

Vernacular heritage in Bhutan at risk:

a manual for conservation and
maintenance of rammed-earth
buildings

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Master's degree thesis:

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“People are the basis of every piece of work” F.K.

Abstract

Bhutan is a small country located on the slopes of the Himalayas, which is an area characterized by frequent earthquakes due to the collision of the Indian and Eurasian plates; despite there's no record of earthquakes greater than 7 magnitudes in the twentieth century, the country appears to be in an area at risk and with a high probability of having other earthquakes of greater intensity in the future. Furthermore, the climatic conditions, the difficult environment and the predisposition to natural disasters put the population and its housing to frequent tests. Nowadays, it is not very hard to find buildings constructed of reinforced concrete in the urban areas of the country; on the contrary, in the rural ones, where the majority of the population reside, the buildings are constructed of raw earth or stone. These traditional constructions are particularly vulnerable to earthquakes due to the lack of seismic resistant technologies, as happened in 2009 in the east of Bhutan and in 2011 with the earthquake on the Indo-Nepalese border. At present there are no guidelines or policies for the conservation and structural reinforcement of traditional earthen buildings, although the government has focused in particular on the preservation of Bhutanese vernacular buildings, especially with the publication of the last "Five Years Plan".

The Kingdom of Bhutan due to rapid urbanization and modernization of construction technologies is placing more attention and efforts to promote and preserve the cultural heritage that comes from vernacular architecture, represented by temples "Lhakhang", fortress "Dzong" and traditional dwellings "Yue Chim"; thanks to this conscious vision of the uniqueness

and richness of the heritage that there is the possibility of developing a search for conservative technologies for buildings built of rammed-earth.

This thesis work therefore arises with the aim of proposing a manual of intervention for vernacular buildings in rammed earth damaged by the earthquake. In the light of the damages assessments, it has been done an analysis of the causes that may have contributed in the case of damage or collapse of a building, which is not always related only to the earthquake tremors. The research therefore, continued with the identification of appropriate techniques and materials to repair the effects of the damages, always in consideration with the socio-economic possibilities and local resources of the population in respect of the traditional architecture style. The concepts introduced, try to focus onto the development of a seismic culture by the local population for the vernacular buildings in which they reside, in order to mitigate and prevent structural damage in future earthquakes. Although the manual itself will not be distributed directly to the population, if not with accurate experimentation by researchers of the Satreps program and workshops to craftsmen, this arises with a language as simple as possible and with the use of graphic drawings to explain step by step the repair actions that have to be undertaken, as the final goal is the proposal of interventions easy to understand and repeat by the local population.

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Introduction

The Earthquake of Magnitude 6.9 on September 2011 that caused severe damages to the buildings in Western Bhutan, has re-confirmed the level of seismic activity which is subjected the country, and has exposed exponentially the vulnerability of many infrastructures, particularly the houses in rural area. While earthquakes cannot be predicted and prevented, homes could be made stronger, resilient to shocks and vibrations and therefore safer.

The earthquake creates a great devastation in terms of construction, money and often also human lives; for this reason, the mitigation of risks involved in earthquakes is here analyzed, not only with regard to the prevention of sacred buildings or monuments but also and especially for rural buildings.

The motivations that have pushed me to address this topic of thesis are twofold: first of all, it comes from my interest born during exchange experience in Brasilia for alternative low-cost construction technologies that often still characterize the rural villages of the developing countries (reason why I approached Crd-Pvs), and in particular the raw earth for the strong link with the environment and the human skills. Following the meeting with professor Aoki, the hypothesis to participate in the research carried out by Satreps with a thesis project has been embraced. I also had the opportunity to spend a month in Japan at the professor's laboratory and in close contact with the Bhutanese PhD student, Phuntsho Wangmo, who helped me to clarify many trivial aspects, but unknown to me from the Bhutanese tradition.

The international project carried out in Japan has the aim to study technologies that mitigate the effects of the environmental disaster on traditional Bhutanese architectures, through international research, field and laboratory tests, thanks also to a wide collaboration of various Universities and Japanese research centers. The final aim of this project that will last in total 4 years is to find seismic resistant technologies that reduce the loss of lives and homes, but at the same time increase the awareness of seismic risk through the development of four different manuals, both for new and old built in rammed-earth or masonry stone.

In the first research, I started to analyze the actual situation after the opening of the country to "westernization", focusing on the aspects of cultural preservation of the country's identity with reference to the GNH as a government approach to the preservation of Buddhist values; on the other hand, the negative impact that it brought is a change in the landscape and in the types of construction, especially in agricultural villages. Then, it follows a review of the natural aspects and therefore the resulting seismic risk and the effects of recent seismic disasters, concerning the policies about the reconstruction of the buildings damaged by the earthquake and territorial planning, expressing the clear need to have a code of construction and conservation for buildings in raw earth. Consequently, the experience with rammed-earth of Bhutan is analysed, taking in consideration the aspects of seismic risk and the solutions technology already carried out by other countries for the introduction of a seismic culture.

Finally, the last part is dedicated to the project research and the proposal of the manual; here are evaluated all the possible causes and effects that do not always refer only to the earthquake but also human and natural degradation factors.

The aim of this manual is therefore to propose intervention for the recovery of earthen buildings damaged by the earthquake; buildings that often cannot be rebuilt and represent sources of danger to the owners themselves if they are not settled after catastrophic events.

The manual shows several cases of common damage (found in the post-earthquake assessment) with possible repair techniques, also providing details of in-depth analysis of the damage before starting to repair.

part I



Chapter one: Bhutan and the modernity challenge

1.1 General Context: the recent opening of the country

Bhutan is a small Asian country, located on the slopes of Himalaya, which has been isolated from the rest of the world until the second half of the 20th century. The country had always been a peaceful Kingdom found onto the principles of Tibetan Buddhism, but the situation dramatically changed between 1947 and 1960 when the country felt the need to preserve its independence from the neighbors; in the fifties China occupied Tibet with military forces, threatening Bhutan, with which it has always shared not only cultural aspects but also ways of commercial exchanges. Some years later, the country was experiencing the same threat along the Indian border; for this reason, the third King Druk Gyalpo Jigme Dorji Wangchuk and parts of the upper class drove the country to its modernization in order to secure the nation's sovereignty and independence.

Bhutan became quickly aware that without an international presence it would have been a weak and desirable power always in danger, so that the King imposed the end to the self-isolation that affected the kingdom so far; in 1962 Bhutan joined the Colombo Plan, and in 1971, the country became a member of the United Nations.¹

The third King Druk Gyalpo also contributed to a general

1. Akiko Ueda, *Culture and Modernisation: From the Perspectives of Young People in Bhutan*, Center of Bhutan Studies & GNH, 2003 <http://www.bhutanstudies.org.bt>

2. *Ibidem*

reformation of the government, which led to a switch from absolute monarchy toward the institution of a parliamentary democracy in 2008. Obviously, all these changes were not supported from all the parts, as the biggest concern was the effects of this opening to westernization on a population deep focused on traditions, such as Buddhist values and simple lifestyle.

Even the foreign Minister of that time claimed:

“Modernization exacts a high price. I’m not sure it’s ideal, but we have no choice. In the modern world you can’t live isolated [...] But there is going to be an effect on peoples’ values and way of life.” (New York Times, December 11, 1973)²

With the firsts publication of “The five years program”, the government put all its strength in improving the road networks between the capital, Thimphu, and the smallest villages, till the borders of India to ensure its power, growing the economy and assuring good living standards to the citizens through electricity and water supplies. On another point of view, in these years Bhutan government started a great development in several sectors, for instance women’s participation in day life, agricultural developments and interests in the environmental protection. Even if the beginning of these programs introduced many changes to people’s life, it has been kept on a balanced level between the identity of Bhutan and its development towards modernity. Nevertheless, the government realised that Bhutan’s unique identity

should be preserved from the negative attitudes and influences that emerge during the development process; only in the sixth “Five years plan” it has been shown interest in the preservation of culture and the promotion of national identity through encouraging all aspects of the nation’s traditions.³ The economic policy recently published by the Bhutan Royal government establishes several objectives of future economic planning directly related to the building sector, in particular, in regards of housing and improving living standards. These goals have led to specific recommendations for improving construction practices that could strengthen government efforts in preserving the cultural aspects of Bhutan.⁴

3. Akiko Ueda, *Culture and Modernisation: From the Perspectives of Young People in Bhutan*, Center of Bhutan Studies & GNH, 2003 <http://www.bhutanstudies.org.bt>

4. Watson D., Aia And A. Bertaud, *Indigenous Architecture as The Basis Of House Design In Developing Countries: A Case Study Evaluation Of Traditional Housing In Bhutan*, Habitat Journal, Pergamon Press, Pp.207

1.2 Gross National Happiness and government approach

In the same period of opening towards the rest of the world, both from an economic and social point of view, the State found itself facing the need to protect its population through the refusal of the GDP; this is considered today the only means to consider the progress and economic situation of the country, by contrast introducing a different principle based on the measure of physical and spiritual happiness of the population called GNH. This happened in particular thanks to the deep attachment to the Tibetan Buddhist foundations or the thought that the psychophysical well-being of man should derive from his spirituality and not from the possession of materials; now looking at this concept from a world in which the financial system is in a severe crisis this small state seems to be a step forward and proposing a belief that attracts a lot of interest from sociological economists and jurists all over the world. This holistic approach to development embraced by Bhutan has therefore become a model that has been reflected in world conferences and interests by the UN and sees the principles on which Gross National Happiness is based in other parts of the world.

Gross National Happiness is found on the principle of “one Nation, one people” to stress the idea of a very close relationship and uniqueness between the population and those who represent its sovereignty, in an increasingly global and dispersive climate of the States with which it is confronted. For this reason, this ideology is rooted in all aspects of Bhutanese life: from the preservation of culture and the environment, the economic sustainability of the country,

administrative transparency and fairness.⁵ There are many positive aspects that this system of evaluation, and therefore the country's development footprint, has brought: just think of free schooling, the philosophy of life of respect for others and for the environment, developments in life quality and infrastructures. Despite this, the country is still facing major challenges against poverty, remaining one of the poorest countries in the world with a GDP rating of 171th place between the Central Republic of Africa and Congo⁶, but has become an important starting point to shape the process of Bhutan transformation in a modern country, conscious of its unique identity that needed to be preserved.

5. Susan M Walcott, One of a kind; Bhutan and the modernity challenge, National Identities vol 13, September 2011

6. Ibidem

7. Napur Saran Saboo, Guiding the change in transforming townscapes of Bhutan, International Journal of Environmental Studies, 2016

8. Langenbach Randolph, Earthquake Resistant Traditional Construction Is Not An Oxymoron, The Royal Government Of Bhutan, International Conference On Disaster Management And Culture Heritage, 2010

9. Mowhs, Royal Government Of Bhutan, Bhutanese Architecture Guidelines, 2014

1.3 Preservation of cultural and unique identity

Since the end of isolation in the Seventies, Bhutan has endured on strong beliefs, religion and culture, which formed the physical landscape of towns. In a certain way, the isolation of the Bhutan state from the external influences of the modern world, has allowed the conservation of its vernacular architecture to these days. Despite this, interaction with the outer world, the influence of neighboring nations, tourism, migration and diversification of economy have led to certain impacts on people's lifestyle, which has consequently drowned to radical changes to the built environment.⁷ Western construction technologies have been taking in consideration in the last few decades and will probably mark their continuity in the future, partly due to the need to import materials such as cement and steel, and technicians who are experts in these construction technologies, but at the expense of a superficial knowledge of the vernacular heritage of the country. As a result, newly constructed buildings appear out of the cultural context, as well as with the climate and local resources of Bhutan. Taking into account the uniqueness of the cultural heritage of his country, the Bhutanese government inserts a program of "Conservation of traditional arts and culture" in the nine established guidelines for a modern development and it determines its legislative importance through Article 4 of the Constitution.⁸

Architecture and the Arts and Crafts, nowadays represent a prerogative of the State, so that it has been published a code named "Traditional Architecture Guidelines", which is auxiliary to preserve the nation's iconic stylistic traditions.⁹ Since knowledge and traditions have been transmitted only

orally for centuries, with the advent of modern techniques which on one hand have brought many opportunities and possibilities to build in a different way and probably with more facility (omitting the costs), on the other hand, they have brought a wave of negativity and loss of the values of vernacular techniques. It must also be said that, in the last years because of this of modernization, there has been a gradual loss of interest in the knowledge of vernacular architecture, considering structures in cement and steel as more attractive and resistant, consequently, a fundamental loss of knowledge of good construction in raw earth. In fact, it often happens that in the case of natural disasters, such as earthquakes in Bhutan, buildings exhibit a lower level of safety despite the modernity of the technologies involved. This explains how new technologies imported and used without the real familiarity of their structural behavior can cause greater damages than technologies used for centuries and improved over the years following these seismic events. It is often possible to find houses built in raw earth or in stone with slabs or other parts substituted with reinforced concrete; in the case of an earthquake these two materials behave differently and create greater damage to the structure than a traditional structure could do. From another point of view, in praise of vernacular heritage, Bhutan opened up to the world during the energy crisis derived from fossil fuels in the 1970s, and in a certain way it has been exempt. While the rest of the world is now trying to move on a more ecological line, especially in the field of construction, these vernacular architectures have always been characterized by the sustainability of the processes and materials involved. Wood, raw earth and stone, are always locally present and versatile materials, requiring a considerably lower energy consumption compared to the production of cement and steel for construction.

1.4 Rural vs Urbanism: rapid change of landscape in the last years

The State of Bhutan has seen rapid urbanization in the last decades and unplanned growth of the medium-large city, due to a migratory flow of the population from the valleys towards the urbanized towns and with more services such as Thimphu, Puentsholing and other nascent cities. Although the Bhutan is one of the least urbanized countries in the world, the situation we have seen is changing rapidly; from some estimated data more than one hundred thousand inhabitants are migrating from rural areas to towns with an increase of the population of 40-50%¹⁰ in large cities. A large portion of the population sees this shift as a new opportunity for better life and jobs, as most of the inhabitants in urban areas are administrative employees in government offices. The risk that this migration entails involves not only the congestion of overcrowding in the cities but also socio-economic problems, environmental problems as well as the fact that the aspects linked to society and life of rural environments will be gradually lost; according to the government's vision for 2020 about half of the population will live in urbanized areas while those in towns and natural villages with very limited access will suffer more of abandonment and poverty.¹¹

According to some estimates about 60% of the population resided in urban areas and lived mainly in agriculture and animal breeding; seen in a rapid urbanization and displacement of the population of the last 10 years, the proportion of the population living in cities has increased from 13% in 1985 to 32% in 2005 with a growth of 6%; it is estimated that in 2014 almost 38% of the population was living in ur

10. Bhutan National Urbanization Strategy, MoWHS Gov. Bhutan, 2008

11. Planning Commission, RGoB, Bhutan 2020: A Vision for Peace, Prosperity and Happiness, part II

ban areas with an annual growth of 3.4%. This high rate of urbanization in the last decades therefore originates with the search for accessibility to services and the economic market or a job search and education for young people.¹²

This rapid urbanization expects it to be environmentally destructive, both for the use of resources and for the lack of laws or territorial planning that could help the development of cities and territories, such as the possibility of renting or buying houses in the city it is less and less affordable as services and infrastructures are lacking and they cannot cope with this rapid shift towards the cities going to put a great pressure on what are the resources and systems currently present. On the other hand, in the remote areas there will be a reduction in competition for the use of resources such as arable land and animal breeding so at the same time it will be possible for farmers to maintain a certain quality of life in rural areas; this suggests that urban migration can be a positive stimulus for the development of agriculture and present itself with a gain or supply for farmers while at the same time the secondary and tertiary sector would have a greater development in urban areas to the detriment of the potential of the villages more remote.

Unlike urban areas such as the capital of the country, Thimphu, the buildings are constructed particularly with simple materials and techniques such as earth and stone. According to some recent statistics, about 66% of citizens live in houses made with traditional materials, of which 83% living in the rural area live in traditional houses. On the other hand, less than 8% of people across the country have reinforced concrete buildings as those are constructions that require the importation of both the materials and the foreign workforce of the technicians, as often comes from the border with In-

12. Department Of Disaster Management, Ministry Of Home And Cultural Affairs, Royal Government Of Bhutan, Bhutan Risk Disaster Management: A Status Review

dia.¹³ Throughout the country, the community relies on typically traditional constructions for both materials and construction techniques, through the use of rammed-earth and stone bearing buildings. The government is pursuing a policy that guides citizens to the use of traditional constructions in order to maintain a sustainable nation from both an economic and a preservation of the landscape and the fragile natural environment, trying to encourage the use of these materials to the detriment of reinforced concrete and of houses built of bricks. However, the population is seeing the use of traditional techniques less and less favorably due to the two important earthquakes that occurred in 2009 in 2011 which destroyed an important number of buildings especially in rural areas; an important task of the Royal Government now is to guide citizens to the use of vernacular techniques and technologies but resistant to the earthquake in accordance with the geographical and economic conditions of the villages in which they live.

A particular phenomenon that has been taking hold in recent years thanks to the increase in tourism, is the transformation of the rural pattern into a choice of modern buildings to allow the rent of rooms. Although the community is very rooted in traditions and culture, at the urban and architectural level the characteristic profile is undergoing profound changes; once it was very easy to meet individual buildings with a large plot of private land around used for the cultivation and breeding of some animals or small groups of farmhouses with baths, and granaries detached from the house and marshy land in the neighborhood where the spaces we see are mainly dedicated to the common cultivation of several families. However, with the arrival and the request of residences for sleeping by tourists, the typical houses are transformed according to the needs, in small units with commercial spaces on the ground

13. Department of Culture, Ministry of Home and Cultural Affairs, RGoB, National Research Institute of Cultural properties Tokyo, Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan, 2015

floor for the sale of souvenirs and products of the arts and Crafts and even small rooms dedicated to renting for tourists. So, it is going to be lost, with this new attitude to transform houses according to needs, the typical character of rural valleys that give the symbolic aspect of the country. The traditional Bhutanese architecture is therefore faced with the loss of meanings and uses that have always been connected to it, such as the lack of insane food storage and the lack of space for the animals, leading to a profound therefore also changes in people's daily lives.



Img.1: New concrete building in the urban city



Fig. 2: Rammed-earth building in the rural area



Fig. 3: Stone house building in the urban area

1.5 Conservation of farming village landscape

The striking aspect of the country of Bhutan is its natural appearance, in fact the population is based on agriculture as the main source of income. The landscape is purely rural although some cities are taking shape and scattered throughout the country you can find historical buildings like Dzong and Lhakhang but mainly private houses and farms villages; these are considered important buildings for preservation as represent the vernacular heritage in the country. The private and rural houses are built mainly with rammed earth and have wooden partitions finely hand-painted such as Rabsel, according to the tradition of arts and craft. The main scenery of the country is that of a purely natural country with groups of farms and small villages scattered on the terraced rice fields along with sacred buildings and monasteries. The predominant agricultural aspect of the villages in Bhutan represent not only an aesthetic factor but mainly a cultural attachment to the typical landscape and a value for the society, which according to the Kingdom of Bhutan must be preserved. On the other hand, we are witnessing more and more an inappropriate use and importation of “modern” materials such as reinforced concrete in the most remote areas with the idea that this method could probably give a better sense of security and visibility compared to houses in which the population lives today; but in the long term we can observe negative effects regarding the conservation of vernacular constructive techniques and above all a consequent abandonment of rural areas, and a sprawl towards the larger cities. It is easy to imagine, therefore, that the use of buildings that are not typical leads to a decrease in the technical knowledge of the

craftsmen and carpenters who have always used the technique of ramming and in the worst case leading to the extinction of these. So, if this is no longer used other techniques such as carpentry and wood carvings would no longer make sense to be introduced in new buildings with more innovative technologies; in this way the essence of the country founded up to now on traditions and culture would be lost.¹⁴ Unfortunately, with the rapid change of the urban profile there is a great impact of modernism in big cities and slowly in the rural clusters too; tradition linked to culture and religious influence are gradually lost and the housing typologies pass from the typical agrarian house to the use of modern block constitutions. The innovative materials are introduced as concrete, reinforced concrete blocks and cement mortars or as already widely seen the use of a roof cover in corrugated sheet that causes disharmony and contrast with the natural environment, compared to the original stone cover. The use of these new technologies and therefore not provided by the guidelines strongly proposed and disseminated by the government make the aesthetic and technological qualities always used in the past less valuable in qualities. Although the community is very rooted in traditions, and the access to modern materials is very difficult (both for price and for knowledge), scarce resources and sometimes hostile environment lead to greater interest in these imported technologies because considered more suitable and safe. The government is therefore carrying out a prevention and knowledge campaign, through workshops and meetings with craftsmen and carpenters for the enhancement and conservation of traditional architectures, with the hope of giving knowledge to citizens of the great value of their traditional architecture in a world where everything has become easy disposable.

14. Department of Culture, Ministry of Home and Cultural Affairs, RGoB, National Research Institute of Cultural properties Tokyo, Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan, 2015



In order from top to bottom:
 Fig.4: Rural Rammed-earth house
 Fig.5: Kitchen
 Fig.6: Room



In order from top to bottom:
 Fig.7: Typical "flying" roof
 Fig.8: Attic
 Fig.9: Pray Room



Pictures: Division for Conservation of Heritage Sites, Department of Culture, MoCHA, Study of typology of Bhutanese rammed-earth buildings

In order from top to bottom:
Fig.10: Storage
Fig.11: Internal entrance

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Chapter two: Natural vulnerability of the country

2.1 Natural Environment of Bhutan

Bhutan is a small country of south-central Asia, closed to the eastern borders of the Himalayas and by two Asian countries: the Indian regions in the South and East such as Assam, Arunachal Pradesh, and Bengal and the Independent Chinese region of Tibet in the Northern border. The maximum distance the country reach in east-west orientation is approximately 300 km and north-south are about 150 km.¹⁵ On the physical point of view, the main part of the country is mountainous with a range of elevation from the lowest 100 m along the Indian border to the highest 7,554m Kula Kangri peak on the Tibetan border. Bhutan has a particular geomorphology as it touches three different zones from South to North; this division is almost related to meteorological, ethnographical and geographical divisions of the country: The Great Himalaya region which is mostly under permanent snow, the Inner Himalaya, where are situated most of the biggest cities and villages and its climate is temperate, and in the south the Teraj region, which has a sub-tropical climate almost though the whole year. These two extreme conditions create a landscape which reach sub-tropical to arctic environment, with lowland fields and hills, till the highest peaks in the Himalayas mountains.¹⁶

15. <https://www.encyclopedia.com/places/asia/nepal-and-bhutan-political-geography/bhutan>

16. http://www.visitbhutan.com/geography_of_bhutan.html

17. Yeshey Dorji, Water – Securing Bhutan Future, Asian Development Bank, National Environment Commission, RGoB, Bhutan 2016

18. <https://www.worldwildlife.org/projects/bhutan-committed-to-conservation>

19. Yeshey Lotay, Asian Disaster Reduction Center, Country Report Bhutan Disaster Management, February 2015

Rivers and water resources represent the most important character of Bhutan both in the physical, economic and social aspects, so much so that, this important power resource has growth the national economy in the last years thanks to the empowerment of hydroelectric.¹⁷ The variety of climatic conditions gives Bhutan a rich biological diversity in flora and fauna too; the ecosystem has remained intact due to the conservation efforts of the Bhutanese people and government to keep its natural background and today almost 60% of the kingdom's area has been designated as protected nature preserves.¹⁸

On the other hand, there are always two sides of the coin; in fact, due to the location of the country in geological and climatic delicate conditions, Bhutan faces many natural disasters, such as earthquakes, windstorms, fires, landslides, flash floods and glacial lake outburst floods, which are mostly seasonal hazards of the monsoon period or the dry one. The country is experiencing extreme climate change through the increase of climatic disasters, even though those not seem to hit the country on a large scale they are affecting people's life and living; for examples the recent GLOF in 1994 in Punakha-Wangdue valleys, the cyclone Aila in 2009 which brought a serious impact on livelihood, with lives loss and damages estimated for 719 million Nu, frequent landslides caused by flooding events, heavy seasonal rain and seismic events.¹⁹

2.2 Bhutan seismic hazard status

The Earth consists of a mosaic of six major and several smaller plates which are in relative motion since the creation of the world, and for this reason, the energy produced during this movement react in a frequent seismic swarm. The Himalaya is located at the boundary between the Indian and Eurasian plates where originally the India pushing force induced a crustal movement that is ended in the formation of the Himalayas and Tibet mountains.

The Himalaya Mountains have the shape of an arc barrier and extend for 2500 km from Nanga Parbat (8215 m) in northwest limit to Namche Barwa (7755 m) to the northeast one. Due to the concentration of stress energy in the last 55 million years since collision, and the continuous movement of the tectonic plaques, the Himalayan ones gave birth to an extensive seismic activity which is still in motion. From GPS measurements, we know that each year the Indian plate advance about 20 mm towards Eurasian Plate; this friction connote an accumulation of stress in the soil when smallest earthquakes occurs, while the great ones signify a northward motion of the Indian Plate.²⁰

20. UNDP, USAID, MoHCA, Earthquake resistant construction training manual (stone masonry), 2014

21. Kinzang Thinley, Hong Hao and Choki Tashi, Seismic Performance of Reinforced Concrete Buildings in Bhutan, Australian Earthquake Engineering Society 2014 Conference

22. Department of Risk Management, MoHCA, RGoB, Bhutan Disaster Risk Management Status Review, http://www.ddm.gov.bt/download/Bhutan_DRM_Status_Review.pdf

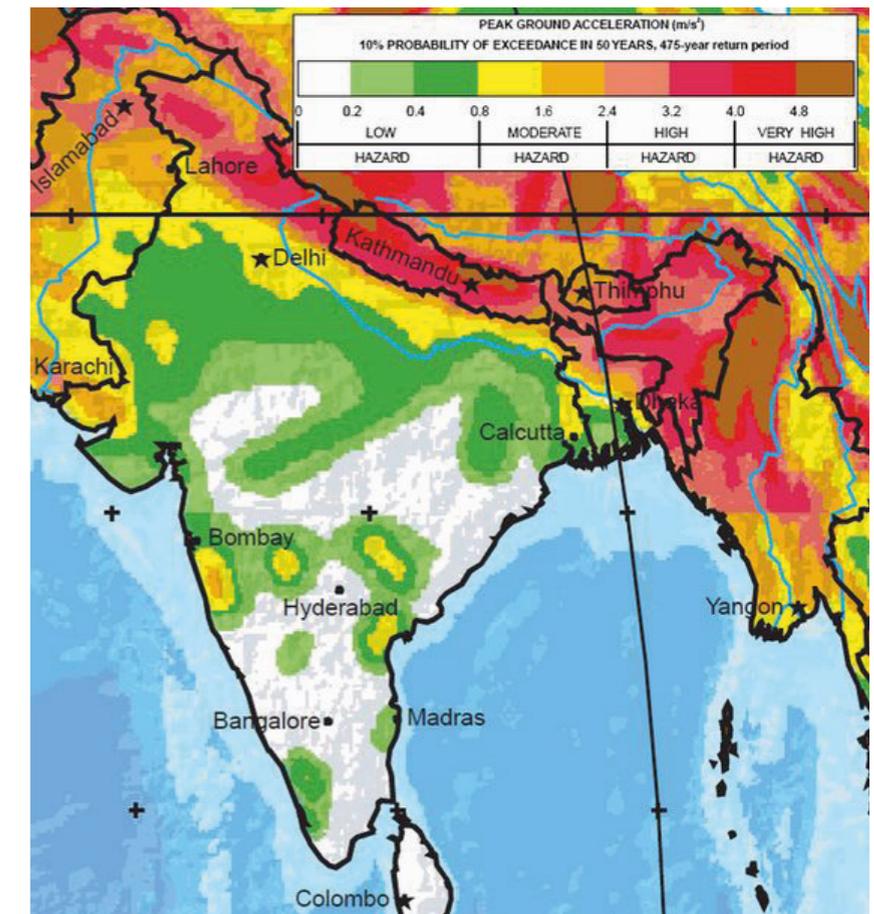


Fig. 12: Seismic Hazard map of Himalayan plate²¹

It is assumed that the collision of the continents results in a stress in the Himalayan region put the country either in Zone IV or V seismic risk. According to the classification of Indian Standards, Zone V and Zone IV cover the areas with the highest risks zone that suffers earthquakes of intensity from VIII to IX or greater MSK shakings.²² Consequently, these recent seismic events show a high probability of other strong earthquakes in the Himalayan region.

Seismic Hazard zonation of Bhutan

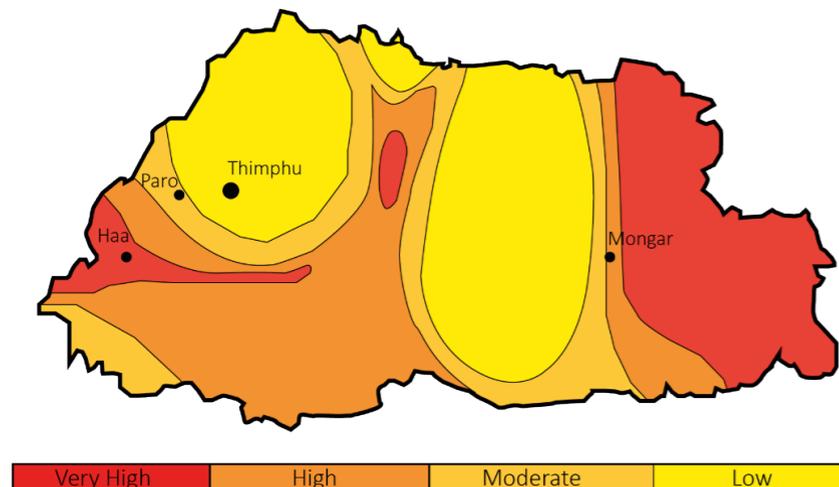


Fig.13: Seismic hazard map of Bhutan (Source SAARC Disaster Database)

Although we actually couldn't predict when it is time for future earthquakes, there is no doubt that great earthquakes ($M \geq 8$) will happen along the front of the Himalaya which may produce large scale damage in the surrounding areas.²³ Obviously, humans will never be capable to avoid completely the occurrences of these natural events but try to provide better and safer measures through prevention and citizen information on the risks involved in a seismic event.

Due to its geographical position, Bhutan, together with India, Pakistan and Nepal, which are located along the boundary between the Indian and the Eurasian tectonic plates, is considered one of most seismically active zones in the world. This is a vulnerable area predisposed to a range of natural disasters not only in regard for earthquakes, but also flood-

ing, windstorms, forest fires and landslides that in the past have caused significant loss and damages to lives, properties and public infrastructures.

