Bhutan 2013.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

FRITH, Oliver, Nripal ADHIKARY, e Sonam PELDON. 2015. *«Bamboo construction in Bhutan: a feasibility and market study.»* Beijing, China: International Network for Bamboo and Rattan, paper n. 75.

Ministry of Agriculture and Forests. 2011. *«National Forest Policy of Bhutan.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2017. *«Retrofitting manual for load bearing structures.»* Thimphu, Bhutan.

National Council of Bhutan. 2013. *«Socio-economic and environmental impact assessment of mining and quarrying activities in Bhutan.»* Thimphu, Bhutan.

National Environment Commission. 2016. *«National integrated water resources management plan 2016.»* Thimphu, Bhutan.

National Statistic Bureau. 2019. *«Statistical yearbook of Bhutan 2019.»* Thimphu, Bhutan.

Natural Resources Development Corporation Limited. 2019. *«Annual report 2018.»* Thimphu, Bhutan.

Renewable Natural Resources Statistics Division. 2018. *«Bhutan RNR statistics 2017.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

Royal Audit Authority. 2014. *«Performance audit report on tax on mining and quarrying sector.»* Thimphu, Bhutan.

SATHIPARAN, Navaratnarajah. 2015. «Mesh type seismic retrofitting for masonry structures: critical issues and possible strategies.» *European Journal of Environmental and Civil Engineering* (Taylor & Francis) 19 (9): 1136-1154.

Social Forestry Division. 2010. *«National strategy for community forestry: the way ahead.»* Thimphu, Bhutan: Ministry of Agriculture and Forests.

The Engineering Adaptation and Risk Reduction Division. 2013. *«Bhutan green building design guidelines.»* Thimphu, Bhutan: Ministry of Work and Human Settlement.

The World Bank. 2019. *«Bhutan forest note: pathways for sustainable forest management and socio-equitable economic development.»* Washington DC, U.S.A.

TOBGAY, Sonam. 2008. *«Consultant report on developing a national strategy for NWFP development in Bhutan.»* Thimphu, Bhutan.

Trade Negotiation Division. 2019. *«Annual trade statistic 2018.»*Thimphu, Bhutan: Ministry of Economic Affairs.

UGYEN, Yangchen, Thinley UGYEN, e Wallentin GUDRUN. 2015. *«Land use land cover changes in Bhutan: 2000-2013.»* Thimphu, Bhutan.

WEBB, Edward L., e Lam DORJI. 2004. *«The evolution of forest-related institutions in Bhutan.»* Asian Institute of Technology.

5 | PLAN OF ACTION

ARYA, Anand S. 2000. «Non-engineered construction in developing countries - an approach toward earthquake risk preduction.» *12th World Conference on Earthquake Engineering*, paper 2824. Auckland, New Zealand.

ARYA, Anand S, Teddy BOEN, e Yuji ISHIYAMA. 2010. *«Guidelines for earthquake resistant non-engineered construction.»* IAEE, UNESCO, IISEE.

ARYA, Anand S, Teddy BOEN, e Yuji ISHIYAMA. 2014. *«Guidelines for earthquake resistant non-engineered construction.»* IAEE, UNESCO, IISEE.

BEESLEY, John. 1987. *«Wood deterioration in buildings: a guide to the identification and treatment of wood deteriogens.»* Melbourne, Australia: National Trust of Australia (Victoria).

BHATTACHARYA, Subhamoy, Sanket NAYAK, e Sekhar Chandra DUTTA. 2014. «A critical review of retrofitting methods for unreinforced masonry structures.» *International Journal of Disaster Risk Reduction* (Elsevier) 7: 51-67.

BOTHARA, Jitendra Kumar, Ramesh GURAGAIN, e Amod DIXIT. 2002. *«Protection of educational building against earthquakes.»* Nepal: National Society for Earthquake Technology (NSET).

BOTHARA, Jitendra, e Svetlana BRZEV. 2011. *«A tutorial: improving the seismic performance of stone masonry building.»* Oakland, California: Earthquake Engineering Research Institute.

CHIDIAC, S.E. s.d. *«Seismic guidelines for stone-masonry components and structures.»* Ontario, Canada.

D'AYALA, Dina Francesca, e Elena SPERANZA. 2002. «An integrated procedure for the assessment of seismic vulnerability of historic buildings.» *12th European Conference on Earthquake Engineering*, paper 561. London, UK.

EKLUND, Julie A. 2013. *«Biological growth on masonry: identification & understanding.»* Edinburgh, UK: Historic Scotland.

FLORIO, Gilda. 2010. *«Vulnerability of historical masonry buildings under exceptional actions.»* PhD Thesis, Università degli Studi di Napoli Federico II. Napoli, Italy.

GRIMMER, Anne E. 1984. *«A glossary of historic masonry deterioration problems and preservation treatments.»* Washington DC, United States: National Park Service. Preservation Assistance Division.

JENKINS, Moses. s.d. *«Insect attack to timber.»* Edinburgh, UK: Historic Scotland.

LANGENBACH, Randolph. 2010. «'Earthquake resistant traditional construction' is not an oxymoron.» *International Conference on Disaster Management and Cultural Heritage.* Thimphu, Bhutan.

LUTMAN, Marjana. s.d. *«Stone masonry construction.»* World Housing Encyclopedia.