The region of interest is one of the most seismic and affected in the area, one of the most recent earthquake to occur in this zone is Gorkha earthquake in central Nepal, with magnitude M7.8 in 2015 which causes 8,800 lives and damages in the whole the country, while in the recent decades, occurred Kashmir earthquake in 2005 of magnitude M7.6 with 90,000 deaths in the region.

Bhutan, on the other hand, has not experienced any major earthquake exceeding magnitude M7 during the 20th century. The last major earthquakes close to Bhutan were Shillong earthquake measuring M8.3 on year 1897, that occurred in Assam region of India close to the southern part of Bhutan. An earthquake of magnitude M6.1 occurred on September 2009 with eastern Bhutan as its epicentre, furthermore, in September 2011, India-Sikkim earthquake of magnitude M6.9 caused important damages in the district of Haa and Paro, the western part of Bhutan.²⁴

Even though the Kingdom of Bhutan has faced several and strong natural hazards, it is the human irrational intervention that put the country into further disaster risks; first of all, it has to be considered the complexity to have good construction techniques and the lack of adequate building laws that put limits and awareness to constructors; then the problem with the rapid urbanization that the biggest cities have seen recently and the consequent need to have rapid spaces for people. The environmental degradation that derived from the

23. Dr. Harihar Paudyal and Ananta Panthi, Seismic Vulnerability in the Himalayan Region, Seismic hazard in Asia, January 2010

24. <http://www.satreps-bhutan.jp>

urban growth and the poor consciousness of disaster risk of people, together with the limited availability of qualitative land for construction in mountainous regions of the scattered villages increase the hazard have played an important role in increasing the power of natural hazard.²⁵

Bhutan has a strong tradition of vernacular houses, made of stone, rammed earth and timber; however, in the last decades safety regarding traditional constructions has suffered due to the loss of knowledge on traditional construction practices and the lack of adequate masonry skills, particularly in the rural areas. In fact, the past two earthquake events caused extensive damages to rural homes all over Bhutan demonstrating high vulnerability of traditional buildings to earthquakes and other natural hazards, as well as the lack of adequate disaster risk reduction politics has revealed how much the Bhutanese constructions are susceptible both public and private properties.

In addition, insufficient technical knowledge among engineers, architects and other building artisans on disaster-resistant construction technologies also increases vulnerability of buildings considering also that they have the role of monitoring the process and checking the quality of construction and materials.

This effect is also an implication of the stream of urbanization which Bhutan is facing in the last few decades; this growth has been unplanned and chaotic, so that the increasing population, densities and built structure have extended the exposition to hazards in urban centres like Thimphu and Phuentsholing and other emerging towns. The lack of emer-

25. Department of Risk Management, MoHCA, RGoB, Bhutan Disaster Risk Management Status Review, http://www.ddm.gov.bt/download/Bhutan_DRM_Status_Review.pdf

gency facilities as well as the fragile road network and transportation system is also putting pressure on the surrounding environment due to the inappropriate infrastructure planning and construction, such as the development of roads which required cutting and mining the fragile mountain sides causing landslides and floods.

This rapid development lead to an increasing exposition to higher vulnerability resulting in irrecoverable losses during natural disasters which can either be attributed to the lack of land use planning or a hazard zonation. On the other hand, the fact that a great part of the population is still living in rural villages and are in socio-economic disadvantages, living in unsafe and hazardous areas such as steep slopes or flood-prone riverbanks, expose them to a high rate of risk that may inflict suffering and damage greater than what might occur when living in the city.²⁶

26. Department of Risk Management, MoHCA, RGoB, Bhutan Disaster Risks Management Status Review

2.3 Recent earthquakes disasters

In the past Bhutan has experienced many times strong earthquakes that strove the population, although not in the Kingdom itself, like in 1897 during an earthquake with the epicentre in Indian border which affected the closer Dzongs. Even if Bhutan may not seem to suffer disasters on large scale, seasonal hazards during monsoons and other frequent events are affecting the life of people and the development growth that has been gained.²⁷ The last major disasters are the 2009 earthquake and the following in 2011.

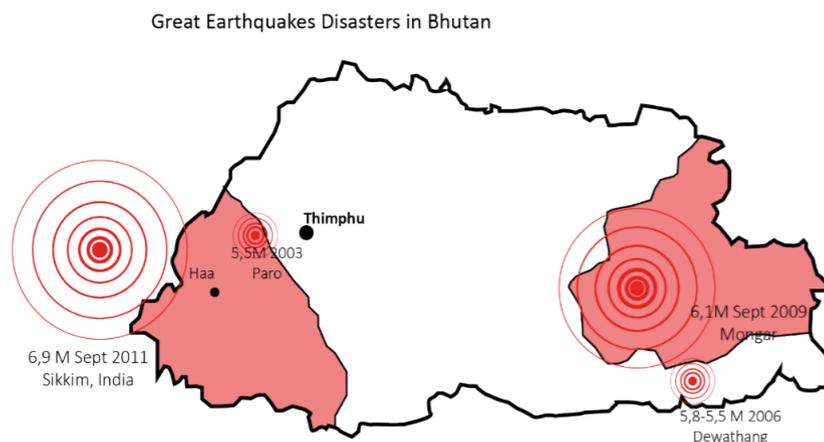


Fig. 14: Lasts earthquakes affecting Bhutan (source Disaster Risk Management)

The earthquake of 6.1 magnitude that hit the east part of Bhutan in 2009, with its epicenter in Narang, Mongar Dzongkha, has been the most damaging disaster that Bhutan has experienced so far. The earthquake lasted for 95 sec-

onds and had a shallow depth of 14 Km in and around the epicenter.²⁸ In the following days more than 100 aftershocks and two major earthquakes of 5.3 and 5.5 magnitude have been registered causing further damages to the houses and public buildings. Both vernacular architectures and public buildings of many districts closed to the Indian border, have been damaged and in some cases totally collapsed, most of them constructed with stone masonry and wood. Another disadvantage point was that the country wasn't prepared to face such extended injuries; engineers and architects hadn't any damage or safety assessments to proceed in the first reconstruction strategy.

According to RGoB data, 12 people died and 47 have been injured; 4,614 houses have been affected in the 12 dzongkhags around the epicentre, leaving more than 7000 people without any shelter. In addition to this, during the seismic event 91 schools, 25 health centres and hospitals, 281 monasteries, 485 chortens (stupas) and 7 Dzongs have been damaged.²⁹

The earthquake not only left population without shelter but also protracted fear among the community so that they wouldn't go back in their houses and asked for psychological support. The RGoB also asked for international support among UNICEF, OCHA and UNFPA for immediate intervention, as it was the first time that the country faced such a relevant disaster and wasn't prepared to give reliefs and goods such as emergency kits, tents and blankets.

In the damage assessment the RGoB has classified the structural damages into four categories: from beyond repairs to

27. Yeshey Lotay, Bhutan Disaster management, Country Report, Asian Disaster Reduction Center, 2015

28. Department of Disaster Management, MoHCA, National Recovery and Re-construction Plan "Building back better" 2009 Earthquake, 2009-2013

29. The Royal Government of Bhutan, the World Bank and the United Nations, Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction, October 2009

minor repair. It has been estimated that 446 houses were classified beyond repair and 1012 needed major repairs, 1749 and 1407 suffered from partial and minor repairs. The total costs of the damages estimated in shelter was about 1118.8 million of Nu (about 23.3 million\$). The total cost considering the damages caused to the cultural and religious heritage which needed restoration to save their inestimable value of paintings, crafts and history, reached almost the total of 2501 million of Nu (52 million\$).³⁰

In 2011, another great event of 6.9 magnitude hit the country, this time the western part in Nepalese-Sikkim border. In these districts vernacular architecture is made with rammed earth technologies and suffered heavy damages and collapses; even if the epicentre was 100km far away and the shakings were light, mostly all 20 Dzongkhags have suffered damages resulting in one death (due to landslide) and 14 injuries. In the aftermath of the 2011 earthquake, 345 houses were completely destroyed, 1660 suffered major damages, from substantial to heavy damages, and 5,960 suffered minor damages. In addition to this, private houses, religious and cultural heritage monuments including 13 Dzongs, 119 Choetens and 355 Lhakhangs were affected in different seriousness. Several government and about 47 public buildings suffered damages; then 117 school buildings including non-formal education centres were also affected, and 50 health facilities were included in the damage assessment.³¹

Rural houses, religious and cultural heritage building, as public buildings too have been involved into the major visible damages. In this case the damage classification has been divided into 3 categories: category 1 which refers to minor

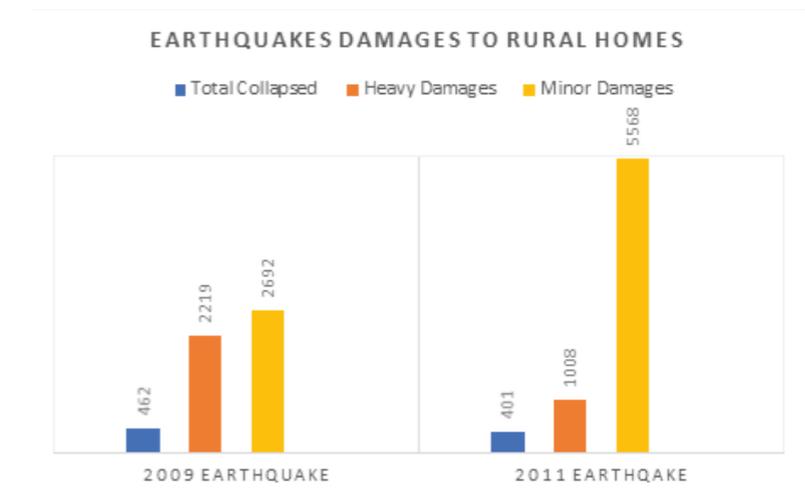
30. The Royal Government of Bhutan, the World Bank and the United Nations, Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction, October 2009

31. The Royal Government of Bhutan, the World Bank and the United Nations, Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction, 2011 earthquake

32. The Royal Government of Bhutan, the World Bank and the United Nations, Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction, 2011 earthquake

damage and category 2 about major damages, and category 3 which consider total collapsed buildings and beyond repair. This estimation provides the 100% recover of costs for category 3 (total collapse), 30% and 7.5% for category 2 and 1 respectively.

Most of the houses were placed in category 2 and 1, while just 345 of them in category 3; the total costs estimated for repairs was about 774 million Nu (15.8 million \$). Religious and cultural heritage were damaged for 340.91 million Nu, while public buildings and educational institutions and health facilities estimated a cost of 77.4 million of Nu. The total cost estimated is 1197.63 million Nu, about 24.46 million dollars.³²



The earthquake had a great impact on ordinary life of people, especially those living in rural areas which lived with agricultural livelihood; damages have been affected to storage facilities and irrigation channels too. Government disposed psycho-social helps to the population, especially children in the schools and monks.

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Chapter three: Disaster Risk Management Policy

3.1 Bhutan legislations on earthquakes

The political system of Bhutan is born recently, when the Monarchy in 2008 has been transformed into a Democratic Constitution Monarchy and a written Constitution of 35 articles has been set. The power, which was figured out by the King Druk Gyalpo one time, now has been separated in the Executive, the Legislative and the Judiciary and no encroachment of each other's powers is permissible.

Power and authority are decentralized and given to elected Local Governments to facilitate the direct participation of the people in the development and management of their own social, economic and environmental well-being. Those are divided into Dzongkhag, Gewog and Thromde, which are respectively the primary, second and third level of administrative subdivisions of the Kingdom. Their objective is to ensure that local interests are considered in the national field of the Government by introducing a forum for public consideration and discussion on actual issues affecting the local territory.

The Royal Government of Bhutan has 10 ministries which work in bringing the goal of Gross National Happiness closer to the real needs. Each Ministries are usually furthermore subdivided into departments, whose have the function of coordinating better on all issues between the decentralized

administrations and the central government, providing consulting services and create a supportive communication in various sectors, especially those departments working on the preservation of culture and disaster risk management.

The earthquakes that affected the State of Bhutan in 2009 and 2011, represent the turning point for the development of an emergency management plan, called the Disaster Management Act (2013). At national level it has born at the same time, the National Authority for the Disaster Management, composed of the highest decision-makers of the Government, responsible for the approval of a national plan for the reduction of vulnerability and risks deriving from natural catastrophic events. In the same way, the Department of Disaster Management is the right arm of this organ, with the task of helping it to develop emergency response plans, which is a delineation of key points to inform and educate the population in case of these events.

At the local level, on the other hand, a body that collaborates with these government figures has been set up, called the Dzongkhag Disaster Management Committee and it is also present till the municipal administrative subdivisions of the Gewog. Their function with regard to DM Act is to monitor at local level the risks that could turn into emergency disasters; on this basis are studied the prevention and mitigation lines through zoning maps, regularly run simulations, draw up communication reports for the DDM and NDMA and finally inform the population on the expected risk, on the structural capacity of their homes and on the sensitivity and preparation for the management of natural hazards.³³

33. Yeshey Lotay, Asian Disaster Reduction Center, Bhutan Disaster Management, February 2015

3.2 National Recovery and Reconstruction plan

Despite the lack of experience and preparation to deal with major emergency, such as the first earthquake that devastated the Eastern part of the country in September 2009, leading to destruction of many buildings and even 12 deaths, and the second in western Bhutan, the Royal Government launched a plan to give a quick response to all the families affected by the earthquake for the reconstruction of buildings. This is how the National Recovery and Reconstruction Plan was born, with the aim of “Building Back Better” and a more careful and secure reconstruction.

As an immediate response of the King’s help, those affected, injured or lost family members were rewarded with free assistance. A technical team then produced a report dividing the damaged buildings into a classification: from those totally collapsed that could not be repaired to minor damage repairs; in this way the Corporation of the Real Insurance of the State could compensate all the affected families who were enrolled in the Rural Housing Insurance. Important first help has been promoted also by the United Nations, both with emergency kits and tents, both to facilitate reconstruction and return to normality. Thanks also to the help of external bodies, the plan has been able to provide a fund of about 400 million NUS³⁴ for the management of disastrous events such as the flooding of 2009 and the 2009-2011 earthquakes.³⁴

34. Department of Disaster Management, MoHCA, National Recovery and Re-construction Plan “BBB”, implementation period 2009-2013

The Joint Rapid Assessment team (RGoB/World Bank/UN) has carried out a project with three major aims:

1. give support in restoration of social and community services
2. give support to return to rural livelihoods
3. re-build and recover damaged constructions

The priority of the government expressed in this plan was to bring the country back to social life by reconstructing rural homes, and to restore water supply and sanitation facilities, as almost 5,000 homes have suffered irreparable, large or minor damage leaving most of citizens without a secure home to live in; the rural population affected in the event are the poorest section of the Bhutanese population with very less or no capacities to rebuild their homes and their lives. To support these families living in rural areas, the government has express his help furnishing materials for an easy reconstruction such as timber and CGI sheets.

Later, the reconstruction of schools and public health buildings was carried out, the restoration of sacred or cultural and administrative buildings that had generally suffered less damage. The greatest concern during the reconstruction of rural buildings, was to ensure a design and construction techniques suitable for seismic resistance and that would ensure safety even in future earthquakes. Other State intervention measures in this view, have been the education of about 350 constructors and carpenters in rural areas to use seismic construction techniques, focused on the “Building Back Bet-

ter” aspects and prevent catastrophic results of risky events in the future. Moreover, the rapid supply of large quantities of materials for the houses reconstruction has been carried out, as the affected population, mostly very poor, lived in improvised tents and had to complete the reconstruction before the arrival of the monsoon rains.

Consequently, the National Recovery and Reconstruction Plan has been included as an important aspect in the 10th Five Years Plan, with the aim of continuing to carry out preventive measures and also to guarantee a financial fund in the case of priority reconstructions after catastrophic events.³⁵ The plan objectives are firstly to understand the possible risks and to develop wide range hazard charts engaging technical experts, while at the same time improve the information tools. Then, to strengthen disaster risk governance through all the coordinating sectors till the Dzongkhag Disaster Management Offices and consequently, to invest in resilient infrastructures as the most vulnerable sectors such as road and bridge infrastructure, and resilient constructions needed to advance new technical standards laws regarding disaster preventions and climate change considerations, that had been carried out in the 11th “5 Years Plan”, and probably will be continued in the 12th one.³⁶

In this focus, the government started to put efforts in an earthquake safety plan, evaluating the seismic hazard assessments, giving efforts on earthquake resistant technologies and educating citizens to be ready for the next seismic event. As consequence of the government participation, Bhutan received substantial help from international donors, such as Geohazards International began to support the Department

of Disaster Management and the Department of Engineering Services through a series of intervention aimed to provide a complete assessment from previous to post earthquake losses.

35. Department of Disaster Management, MoHCA, National Recovery and Re-construction Plan “BBB”, implementation period 2009-2013

36. Department of Disaster Management, MoHCA, National Disaster Risk Management Strategy “Safe, Resilient and Happy Bhutan”

3.3 Construction and planning regulations

The Bhutan Building Rules elaborated in 2002 from the Department of Urban Development and Housing with the purpose of regulating those aspects of construction and urban planning, and in particular, facilitating and encourage builders and all professionals figures to produce a project which pay attention to current regulations and to follow safe construction practices.³⁷ Furthermore, the document clarifies and promotes some standard design principals concerning the preservation of the traditional Bhutanese architecture. First of all, the document lists a series of definitions that explain in detail all the aspects mentioned in the rest of it. As a common duty present in any State nowadays, the document expresses the necessary procedure to obtain a building permit, its validity and a list of aspects for urban planning standards. In detail, the minimum requirements for spaces and access are described, both at the master-plan level and at the architectural one. Regarding the design and the structural analysis though, the state of Bhutan refers to the Indian codes and standards, which, going to the detriment of traditional Bhutanese architectures, concern with reinforced concrete and steel architectures. Finally, the requirements for the installation of the electrical, water supply and sanitary control system are described.

The Bhutanese Government realized that the environment and the natural landscape of the state represent an important fulcrum that must be preserved; with the introduction of mod-

37. Department of Urban Development & Housing, Ministry of Communications, "Bhutan building Rules 2002", 2002

38. Department of Human Settlement, Ministry of Works and Human Settlement, "Rural Construction Rules 2013", Thimphu, 2013

39. It refers to Bhutan Building Rules as cited before

ern architecture, new methods and construction materials, especially in the larger cities, headed to the loss of this traditional value together with the vernacular architecture originally carried on by artisans and craft masters. As regards the situation in rural areas, they faced with an aggravation of this problem due to the lack of regulations and guidelines proposed by the local government.

From this perspective, in 2013 the Government together with the Ministry of Works and Human Settlement edited the act "Bhutan Rural Construction Rules" with the aim of promoting the construction of safe and functional housing, improving the living standards and the quality of the inhabitants of rural areas, always respecting the environment and the natural landscape.³⁸ This document objective is to be a complement of the BB Rules previously published with specifications for the rural settlements.

As in the first document on the construction of the BB Rules³⁹, here are listed the fundamental definitions and requisites in terms of building permits, land use, planning and construction; in particular, the latter with reference to site excavations, distance requirements, dimensions and promotion of traditional architecture. At the end, a section on penalties is inserted for unauthorized constructions, and it is made reference to the power of the Gewog administration as a controller and coordinator organ on these matters.

Last year, the 8th conference of architects, engineers and planners took place; the purpose of this meeting was to develop a regulation directory that could be used to replace the Bhutan Building Rules and Rural Construction Rules actually

in force and which should be extended to the entire State.⁴⁰ The objectives discussed are those to reach a level of completion that ensures safe and accessible constructions also in prevision of possible future earthquakes and obtaining a national Standard Code for constructions. Moreover, territorial planning acts have been discussed, which will have to increase the current land pooling law and explain all the steps to take for a site plot planning, before obtaining the building permit. The Land Pooling Regulation should therefore regulate the programs for a coherent territorial development with the possibilities of the country itself and define the budget necessary for the construction of infrastructures. In the same way, it has been described the path to follow before the construction process between the application for the building permit (architectural, technical drawings, structural and installation plants are requested) and the effective issue of the Occupancy Certificate. An important part of this document concerns the regulation of buildings built in rural areas; it is underlined the need to be supervised by a local artisan expert in vernacular constructions and the promotion of the same, while the use of reinforced concrete in traditional settlements should not be allowed.

A Building Code should be then drawn up, with the aim of attaching to the Building Regulation 2017, specifications in sizing, installation requirements and fire safety.

Despite the fact that Bhutan is a state that strives to keep CO² levels low in the air, they adopt not only a “carbon neutral” system but also an absorbing filter for global pollution; since the country is mostly covered by forests and National parks, it absorbs more CO² of the one it emits annually.

40. Ministry of Works and Human Settlements, Enhancing Sustainability of Infrastructure Conference, Building and Land Pooling Regulations, June 2017

Obviously, the climate change is a growing concern even for this State, despite the measures adopted so far for a “zero carbon footprint”. The Himalayan glaciers are melting causing flash floods, long periods of drought alternating with increasingly violent monsoon seasons. Even if its responsibilities regarding global warming are minimal, the Government has promoted new regulations also in the field of buildings, to protect the fragile environment.

The Bhutan Building Energy Efficiency Code, in this sense, promotes guidelines for the construction of energetically efficient buildings; with particular regard to the external envelopes of buildings (insulation materials, transparent closing systems and claddings) that possess mechanical HVAC heating and ventilation systems. In addition, are described requirements for energy saving, lighting and production of domestic hot water with solar panels. This code has been elaborated firstly from the Pwc commission in relation to India with the ASHRAE supervision and successively modeled to Bhutan climate needs.

The Bhutan Green Building Guidelines instead, have been developed with aim of giving simple instruction to people on how become responsible about energy of their homes and the natural resources.⁴¹ As the guidelines are not mandatory, they represent a valid source of information and recommendations both for professional figures and owners on sustainable planning and design of buildings, with specific considerations on the climate, orientation, materials and their LCA, indoor air quality and project management.

41. Ministry of Works and Human Settlements, Department of Engineering Services, Bhutan Green Building Guidelines draft no. 3, 2013

3.4 Need of a construction rammed earth code

It is good to remember that, at present day, the Government does not provide codes or rules of intervention for the preservation of existing vernacular architectures; it is also contradictory that the Government promotes a policy aimed at the construction of new buildings in respect and compliance of the Bhutanese vernacular architecture.

In particular, there are no studies and codes useful to give a broad spectrum of guidelines for the construction of building in raw earth. Even if there are plenty of disaster management policies nowadays, the country still lacking a code for non-engineered constructions of rural homes in rammed earth; these are usually built by the community of the village and do not follow earthquake resistant technologies as are the consequent reproduction of what has been handed down from indigenous knowledge till now. There is also the lack of consolidation and conservation programs of traditional buildings that would help in reinforcing structural features of rural buildings before hazardous events; this is also due to the need of trained man force, masons and carpenters in the whole country, that would help in build safer buildings.

On the contrary, the Ministry of Works and Human Settlements has proposed a document entitled “Guidelines on proper construction practices for non-engineered Buildings-Stone Masonry”, prepared in agreement of the Standards and quality control authority with the financial assistance

from UNDP. After the earthquake of 2009, the government took more seriously the seismic risk affecting the state of Bhutan, also as a consequence of the huge damage caused by this event to the houses in rural areas and to the vulnerability to which it is continuously exposed. For this reason, this document, aims to present simple guidelines to improve the resistance of stone buildings to seismic events that could be followed in the construction with these types of technology, even if it is highly recommended to consult always to professional experts.⁴²

First of all, at the decision making level, there is a need to understand the level of risk that is exposed the country, underline the factors that could lead to such disasters as the climate change or irresponsibility of community, as well as the rapidity in taking actions after these striking events; at a local government level there is a need to understand the importance of being prepared to face such disasters and giving rapid responses to citizens, while at the community levels, both urban and rural, there is a need to aware and instruct people to take actions before these events occur. For this reason, it still a need to revisit the Disaster Management Plan prioritizing and putting attention to buildings that has to be resistant during earthquakes, such as health centres, schools, public and sacred buildings that could hosts a great number of people and so increase the vulnerability.⁴³ Safety of heritage buildings and monuments has great importance too, as the loss of such heritage structures means losing buildings that are irreplaceable due to their unique and high cultural value.

42. Ministry of Works and human settlement, standard control and quality authority, Guideline on proper construction practices for non-engineered buildings- stone masonry.

43. Department of Disaster Management, Ministry Of Home And Cultural Affairs, Disaster Risk Management Status Review

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Chapter four: Traditional Construction with Rammed-earth

4.1 Earth as a building construction material

The architectures in raw earth together with the use of wood and stone are considered the first materials in the history of man that marked the end of the culture of nomadism to that of the sedentary society of farmers where they moved from building shelters to fixed houses in a certain place. There are traces of buildings along the coasts of the Russian empire, the current Turkey, while in Europe the oldest traces date back to about 6000 years ago on the Aegean Sea with constructions in raw earth and tufa. In reality, examples of these buildings can be found in all continents, from Europe to the Far East, to Africa, but also to Australia and the Americas; it is difficult to understand the true origins of this technology because it is a material that easily degrades and if not maintained, it risks being abandoned and destroyed by nature itself. It is easy to understand that the earth as a building material has been used by many populations all over the planet because of its easy to find and use; the raw earth thus represents a very ancient construction method which however today is losing importance especially in developed countries as it is replaced with reinforced concrete and steel constructions or faster construction materials. In Europe and especially in Italy, due to the constructive mainly anti-seismic policies, it is not possible to build anymore but there are still

examples throughout the territory, these are buildings built during the 900 that are preserved until today.

When we talk about constructions of earth we always think of fragile, poor, in some way temporary buildings, built due to the lack of nobler and lasting resources. In fact, the lack of more durable materials such as wood and stone has been at the origin of the development of earth constructions. When the use of the land was not only a substitute to other materials, but gave rise to a solid constructive tradition, developing specific techniques able to exploit the qualities of the earth, architectures of great value are born, which have nothing to envy to the great architectures made with other materials more "enduring". Examples of earth constructions are still an evidence in various countries, including the Egyptian fortresses of Urinati and Wadi Halfa, the Inca fortress of Paramonga in Peru, the Mosques of Mali, the Persian synagogues, the Great Wall of China, the Tibetan monasteries, the ancient scale structures of astronomical observatories in Muslim India and the great city of Bam. These architectures stand to illustrate the quality of earth buildings that have resisted through millennia, and which assume a considerable technical evolution of construction systems.

From recent researches, between 30% and 50% of the population still living today in earthen buildings, however, it has to be considered that of this percentage more than half of the population comes from developing countries while only 20% live in housing in earth in urban areas.⁴⁴

44. Marcial Blondet, Gladys Villa M., Svetlana Brzev, Rubinos, Earthquake Resistant Construction of Adobe Buildings, EERI/IAEE, World Housing Encyclopedia 2011

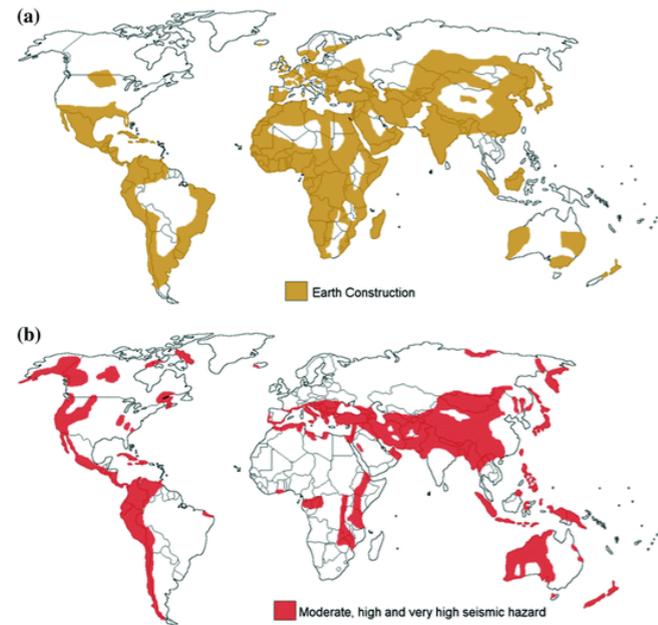


Fig. 1.5: Earth construction in the world related to the seismic hazard areas⁴⁵

Its use has been spread to all continents, adapting to the most different climates, to different resources and to local economies, except for rare cases the land to build is available everywhere.

In warm-arid areas with large temperature ranges, the common constructions are compact settlements with a terrace roof, with streets and alleys protected by the shadows brought by the buildings. In temperate areas, on the other hand, there are volumes of isolated buildings covered with protruding roofs able to protect the walls from the pouring rain.

The earth has been in use for thousands of years as a building material as it is extremely versatile: extracted below the

arable layer, sieved and worked with water, it becomes a good mixture easy to work with many different techniques. Drying, it solidifies, and subsequently undergoes a certain shrinkage that depends on the quantity and quality of clay contained in the earth and it comes similar in the aspect and consistency to soft rocks such as tufa or sandstone. All types of land, whatever its composition, have been used to build, with the addition of any possible additive to improve its performance: straw, animal dung, succulent plants, rice husk, hair of animals, blood and fine cement, wood, asphalt, lime and much more. But although it is possible to change the quality of the material with the addition of additives, the characteristics of the mixture depend mostly on the quality of the earth used. The land that gives the best performance if used to build is a rather clayey-sandy land, which usually collects along the path of the waterways; a “dirty” and silty land will never have good constructive characteristics, necessary to guarantee durability to the manufactured articles.

Another important factor that helped in the spread of various techniques with raw earth, is the independence from markets and economic currency; therefore, it is easy for people living in developing countries to have access to it without the need of investing money and the costs remaining are those for other materials, for the carpentry and the labor force. This way of building becomes a way for guaranteeing housing for the population of poor countries, as in our rich countries it represents the choice of living with an ecological footprint, becoming the support for development, social know-how and a valid opportunity to respond to the basic needs.⁴⁶

45. Subhamoy Bhattacharya, Sanket Nayak, Sekhar Chandra Dutta, A Critical Review of Retrofitting Methods for Unreinforced Masonry Structures, International Journal of Disaster Risk Reduction, January 2013

46. Yves de Morsier, Our experience with rammed earth: A manual for rammed earth building, www.desertcreekhouse.com.au

4.2 Building Green with Earth

Building today with raw earth has many advantages: the economy, the low environmental impact and the healthiness of the environments are just some of the most obvious and more appreciable. The earth is a building material that, by virtue of its versatility, is able to put itself perfectly in balance with the environment: on one hand the earth lends itself to achievements accessible to anyone, from the simplest technological use to the most complex. Then it is a resource easily found in most of the geographical contexts and the variety of performances obtainable by the various techniques allows to reach comfort in different climatic contexts. It is a material that doesn't emit toxic gases or harmful fumes from compounds, it does not emit radiation or breathable powders, it gives comfort and healthy environment to the spaces.

It is considered also an eco-friendly material as considering the entire production and life cycle (LCA) it requires very low levels of embodied energy, low emission of pollutants and processing waste and finally in the disposal. The energy needed for raw earth in the entire production cycle is low, since heavy industrialization at the base of the production process is missing and the main materials used in the construction site come from the place of the project itself, encouraging a "0 km architecture". Finally, the earth can be totally recyclable unless it is stabilized with chemicals, if a building on earth is abandoned it will slowly return to its initial state.

4.3 Bhutan experience with rammed earth

The rammed earth construction method of Bhutan is considered to have its origin from the closed country of Tibet and the southern parts of the Himalayan kingdoms of Ladakh, Mustang,⁴⁷ differing from these just in the wooden pitched roofs used to protect the structure from the heavy rains of the monsoon season. This technique has been widely used for the construction of Dzong, Lhakhang and other historical buildings in Bhutan and still used today for the construction of private buildings. The traditional architecture of rural villages in Bhutan Kingdom has a different construction method based on climatic conditions and the availability of materials in each region. In the western part of the country the rammed-earth constructions represent a large part of the tradition, while in the eastern part the buildings are made of stone bearing masonry with the addition of mortar as a binder. It is said that generally earthen buildings develop in areas where it is not possible to find wooden elements, but in the case of Bhutan it was not this prerogative to push the population to make use of it, because wood is present in many forests both tropical in the south of the country both conifers towards Himalaya. The reason why buildings made of earth have become part of the vernacular construction technologies is the ease of execution and retrieval of the material itself; in fact, the earth is dug around the village where it is built and during the process of ramming it is often women who bring the work force differently from what would be

47. Jaquin Et All, A Chronological Description Of The Spatial Development Of Rammed Earth Techniques, Manuscript Resubmitted To The International Journal Of Architectural Heritage: Conservation, Analysis, And Restoration 2008

needed for wooden buildings with the demand of a large male specified labor force.⁴⁸

The rural house consists of stone foundations and the rammed earth wall is built on these; generally, the floors above ground are two or three, where the ground floor is normally used as a stable and warehouse and has a few small openings to the outside. The first and second floor, on the other hand, are living space and storages; the wooden roof is supported by beams on the walls, while the cover was made of stone slabs, which today has been replaced with a corrugated sheet. Rammed earth buildings are constructed thanks to the labor force of the villages and a master craftsman (Zow-pen) which has the role of conducting the construction on the site; Bhutan doesn't have good transportation ways, so it becomes hard to reach professional figures such as civil engineers or architects working in the capital, in this way the workforce is guaranteed locally from the villagers, especially farmers and women which sing traditional songs at the rhythm of ramming. The master craftsmen usually select the soil, prepare the shutters and set them up and give directions during the constructions; the carpenters prepare all the wooden elements of doors, windows and roofs.

The traditional rammed earth constructions established from the farmers are a sign that this unique technique is still alive in the culture of Bhutanese, it represents also a kind of collaborative society allowing the direct involvement of people, because it does not require a high specialization of labor and because the materials are easy to find and not refined by industrial processes.

48. Department of Culture, Ministry of Home and Cultural Affairs, RGoB, National Research Institute of Cultural properties Tokyo, Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan, 2015

4.4 Rural construction method

Earth for construction is usually selected from the Zow-pen or Pa-zop, who are the craftsmen or the chief in charge for the rammed earth construction; the more suitable material for Bhutanese buildings is dug near the area of construction.

From compressive strength tests it has been discovered that the reddish soil with small pebbles is the best to be used for ramming, on the contrary the yellow and sandy earth is less suitable.⁴⁹ The material is prepared one month before the construction, removing the big pebbles and vegetable parts, then if it is a good mixture it is left for a while on the site covered with a tarpaulin. The craftsmen are considered responsible for the choice of the quality of the material and it has the task of measuring the amount of water in the soil content through some field tests; for example, they use to prepare a compact mixture in the form of a ball between the hands to measure the amount of water to obtain the best composition. The ball is then thrown into the air and measured on the basis of the cracks on it at the impact with the ground; it is considered a good mix of earth if it breaks into a few pieces, otherwise if it crumbles into many small pieces or if it is only cracked on the surface the water content is respectively too little or too much. In this way it is possible to consider obtaining a mix suitable for earthen constructions and consequently based on the test result, various granularities are further mixed according to the need if too liquid or too compact. It has been also a frequent practice also to reuse the earth from

49. Department of Culture, Ministry of Home and Cultural Affairs, RGoB, National Research Institute of Cultural properties Tokyo, Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan, 2015

ruins of buildings which no longer are used or abandoned. A soil must be made up of different sizes of soil size so as to have the largest pieces to be interlocked together with the pieces of smaller particle size; everything must be presented as a dense mixture that must fill all the spaces and the larger holes.

Subsequently, the craftsman takes care of the preparation of the formworks which are mainly composed of shutter planks and horizontal panels that are joined with the others through the insertion of timber components in the bottom and the upper part to keep the formwork firm and to connect the blocks with the remaining masonry; these are called Ju-shings and Gu-shings and are blocked by vertical poles called raw. The whole of these parts constitutes a solid formwork where the premixed earth from the base of the construction site is then poured into; two or three bags of earth constitute a layer for a section, which represents one third of the total block, in correspondence with the horizontal parts. Generally, for each block it has to be beat 8-9 layers of earth (per section) until they reach a size of about 3.5 meters in length, 65 cm in height for a minimum of 50 cm in thickness.

Two or three people are employed for the ramming process for each section at the same time, it can be used more fine rammers called Hiw or plank called Sotee according to need and to the point to beat in the form-work. The beating process does not require the use of a great human force, in fact many women are involved in the job because it is simply necessary to use a rammer, lift it and slam it on the ground, which is slowly being compacted. In fact, during the process are singed specific songs for ramming and to give the

rhythm. When a layer is finished the surface becomes smooth and polished and reaches a sufficient hardness such as it is possible to continue the work. To do this, it takes about 30 minutes to an hour until a block of 8-9 layers of a total of 80 cm is obtained; when a block is completed the formwork is removed directly and moved to continue beating another block; the process thus turns out to be very slow although many people stand at the same time. It has been discovered that some techniques to improve the resistance of the walls are taken into account, depending on the master craftsman who supervise the construction as all of them have a different method to face it. In some cases, the walls are made thinner while going up in the storeys, some other (but mostly for monasteries) presents tapered walls; as a structural reinforcement it is used sometimes timber pieces, such as logs or bamboo canes, in the centre of block or towards the base.⁵⁰ All these methods represent a valid technology, even if they need to be tested and assured that are executed in the correct way, and for some aspects means that all those craftsmen have a particular awareness on which are the most fragile parts of the building and the brittle material itself.

Particular consideration must be placed on the uniqueness of this constructive method, not only in terms of technology, but above all in terms of the character of social collaboration that implicate within the rural and farming communities of the most remote valleys of the western Bhutan.

50. Department of Culture, Ministry of Home and Cultural Affairs, RGoB, National Research Institute of Cultural properties Tokyo, Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan, 2015

4.5 General considerations on seismic risk

Since 90 percent of the world population still living in areas under great seismic risk and that most of the deaths during these events are due to the collapse of their buildings, the research on safety of non-engineered buildings constructed in traditional materials such as wood, stone and earth, is now emphasized. The term “non-engineered” refers to buildings that are constructed in the traditional way especially without the supported project of any qualified architects or engineers, or rather an oral transmitted code of intervention derived from the observation of buildings effects under past earthquake stress.⁵¹

Actually, it is not always possible to choose to build with a greater level of safety, especially when socio-economic factors act as a limit for the selection and assessment of safe constructions. First of all, we must consider the fact that most of the earthen buildings are located in developing countries and therefore the limited budget of the families is a limit for the choice and importation of more expensive materials such as the cement, steel in some cases wood. Another point of view to consider is the fact that earthquakes often in these areas are not so frequent (even if they present a high intensity) thus leading to the loss or non-improvement of resistant earthquake construction techniques. So far it is difficult to understand what the means are to reduce the effects of earthquakes on the structure, but it is our duty to find a design that can reduce the risk and minimize the effects of earthquake

51. A.S. Arya, T. Boen, Y. Ishiyama, Guidelines for earthquake resistant non-engineered construction, IAEE-UNESCO-IISEE, February 2012

shocks. In some cases not only the earthquake itself is a danger to buildings and primarily to people because they are often generated by the breaking of large faults in the ground, fires due to short circuits and tsunami, as happened in Japan in 2011 in Indonesia in 2004 where about 200,000 people died; breakage of soil faults are very common in the case of major seismic events and create breaks along faults that can occur in cracks of a few cm or meters causing landslides and landslides buildings built nearby. Generally, the performance of a building during an earthquake reveals important characteristics on the strength and ductility of the materials and technologies involved. For example, the geological conditions of the land where the house is built, and the technologies and design of the house must be considered, as in this case the quality of the materials used and the recipe for a good composition are very important for the raw earth.

In this way it is easier to control the damage caused not by the force of the earthquake but mainly by the possible human errors; the earthquake presents a huge difficulty in defining the possible shakings at each event and the effects of these on the structure. After numerous research and evidence from the past earthquakes that have destroyed a huge amount of buildings in raw earth, it is possible to risk giving some technological solution that guarantees a more secure feedback of the structure.

4.6 Introductory concepts for earthquake resistant buildings

When designing a new building in an area that is affected to strong earthquakes, some principles have to be taken in consideration, in order to guarantee the integrity of a building even under stress motion.

First of all, the site composition of soil can determine significantly the final damages of the building; usually a soil that is solid and stable perform better to the ground motion because it wouldn't crumble in pieces leaving the building footings without support. Then, the shape of the building and the number of openings in the walls may affect its failure or cracks: regularity and symmetry in the shape, few and small openings in the walls are considerable aspects to attest its firmness. From a mechanical point of view, asymmetry in the shape and elevation give possibility of creating torsions moments in the block; to solve this fact, it is suggested to separate large buildings in simple square-rectangular shapes with a separation of the blocks of some centimeters.

Moreover, the choice of the types of foundations have to present regularity, for example the employment of different piles and footings may alter the structural response during earthquakes. In the same way, it is relevant not to change the stiffness distribution of the structural body from one floor to another; columns and load systems have to be continuous till rooftop.⁵² From the mechanical point of view, it is possible

52. Bollini Gaia, Terra battuta. Tecnica costruttiva e recupero. Linee guida per la procedura di intervento, EdicomEdizioni, 2013

to assert that the best thing would be using a material that is ductile, and so it is able to deform under significant amounts of tensile stresses before collapsing. It is quite easy to understand that concrete blocks, adobe, fired bricks and earthen structures are instead brittle materials which quickly break under stress.⁵³ For this reason, addition of steel, bamboo, wood or fibers reinforcements can add a ductile property to the structure with those materials. All the structural parts, such as foundations, walls and roof should be bonded together in order to react as a unique system during earthquakes and dissipate the energy without separating.

Last but not least, as it has been said before, the construction quality represents a substantial aspect that sometimes mainly affect the building performance to the ground motions, and it includes both the quality of materials, the human skills in the construction time and the maintenance during its life-cycle.

53. A.Arya, T. Boen, Y Ishiyama, Guidelines For Earthquake Resistant Non-Engineered Construction, IAEE, IISEE, UNESCO, February 2012

4.7 Learning from other countries experience

In some regions frequently exposed to seismic risk, specific techniques have been developed over the years to prevent damage related to earthquakes, especially in areas where buildings are built by the community and the owner. Due to a long exposure to seismic risk, local communities are forced to adapt their buildings to protect them from damages coming from the earthquakes. In fact, it has been seen in the past that many techniques, which are now considered traditional, were born as a result of the need to repair public buildings and private buildings. Thus, a strong local anti-seismic culture is born which has as its main purpose the preservation of local and vernacular heritage. The use of these innovative technologies and materials on the other hand has led to a globalization of construction systems and a loss of vernacular culture; in this sense, the enhancement of cultural heritage is very important as we have seen for the state of Bhutan.⁵⁴ There is a close correlation between the development of anti-seismic construction techniques and the frequency of earthquakes in one place, as it leads to the development of preventive techniques in accordance with the availability of materials and resources available in compliance with the construction tradition. However, it often happens that in some areas considered to be at high seismic risk, as in the case of the Kingdom of Bhutan, earthquakes are not so frequent as to allow the creation and modification of technologies in anticipation of new shocks; so it happens that the houses are rebuilt with the same technologies and are rather impoverished by the introduction of materials such as cement

54. Ortega, Vasconcelos, Rodrihues, Correia, Lourenço, Traditional Earthquake Rechniques For Vernacular Architecture And Local Seismic Cultures: A Litelature Review. Journal Of Cultural Heritage27, 2017

55. Randolph Lagenbach, Earthquake Resistant Traditional Construction Is Not An Oxymoron, International Conference On Disaster Management And Cultural Heritage "Living In Harmony With The Four Elements" December 2010

that doesn't lend itself to work with the rammed earth.

In evidence of what has been said so far, there are some innovative technologies that have developed post-earthquake according to the adaptability of the place and the availability of materials; technologies are mostly constructed of a wood and bamboo grid with an adobe brick fill, raw earth or stone. These technologies are effective in the case of the need for resistance to earthquakes that are relevant for their help in the dissipation of internal forces due to the earthquake and an increase in tensile strength. Major earthquakes such as those of 1755 in Lisbon or Calabria in the same century in 1783, saw the birth of innovative earthquake-resistant techniques called gaiola or Pombalino, or in the Italian case Casa Baraccata: this anti-seismic technology provides the replacement of a wooden frame with wooden joists very similar to a cage well bonded together where the filling is often in raw earth or in stone;⁵⁵ in this way it is possible to construct buildings with a maximum of five or six floors. Over the years many tests have been carried out in this regard, in both cases the ability of this wooden structure to dissipate energy from earthquake shocks has allowed buildings to maintain their structural integrity.

The earthquakes that struck Nicaragua and El Salvador respectively in 1971 and 1986 profoundly affected the stability of the buildings, revealing a basic structural lack; the technologies developed hereafter are called Taquezal or Bahareque, they are pocket systems as a variation of the wooden frame system very common in many countries of Central America. In these types the frame is made up of joists and poles that support the stone masonry of blocks of about 5 x

10 cm to have a final wall of 60 cm thick. The vertical wooden structure is positioned in the corners every 2 meters, while the horizontal partition forms pockets to be filled with small pebbles, Taquezal con Piedra, or Adobe bricks, Taquezal con barro de tierra.⁵⁶ The structure is then covered with a layer of mud plaster which is the major problem of this type of construction affected by the earthquake as it leads to an easy degradation of wooden structures due to the hot humid climate favours the attack of insects and termites.

In the case of the near Kashmir two technologies have been developed, the first defined Taqq which is constituted by a brick and stone supporting structure with wooden beams evident in the wall at each floor, used to tie the perimeter walls together with the floor acting as a diaphragm between one floor and the other. In the case of the earthquake, the structure moves sliding between the masonry and the beams, damping a high quantity of energy, following this wave movement rather than resisting the same forces. The other developed technique is called Dhajii Dewari and consists of a modular wooden grid with a fully integrated masonry filling, often in fired bricks or adobe. The grid has further diagonal subdivisions in the corners that allow greater ductility and dissipation because the division into panels causes the structure to act separately and not as a single block.

In Turkey, on the other hand, there is a structure called Himis, typical of the Greek Turkish area, consisting of a wooden supporting structure for the ground floor and a filler frame in the upper parts. The load-bearing stone filling structure of the first floor is often held together by horizontal wooden courses; unlike what is used in Kashmir, they are very thin tables

56. *ibidem*

and placed at an interval of one meter and overlapping in the corners by binding the layers of stones without interrupting the continuity of the masonry. This technology makes it possible to reinforce the structure because the cantilevered beams hold the structure underneath thanks to the weight of the masonry built above.⁵⁷

The primary objective, therefore, for the reduction of seismic risk is to protect the buildings and consequently the economic losses that it entails, and of course, to reach an adequate level of safety of the historical and vernacular heritage that puts the life of the population in danger. This type of intervention requires a series of different actions: on one hand, the improvement of technical knowledge by those who then develop the buildings, reducing vulnerability and exposure and mitigate the effects that may affect the building. By focusing on other aspects, it is therefore necessary to carry out a process of disseminating a culture of prevention in the same way as this manual propose, recognizing the other causes that could affect the damage and the collapse of the building in case of a seismic event.

57. *Ibidem*

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Chapter 5: Project

5.1 Risk mitigation for Bhutan

The recent earthquakes that hit Bhutan have once again brought to the attention of the government the need to find a system of conservation and reduction of seismic risk of public and private buildings. This problem was presented each time following the earthquakes of 2009 and 2011, especially when they influenced not only the loss of historical heritage but above all the huge rural one, sometimes causing the death of some human lives; for this reason, the absence of a code for the repair and construction of buildings in raw earth and masonry stone appears to be a limit for the safety and reduction of seismic risk.

Currently, the Satreps team is carrying out a research for the development of technologies that strengthen the existing structures and especially the new ones to cope with the loss of the Bhutanese cultural heritage, respect for and preservation of the arts and of culture. In Bhutan it has been noticed that the stone and raw earth bearing buildings and sometimes even the wooden ones are substituted totally or partially with buildings constructed of reinforced concrete, a structure that behave completely different, both from the point of view of appearance and respect of tradition, and from the point of view of the static knowledge of the structure itself. It thus hap-

pens that the seismic risk is increased due to the use of these structures that require in-depth knowledge.

5.2 Common mechanism of structural instability

Buildings built in raw earth with continuous and load-bearing walls have a structural performance comparable to a box; in general, the load-bearing walls have a primary role in the static equilibrium of the building because they support the loads of horizontal partitions such as floors or roof, which play an important role for the transmission of vertical loads and horizontal thrust on the external and internal walls. It has been also seen how the internal walls play a fundamental role in connecting the perimeter walls and helping to contrast the loads pushing towards outside and opening the static "box" system. If, for various reasons, this equilibrium fails, the building may undergo various mechanisms of structural or minor instability, which can be further linked to other causes of deterioration and lead to the collapse of the structure.

When a strong earthquake occurs, it is easy to think that the effects of tremors overlap with minor damage or structural defects which are already present in the load-bearing masonry, thus suffering greater damage that can jeopardize the integrity of the building and in the worst cases life of people. For this reason, it is very important to make an upstream assessment for the correct execution of the construction technologies and above all the connection of the structures that bring loads and pushes onto the perimeter walls system, as well as the control and maintenance. The raw earth structures are difficult from a mechanical point of view because,

due to the intrinsic characteristics of the material being fragile, they work better when stressed by compression, on the contrary they have a low tensile strength so it is important to consider it as a box block to which it is necessary to prevent the application of these functional shearing forces.⁵⁸ Another important aspect that needs to be assessed is the concentration of horizontal loads such as the floors and the roof that are not connected to the vertical partitions. In this way when they are not connected directly to the whole box, the forces are not distributed over the rest of the building and the walls become independent elements that are stressed by external forces. The breakages that lead to collapse can be classified into two types: in the first case it considers the global mechanisms that involve the structure and are connected to the static and the balance of all partitions, in the second case there are local mechanisms that present themselves as applied forces to the marginal part of the structure and although they can lead to a collapse of the wall box, intended as a single element, they act on the structure in a local way. We consider as forces acting on the global structure the in plan shear mechanism, which lead to cracking mechanism with x-shaped cracks in the low part stressed more by compression, due to a low quality of the box or the presence of discontinuity. In the case of overturning, the masonry becomes independent due to a locally applied thrust force and leads to the behavior for independent rigid elements which can not rely solely on their own strength to withstand external thrusts. In the event of an earthquake, the structure connected to this part collapses, bringing with it part of the essential structure that generated the mechanism; In fact, the lack of

58. Quiteria Angulo-Ibáñez,, Ángeles Mas-Tomás, Vicente Galvañ-Llopis, José Luis Sántolaria-Montesinos, Traditional braces of earth constructions, *Construction and Building Materials* 30 (2012) 389–399

connection with horizontal elements and between the wall to wall orthogonally leads to the end of mechanism generally involving most of the façade and therefore of the building structure. Other mechanisms to consider are the failure of the lintel of doors and windows, and manifests itself with a partial dislocation in-plane; it is mainly due to the inefficiency of the technology, such as the length of the lintel inserted too short or the lack of connection with the surrounding structure. Finally, significant are the beams inserted into the masonry or resting on the structure of the roofing slab, bringing shear forces that intensify the thrust effect and therefore expelling the support from its positioning causing serious damage of structural cracks and collapse of the part horizontal of the building. In this case, it is mainly the lack of connections between vertical horizontal elements, accompanied by the dislocation of the oscillations of the earthquake that lead to the loss of the building box function.

5.3 Natural and human factors of degradation

The phenomena of failure are usually ascribable to two different factors that often coexist, leading to specific damages or aggravating the situation over time. These refer to natural factors such as the erosive action of water, earthquakes and the natural environment that surrounds the house or more often to human factors of incorrect construction technologies or negligence and lack of maintenance of the same.

The earth structures work on compression, so that the incorrect management of the other forms of stress, such as shear and rotation forces, can lead to major disruptions, thus resulting to be one of the main causes of collapse in case of seismic events. Despite the masonry in raw earth, generally being stressed by other forms of deterioration related to the effect of water that cause the first degree of deterioration, the constructive errors (dating back to the time of realization or subsequent interventions) combine with these generating a very high damage potential.

The diseases that affect the construction on the ground are not so different from those of other materials, except for the fact that it has a greater sensitivity to water and humidity and its characteristic of being a fragile and brittle material in contact with water, which can bring to superficial or specific and severe degradation.

The main forms of deterioration deriving from the natural effects of water can be superficial erosion, the abrasion of the material following the action of rains and wind, the detach-

ment and loss due to the constant presence of humidity and dry wet cycles in the masonry which creates effects of surface delamination and bulging. Infiltrations from the roof or raising damp from the terrain as well as water ponding on the top wall are causes that bring to the reduction of mechanical resistance of the box system, visible due to the formation of vertical cracks. Stagnation of water on the ground is usually an indication of insufficient drainage with a consequent swelling of the material that generates the change of the state of the material, resulting in efflorescences and mold on the wall surface.

The natural environment with a strong presence of rivers and tall vegetation near the houses, such as the presence of farm animals on the ground floor of the houses themselves, are causes that can increase the vulnerability to the formation of damage and degradation. The vegetation too close to the masonry or even covering it with climbing plants tends to keep the surface wet thanks to the capillary rising from the roots of these as in the same case of tall trees that can be a further means of water infiltration through the basement. Further damages can be brought from birds nests or rodent holes where the surface has not been plastered and above all the presence of insects that can affect both the wall surface and the wooden partitions of the rabsel and the floor.

The country's vulnerability to strong earthquakes is the main reason why damages of rural houses are often taken into consideration, although the causes can not always be ascribed to the seismic effect on the structure but also to natural causes mentioned above and anthropic factors. The movements of the earthquake in relation to the building can not

be controlled and avoided, on the contrary the other types of causes, natural or human, must be taken into consideration to reduce the risk of damage in the case of earthquakes.

The in plan movements that are generated by thrusts in parallel to the masonry and out of the plane movements of the thrust of the horizontal structures lead to the formation of vertical cracks in the junction points, and diagonals cracks on the central wall. Sometimes the pushing forces of the seismic and compression movement generate overturning and detachment of the load-bearing walls with consequent collapses of the wall structure.

The anthropic factors of damage are found mainly in the structural elements and in the lack of technology that may be due primarily to design and construction errors of the building or the lack of maintenance of the same. In the first case it is therefore necessary to verify the causes that led to failure such as the lack of anchoring measures between orthogonal walls and especially in the case of expansions with the use of old walls, the lack of supports for the beams in the masonry that lead to increase the effect of seismic damage especially on the box structure. If these are present, it is necessary to verify that the technological systems carry out their proper function. It has also been noted that insufficient compaction of the earth mix in the formwork or the choice of a mixture not suitable for processing, such as the excess of clay which leads to shrinkage cracks or the opposite of a soil composed of too much aggregate, lead to greater stress on the part from the external erosive effects.

Finally we must mention the causes due to the lack of maintenance that show the criticality of the structure to the effects of water such as the lack of leaks repair of the structural nodes especially after heavy monsoons rains and the presence of stagnant water due to the lack of a drainage systems or waterproof materials that do not allow water to flow far into the ground. In the same way, the common use of avoiding to cover the masonry with a final protective layer and above all not to fill the holes left by the form-works lead to damage and deterioration that would be easily avoidable with small tricks and care of the home.

5.4 Damage assessment after 2011 earthquake

The 2011 earthquake that struck the western part of the country has caused extensive damages to traditional constructions located in the remote valleys. One again, bringing attention to the vulnerability of construction technologies in raw earth and the need to intervene with effective and easily implemented repair systems that can be carried out from the local population itself, since the traditional approach to community construction is still felt. The damages caused by the earthquake of 2011 are similar to those caused by the earthquake of 2009 to the stone buildings of the east of the country, having a similar structural scheme consisting of load-bearing masonry with wooden components. It has been seen that during the earthquakes these two types behave in a similar way if it were not for the difference in material composition and therefore in resistance to the stresses of the material, which determines the strength and stability of a masonry in raw earth. The solidity depends a lot on the composition of the earth mixture that is beaten and in large part also by the thrusts that are imposed by the beams and horizontal partitions.

From recent surveys of buildings collapsed and damaged during the earthquake it was found that in many buildings have been determining causes behind the construction industry as the poor quality of the material that make up the blocks, due to the incorrect compatibility of the ground during the beating, the quality of the earth and the amount of water used to form the dough. Following the earthquake, therefore,

it was observed that many buildings have similar cracks, in particular points of the building where seismic stress has highlighted previous vulnerabilities to the seismic event.⁵⁹

In this chapter are described major damages founded in rammed earth buildings after the evaluation of the seismic event:

External erosion of wall it is usually caused by natural weathering, such as wind and rain; as rural homes usually don't have an external plaster which finish and protect the wall (as happens in Dzongkha and Lhangkha) in addition to the absence of eaves and proper projecting roof wings, it is possible that the water splashing has removed the external layer of wall. Moreover, as the earth wall is highly hygroscopic, the process of water wet and drying may lead to shrinkage of the wall, leaving it brittle and soft, a weak point for further damages.

Delamination happens sometimes when part of the wall separates from the external layer, and it happens mostly when the compaction of the rammed earth wall is not strong enough as consequence of the difficulties in ramming the earth near the form work and the timber insertions. In addition to this, controversial climatic conditions such as humidity and monsoon rains, may bring to shrinkage and weaken the monolithic structure. As a consequence of infiltrations of water from the roof or the form work put-log holes and stagnation of water on the ground, it is possible to find efflorescences and mildews, which are recognizable as white and dark humid spots on the surface, and signify a constant presence of humidity in the wall.

Vertical cracks are seen in all the houses affected by the

59. Divison for Conservation Heritage Sites, Department of Culture, MoHCA, Damage Assessment of Rammed Earth Buildings, December 2011

earthquake, depending on the thickness of the crack in the wall can be determined how vulnerable is the damage. If vertical cracks are light they may affect only the surface, but if the cracks passed throughout the wall they may cause structural damage. In the case of water infiltrations such as water ponding on the top wall or capillary rising damp, when cracks occur they have the shape of vertical and linear breaks. Frequent cycles of freeze and thaw can further increase the effects of deterioration of the wall.

The natural environment sometimes can bring to degradation of the houses, involving the presence of rivers and high vegetation that bring humidity and raising damp to the footings, added to the natural soil moisture. Animals, insects and infesting vegetation on the wall work as a depletion of earth quality conditions, as they cause biological attacks and infiltrations.

When strong earthquakes occur, it has been seen that the natural ground shaking and excess of loads of the timber components in the walls react in cracks, buckling and collapses. Vertical cracks are seen in the top of the wall following the conjunctions of the blocks and eventually dividing them; this is because of the in-plane movements of the walls and the loads of the roof structure. In other cases, the tremors create cracks along the holes left by *ju-shings* and *gu-shings* (timber pieces inserted on the bottom and top of the rammed earth block to sustain the *parshings* (shutter) at the distance of 60-90cm) that have not been covered with plaster; as the wall works as a monolithic load bearing structure the long series of holes may weaken the stability of the wall, in the worst case the cracks lead to a collapse of the wall.

Corner cracks are one of the most common damages developed in the massive load bearing walls and usually the cracks develop throughout the thickness and the height of the wall. The crack develops because of the different direction of movement of in-plane and out-plane of the two walls, usually leaving the corner portion as a standing column. This has to be attributed also to the lack of strong bonding connection in the corner blocks, as the lack of overlapping blocks and bonding measures. As a consequence of strong stresses in this area and excess of horizontal loads, the corner wall may collapse.

The failure of the top wall is observed when large movement displacements occur as well as shear stress of the roof beams laying on it. In the same way, the crack occurred due to strong stress in the middle wall, probably because of the timber joists of the floors unbonded in the wall, may cause buckling. Those cracks are perceived as they present diagonal cracks in the position of wooden beams.

Some evident causes of technological inaccuracy are lintel and beams cracks. The first are common in the corners of openings because of shear stress and in the most cases are non-structural, unless they combine with vertical cracks; sometimes the cause is related due to unfulfillment of good construction techniques, such as the lintel should be inserted in the wall at least for 25 cm, and the openings position should be homogeneous and in the central part of the façade. Cracks in beams also develop especially when a wooden plank to support trusses and joists is missing. The cracks develop as different movement of the wooden components, which shake as a unique structure and so create shear stress on the bearing wall.

Structural slit and overturning of walls during the earthquake have been noticed in many houses, as portions of external wall collapsed revealing that horizontal connection of T shape walls was missing, so in many cases the rest of the external wall and the inner one was standing. The clear section of the wall shows that neither overlapping of blocks nor appropriate junction was existing, and because of out-plane movement, the wall split. It has been recorded that some houses were constructed with the use of old walls of previous building, with the aim of making them stronger or just saving labor. In the cases of collapse, it was mainly because of the lack of proper joints or overlapping system between the old and the new wall. Sometimes it has recorded that new walls were constructed with a different percentage of water in the earth mixture, resulting in a different strength support.

Obviously, negligence and low maintenance of the structure and the walls themselves, are the first possibility to have damages in the house. First of all, the fact that is a common practice to leave the façade without a final render and a covering plaster for formwork put-logs, wind and water erosion are great forms of attacks and infiltration. When leaks occur in the roof the rain is free to enter and infiltrate in the wooden structure and the top of the wall, bringing to deterioration of the wood (sometimes causing mildew, change of nominal section) and vertical cracks. The lack of good drainage systems and gutters for the rain are technologies that have to be taken in consideration while correcting the causes of damage and restoring the walls.