MINDESS, S. 2007. «Environmental deterioration of timber.» *WIT Transactions on State of the Art in Science and Engineering* 28: 287-305.

Ministry of Works and Human Settlement. 2014. *«Earthquake resistant construction training manual (stone masonry).»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2010. *«Guideline on proper construction practices for non-engineered buildings (stone masonry).»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2017. *«Retrofitting manual for load bearing structures.»* Thimphu, Bhutan.

Ministry of Works and Human Settlement. 2016. *«Windstorm resilient roofing system (Guideline).»* Thimphu, Bhutan.

NORMA ITALIANA. 2006. «Beni culturali - Materiali lapidei naturali ed artificiali - Descrizione della forma di alterazione: termini e definizioni.» *Commissione Tecnica UNI, UNI 11182.* Italy.

ORTEGA, Javier, Graça VASCONCELOS, Hugo RODRIGUES, e Mariana CORREIA. 2018. «Assessment of the efficiency of traditional earthquake resistant techniques for vernacular architecture.» *Engineering Structures* 173: 1-27.

ORTEGA, Javier, Graça VASCONCELOS, Hugo RODRIGUES, Mariana CORREIA, e Paulo B. LOURENCO. 2017. «Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: a litarature review.» *Journal of Cultural Heritage* 27: 181-196.

Prof. GIANNATTASIO, Caterina, e Maria Serena PIRISINO. a.a. 2013-2014. *«I fenomeni di degrado.»* Laboratorio integrato di Rilievo e Restauro, corso di Laura magistrale in Architettura. Università degli studi di Cagliari, Cagliari, Italy.

SATHIPARAN, Navaratnarajah. 2015. «Mesh type seismic retrofitting for masonry structures: critical issues and possible strategies.» *European Journal of Environmental and Civil Engineering* (Taylor & Francis) 19 (9): 1136-1154.

SMITH, Andrew, e Thomas REDMAN. 2009. «A critical review of retrofitting methods for unreinforced masonry structures.» *EWB-UK Research Conference.* London, UK.

THINLEY, Kinzang, Hong HAO, e Choki TASHI. 2014. «Seismic performance of reinforced concrete buildings in Bhutan.» *Australian Earthquake Engineering Society Conference (AEES).* Lorne, Australia.

Ringraziamenti

Estate 2020. Dopo più di un anno dall'inizio, volge così al termine il lavoro sulla tesi di laurea magistrale. È stato un lungo percorso: mi sono trovata faccia a faccia con i miei limiti e ad ogni passo ho tentato di spostare l'asticella sempre un po' più in alto. Guardando indietro, quasi mi stupisco di vedere dove sono arrivata. Ma questo cammino è iniziato molto prima e fin dal primo giorno in questa università posso vantare di aver avuto persone che mi hanno ispirata e aiutata. Desidero quindi ringraziare queste persone.

Per prima la mia relatrice, la professoressa De Filippi: lei non lo sa, ma le sue lezioni mi hanno aperto gli occhi su un mondo nuovo e per la prima volta in cinque anni ho sentito di aver imboccato la strada giusta. La cosa più assurda? Io quel corso neanche lo avevo scelto, mi ci sono ritrovata, e posso affermare che mi ha dato non poche soddisfazioni.
Vorrei ringraziare il professor Pennacchio, sempre interessato e pronto ad ascoltare le mie idee: i suoi consigli sono stati preziosi.
Una delle esperienze più formative dell'ultimo anno è stato senza dubbio il periodo in Giappone. La tesi mi ha portato lontano e mi ha permesso di collaborare con il professor Aoki che desidero ringraziare: nonostante il periodo complicato, il suo supporto è stato fondamentale. Grazie a tutti per avermi permesso di realizzare questo viaggio.
Un grazie speciale va anche a Phuntsho: grazie per avermi aiutato a capire ed amare il tuo paese. [A special thanks also goes to Phuntsho: thank you for helping me to understand and love your country.]

Ma come ho detto prima, i ringraziamenti si estendono a molte più persone che nel corso degli ultimi anni sono state parte della mia vita. Ringrazio tutti i professori e gli assistenti: chi mi ha fatto amare l'architettura, chi mi ha fatto desiderare di essere più brava, chi mi ha fatto sentire di esserlo, e anche chi non ho apprezzato, perché in fondo non tutte le strade corrono parallele e spesso quelle che non vogliamo percorrere ci fanno crescere più in fretta.
Ringrazio i compagni, o meglio colleghi: Torino, Madrid, Cartagena, ovunque ho trovato persone splendide e voglio ringraziarle per il tempo trascorso insieme, e per tutte le conoscenze che mi sono state trasmesse.
Inoltre, voglio ringraziare gli amici, chi conosco da tanto, chi da poco, chi ancora mi è vicino e chi, per qualche ragione, ho perso nel tempo: grazie per condividere un pezzo della vostra vita con me, senza questo non avrei avuto l'energia per portare a termine questa tesi.
Per ultima, ma ovviamente non per importanza, ringrazio la mia famiglia: sempre mi ha incoraggiato nelle mie scelte e sempre ha creduto in me, non potrei desiderare di meglio.

Ringrazio tutti perché è grazie a voi, che riempite le mie giornate, che io sono diventata la persona che sono.
Grazie.