5.5 Photo report of damages ⁶⁰



Crack in the connection between old and new walls



Attempt in T-shape connections



Profound corner crack



Typical cracks due to uncorrect mix and shear forces

60. Pictures: Division for Conservation of Heritage Sites, Department of Culture, MoCHA, Study of typology of Bhutanese rammed-earth buildings



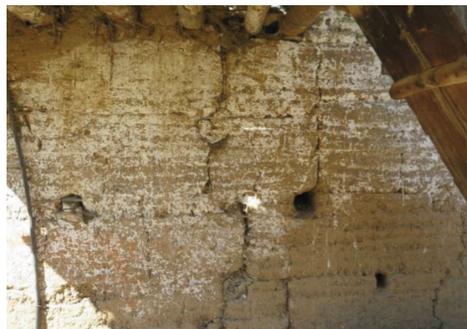
Wood beams deterioration because of biological attack



Deformation of timber joist



Cracks in the basement



Cracks following formwork putlogs holes



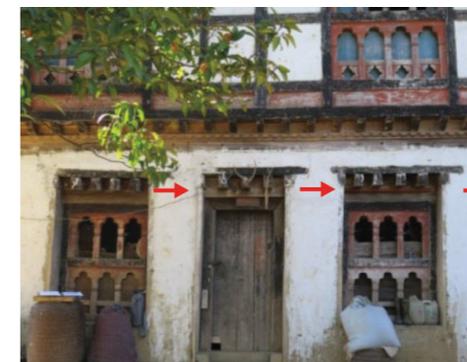
Cracks and surface erosion due to infiltrations



Cracks and surface erosion due to water ponding



Bending cracks over the lintel



Lintel displacement of doors and windows



Delamination of façade due to profound cracks and erosion



Insertion of new timber beams and cracks



Absence of connection in the corners



Mildew and bulging of façade

5.6 Possible interventions in restoring damages

In light of the causes of the damage found for the effects of instability and degradation, it is necessary to propose a brief description of the possible interventions to be implemented to repair the damage and restore the entire building to a good condition. It should not be taken for granted, however, that before taking on the steps of removal of the damages, the actual causes that are involved must be investigated by carefully lecture of the effects; defined this, it is possible to start to solve the damage manifested.

The possible interventions to be implemented will, therefore, reflect the five categories that have been identified, damage discovered due to the effects of water and the environment, the effects of the earthquake and the causes of negligence and incorrect technologies. In order to resolve the rising damp and the presence of infiltrations in the masonry, it is necessary to remove the causes that lead to this such as possible leaks in the roof, presence of vegetation, and stagnation of water, leading to a correct transpiration of the footings and outflow of rainwater. It is therefore necessary to find systems to remove or drain the water in case of infiltration from the ground, considering therefore to install drainage systems in the ground with the application of a slope necessary to remove the water and make it convey into a drainage system.

It is also appropriate to remove the infesting vegetation, and the presence of insects and animals that can deteriorate the surface with the use of biocides. It is advisable to install a gutter with attached pluvial pipe to convey the waters and remove them from the possible splash on the façade. Finally it is advisable to consider to intervene on the facade itself, going to eliminate the damaged parts

such as efflorescences, molds, dark spots and surface detachments. To restore the continuity of the wall, it is also necessary to close all the small cracks and the holes left by the removal of the form-works, and then finish with a layer of protective mortar and plaster on all the facades of the building.

As far as injuries and cracks are concerned, it is possible to intervene differently depending on the severity of the pathology presented, verifying whether it affects only the layer of plaster or more seriously the masonry. It often happens that there are multiple causes such as thermal expansions, insufficiency for concentrated loads, infiltrations, erosion, so it is advisable to check the type of lesion in its temporal evolution to understand if it is a sleeping adhesion or active; the techniques and types of materials to be worn in this type of interventions should be always compatible and similar with those on which one is going to act, therefore more or less fluid earth mortars according to the composition of the masonry in front of it.

For superficial injuries it is necessary to establish the continuity of the masonry through the injection of a binding mortar through the fissures and the protection of the surface with a lime-based finish. In other cases, involving the load-bearing and therefore structural masonry, it is possible to foresee the filling with a plastic mortar or a filling through the creation of cuts to allow the insertion of wooden ligatures. The use of stabilized Adobe bricks produced with the use of a press available on the market should also be evaluated; these bricks have a greater resistance capacity and chemical-physical characteristics more similar to clay masonry than the classic Adobe bricks, which have a higher water content.

Systems of reinforcement of the structure and consolidation of the partitions that could lead to rupture are always necessary where there is the need of structural interventions, which therefore always

require the supervision of some experts. Ligature techniques of orthogonal walls are contemplated with the use of wedges and chains passing through the masonry and external support; the insertion of a support for the masonry beams, since it has been seen is common practice to place the joists directly on the wall without a support that can dissipate the cutting effects. For the repair of the corner, it is necessary to consider the insertion of wooden fastening brackets, better anchored in the external part of the building. Also in this case, if the reconstruction of the corner is necessary, it is possible to use stabilized adobe bricks with the insertion of wooden reinforcing strips.

In any case it is advisable to replace the deteriorated beams or subject to putrefaction and attacks by insects with new and green beams to ensure the function of the nominal section and avoid shrinkage. In the event that it is not necessary to replace it, is advisable to clean with oils and biocides.

Obviously in the case of restoration and consolidation of buildings, especially those in raw earth, it is necessary to consider a schedule of interventions and maintenance that cover all aspects of the building. The cleaning of the pipes for the outflow of water and maintenance of the proper functioning of the same as the replacement and cleaning of the damaged parts of the roof especially following the monsoon rainy season, the removal of weeds and insects are actions to be undertaken frequently, expiring at least six months. Crack control interventions due to the shrinkage of the mortars or cracks created by the movement of the horizontal partitions must be checked regularly to avoid the formation of deeper lesions that damage the structure and the rapid deterioration of other parts. Extraordinary interventions, on the other hand, as structural consolidation, operations of bonding and reinforcement are to be carried out every time they become necessary; obviously the frequency will

be less if all the other parts will be checked and maintained to avoid reaching this type of injury. It is however necessary, every two years, to check the stability and functioning of all the elements of the structure; only in this way can homes be kept in good condition.

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part II-

**Manual for conservation and
maintenance of Rammed-earth
buildings damaged by
earthquakes**

Introduction

How to read the manual

Damage assessment charts

Water actions
Earthquakes
Natural environment
Technological inaccuracy
Negligence and low maintenance

How to read a damage

Interventions

Legend

A.

Interventions for damp and infiltration control

- A.1 Creation of a drainage channel
- A.2 Roof leaks repair
- A.3 Drainpipe and gutter installation
- A.4 Protection and removal from biotic attacks

B.

Interventions for external walls renovation

- B.1 Cleaning of the superficial layers from efflorescences and mildew
- B.2 Cleaning of the superficial layers from bulging and delamination
- B.3 Restoration of the façade and application of final plaster
- B.4 Light cracks refill

C.

Interventions for structural consolidation of walls "box system"

- C.1 Profound cracks stitching
- C.2 Wall reconstruction
- C.3 Lintel replacement
- C.4 Insertion of beams supports
- C.5 Insertion of reinforcement systems: wooden chains
- C.6 Insertion of corner bonding measures
- C.7 Insertion of wooden connectors between orthogonal walls
- C.8 Bonding retrofit with organic fabrics

Appendix

Maintenance actions
Earth mix compositions
Field tests

The Earthquake of Magnitude 6.9 on September 2011 that caused severe damages to lives and properties in Western Bhutan has re-confirmed the level of seismic activity taking place in the country. The severity of the earthquake and the repeated recurrence of aftershocks reminded the need of ensuring the traditional heritage and prevent damages. The event and the aftermaths have exposed the vulnerability of many infrastructures, particularly the houses in rural area. While earthquakes cannot be predicted and prevented, homes could be made stronger, resilient to shocks and vibrations and therefore safer. The earthquake creates a great devastation in terms of construction, money and often also human lives; for this reason the mitigation of damages due to the earthquake must be studied not only with regard to the prevention of sacred buildings or monuments but also and especially for rural buildings.

The aim of this manual is therefore to propose intervention for the recovery of earthen buildings damaged by the earthquake; buildings that often can not be rebuilt and represent sources of danger to the owners themselves if they are not settled after catastrophic events.

The manual presents several cases of common damages (found in the post-earthquake assessment) with possible repair techniques, also providing details of in-depth analysis of the causes and control of their effects to understand how to repair them before starting the intervention. Each framework provides also a timetable for maintenance to help in checking and preventing the deterioration of the building.



HOW TO READ THE MANUAL

-WHO?

WHO IS THE MANUAL FOR?

The manual has been intended for the Bhutanese population living in rammed-earth homes; technicians and craftsmen will receive instructions from engineers who give support in repairing their homes.

-WHAT?

WHAT IS THE MANUAL?

The manual is an essential reference about conservation intervention of rammed earth buildings damaged during the earthquakes, which show easy worksheets for the identification and repair of damages as well as maintenance instructions.

-WHEN?

WHEN DO I NEED TO USE THE MANUAL?

When the house has been damaged during the earthquake you should consider the manual to repair the damages; it is possible to consider its use for general maintenance and prevention of rammed earth houses that haven't been seriously involved during the seismic event.

-WHY?

WHY SHOULD I FOLLOW THE MANUAL?

The advice is to follow the manual step by step to safely restore your home before the deterioration of actual damages lead to greater ones.

-HOW?

HOW SHOULD I READ THE MANUAL?

First of all, you need to understand which are the causes of damages occurred to your home, you find a damage assessment chart that will help you identify them.

There is a legend which gives you information about symbols and boxes descriptions you will find in each intervention framework.

Before you start, always consider to contact an expert which can help you with the assessment of damages affecting your home.

DAMAGE ASSESSMENT CHART

CAUSES OF DAMAGES

EFFECTS

INTERVENTIONS

NATURAL FACTORS

WATER ACTIONS



- Infiltration from the roof
- Infiltration in formwork holes
- Running water on the surface
- Water ponding at the top of wall
- Stagnation of water on the ground
- Capillary rising damp

- Erosion
- Delamination
- Putrefaction of timber beams
- Cracks
- Efflorescence
- Bulging and mildew

- Creation of drainage channels
- Increase ground slope
- Facade restoration and application of plaster
- Cracks refill
- Installation of drainpipes and gutter

EARTHQUAKES



- Natural ground shakings
- In plane movements
- Out of plane movements (shear stress)
- Roof weight
- Pushing horizontal forces of floors

- Vertical cracks
- Corner cracks
- Buckling and toppling
- Corner collapses

- Light cracks refill
- Profound cracks stitching
- Wall reconstruction
- Insertion of chains and wooden planks

NATURAL ENVIRONMENT



- Presence of vegetation nearby
- Proximity to rivers
- Wildlife surrounding
- Wind loads

- Vegetation/insects attacks
- Infiltrations
- Rising damp
- Cracks

- Removal of vegetation
- Use of biocids
- Installation of drainage system

HUMAN FACTORS

TECHNOLOGICAL INACCURACY



- Lack of overlapping blocks
- Lack of bonding measures between T shape walls and new/old walls
- Lack of supporting planks for dingris and chams in the wall
- Improper length insertion of lintel in the wall
- Uncorrect earth mix and shrinkage
- Weak compaction in the formworks

- Vertical and corner cracks
- Corner collapses
- Wall overturning
- Openings displacement
- Joists collapses
- Delamination

- Structural consolidation
- Cracks repair
- Wall reconstruction
- Insertion of wooden chains and planks
- Insertion of connectors between Tshape walls
- Lintel replacement
- Insertion of corner bonding measures

NEGLIGENCE AND LOW MAINTENANCE



- Roof damages and leaks
- Absence of final rendering
- Uncovered Ju-shings and Gu-shings holes
- Absence of drainage system
- Lack of adequate slope of terrain

- Infiltrations
- Erosion
- Water ponding on the top wall
- Cracks
- Stagnation

- Roof leaks repair
- Grout injections in the holes
- Use of render
- Drainage pipes
- Creation of slope for the downflow of rain

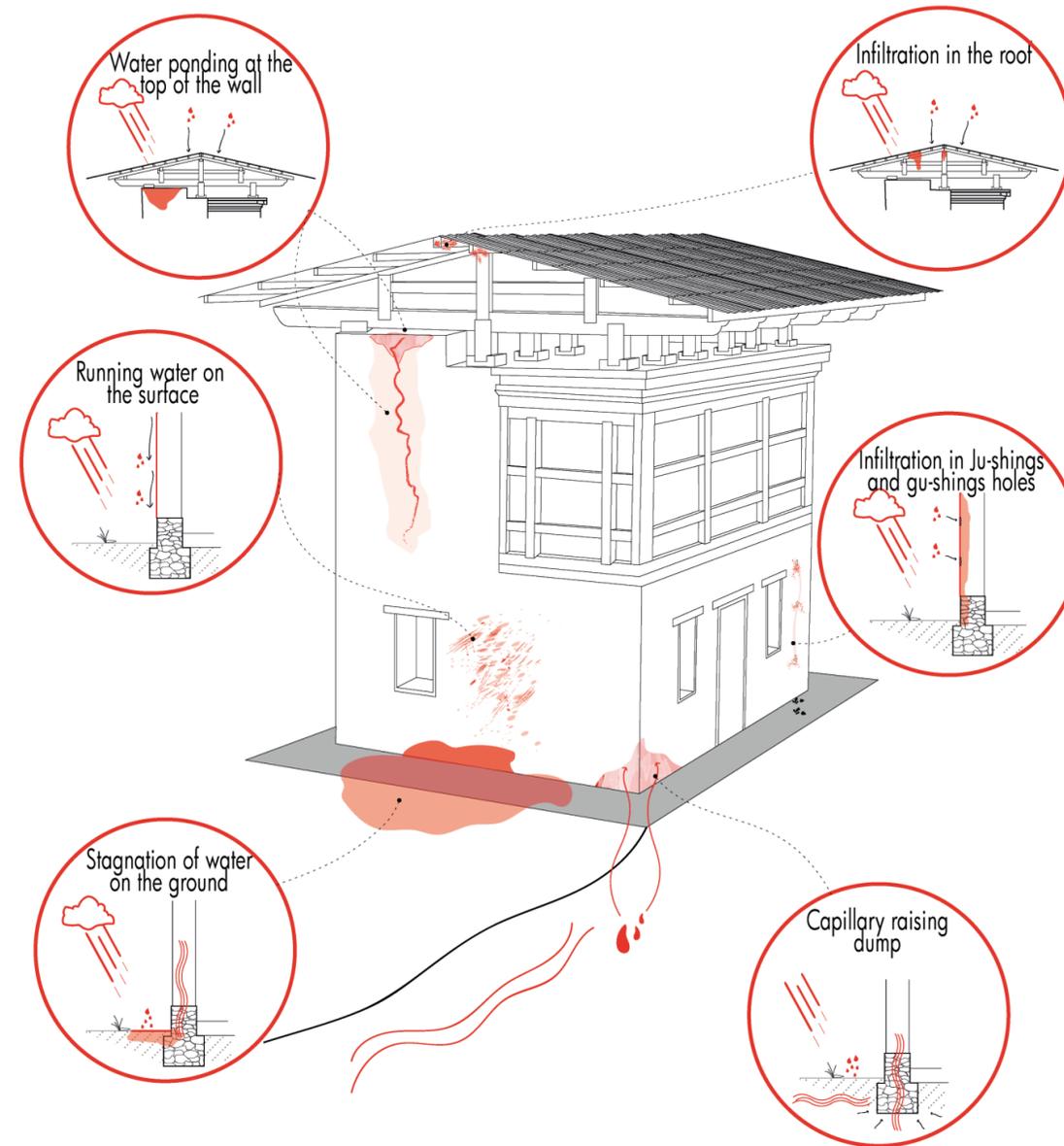
WATER ACTIONS



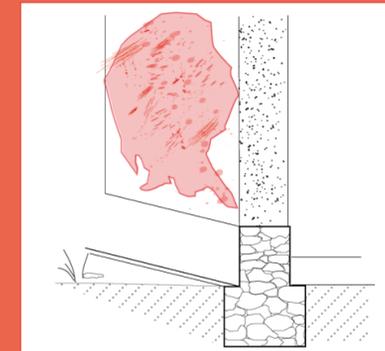
- Infiltration from the roof
- Infiltration in formwork holes
- Running water on the surface
- Water ponding at the top of wall
- Stagnation of water on the ground
- Capillary rising damp

- Erosion
- Delamination
- Putrefaction of timber beams
- Cracks
- Efflorescence
- Bulging and mildew

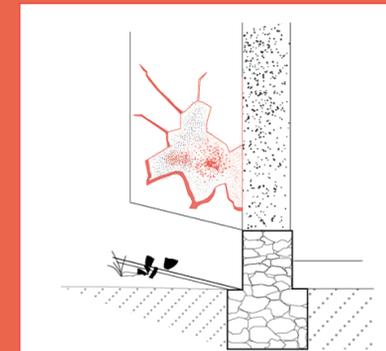
- Creation of drainage channels
- Increase ground slope
- Facade restoration and application of plaster
- Cracks refill



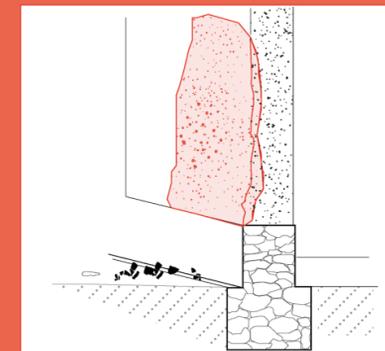
EFFECTS



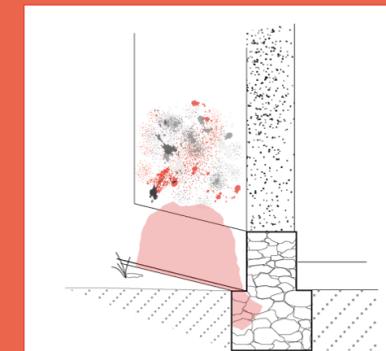
Erosion of the rammed-earth facade, and abrasion of the material as a consequence of rain and wind effects



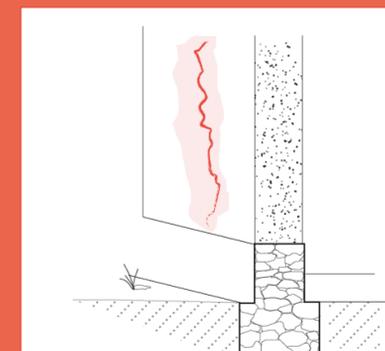
Bulging and superficial ruin of the wall is due to constant presence of humidity and wet-dry cycles



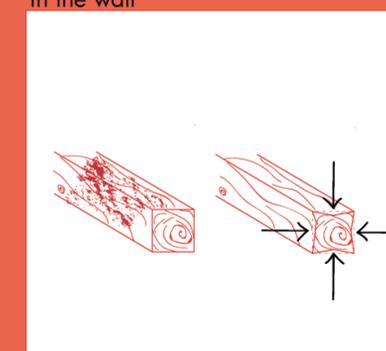
Delamination of the wall in layers due to the progressive weakening of the wall cohesion



Efflorescence and mildew, typified by white and dark humid spots on the surface due to presence of humidity in the wall



Vertical cracks are the most evident damage of water infiltration and erosion in the wall, especially after freeze and thaw cycles



Putrefaction of timber beams and reduction of nominal section due to infiltration in the roof

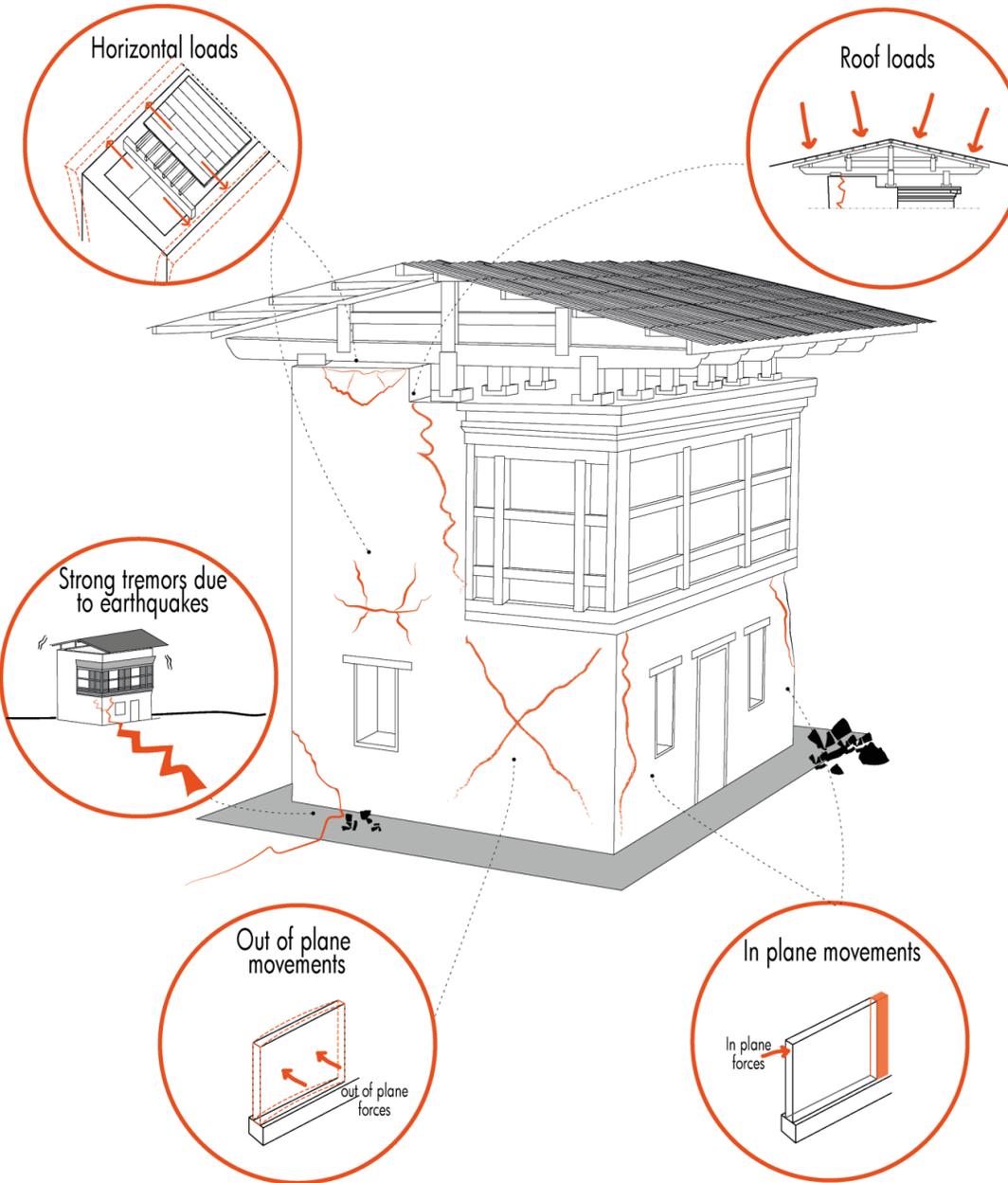
EARTHQUAKES



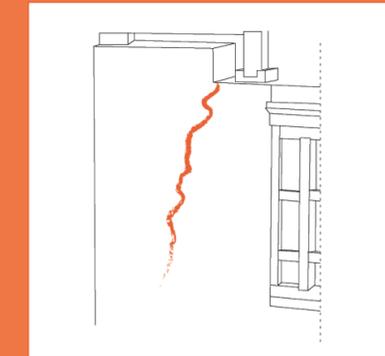
- Natural ground shakings
- In plane movements
- Out of plane movements (shear stress)
- Roof weight
- Pushing horizontal forces of floors

- Vertical cracks
- Corner cracks
- Buckling and toppling
- Corner collapses

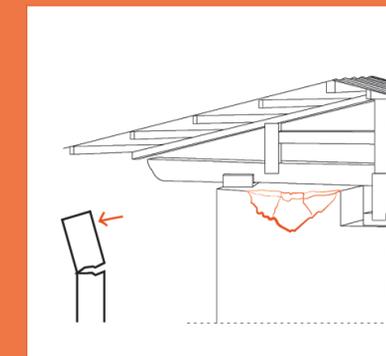
- Light cracks refill
- Profound cracks stitching
- Wall reconstruction
- Insertion of chains and wooden planks



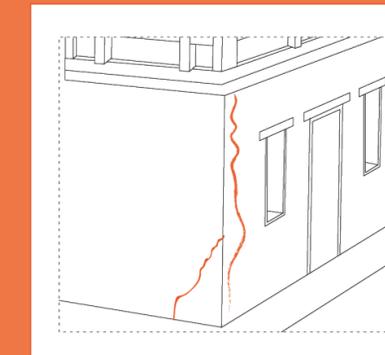
EFFECTS



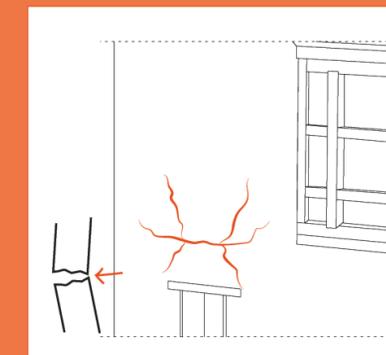
Vertical cracks are visible due to excess of loads and displacements



Top collapse of wall is visible due to shear stress of beams in the wall



Corner cracks are visible due to in plane movements



Buckling is visible due to out of plane movements and extreme force of unbonded walls of floor beams

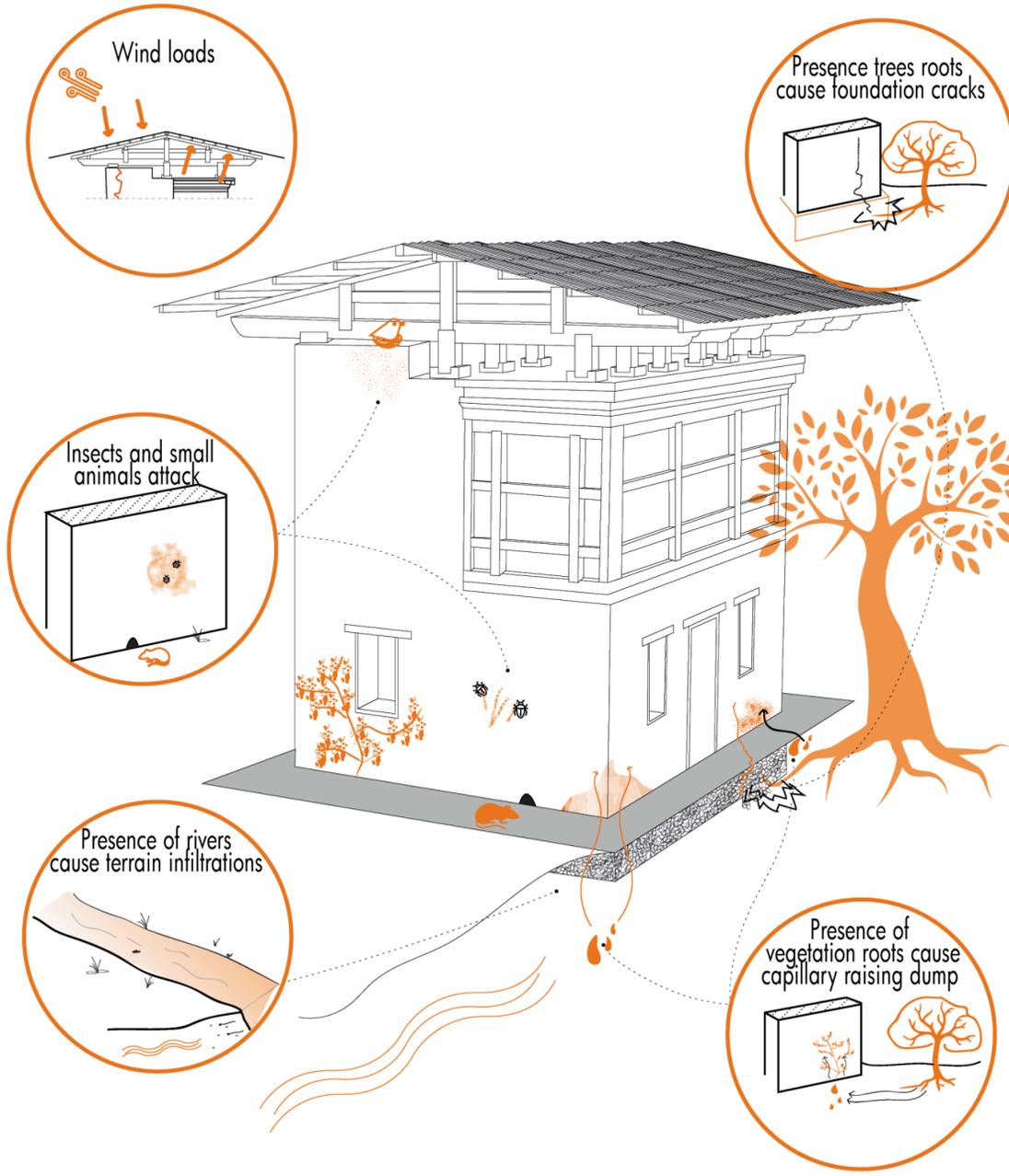


Corner collapse are visible due to in plane movements and excessive horizontal loads of floors

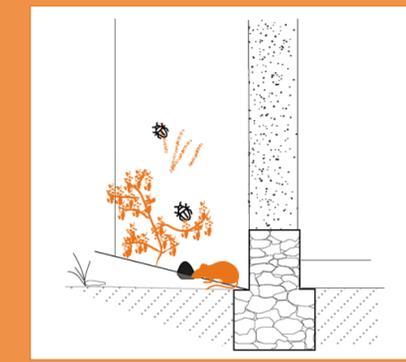
NATURAL ENVIRONMENT



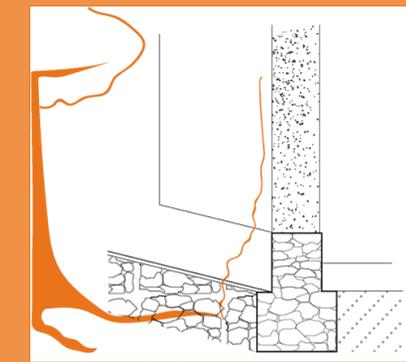
- Presence of vegetation nearby
- Proximity to rivers
- Wildlife surrounding
- Wind loads
- Vegetation/insects attacks
- Infiltrations
- Rising dam
- Cracks
- Removal of vegetation
- Drainage system



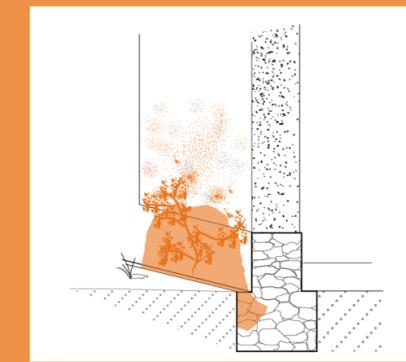
EFFECTS



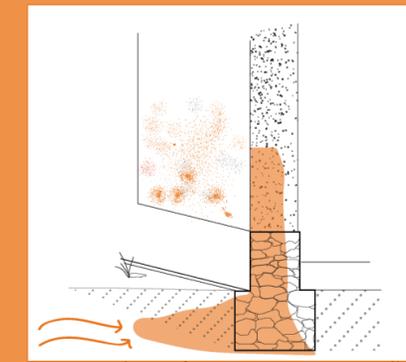
Biological attacks from vegetation and small animals/insects



Cracks in the basement caused by crashing roots



Infiltrations and constant humidity in the wall due to presence of vegetation on the façade (refer to water effects)



Raising damp from terrain, especially in presence of roots and rivers closed (refer to water effects)

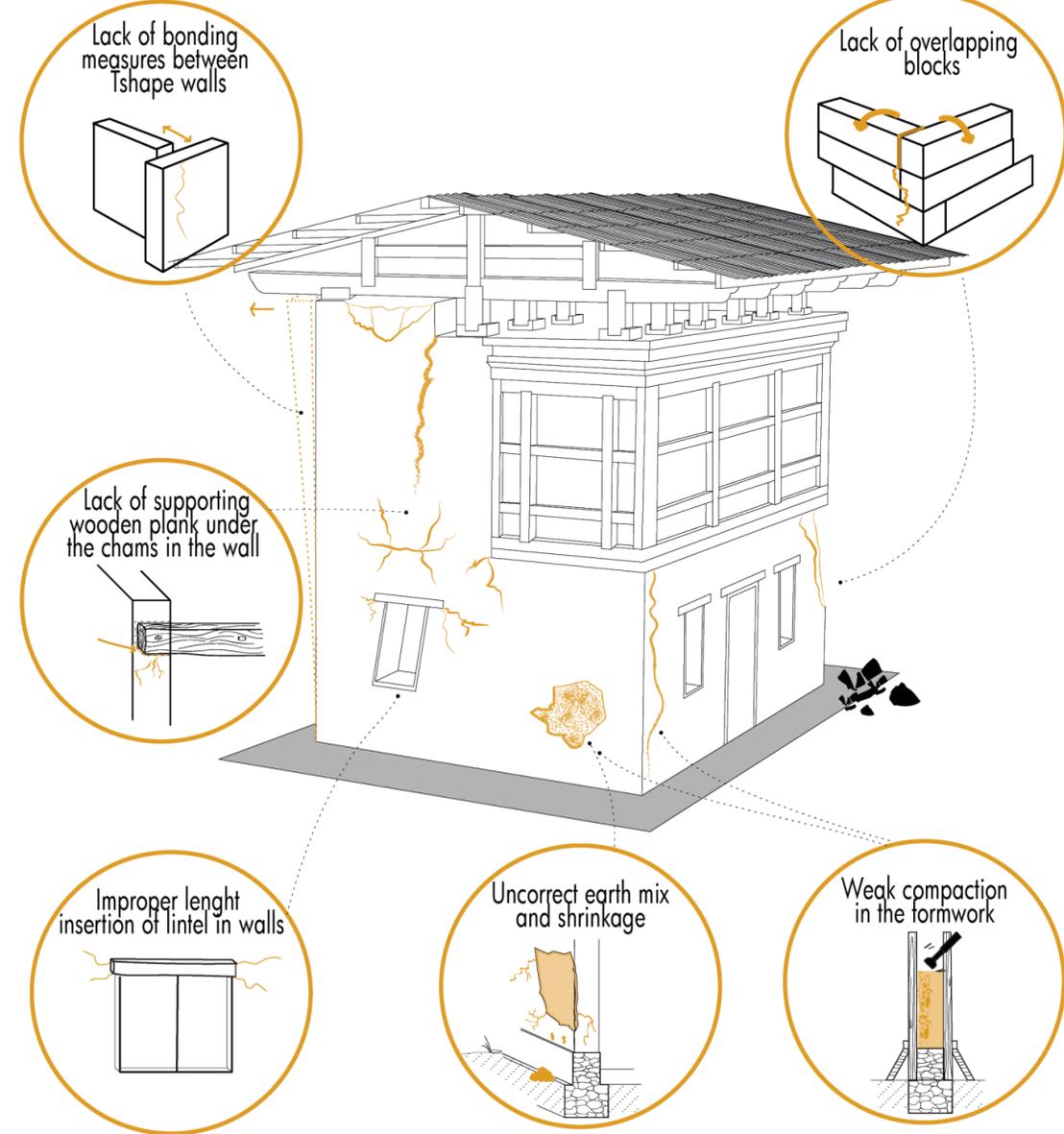
TECHNOLOGICAL INACCURACY



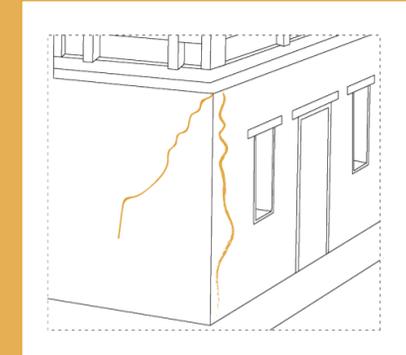
- Lack of overlapping blocks
- Lack of bonding measures between T shape walls and new/old walls
- Lack of supporting planks for dingris and chams in the wall
- Improper lenght insertion of lintel in the wall
- Uncorrect earth mix and shrinkage

- Vertical and corner cracks
- Corner collapses
- Wall overturning
- Openings displacement
- Joists collapses
- Delamination

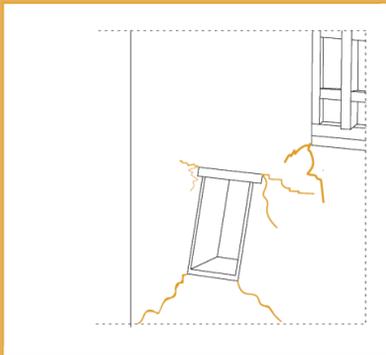
- Structural consolidation
- Cracks repair
- Wall reconstruction
- Insertion of wooden chains and planks
- Insertion of connectors between Tshape walls
- Lintel replacement
- Insertion of corner bonding measures



EFFECTS



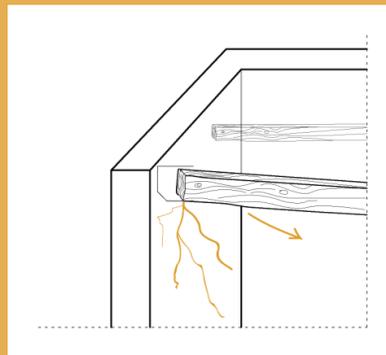
Vertical and corner cracks due to absence of strengthening measures or easily shrinkage



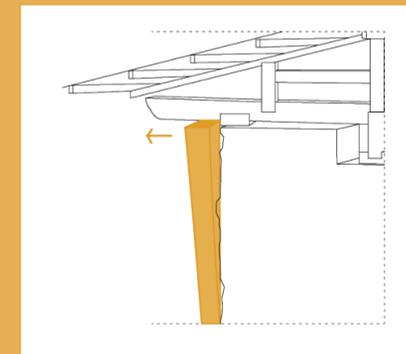
Openings displacements and corner cracks due to uncorrect lenght of lintel in the wall



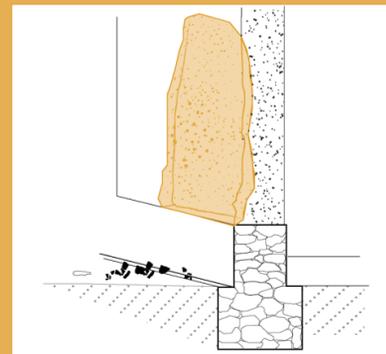
Corner collapse mainly because of lack of overlapping blocks and bonding measures



Joists collapse as a result of absence of proper timber support plank in the wall



Wall overturning due to horizontal forces and lack of bonding measures



Delamination of the wall in layers due to the progressive weakening of the wall cohesion

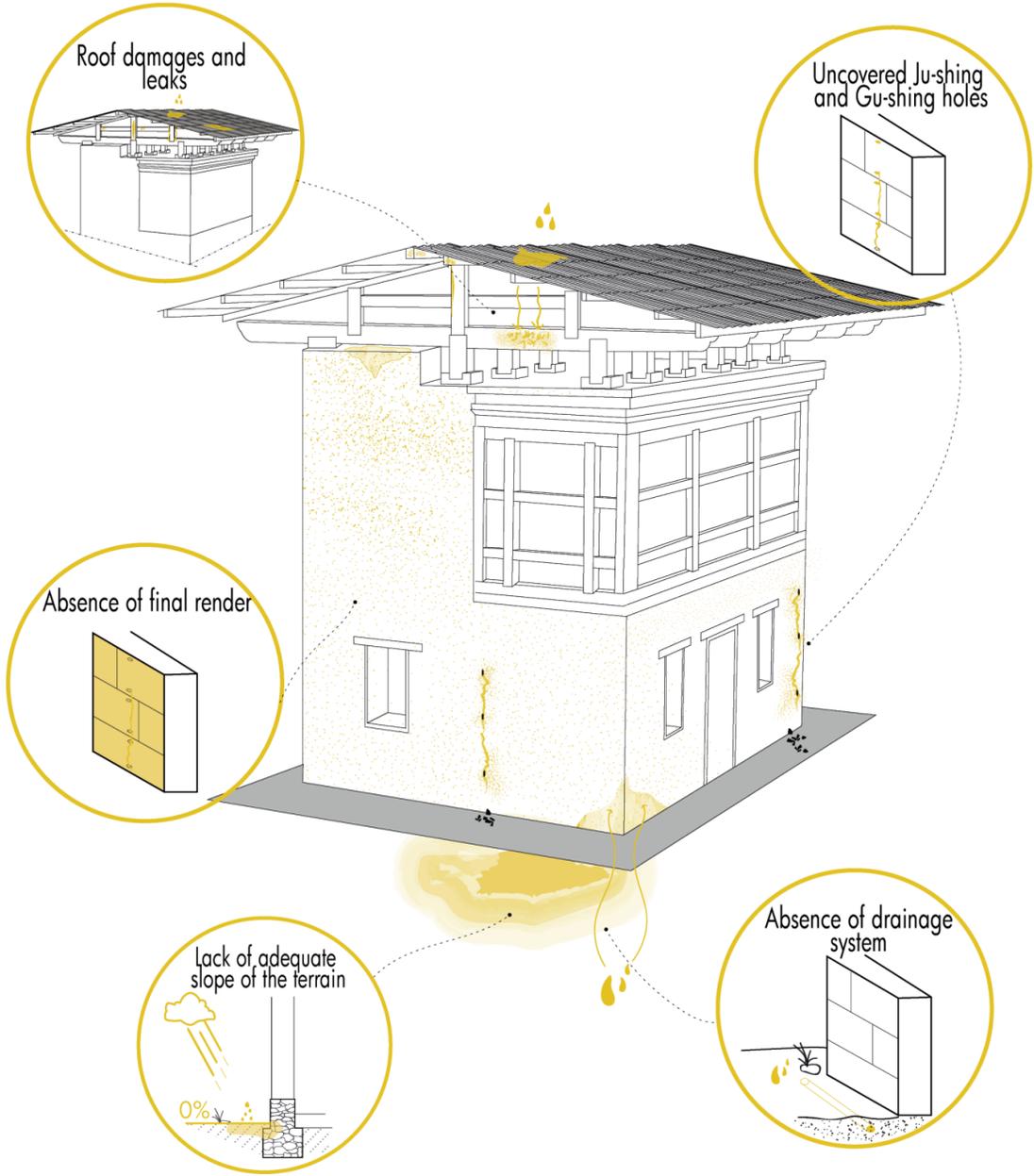
NEGLIGENCE AND LOW MAINTENANCE



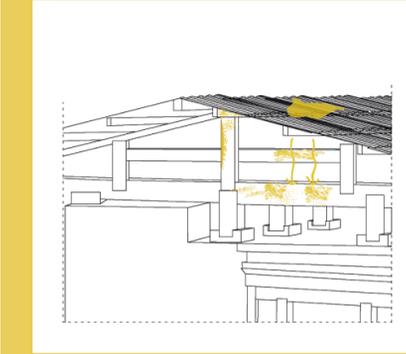
- Roof damages and leaks
- Absence of final rendering
- Uncovered Ju-shings and Gu-shings holes
- Absence of drainage system
- Lack of adequate slope of terrain

- Infiltrations
- Erosion
- Water ponding on the top wall
- Cracks
- Stagnation

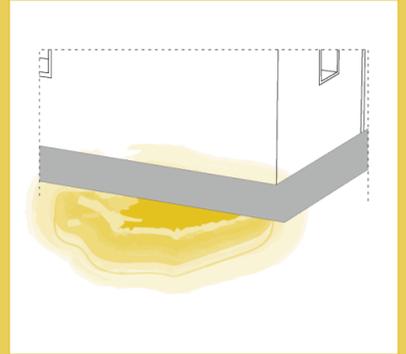
- Roof leaks repair
- Grout injections in the holes
- Use of render
- Drainage pipes
- Creation of slope to the downflow of rain



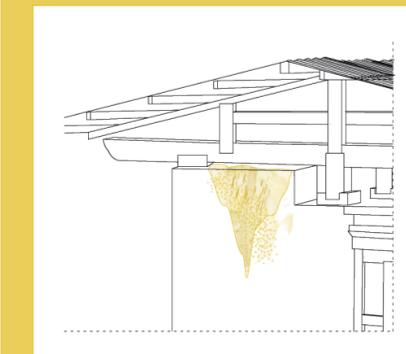
EFFECTS



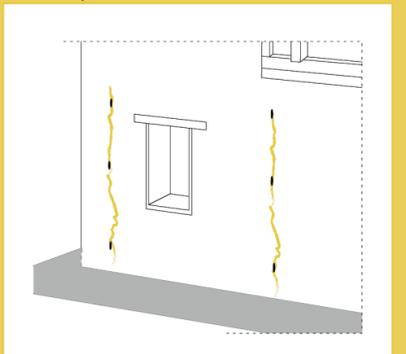
Infiltration from the roof due to damages and leaks which allow water filter in



Stagnation of water on the ground due to inadequate slope % of terrain (see water damages for further causes)



Water ponding on the top of the wall due to roof leaks



Cracks following holes left by the formworks that haven't been covered with plaster



Wall erosion due to absence of final render that protect it from rain

⚠ Intensity of damage

The presence of cracks and fissures in a rammed-earth wall should never be underestimated because it may be a sign of instability of the structure and in some cases can be dangerous for the safety of people. The first considerations to be made concern the understanding of the damage and its origin, as well as the correctness of the technology performed or the presence of external forms of aggravation. Often damages due to environmental degradation and instability go hand in hand and it is hard to identify from which one had the origin.

Generally, it is possible to determine the severity of the cracks through a visual inspection, evaluating the **shape, position, width and depth** of the crack.



Hairy cracks:
 $< 0,1-0,2$ mm width
 It has light cracks on the surface due to shrinkage or light erosion of façade



LOW



Light cracks:
 $> 0,2-20$ mm width
 Light to moderate cracks on the surface which are related to house settlements and water effects



MEDIUM



Profound cracks:
 > 25 mm width
 Profound cracks in width and depth that may have structural failure origins

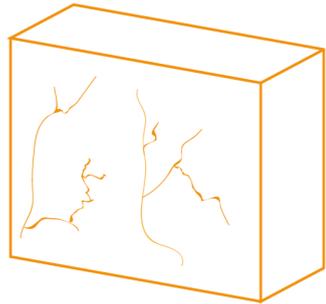


HIGH

Crack identification

1. Visual analysis of any failure and control of the entire building and the surroundings;
2. Understand if it is "dead" or "alive", monitoring it over a long period that could be even months, applying specific rulers to see the variation of the fracture size;
3. Identificate the direction: vertical cracks are usually due to shrinkage and settlement, while diagonal and stepped ones refer to structural movements;
4. Measure the width: cracks wider than 10 mm implicate serious damages, but also smaller need to be checked;
5. Control the depth of the damage;
6. Control the position of cracks: closed to horizontal slabs, beams in the wall, corner or lintel;
7. Inspect the distribution and frequency of cracks, control of the possible repetition of the cracks in similar parts of the building;
8. Identify the cause of damage, if there are water leaks and infiltration that have further damaged the crack. (it can be also the opposite situation: a crack due to infiltrations worsen by earthquake shakings)

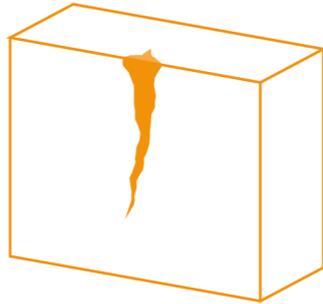
Common failures



Shrinkage crack:
regular in shape and dimensions, most of them hairy or light cracks. It can be dangerous if combined with structure forces.



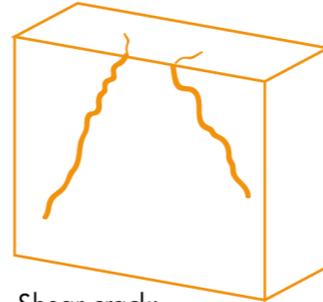
Low



Bending crack:
V shape cracks of 45° angle directions, that widen in direction of bending. It is possible to see this type of crack in case of lack of bonding and compression loads



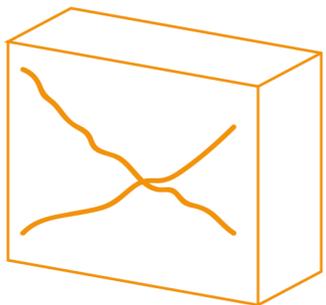
High



Shear crack:
45° diagonal crack. It is possible to see this type of crack where a horizontal loads are leaning on the wall



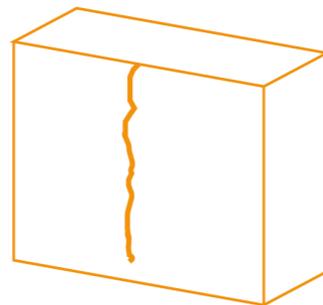
High



X shape diagonal crack:
It occurs because of rotation of the walls during earthquakes and create discontinuity of the load bearing walls.



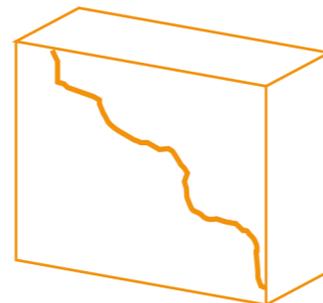
High



Vertical crack:
linear and regular crack, usually due to water leaks. Depending on the width and depth it can be determine the intensity.



MEDIUM



Stepped crack:
crack passing through the crack passing through the blocks and separating the monolithic structure. Potentially dangerous as it implicate structural failures.



MEDIUM

Interventions

A.

Interventions for damp and infiltration control

B.

Interventions for external walls renovation

C.

Interventions for structural consolidation of walls "box system"

A. Interventions for damp and infiltration control

- A.1 Creation of a drainage channel
- A.2 Roof leaks repair
- A.3 Drainpipe and gutter installation
- A.4 Protection and removal from biotic attacks

Origin of damage analysis

Stagnation of water on the ground

Capillary raising damp

Presence of vegetation roots cause capillary raising damp

Presence of rivers cause terrain infiltrations

Lack of adequate slope of the terrain

Absence of drainage system

Permanent water in the footings causing weakening of the wall and deterioration, efflorescence, molds and bulging.

Natural environment bringing raising damp and infiltration and permanent moisture.

Lack of drainage system and inadequate slope that cause stagnation of water and keep humid the foundations.

Damage control actions

- check the flow of the water during rainy days, and verify the presence of stagnation at the base of the building
- check the presence of humidity stains, molds and efflorescence through a visual and tactile examination of the surface (REFER TO INTERVENTIONS B.1 AND B.2)
- check the presence of the climbing weeds on the surface (REFER TO INTERVENTIONS A.4)
- check the slope of the terrain and materials that retain water

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage

Description of intervention

The intervention consists in the creation of a drainage channels and a gravel pitch to remove raising damp and water infiltration from the foundations of the house in order to reduce the presence of humidity in the walls.

Workers involved

Time needed

Materials

- stones and gravel of medium size
- plastic pipe drilled in the upper part
- waterproof barrier for the foundation (TNT if possible)

Working tools

- shovel
- trowel and chisel

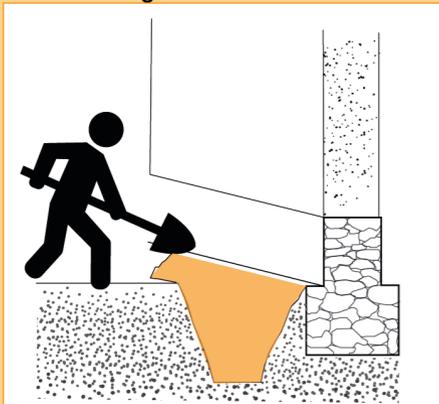
- check the presence of high vegetation that can bring water flows towards the foundations, especially if closer that 10 meters (REFER TO INTERVENTIONS A.4)
- check the presence of other causes of water downflow in the neighbouring, such as rivers



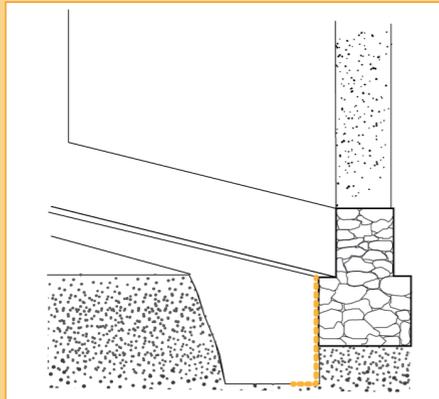
Repair process



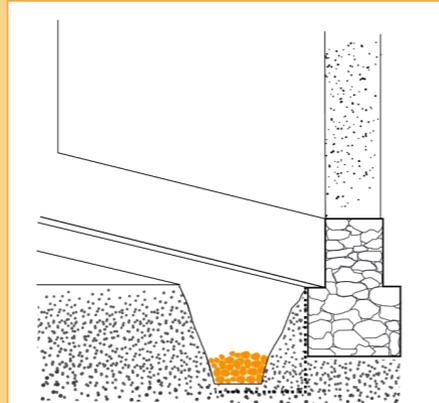
1. Remove all the climbing weeds in the proximity of the footings and façade, especially the roots of high trees in the ground



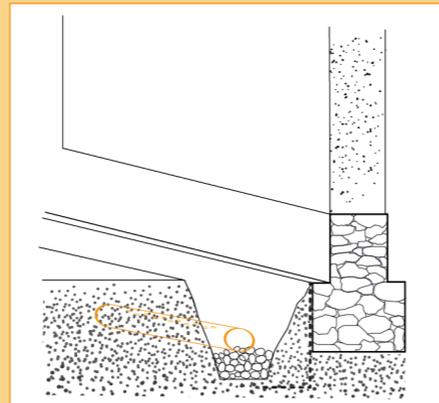
2. Realize the excavation manually and gradually so as not to undermine the foundation of the wall



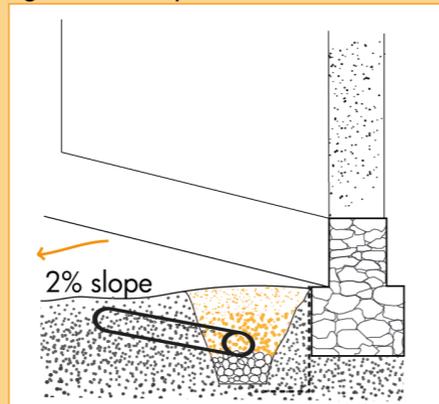
3. Consider to place a waterproof barrier on the surface of the foundation, to protect from ground moisture



4. Position at the bottom of the hole a layer of medium-sized gravel, that work as a filter



5. Place a drilled pipe for collecting rainwater; water collection point as to be away from the building and having a soakaway examinable



6. Refill the hole with smaller gravel and original earth on the top, creating a slight slope to flow the rain outward



Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade
- Eliminates poor drainage issues and pooling water around the foundations
- Clean the deterioration of the walls from dirtyness and molds



REGULAR

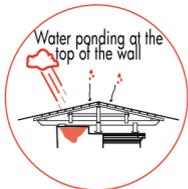
- Prevents the correct flowing of water into the subsoil keeping clean the ground
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks



SPORADIC

- Be sure not to cover the soil with impermeable materials that retain the rain on the surface
- Control the formation of cracks
- Keep checked the function of the drainage pipe and the soakaway

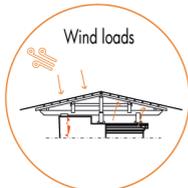
Origin of damage analysis



Infiltration from the roof nodes and water ponding on the wall which bring to deterioration and vertical cracks



Damages of the roof structure that are related to the low maintenance from the owner.



Wind can be really destructive during monsoon season resulting in loss of partitions and overall damages.

Damage control actions

- Check the continuity and stability of the covering mantle, controlling the water resistance of the nodes which are connected with the wall structure
- Check the presence of high vegetation that can leave seeds and greenery stucked in the CGI sheets
- Check the integrity of the wooden partition that compose it and those of the structural support (REFER TO INTERVENTIONS A.4)

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage



Description of intervention

The intervention consists in the punctual repair of the existing layer consisting of sheets of corrugated sheet or in the most remote cases of stone slabs to supplement or replace the existing damaged one.

Workers involved 

Time needed 

 **Materials**

- corrugated iron sheets
- nails to secure sheets
- new wooden slats

 **Working tools**

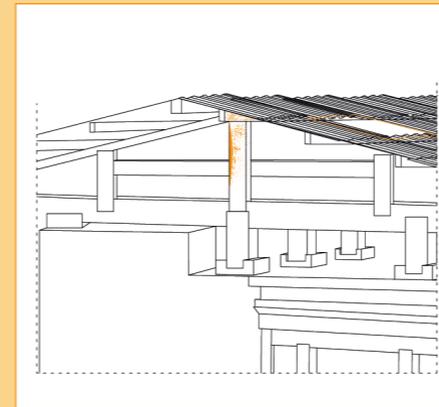
- eventually a scaffolding
- hard brushes
- protective oil for wood

- check the presence of water ponding on the top wall that may weaken and erode the material cohesion. (REFER TO INTERVENTIONS B.1 - B.2 AND A.4)

- check the formation of vertical cracks (REFER TO INTERVENTIONS B.4)

- consider the installation of drainpipes (REFER TO INTERVENTIONS B.4)

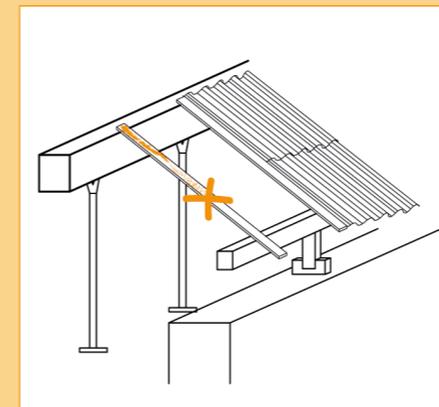
Repair process



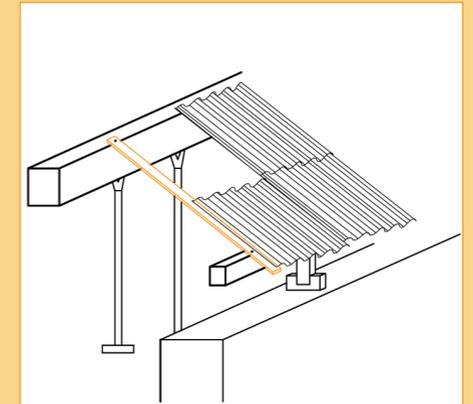
1. Disassemble the damaged part of the covering mantle



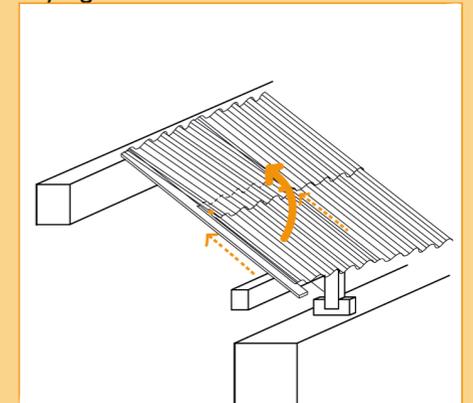
2. If present, remove mosses stucked and greeneries with a hard brush



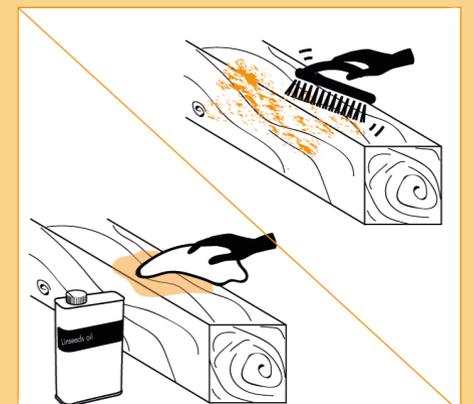
3. Remove of the wooden slat subjected to decay (if necessary shore up the bearing elements with a scaffolding)



4. Insert a new slats fixing it on the underlying structure



5. Reposition the mantle by nailing it in the upper part on the wooden beams, start from the lower and be sure to cover the nailed part with the next one



6. Prevent deterioration of wood beams from mildews, insects attacks and infiltrations, using linseeds oil as a preventive system after cleaning wood with a brush from dust or putrid parts.

Maintenance



FREQUENT

- Keep checked the water flows from the roof and the deterioration of the covering mantle
- Remove seeds and vegetation brought from closed trees that may be stuck in the roof
- check the stability of the single CGI sheets after strong windy days and consequently the outflow of rain



REGULAR

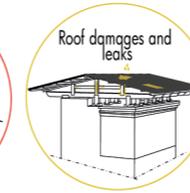
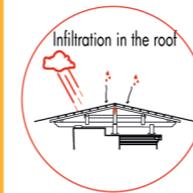
- Check roof leaks, especially before and after monsoon seasons
- Repair the mantle using the same materials and technologies of the existent
- Control the condition of the wooden elements



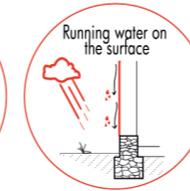
SPORADIC

- Control the position of beams in the wall
- Control the formation of cracks
- Control regularly the structural support of the dingris and their deterioration
- Keep clean and protected the wooden beams to prevent putrefaction

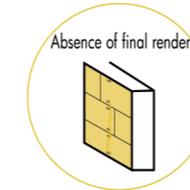
Origin of damage analysis



Infiltration from the roof nodes and leaks due to low maintenance bring to deterioration and vertical cracks



Running water on the surface and infiltrations lead to erosion and formation of decays on the façade



Absence of final render is an easier transmission of water inside the wall, as well as formation of decays and general erosion

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage



Description of intervention

The intervention this time not consists in the repair of a damage, but in the installation of drainpipes and a gutter for the prevention of raising damp and infiltration control, and the consequent effect of erosion and cracks.

Workers involved 

Time needed  

 **Materials**

- gutter and drainpipe
- small metal grid

 **Working tools**

- hooks
- nails

Damage control actions

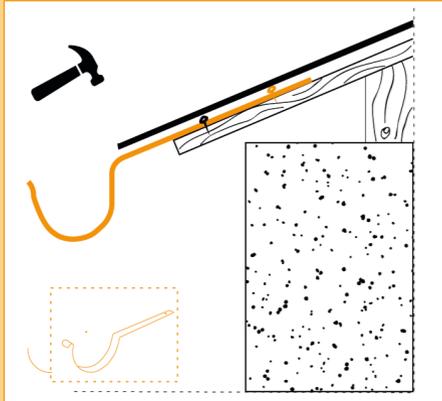
- Check the continuity and stability of the covering mantle, controlling the water resistance of the nodes which are connected with the wall structure
- Check the integrity of the wooden partition that compose it and those of the structural support (REFER TO INTERVENTIONS A.4)
- Check the presence of running water and infiltrations that may cause erosion and bulgings of the exterior wall (REFER TO INTERVENTIONS B.2 AND B.3)

- Check the presence of water ponding on the top wall that may weaken and erode the material cohesion. (REFER TO INTERVENTIONS B.1 - B.2 AND A.4)

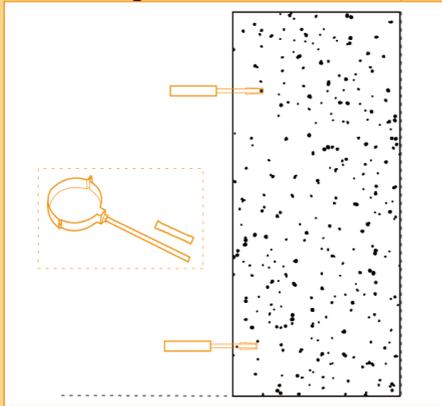
- Check the formation of vertical cracks (REFER TO INTERVENTIONS B.4)



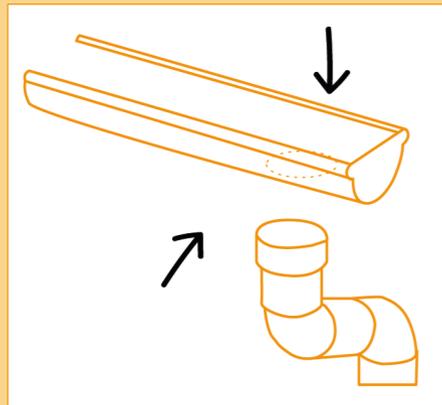
Repair process



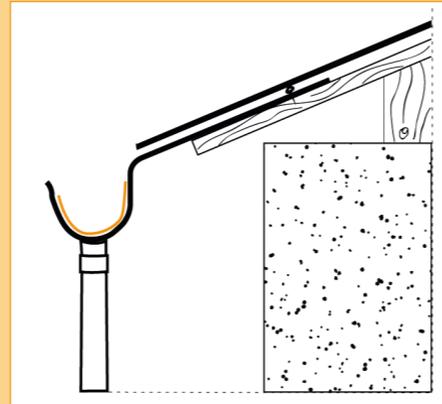
1. Insert the anchoring brackets through nails on the roof structure (do not fix the CGI together with the brackets)



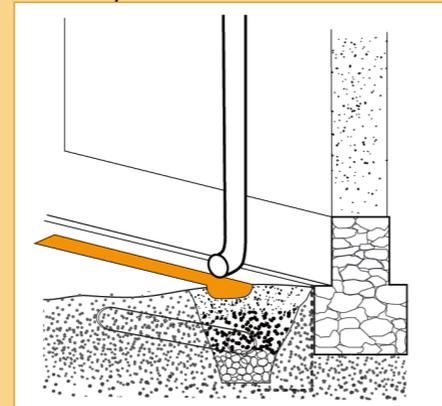
2. Insert of anchoring brackets into the wall to fix the pipe along the wall



3. Install the gutter on the supports and connect it with the drainpipe



4. Place the metal mesh covering the drainage hole to prevent obstructions with dirty and leaves of trees



5. Dig the channel on the ground for the water collection and discharge it in the drainage system in the terrain



Maintenance



FREQUENT

- Keep checked the water flows from the roof and the deterioration of the covering mantle
- Remove seeds and vegetation brought from closed trees that may be stuck in the gutter



REGULAR

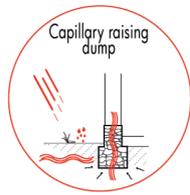
- Check the stability of the pipes after strong monsoon season and the connection of the pipes



SPORADIC

- Control the formation decays in correspondance of the pipe
- Keep clean and protected the wooden beams to prevent putrefaction

Origin of damage analysis



Capillary raising damp



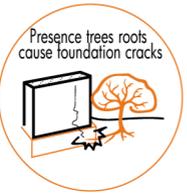
Presence of vegetation roots cause capillary raising damp

Capillary raising damp due to natural moisture of the soil and presence of vegetation that bring constant humidity in the wall



Insects and small animals attack

Insects and rodents find a favourable place to live, attacking the surface of the earth wall



Presence trees roots, cause foundation cracks

Big trees closer than 10 m are a good way to bring humidity and braking the base of the foundations

Damage control actions

- inspect around the constitution to verify the presence high vegetation that could increase the capillary rise
- check the distance of the tall vegetation with roots that can affect the foundations, distance at least 10 meters
- check the presence of discontinuity in the walls as possible ways of penetrating water inside the building (REFER TO INTERVENTIONS B.4)
- check if there are holes in the wall caused by animals and rodents

Classification of damage

Low potential of damage, as it entails superficial defects.

Intensity of damage



Description of intervention

The intervention therefore involves removing the climbing vegetation on the surface and the plants in immediate vicinity, removing insects attacks and pushing away small animals (such as rats).

Workers involved 

Time needed 

 **Materials**

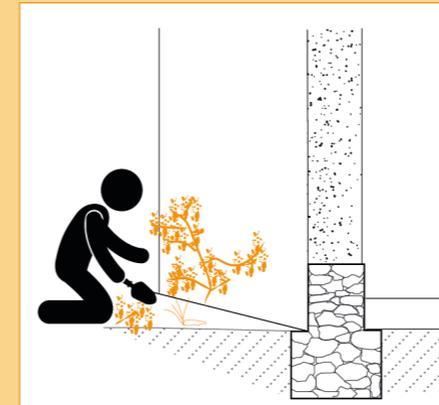
- biocide solution for insects and vegetation
- earth mortar on the need (see mix composition)

 **Working tools**

- Brushes hard or soft depending on the firmness of the decay
- clothes

check the presence of running water and infiltrations that may cause erosion and bulgings of the exterior wall (REFER TO INTERVENTIONS B.2 AND B.3)

Repair process



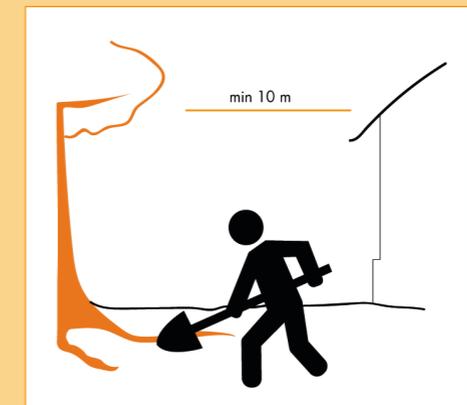
1. Remove manually the vertical infesting vegetation, taking care not to damage the masonry during the act of tearing off



2. If the masonry is covered with moss and lichens it is possible to use a biocide to remove them with the help of a cloth or a brush with soft bristles



3. The same operation can be done for insects that disintegrate the wall in raw earth



4. It is necessary to remove tall vegetation in the neighborhood (<10m), taking care to remove especially the roots in the ground that lead to infiltrations



5. If there are small animals and rodents proceed with the removal and repair of the holes with the reintegration of mortar and plug any dug channels.



Maintenance



FREQUENT

- Keep checked the presence of moss and lichens, especially in the northern façades



REGULAR

- Keep checked the presence of insects and small animals that erode the surface
- control the presence of vegetation, especially roots in the ground, you may need to use regularly a biocide to keep clean
- consider always to protect the wall with a render



SPORADIC

- Cut big trees in the surrounding
- Push away animals that may attack the footings
- In case of livestock of animals, keep clean the area



Interventions for external walls renovation

- B.1 Cleaning of the superficial layers from efflorescences and mildew
- B.2 Cleaning of the superficial layers from bulging and delamination
- B.3 Restoration of the façade and application of final plaster
- B.4 Light cracks refill

Origin of damage analysis

Presence of vegetation roots cause capillary raising damp

Capillary raising damp

Absence of final render

Uncovered Ju-shing and Gu-shing holes

Infiltration in Ju-shings and gu-shings holes

Lack of adequate slope of the terrain

Stagnation of water on the ground

Permanent water in the footings causing weakening of the wall and deterioration, efflorescence, molds and bulging.

Absence of a final render and holes on the façade can be an advantage for atmospheric agents that erode the material

Infiltration in formwork holes are a consequence of low maintenance of the wall surface

Lack of drainage system and inadequate slope that cause stagnation of water and keep humid the foundations bringing to material decay

Damage control actions

- Check the flow of the water during rainy days, and verify the presence of stagnation at the base of the building (REFER TO INTERVENTIONS A.1)
- Check the presence of the climbing weeds on the surface (REFER TO INTERVENTIONS A.4)
- Check the slope of the terrain and materials that retain water (REFER TO INTERVENTIONS A.1)
- Check if there are cracks following the uncovered form-work holes (REFER TO INTERVENTIONS B.4)

Classification of damage

Low potential of damage, as it entails superficial defects.

Intensity of damage

Low

Description of intervention

The intervention of cleaning the masonry surfaces consists in removing the biological patinas, incoherent surface deposits such as dust, mold stains, efflorescences.

Workers involved

Time needed

Materials

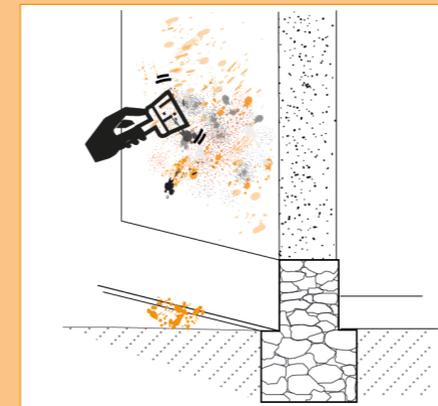
- biocide solution for insects and vegetation
- earth mortar (see mix composition)
- plaster
- spray water

Working tools

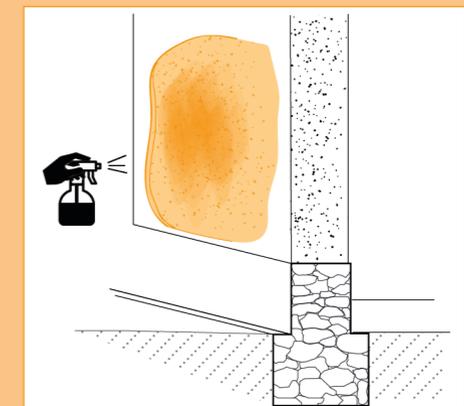
- Brushes: hard or soft depending on the firmness of the coat to clean
- trowel
- sandpaper

- check the presence of high vegetation that can bring water flows towards the foundations, especially if closer that 10 meters (REFER TO INTERVENTIONS A.4)

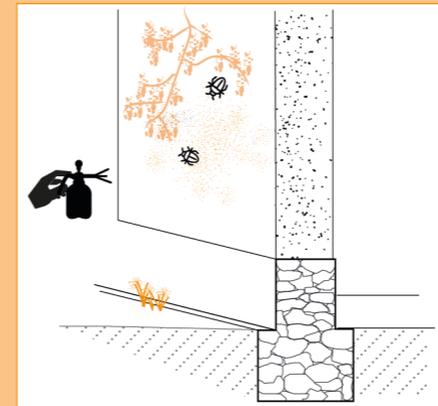
Repair process



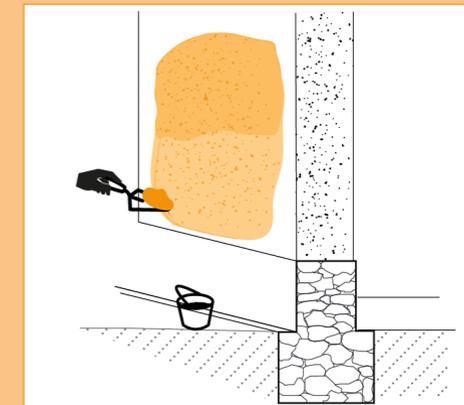
1. Dry removal of the biological patinas with a medium-soft brush to avoid damaging the wall and the detached parts by hand



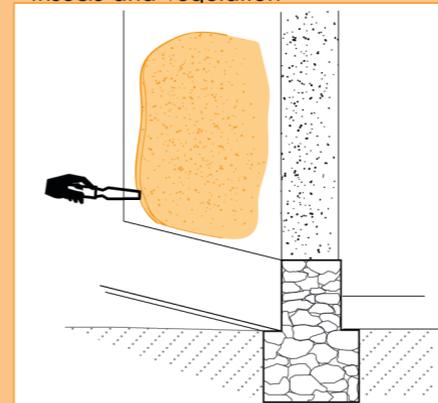
4. Humidification of the damaged part with a brush or a spray bottle to improve adhesion with the new layer



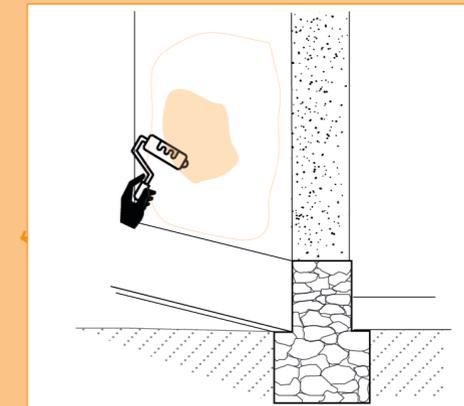
2. Possible use of biocides to remove the degradation from the attack of insects and vegetation



5. Realization of a thin layer of mortar (see earth composition for reference)



3. Elimination of the first wall layer of about 3-4 cm (depending on the depth of the attack)



6. When the surface is dry, cover with a plaster based on earth and lime

Interventions for external wall renovation

Surface restoration from efflorescence and mildew

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade
- Eliminates poor drainage issues and pooling water around the foundations



REGULAR

- Clean the deterioration of the walls from dirtiness and molds
- Prevents the correct flowing of water into the subsoil keeping clean the ground
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks



SPORADIC

- Be sure not to cover the soil with impermeable materials that retain the rain on the surface
- Control the formation of cracks
- Keep checked the function of the drainage pipe and the soakaway

B.2

Interventions for external wall renovation

Surface restoration from bulging and delamination

Origin of damage analysis



Presence of vegetation roots cause capillary raising damp



Capillary raising damp

Permanent water in the footings causing weakening of the wall and deterioration, efflorescence, molds and bulging.

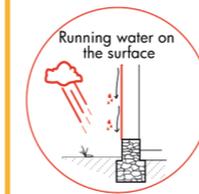


Lack of adequate slope of the terrain



Stagnation of water on the ground

Lack of drainage system and inadequate slope that cause stagnation of water and keep humid the foundations bringing to material decay

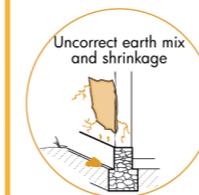


Running water on the surface

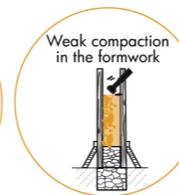


Infiltration in Ju-shings and gu-shings holes

Absence of a final render and holes on the façade can be an advantage for atmospheric agents to infiltrate and erode the material



Uncorrect earth mix and shrinkage



Weak compaction in the formwork

Infiltration in formwork holes due to running water on the surface and lack of the final render

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage



Description of intervention

The intervention consists in the compaction and filling of damaged and bulging parts of the surface, mainly deriving from causes of humidity and infiltrations.

Workers involved

Time needed

Materials

- spray water
- biocid solution
- earth mortar
- plaster

Working tools

- soft brushes
- trowel
- wood awl

Damage control actions

- check the flow of the water during rainy days, and verify the presence of stagnation at the base of the building (REFER TO INTERVENTIONS A.1)
- check the presence of the climbing weeds on the surface (REFER TO INTERVENTIONS A.4)
- check the slope of the terrain and materials that retain water (REFER TO INTERVENTIONS A.1)
- check if there are cracks following the uncovered form-work holes (REFER TO INTERVENTIONS B.4)

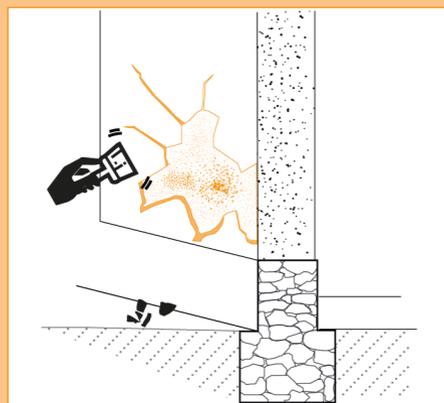
- check the presence of high vegetation that can bring water flows towards the foundations, especially if closer that 10 meters (REFER TO INTERVENTIONS A.4)
- check the presence of molds, efflorescences and dirtiness on the surface (REFER TO INTERVENTIONS B.1)

Interventions for external wall renovation

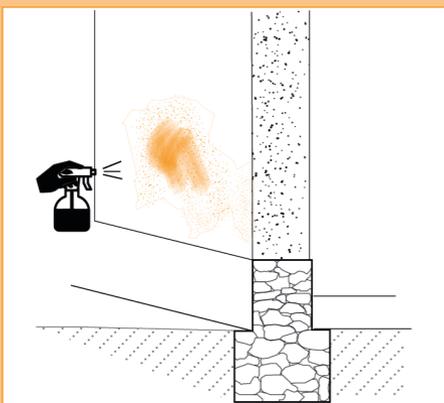
Surface restoration from bulging and delamination



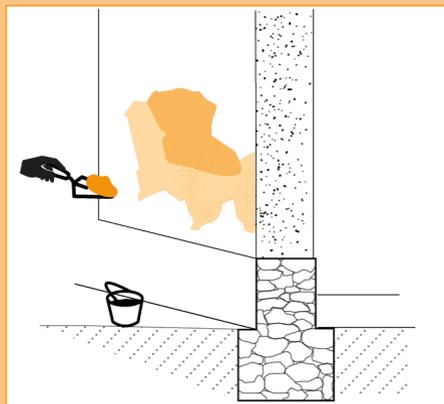
Repair process



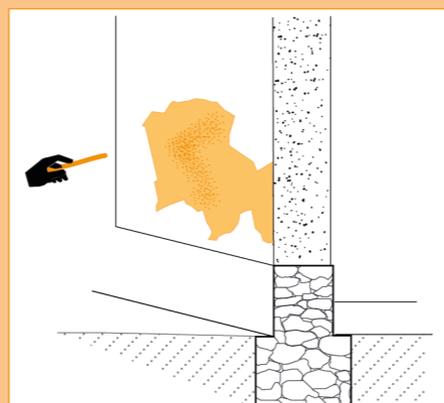
1. Eliminate the unstable parts along the discontinuity and clean the voids with a soft brush so as not to smash the wall



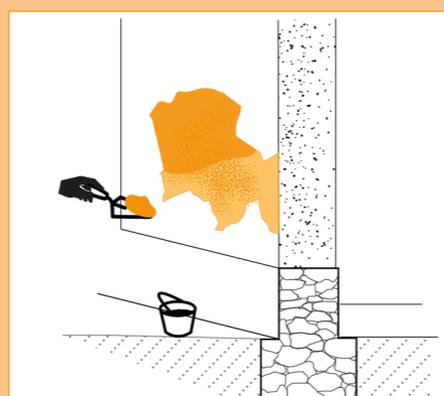
2. Humidify the surface to improve the cohesion of the mortar



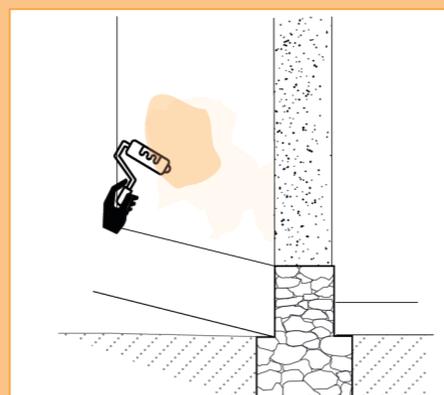
3. Prepare a mixture of medium size grained mortar for the reintegration of the lack, which as to be sticky on the wall



4. Create small holes with a small piece of wood and moisten the surface with a water sprayer



5. Spread a thin layer of mortar with a trowel and level the surface



6. When the surface is dry, cover with a plaster based on earth and lime

Interventions for external wall renovation

Surface restoration from bulging and delamination



Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade
- Eliminates poor drainage issues and pooling water around the foundations



REGULAR

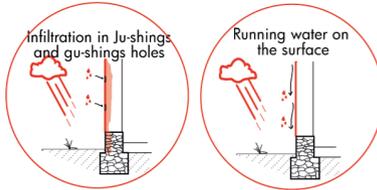
- Clean the deterioration of the walls from dirtiness and molds
- Prevents the correct flowing of water into the subsoil keeping clean the ground
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks



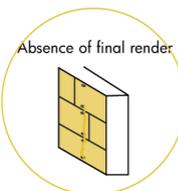
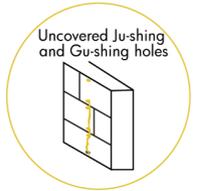
SPORADIC

- Be sure not to cover the soil with impermeable materials that retain the rain on the surface
- Control the formation of cracks
- Keep checked the function of the drainage pipe and the soakaway

Origin of damage analysis



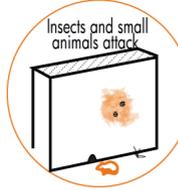
Surface erosion and infiltrations in the holes is the main form of deterioration of the wall surface



The inaccuracy of the owner of not planning the use of proper final render that cover the surface and holes further increase the potential of damage



Errors in the technological use of the earth mix and ramming process bring to shrinkage and delamination



Insects and rodents find a favourable place to live, attacking the surface of the earth wall as well as vegetation

Damage control actions

- check the presence of discontinuity in the walls as possible ways of penetrating water inside the building (REFER TO INTERVENTIONS B.4)
- check the presence of molds, efflorescences and dirtiness on the surface (REFER TO INTERVENTIONS B.1)
- check the presence of running water and infiltrations in the formwork holes, that may cause erosion, bulgings and cracks of the exterior wall (REFER TO INTERVENTIONS B.2)

Classification of damage

Low potential of damage, as it entails superficial defects.

Intensity of damage



Description of intervention

The intervention consists in the repair and integration of faults with mortars in the disconnected parts, above all on the holes left by the formworks and the application of a final protective coat.

Workers involved

Time needed

Materials

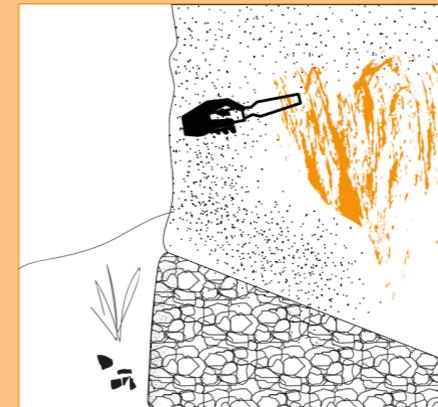
- biocide solution for insects and vegetation
- earth mortar (see references in Appendix)
- final plaster

Working tools

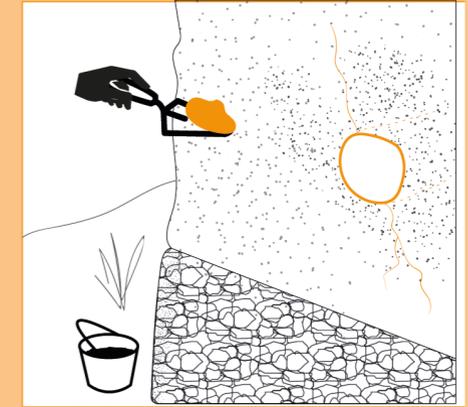
- Brushes hard or soft depending on the firmness of the decay
- sandpaper

- check the integrity of the wall in relation to shrinkage cracks (REFER TO INTERVENTIONS B.3)
- check if there are holes in the wall caused by animals and rodents (REFER TO INTERVENTIONS A.4)

Repair process



1. Remove the damaged or unstable parts from the surface wall



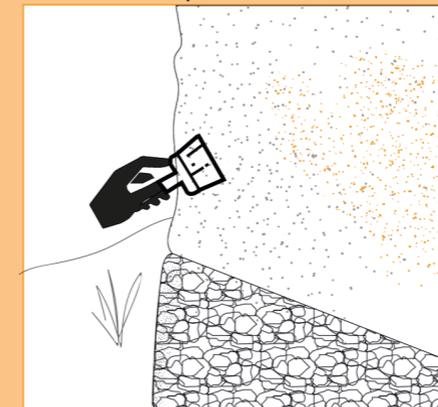
4. Fill the holes left by the removal of the formworks (for any fractures refer to B.4 or C.1)



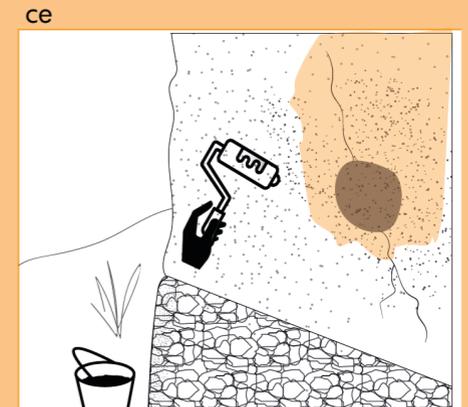
2. Remove any climbing plants and insects using an insecticide as biocids, let dry.



5. Spread a new layer of mortar on dry surface for a thickness of at least 1,5 centimeters and smooth the surface



3. Clean with brushes or sandpaper and a light spray of water the residual parts



6. When the surface is dry, cover with a plaster based on earth and lime

Maintenance



FREQUENT

- Keep checked the presence of moss and lichens, especially in the northern façades
- control the presence of vegetation, especially roots in the ground, you may need to use regularly a biocide to keep clean
- keep checked the humidity of wall with a visual and tactile control



REGULAR

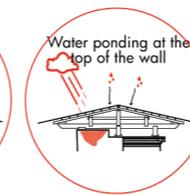
- Keep checked the presence of insects and small animals that erode the surface
- Keep checked the water flows from the roof and periodically the deterioration of the covering mantle
- keep checked water stagnation and raising damp



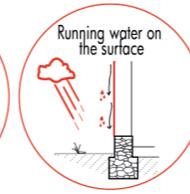
SPORADIC

- Cut big trees in the surrounding
- Push away animals that may attack the footings
- In case of livestock of animals, keep clean the area
- if necessary reuse final plaster to protect the walls

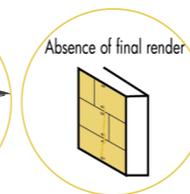
Origin of damage analysis



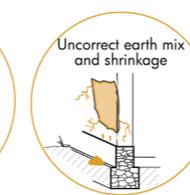
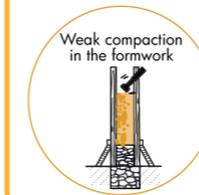
Infiltration from the roof nodes and water ponding bring to weakening of the material cohesion and vertical cracks



Running water on the surface and infiltrations lead to erosion and formation of cracks following the holes



Absence of final render or roof leaks are an easy way for the formation of decays due to low maintenance and inaccuracy



Wrong compositions of earth mix and bad compaction during ramming lead to shrinkage and formation of cracks

Damage control actions

- Verify the crack is “dead or alive” and its intensity (REFER TO HOW TO READ A DAMAGE)
- Check the continuity and stability of the covering mantle, controlling the water resistance of the nodes which are connected with the wall structure (REFER TO INTERVENTIONS A.2)
- Check the integrity of the wooden partition that compose it and those of the structural support (REFER TO INTERVENTIONS A.4)
- Check the presence of water ponding on the top wall that may weaken and erode the material cohesion. (REFER TO INTERVENTIONS B.1 - B.2 AND A.4)

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage



Description of intervention

The intervention consists in the refill of light cracks of 15-20 mm max dimension that affect the superficial layer, or small holes in order to confer continuity and solidity to the external wall.

Workers involved 

Time needed  

 **Materials**

- Earth mortar (see mix composition) be sure not to use mortar with salty compositions
- Spray water
- plaster

 **Working tools**

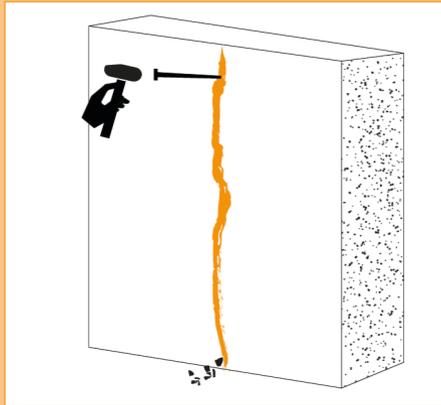
- Hard brush
- Trowel
- Grout injector (it can be a bottle with a straw, a pipe with funnel)

○ check the presence of running water and infiltrations in the formwork holes, that may cause erosion, bulgings and cracks of the exterior wall (REFER TO INTERVENTIONS B.2 AND B.3)

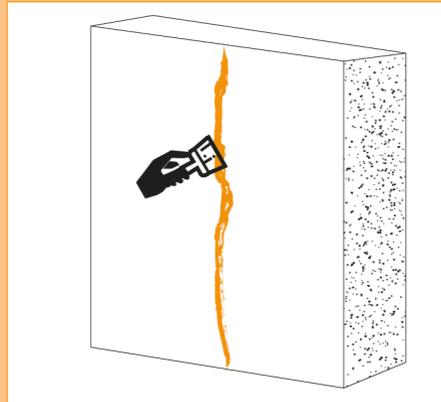
○ check the integrity of the wall in relation to shrinkage cracks (REFER TO INTERVENTIONS B.3)



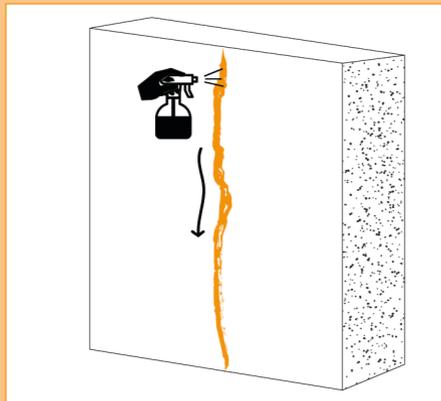
Repair process



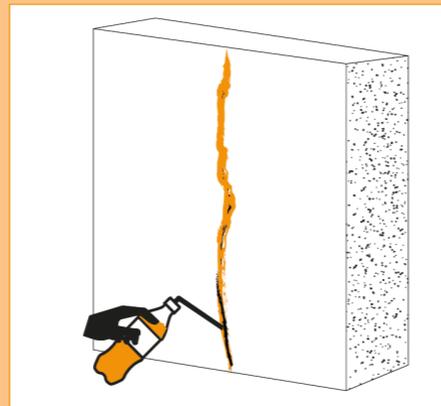
1. Use a fine-tipped picket to remove unstable parts around the crack



2. Clean the inside of the crack from dust and debris as much as possible by using hard brushes



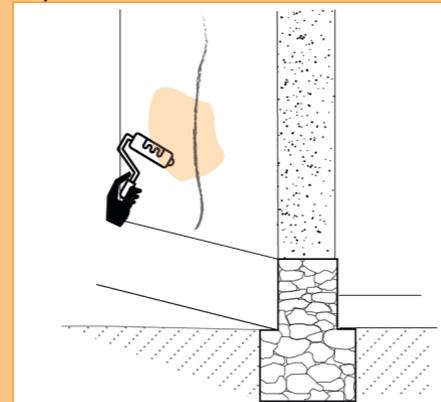
3. Wet the inside of the surface with water, proceeding from top to bottom with a little water at a time



4. Prepare the liquid consistency mortar and insert the tube into the crack to allow the mortar to pass through the crack; start from the bottom and make sure to fill all the spaces



5. Once sealed you can pass a thin layer of mortar outside with a trowel



6. When the surface is dry, cover with a plaster based on earth and lime



Maintenance



FREQUENT

- Keep checked the water flows from the roof and the deterioration of the covering mantle
- Eliminates poor drainage issues and pooling water around the foundations
- Clean the deterioration of the walls from dirtiness and molds



REGULAR

- Check the stability of the pipes after strong monsoon season and the connection of the pipes
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks



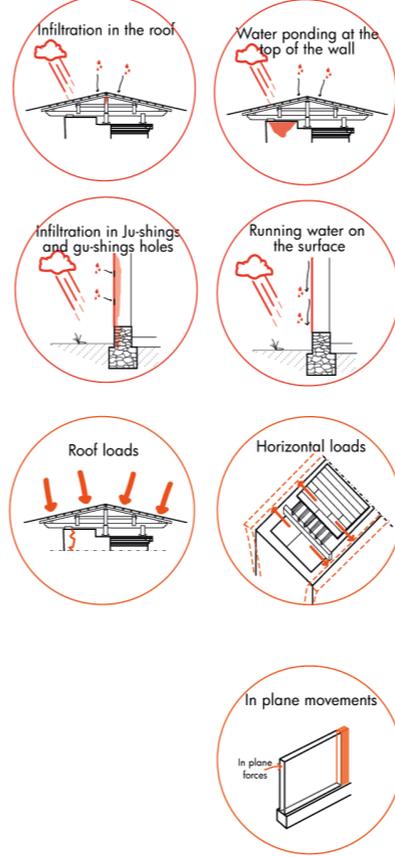
SPORADIC

- Control the formation decays in correspondance of the pipe
- Remove seeds and vegetation brought from closed trees that may are stuck in the gutter

C. Interventions for structural consolidation of walls "box system"

- C.1 Profound cracks stitching
- C.2 Wall reconstruction
- C.3 Lintel replacement
- C.4 Insertion of beams supports
- C.5 Insertion of reinforcement systems: wooden chains
- C.6 Insertion of corner bonding measures
- C.7 Insertion of wooden connectors between orthogonal walls
- C.8 Bonding retrofit with organic fabrics

 Origin of damage analysis



Infiltration in the roof
Infiltration from the roof and water ponding can trigger profound cracks

Water ponding at the top of the wall
Infiltration from the roof and water ponding can trigger profound cracks

Infiltration in Ju-shings and gu-shings holes
Infiltration in formwork holes and general erosion reduce the cohesion of the material which become brittle

Running water on the surface
Infiltration in formwork holes and general erosion reduce the cohesion of the material which become brittle

Roof loads
Loads from the roof and the floors increase the potential of damage when water effects of degradation are present

Horizontal loads
Loads from the roof and the floors increase the potential of damage when water effects of degradation are present

In plane movements
In plane movements that occur during strong earthquakes due to natural settlement of the structure, can give origin to profound cracks

 Damage control actions

- Observe the crack during time to understand its intensity and if it is dead or alive (REFER TO HOW TO READ A DAMAGE)
- Check the flow of the water during rainy days from the roof, and verify the presence of ponding at the top of the building (REFER TO INTERVENTIONS A.2 AND A.3)
- Check the presence of the climbing weeds on the surface (REFER TO INTERVENTIONS A.4)
- Check if there are cracks following the uncovered form-work holes (REFER TO INTERVENTIONS B.4)

 Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage



MEDIUM

 Description of intervention

The intervention consists in the stitching of profound cracks that affected the structural integrity with the insertion of timber staplers in order to confer continuity and solidity to the box system.

Workers involved 

Time needed 

 Materials

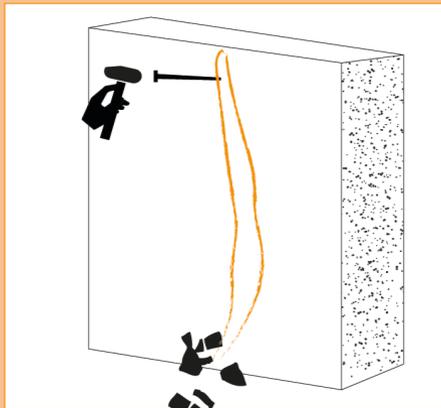
- Earth mortar (see mix composition) be sure not to use mortar with salty compositions
- wooden staplers
- juta clothes

 Working tools

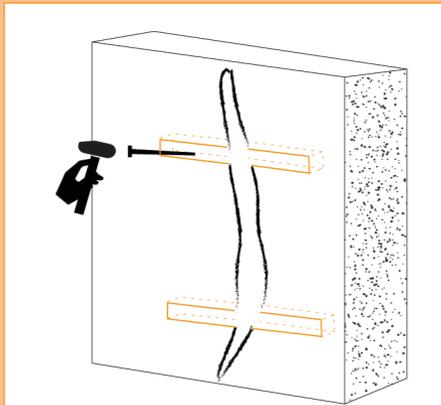
- Hard brush
- Stake
- trowel

- Check the position of timber beams, and eventually the cracks generated (REFER TO INTERVENTIONS C.4 B.4)
- verify the general condition of the wall, its moisture, the presence of molds and efflorescences that can be associated with the crack (REFER TO INTERVENTIONS B.1 B.2 B.3)

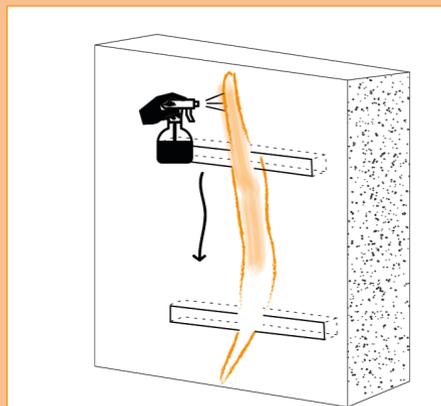
Repair process



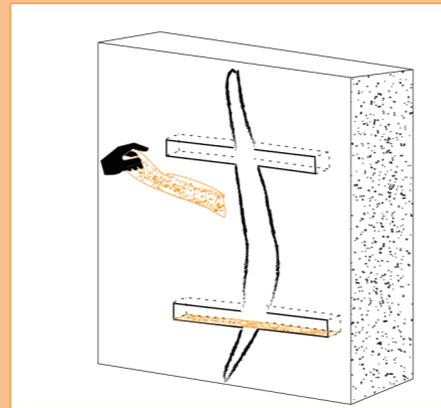
1. Use a fine-tipped picket to remove unstable parts around the crack and clean it



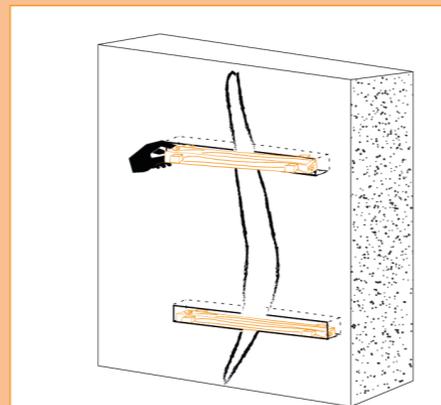
2. Cut horizontal openings in the wall across the crack each 50 cm, cutting the surface with a chisel and remove the excess material



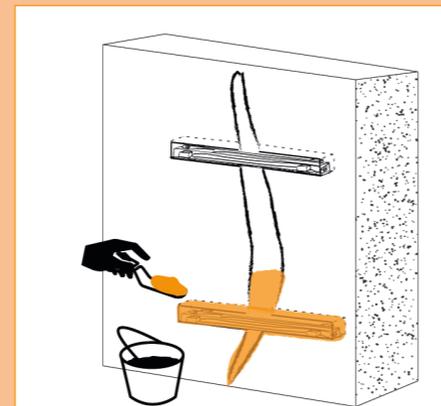
3. Wet the inside of the surface with water, proceeding from top to bottom with a little water at a time



4. Place a wet jute clothes in the horizontal cut, it strenghtens the stitching



5. Cover with a thin layer of mortar and place a timber stapler



6. Fill the crack with mortar, being sure to have filled all the voids and smooth the surface; then consider to use a plaster to protect the wall

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile contol
- Keep checked the water flows from the roof and periodically the deterioration of the covering mantle
- Eliminates poor drainage issues and pooling water around the foundations



REGULAR

- Clean the deterioration of the walls from dirtyness and molds
- Remove animal, and insect attacks
- Remove plants and vege-tation on façade



SPORADIC

- Control the formation of cracks
- Keep checked the functio-nof the drainage pipe and the soakaway
- Check the position of beams in the wall and the formation of cracks

Origin of damage analysis

Lack of bonding measures between T-shape walls
Lack of bonding measures between walls generate cracks and collapse due to out of plane force that those generate during the earthquake.

Out of plane movements
Roof and floor loads generate abnormal thrusts during strong earthquakes, the beams impose shear stress in the walls which may collapse.

Roof loads
Leaks in the roof and holes in the façade can be an advantage for atmospheric agents to infiltrate and erode the material.

Horizontal loads
Innaccuracies of earth mix and during the process of ramming leave a weak and brittle wall, easily perishable.

Infiltration in Ju-shings and gu-shings holes

Infiltration in the roof

Uncorrect earth mix and shrinkage

Weak compaction in the formwork

Damage control actions

- if there are cracks associated with the collapse observe it during time to understand its intensity and if it is dead or alive (REFER TO HOW TO READ A DAMAGE, THEN B.A OR C.1)
- check the flow of the water during rainy days from the roof, and verify the presence of ponding at the top of the building (REFER TO INTERVENTIONS A.2 AND A.3)
- check the presence of the climbing weeds on the surface (REFER TO INTERVENTIONS A.4)

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage
HIGH

Description of intervention

The intervention consists in the construction of new and limited sections of masonry to complete, repair or integrate the collapsed walls, or such an extent degradation as to require intervention to ensure stability.

Workers involved

Time needed

Materials

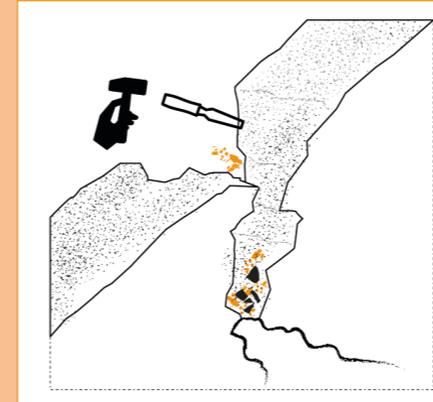
- Earth mortar (see references in Appendix) be sure not to use mortar with salty compositions
- Earth mix for Compressed Stabilized Earth Blocks adobe

Working tools

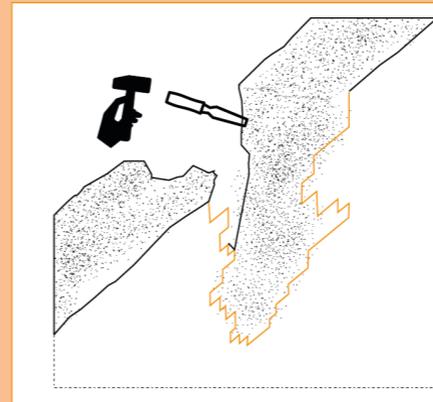
- soft brushes
- trowel
- Adobe brick press

- Check the position of timber beams, and eventually the cracks generated (REFER TO INTERVENTIONS C.4 B.4)
- verify the general condition of the wall, its moisture, the presence of molds and efflorescences that can be associated with the crack (REFER TO INTERVENTIONS B.1 B.2 B.3)

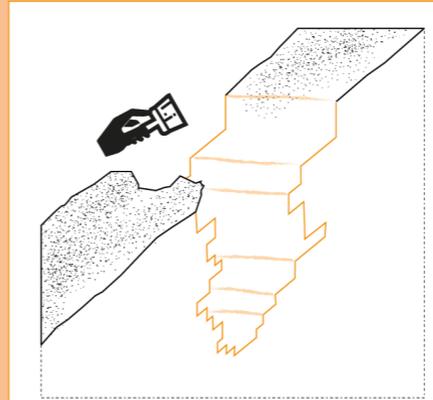
Repair process



1. Stabilize the remaining portions of the wall before proceeding with the construction of new sections by removing the parts of the wall that are unstable



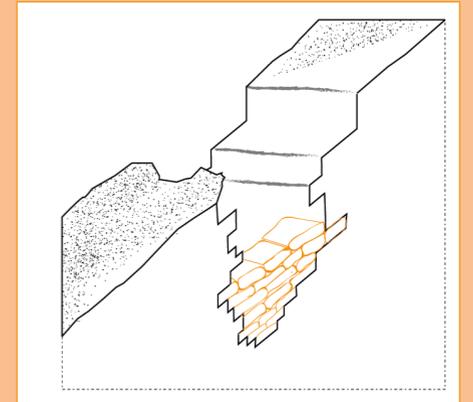
2. Create the space necessary for inserting adobe blocks with a chisel



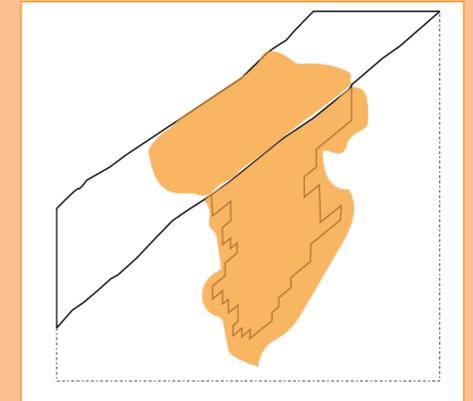
3. Clean the exposed surfaces with removal of the incohesive parts with a hard brush



4. Preparation of the Adobe blocks with the press: prepare the dough in advance and press it taking care to cover all the holes especially in the corners
Preparation of a plastic mortar for the reintegration of the bricks in the masonry



5. Position adobe bricks in rows being sure to overlap them, place a layer of mortar between them



6. When completed, level the surface with mortar and finish with plaster

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from the roof with visual and tactile control
- Remove plants and vegetation on façade



REGULAR

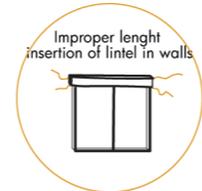
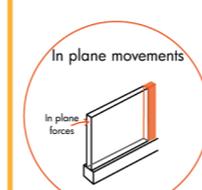
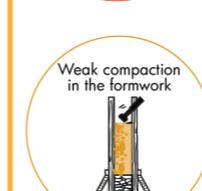
- Clean the deterioration of the walls from dirtiness and molds
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks



SPORADIC

- Control the formation of cracks
- Control the position of beams inserted in the wall
- Keep checked the function of the drainage pipe and the soakaway

Origin of damage analysis

	Technology errors as improper length of the lintel inserted in the wall, lead to dislocation when hit by strong forces
	Running water on the surface and infiltrations lead to deterioration and deformation of the wooden elements
	
	Natural strong movements of the house during seismic events, lead to in plane forces that cause cracks and bending of lintel
	
	Wrong compositions of earth mix and bad compaction during ramming lead to shrinkage and formation of cracks
	

Damage control actions

- identify if the defect is constructive, if the element is not able to fulfill the loads due to insufficient dimensions
- check the integrity of the wooden partition that compose it and those of the structural support (REFER TO INTERVENTIONS A.4)
- check the presence of water infiltrations that may weaken and deteriorated the wood. (REFER TO INTERVENTIONS A.4)
- check the integrity of the wall in relation to shrinkage cracks (REFER TO INTERVENTIONS B.3)

Classification of damage

Medium potential of damage, if not blocked it can evolve through time and involve higher damages

Intensity of damage

 MEDIUM

Description of intervention

The intervention consists in the replacement of existing elements of the opening that are seriously damaged, inflexed or rotting, going to restore the structural function of the opening.

Workers involved 

Time needed 

Materials

- Wooden lintel
- Earth mortar (see references in Appendix) be sure not to use mortar with salty compositions
- Linseed oil or chemical protector

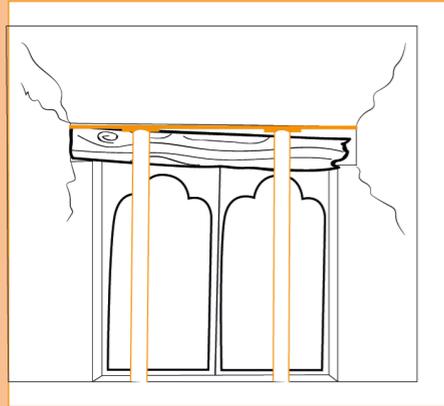
Working tools

- Scaffolding
- Trowel
- hammer

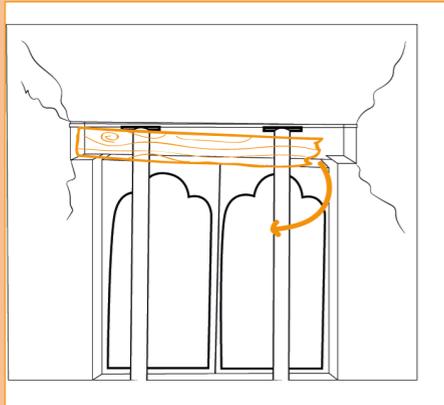
- check the presence of running water and infiltrations in the formwork holes, that may cause erosion, bulgings and cracks of the exterior wall closed to the openings (REFER TO INTERVENTIONS B.2 AND B.3)



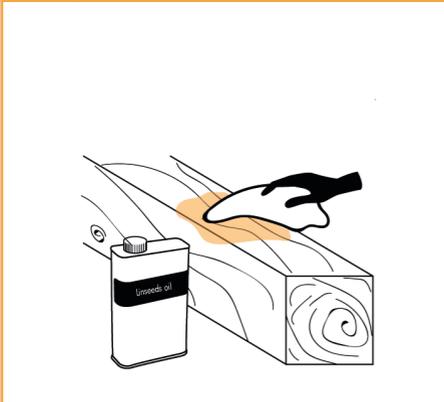
Repair process



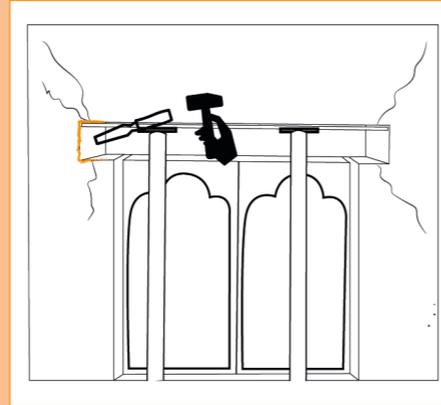
1. Shore the wall portion above the opening with a scaffolding



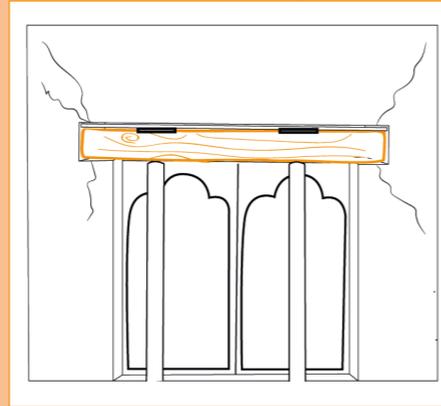
2. Disassemble the damaged element by structural forces or degraded by infiltrations



3. Protect the new wooden lintel with oils and chemicals, that will help to resist better to rotting attacks



4. Widen the location for lintel, at least 25 cm more than window frame but it has to be in proportion with the dimension of the opening



5. Insert a new element (if possible of green wood to avoid the formation of swelling in contact with the humidity of masonry)



6. Compact the damaged parts with bedding mortar to prevent water infiltrations



Maintenance



FREQUENT

- Keep checked the water flows from the roof and the deterioration of the covering mantle
- Clean the deterioration of the walls and the lintel from dirtiness and molds
- keep checked the deformation of the lintel, protecting it with products



REGULAR

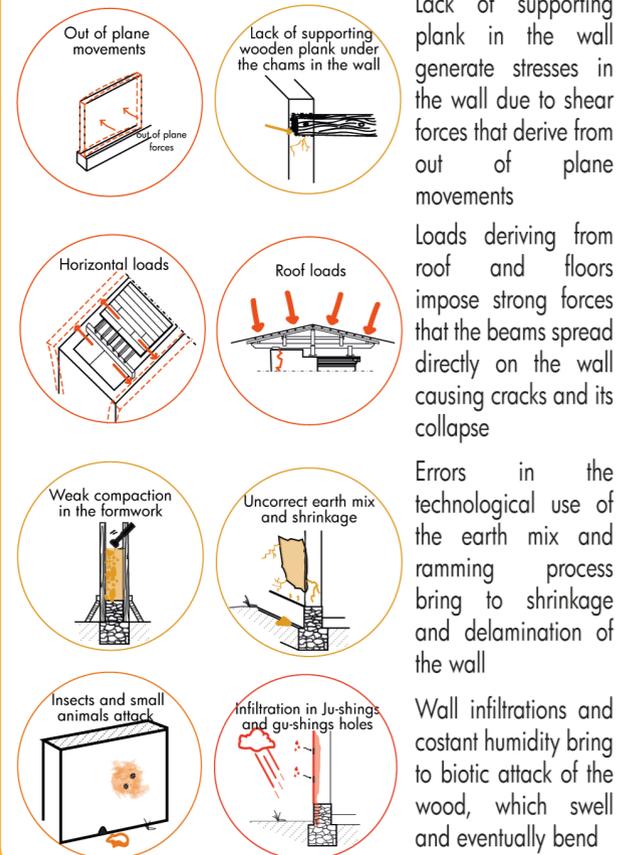
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks with biocids
- control the presence of infiltrations on the façade
- check the eventual formation of cracks in the corners of openings



SPORADIC

- Control the formation decays in correspondance of the pipe

Origin of damage analysis



Damage control actions

- check the structural condition and the presence of moisture in the masonry that leads to the deterioration of the beam (molds, insects, deformations) (REFER TO INTERVENTIONS A.4)
- check the presence of discontinuity in the walls as possible ways of penetrating water inside the building (REFER TO INTERVENTIONS B.2 AND B.4)
- check the presence of molds, efflorescences and dirtyness on the surface (REFER TO INTERVENTIONS B.1)

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage



Description of intervention

The intervention consists in the insertion of a timber plate that support the beam of floors, insted of lying it directly in the wall. In the case of beam deterioration it is necessary to replace it, or if partially, to use a lateral reinforcement with plates.

Workers involved

Time needed

Materials

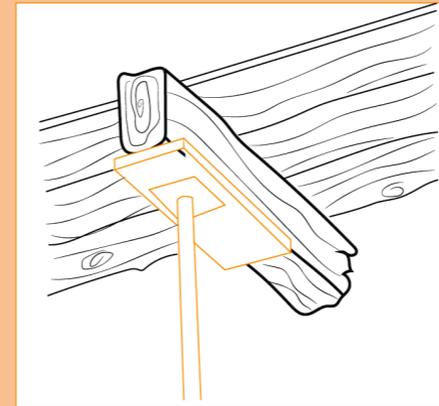
- wooden plates
- chemical treatments for wood
- mortar (see mix composition in appendix)
- lised oil or chemical potector for wood

Working tools

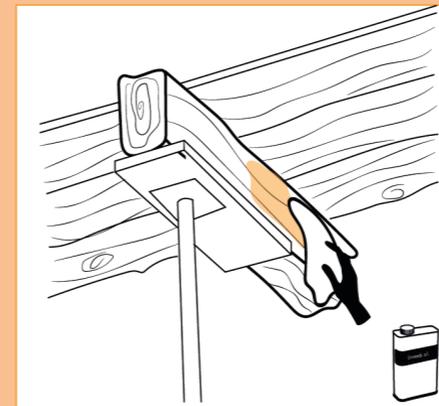
- scaffolding
- chisel
- hammer

- check the presence of cracks and its intensity, the integrity of the wall in relation to shrinkage cracks and delamination (REFER TO INTERVENTIONS B.3 AND B.4)

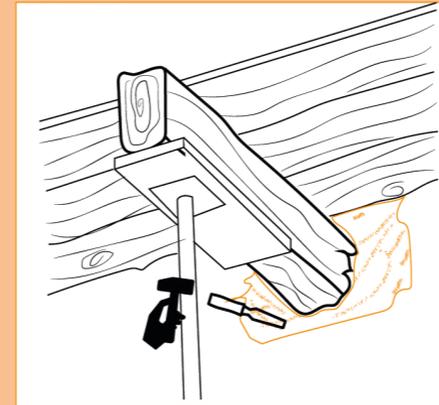
Repair process



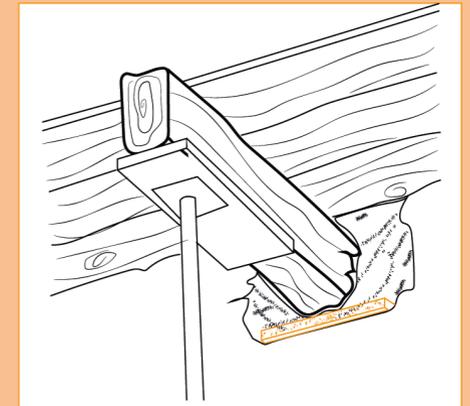
1. Use a scaffolding to hold on beams, if it might need to be replaced, hold on the floor slab



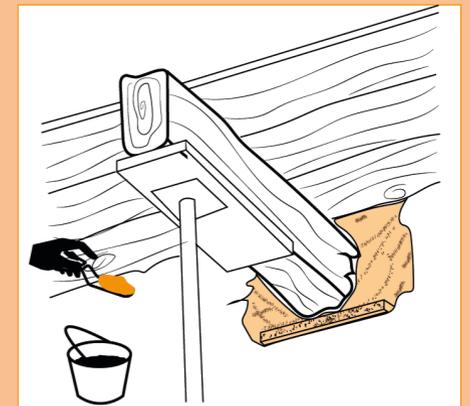
2. Use a protector to clean and restore the wood, it might be linseed oil or chemicals



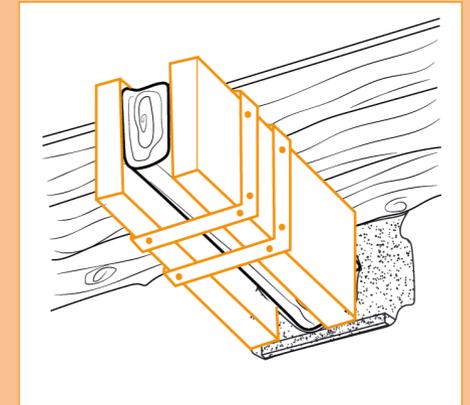
3. Open the slot of the beam in the wall with a chisel and hammer in order to create the space for the support



4. Insert a timber platform as a support element for the beam



5. Fill with compact and plastic mortar, if the hole is to wide use adobe bricks. See intervention C.2



6. If it is not possible to replace the ruined beam, place two wooden supports on the side of the joist, which have to be ironbound around the old one and replace its structural function

Maintenance



FREQUENT

- keep checked the humidity of wall with a visual and tactile control
- control the presence of vegetation and insects that may deteriorate the wood



REGULAR

- control the position of beams in the wall, especially if it create cracks
- Keep checked the water flows from the roof and periodically the deterioration of the covering mantle
- keep checked water stagnation and raising damp



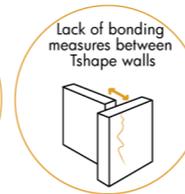
SPORADIC

- if necessary reuse linseed oil ad biocids to protect the beams

Origin of damage analysis

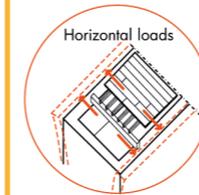


Lack of supporting wooden plank under the chams in the wall

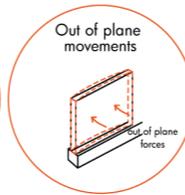


Lack of bonding measures between T-shape walls

Lack of supporting plank and bondings in the walls, generate stresses as shear forces and overturnings that crack or disconnect the T-walls



Horizontal loads

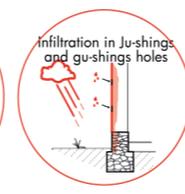


Out of plane movements

Loads deriving from floors and out of plane movements, impose strong forces between beams and walls causing cracks and displacement

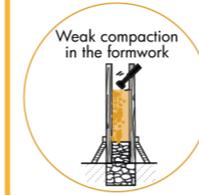


Infiltration in the roof



Infiltration in Ju-shings and gu-shings holes

Wall infiltrations from roof or façade and costant humidity bring to a weak and brittle wall, easy to crack



Weak compaction in the formwork



Uncorrect earth mix and shrinkage

Errors in the technological use of the earth mix and ramming process bring to shrinkage and delamination of the wall

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage



Description of intervention

The intervention consists in the transformation of an existing beam in a chain through a system of anchoring the beam with metal elements (brackets, chains and keys) to the wall structure with an external plate, in order to refrain horizontal loads pushing in orthogonal direction which lead to cracks and bucklings.

Workers involved 

Time needed 

Materials

- metal brackets and chains
- wooden plate
- earth mortar (SEE EARTH MIX COMPOSITIONS REQ)

Working tools

- drilling system
- scaffolding
- trowel and chisel

Damage control actions

- check the presence of cracks, understand the intensity of the damage: depth, width, position. (REFER TO HOW TO READ A DAMAGE P.10-11 AND B4-C1-C2 TO REPAIR)
- check the damages deriving from the lack of bonding measures of walls and horizontal floor (REFER TO INTERVENTIONS C.6 AND C.7)
- verify the working conditions of the wooden structures and the presence of supports (REFER TO INTERVENTIONS A.3 AND C.4)

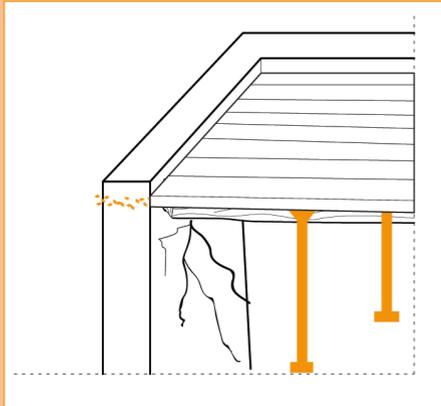
- check the presence of roof leaks and insufficient maintenance (REFER TO INTERVENTIONS A.2 AND A.3)

- check if the wall has been damaged by natural effects such as water erosion, infiltrations from the ground, vegetation on the façade (REFER TO INTERVENTIONS A AND B)

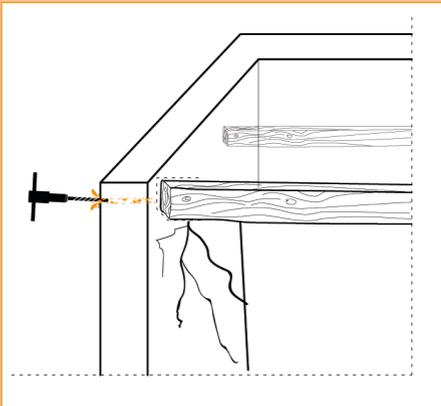
Interventions for structural consolidation of "box system"

Insertion of floor-wall reinforcement : wooden chains

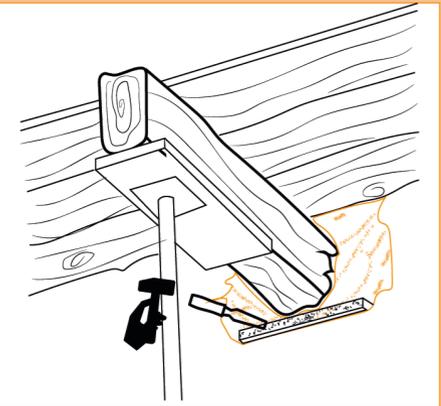
Repair process



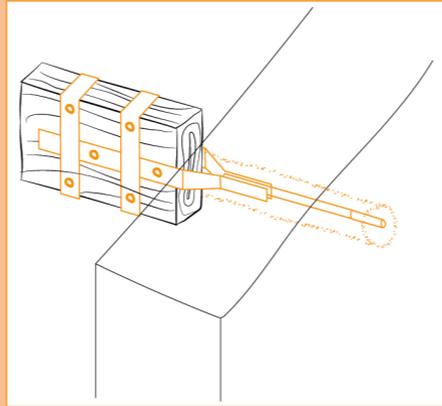
1. Support the wooden floor with a scaffolding. Consider to replace or renovate the beam if damaged.



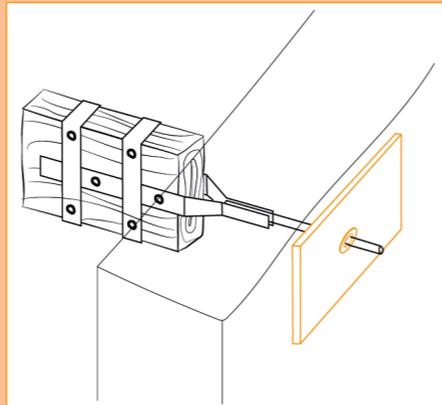
2. Drill the hole to insert the chain in the wall, do not use percussion tools that produce vibrations in the wall



3. Insert a wooden plate that work as a support for the beam in the wall
(SEE INTERVENTION C.4)



4. Bond the clips on the head of the beam with a chain system coming out of the hole in the wall



5. Place wooden support on the wall in correspondence with the metal chain, it is suggested to oversize its dimension to avoid shear effects on the wall



6. Complete with mortar to restore wall continuity

Interventions for structural consolidation of "box system"

Insertion of floor-wall reinforcement : wooden chains

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade
- Eliminates poor drainage issues and pooling water around the foundations



REGULAR

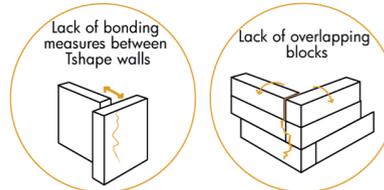
- Check roof leaks, especially before and after monsoon seasons
- Remove animal, and insect attacks
- Control the condition of the wooden elements



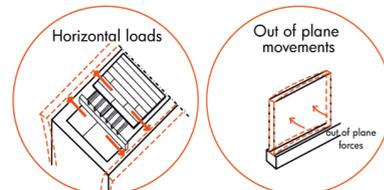
SPORADIC

- Control the position of beams in the wall
- Control the formation of cracks

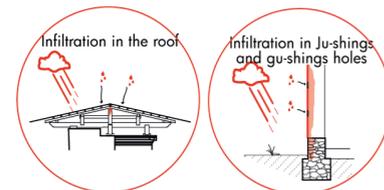
Origin of damage analysis



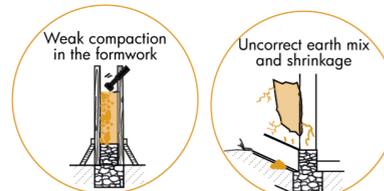
Lack of bondings and overlapping blocks in the corners, generate stresses of overturnings that crack or separate the walls



Loads deriving from floors and out of plane movements, impose strong shear forces between beams and walls causing cracks and displacement



Wall infiltrations from roof or façade and constant humidity bring to a weak and brittle wall, easy to crack



Errors in the technological use of the earth mix and ramming process bring to shrinkage and delamination of the wall

Damage control actions

- Check the aspect of cracks, understand the intensity of the damage: depth, width, position. (REFER TO HOW TO READ A DAMAGE P. 10-11 AND B4-C1-C2 TO REPAIR)
- Check if the damage derives from the lack of bonding measures of walls and horizontal floor (REFER TO INTERVENTIONS C.7)
- Check if the wall has been damaged by natural effects of water erosion, infiltrations from the ground (REFER TO INTERVENTIONS A.1 AND B.2)

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage



Description of intervention

The intervention consists in the insertion of reinforcement systems in the corner to prevent collapses and leaning of the masonry; this time are studied solutions such as the use of external bonding in case of leaning-cracks or internal anchors in the event of collapse and therefore reconstruction of the corner.

Workers involved

Time needed

Materials

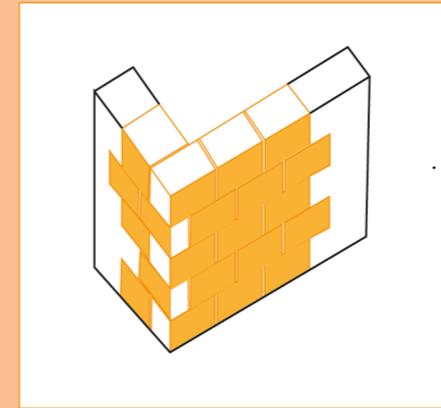
- wooden batten
- bamboo wedges
- adobe compressed bricks
- earth mortar (SEE EARTH MIX COMPOSITIONS REQ)
- nails

Working tools

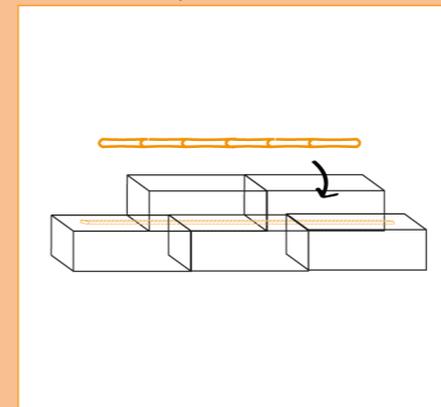
- trowel
- chisel
- hammer

- Check the presence of roof leaks and insufficient maintenance that may lead to infiltrations in the wall (REFER TO INTERVENTIONS A.2 AND A.3)

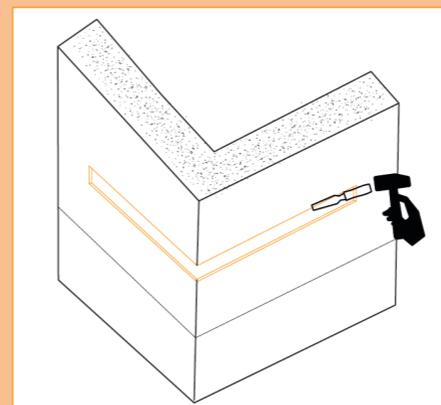
Repair process



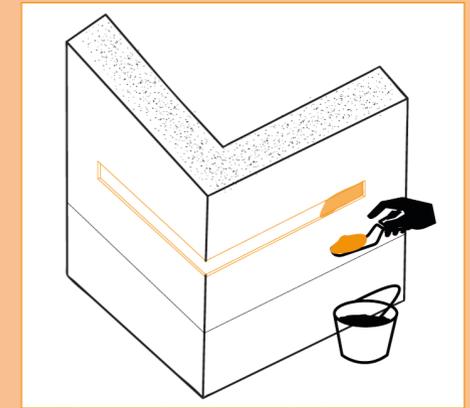
1. Rebuild the corner following "wall reconstruction" intervention C.2. Be sure to overlap adobe bricks.



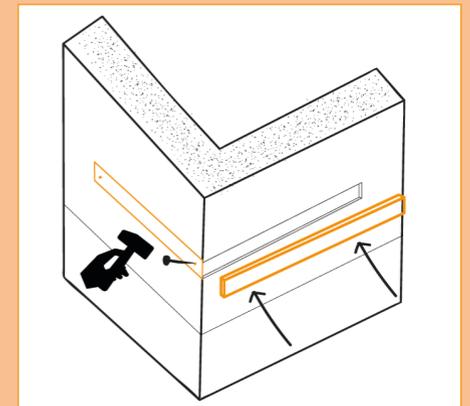
2. Place wooden wedges or bamboo poles between the blocks connecting them to the standing wall



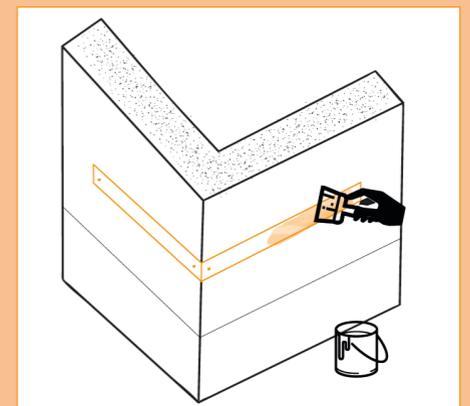
3. Create the space in the wall to insert wooden batten, about 3-5 cm thick at each raw of blocks



4. Place a thin layer of plastic mortar to activate the cohesion



5. Embed the wooden batten into the slit, fixing it with nails on the wall



6. Refill with mortar and protect the wood with painting coat. Eventually cover with mortar and final render. (see intervention B.3)

Interventions for structural consolidation of "box system"

Insertion of reinforcement systems: corner bonding measures

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Check roof leaks, especially before and after monsoon seasons
- Control the formation of cracks



REGULAR

- Control the condition of the wooden elements inserted in the wall
- Remove plants and vegetation on façade



SPORADIC

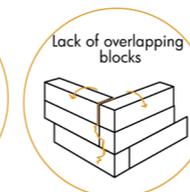
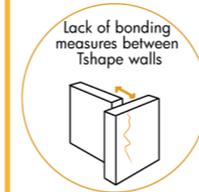
- Control the position of beams in the wall
- Control the movement of the floor slab that may create cracks and overturning

C.7

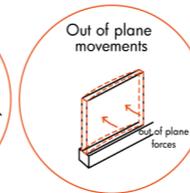
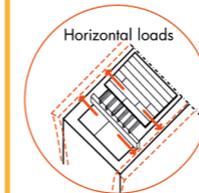
Interventions for structural consolidation of "box system"

Insertion of reinforcement systems: bonding measures between T-shape walls

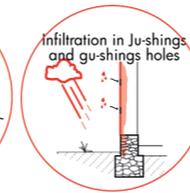
Origin of damage analysis



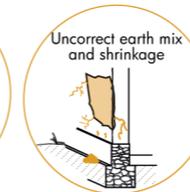
Lack of connections and overlapping blocks, generate stresses as shear forces and overturnings that crack or disconnect the T-walls



Loads deriving from floors and out of plane movements, impose strong forces between beams and walls causing cracks and overturnings



Infiltrations from roof or in the façade and constant humidity bring to a weak and brittle wall, easy to crack



Errors in the technological use of the earth mix and ramming process bring to shrinkage and delamination of the wall

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage



Description of intervention

The intervention consists in inserting a reinforcement system between T shape walls to prevent out-of-plane movements such as buckling and leaning of the structure, through the use of wooden or bamboo wedges and "cuci-scuci" technique with adobe stabilized bricks.

Workers involved

Time needed

Materials

- wooden wedges
- adobe compressed bricks
- bamboo poles

Working tools

- trowel
- chisel
- hammer
- scaffolding
- brush

Damage control actions

- check the aspect of cracks, understand the intensity of the damage: depth, width, position. (REFER TO HOW TO READ A DAMAGE P. 10-11 AND B4-C1-C2 TO REPAIR)
- check if the damage derives from the lack of bonding measures of walls and horizontal floor (REFER TO INTERVENTIONS C.7)
- verify the working conditions of the wooden structures and the presence of supports (REFER TO INTERVENTIONS A.3 AND C.4)

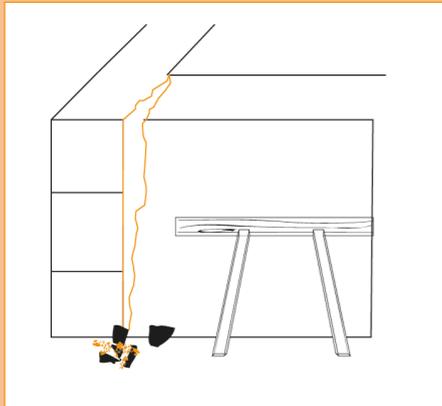
- check the presence of roof leaks and insufficient maintenance that may lead to infiltrations in the wall (REFER TO INTERVENTIONS A.2 AND A.3)

- check if the wall has been damaged by natural effects of water erosion, infiltrations from the ground or formwork holes (REFER TO INTERVENTIONS A.1 AND B.2)

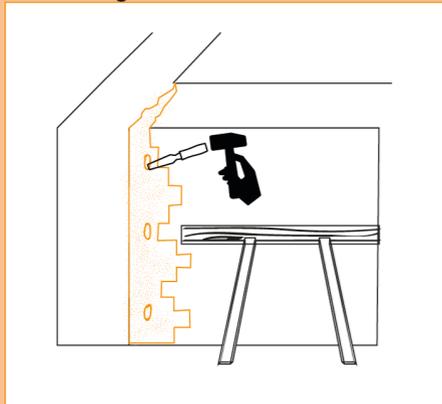
Interventions for structural consolidation of "box system"

Insertion of reinforcement systems: bonding measures between T-shape walls

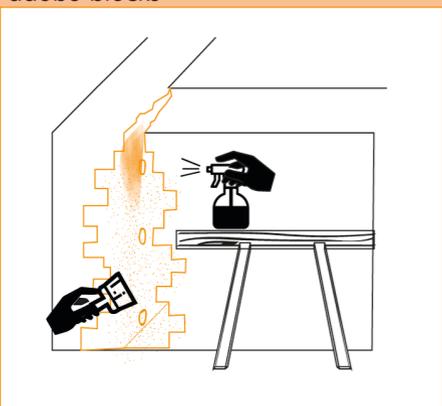
Repair process



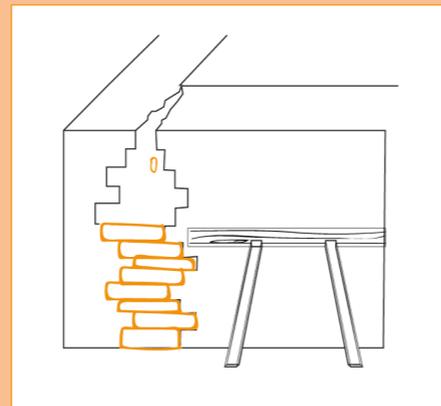
1. Remove all debris and clean the surfaces of the standing walls. If necessary secure the wall with a scaffolding.



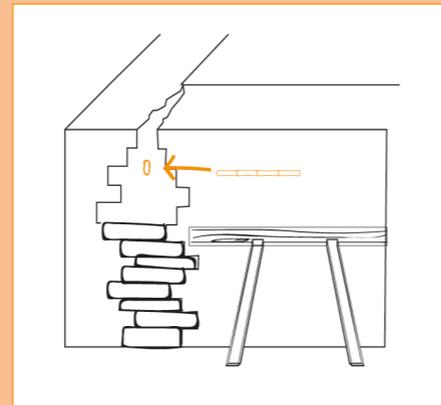
2. Open spaces in the remaining wall to insert the wooden connection in each block on the space for new adobe blocks



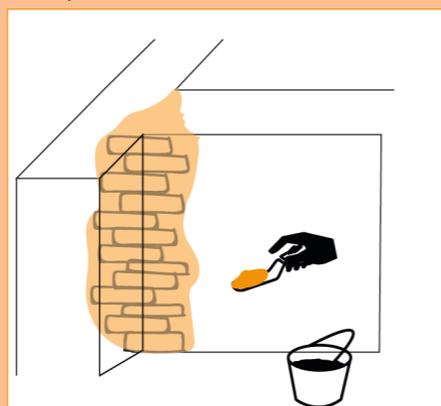
3. Clean the surfaces with a brush and spray water to reactivate cohesion



4. Place Adobe compressed blocks, overlapping them in rows. Lay a layer of mortar at each block



5. Insert wooden wedges in the holes to connect the standing walls with the new part



6. Refill all the spaces with mortar and finish the wall

Interventions for structural consolidation of "box system"

Insertion of reinforcement systems: bonding measures between T-shape walls

Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade



REGULAR

- Check roof leaks, especially before and after monsoon seasons
- Control the condition of the wooden elements



SPORADIC

- Control the position of beams in the wall
- Control the formation of cracks in the position of insertion of bondings

Origin of damage analysis

Lack of bonding measures between Tshape walls
Lack of overlapping blocks in the corners, generate stresses of shear force that may lead to cracks and collapses

Horizontal loads
Roof loads
Loads deriving from horizontal partitions and roof, transmit pushing outwards forces, leading to separation and overturning of walls

In plane movements
Out of plane movements
Movements generated during earthquakes, in plane and out of plane, impose strong stresses on the walls causing cracks and dislocations

Infiltration in the roof
Infiltration in Ju-shings and gu-shings holes
Wall infiltrations from roof or façade and costant humidity bring to a weak and brittle wall, easy to crack

Damage control actions

- Check the aspect of cracks, understand the intensity of the damage: depth, width, position. (REFER TO HOW TO READ A DAMAGE P. 10-11 AND B4-C1-C2 TO REPAIR)
- Check if the damage derives from the lack of bonding measures of walls and horizontal floor (REFER TO INTERVENTIONS C.5 AND C.6 AND C.7)
- Check if the wall has been damaged by natural effects of water erosion, infiltrations from the ground (REFER TO INTERVENTIONS A.1 AND B.2)

Classification of damage

High potential of damage, involving structural injuries such as profound cracks and collapses

Intensity of damage  HIGH

Description of intervention

The intervention consists in the bandage with elements of material resistant to tensile strength of the masonry box to avoid that the deformations and movements connected to cracks and of instability under the effect of excessive loads.

Workers involved 

Time needed 

Materials

- bonding fibres (hemp has a better tensile strenght, but also jute can be considered)
- plastic mortar (SEE EARTH MIX COMPOSITIONS REQ)
- nails

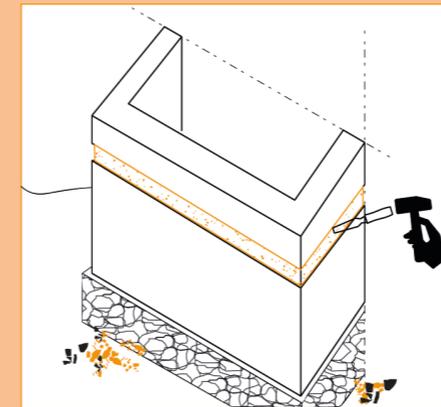
Working tools

- trowel
- chisel
- hammer

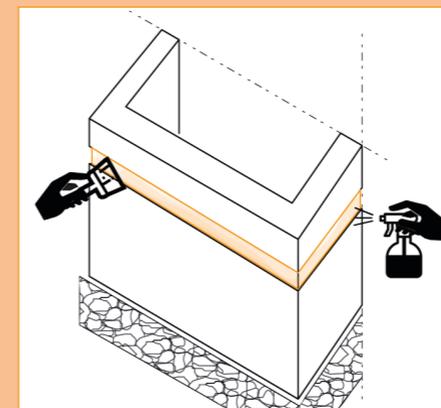
- Check the presence of roof leaks and insufficient maintenace that may lead to infiltrations in the wall (REFER TO INTERVENTIONS A.2 AND A.3)

Repair process

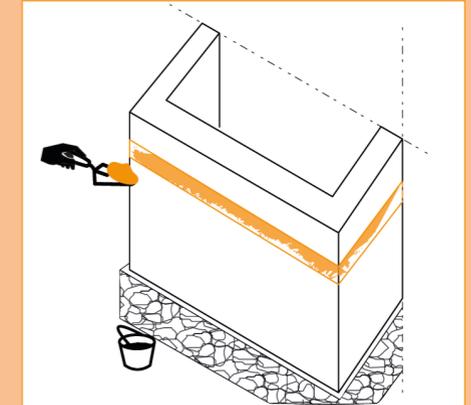
1. Before making structural consolidation with fibers bonding, it is advisable to consolidate any damage found in the masonry, stitching all the cracks and failures.



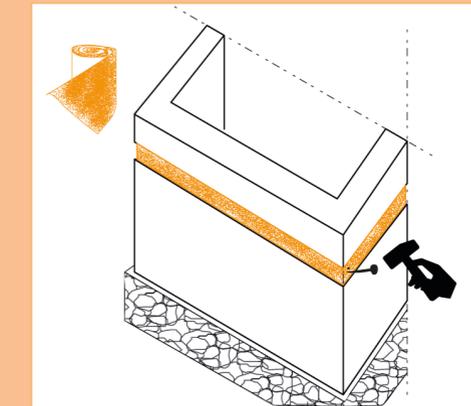
2. Make an excavation of about one cm deep and round the edges where the fiber is going to be positioned. It would be appropriate to apply it in correspondence of the floor to counteract horizontal loads



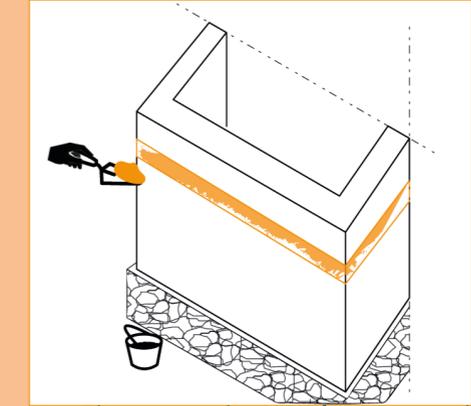
3. Clean the slit from debris and humidify with water spray



4. Apply a thin layer of mortar to activate the cohesion between wall and the fibers.



5. Position the fiber around the building, taking care to put it in light traction. You can use small nails to fix it and tighten it. It has to be considered also the use of polymeric resins



6. Place more layers of mortar and fibers to strengthen the reinforcement. Cover the final layer with a protective mortar.



Maintenance



FREQUENT

- Keep checked the humidity of water infiltrations from ground with visual and tactile control
- Check roof leaks, especially before and after monsoon seasons
- Remove plants and vegetation on façade



REGULAR

- Control the formation of cracks, particularly in correspondance of the fibers
- Keep clean and eventually restore the protective layer of façade



SPORADIC

- Control the position of beams in the wall
- Control the movement of the floor slab that may create cracks and overturning
- Control the resistance of the bonding with fibers

Appendix

Maintenance actions

Earth mix compositions requirements

Field tests

 **Maintenance**



FREQUENT

- Keep checked the humidity of the wall due to infiltrations from ground with visual and tactile control
- Remove plants and vegetation on façade
- Eliminates poor drainage issues and pooling water around the foundations
- Keep checked the water flows from the roof and the deterioration of the covering mantle
- if necessary reuse linseed oil and biocids to protect the beams



REGULAR

- Check the stability of the pipes after strong monsoon season and the connection of the pipes
- Clean the deterioration of the walls from dirtiness and molds
- Keep clean and protected the wooden beams to prevent putrefaction
- Keep checked the function of the drainage pipe and the soakaway, removing leaves and seeds that have stuck in



SPORADIC

- Control the formation of decays in correspondance of the pipe
- Control the position of beams in the wall, if it has changed its position
- Control the formation of cracks in the position of insertion of bondings
- Control the movement of the floor slab that may create cracks
- Control the resistance of the bonding with fibers, if they are well stucked to the wall

Soil composition is made up of four main particle types, classified according to size: **gravel, sand, silt and clay**.

Each particle type plays an important role in the structural integrity of rammed earth such as gravel is the main part and provides the structural stability of composition, together with sand, it also enhances weathering resistance of exposed surfaces. The clay and silt are the binding agents that hold the material together and are responsible of plasticity index and shrinkage.

Rammed Earth

Sand and gravel 40-60%



Silt 30-35% max



Clay 20-25%



Water 12% is recommended

The mix has to be wet, not too dry nor plastic.

See Soil tests

Adobe blocks

Sand and gravel 55-75%



Silt 10-30% max



Clay 15-18%



Water 15-30%

The mix has to be wet and plastic.

Contains less amount of clay because of shrinkage

Compressed stabilized earth blocks

Sand and gravel 45-80%



Silt 10-25% max



Clay 20-30%



Water 4-8% is recommended

The mix has to be slightly wet in order to be easily compacted in the press machine

Mortars and plaster

Sand and gravel 55-75%



Silt 5-12%



Clay 5-12%



Lime 6% can be added



Water 16-20% is recommended

The mix has to be wet, plastic and cohesive, or more liquid for small cracks.

Soil tests are always recommended for correct identification of different particles amount.

Simple Field Tests to Determine Material Composition of Earthen Structures

The original composition of the materials used to build the rammed earth structure must be understood for its proper repair. Often, simple field tests can determine the makeup of the materials. The performance of more extensive laboratory testing is also possible.

Soil identification

Dry sieving: Particle size

- Clays: $\leq 0,002$ mm
- Silts: $> 0,002$ mm to $0,02$ mm
- Sands: $> 0,02$ mm to 2 mm
- Gravels: > 2 mm to 20 mm

Colour inspection: colour from white-gray to yellow-red, depending on the content of iron; Reddish earth of rural areas in Bhutan are preferred.

Cutting: Form a ball of soil sample and cut it with a knife: if results are shiny cut surface= high clay content. If the surface is dull it has a high silt content.

Sedimentation: put some soil sample in a jar with large quantity of water, shake it and allow sample to settle. Stratification occurs with the largest particles settling to the bottom of the jar first, then the other thinner parts above mixed with water. The good proportion of the constituents of the soil can be estimated on the coherence of the mix.

Ball Dropping: Form a ball with the hand and drop onto a flat surface from a height of 1 meter. Minimal cracking= high clay content/ high binding force -> add sand
Cracking and some crumbling= good clay content/soil suitable for rammed earth
Many pieces of crumbling= low clay content/ low binding force -> add clay

Ribbon test: Roll a part of soil sample into a 3 mm diameter rope without breaking. Form a ribbon that is approximately 6 mm thick and 2 cm wide. Hold it in the hand and slid the ribbon allowing it to drop until it breaks. If the free length before breaking is more than 20 cm, the soil has a high clay content; if the ribbon breaks after only a few centimeters, the mixture has too little clay.

Conclusions

The traditional buildings scattered in the rural valleys of Bhutan, generally consisting of structures in rammed earth and wood, despite their simplicity of construction techniques and forms contribute to give its landscape identity whose protection and conservation is a necessity strongly felt, especially in connection with the earthquakes that devastated the country.

With this aim, the manual for the recovery and maintenance of buildings was born as a tool to suggest to the population a correct approach to the resolution of damage and intervention projects on their homes, addressing the most common problems that are encountered, concerning the general degradation of building but also and above all to a structural rehabilitation.

The manual is therefore based on the awareness that before starting a damage it is necessary to know it thoroughly and to investigate not only the evaluation based on the evident effect of the damage but also the causes that lead to it and therefore the constructive modalities of the damaged part. In fact, first of all a path of analysis and knowledge is suggested that tends to strongly highlight the correlation between causes and effect divided into natural and human factors; then follows a careful description for the identification of the severity of the damage and of the typical fractures found in buildings in raw earth.

The text reflects the attempt to propose a path for analytical evaluation of problematic issues rather than an example of cases for the resolution of damages; in fact, the characters of the drawings are very simple and essential as well as the descriptive contents that accompany each worksheet for the repair interventions, so that even the population and craftsmen can find an effective help for the self-repair. For ease of consultation it is divided into chapters

called intervention worksheets, specifically to solve problems related to humidity and water infiltration, a part related to the restoration of superficial façades and a specific section to investigate the behaviour of the structure and possible constructive defects also in relation to the previous ones.

Another objective of the manual is to sensitize readers to careful periodic maintenance and preventive control not only for damage but for the prevention of the development or the aggravation of those present.

Concluding it can be said that the manual will serve as the basis for the development of an anti-seismic culture, with methods of greater self-awareness of the damage and the technologies of the dwellings in which they reside, for the recovery and conservation of existing earth buildings. In fact, this research will be made available to the group that is currently doing research in the territory of Bhutan for the development of repair and new construction manuals with local building techniques, who will verify by means of laboratory and field experiments the effective effectiveness of the proposed solutions and to develop in the future a real manual that will be entrusted to the Bhutanese population and its local builders.

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