THE ANTI-SEISMIC CAPACITY AND ENHANCEMENT OF EARTHEN STRUCTURES.

Earthen Architecture for the Urban Context of Bogotá, Colombia.

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This thesis is dedicated to my parents and sister, for their unconditional support during my career and for always motivating me to keep going.
I am grateful with all my friends for their unconditional company and support, not only during the development of the work done.

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Thanks to Luciana Restuccia, the experimental proposals would have not been possible without her collaboration.

The graphical and technical information of the present thesis is based on several authors, are highlighted:

- **BLONDET.** Manual de construcción con adobe reforzado con geomallas. Lima : Pontificia Universidad Católica Perú., 2010.
- **CARAZAS and RIVERO.** Bahareque: guía de construcción parasísmica. Villefontaine Cedex, Francia: CRATerre, 2002.
- **HOUBEN and GUILLAUD.** Earth construction: a comprehensive guide. Villefontaine Cedex: CRATerre, 1994.
- **MINKE.** Construction manual for earthquake resistant houses built of earth. s.l. : BASIN, 2001.
- **Ministerio de Vivienda, Construcción y Saneamiento, Perú.** E.080 "Diseño y Construcción con tierra reforzada". Lima : s.n., 2017.
- **RUIZ, LÓPEZ and RIVERA.** Propuesta de normativa para la rehabilitación símica de edificaciones patrimoniales. Bogotá : Revista Apuntes, 2012. pp. 226-239. Vol. 25 (2).
- **YAMIN, et al.** Estudios de vulnerabilidad sísmica, rehabilitación y refuerzo de casas en adobe y tapia pisada. Bogotá : Apuntes, 2007. pp. 286-303. Vol. 20.
- **BOLLINI.** Terra batutta: tecnina costruttiva e recupero. Milano: Edicom Edizioni, 2013.
- **RESTUCCIA and FERRO.** Nanoparticles from food waste: a "green" future for traditional building materials. Torino: Politecnico di Torino, 2016. 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures.

Abstract

In consideration of the sustainable advantages of earthen construction, there is questioned the feasibility of an earthen building in the urban context of Bogotá, Colombia. Several aspects of earthen buildings and Bogotá's context are analysed: the construction process of earthen buildings, the constructive regulations and earthen traditions in the country, and the geographical and socio-economic conditions in Bogotá. Hence is made a research on the main earthen techniques of the country: tapia (rammed earth), adobe, bahareque and CEB, their characteristics and construction processes are shortly described in order to find why these are not largely used in cities. In coherence to the seismic hazard of Colombia the investigation has special focus on the structural and anti-seismic capacity of earthen architecture, as an aspect that requires enhancement to enable earthen buildings to be constructed in Bogotá. Thus the present document is proposed as a manual of anti-seismic solutions for earthen buildings. There are identified three main strategies to enhance the earthen buildings in seismic zones: the entire building behaviour; the box-behaviour of the structure; and the enhancing of load-bearing wall strengths. Furthermore than the appropriate constructive procedures, this investigation was deepened in the enclosing reinforcements for earthen load-bearing walls. Based on structural reinforcements for generic plasters and the mechanical enhancement of cementitious composites with micro inert biochar additive, here is proposed as technological innovation the experimental investigation to test an earthen plaster enriched with biochar additive (EPEB) expecting it can contribute to enhance the structure stability during earthquakes.

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Foto from the author.

1. INTRODUCTION

The passive and vernacular technologies in architecture are known for their excellent thermal behaviour, low environmental impact and their cultural value. Mostly, the contemporary projects that has been developed using vernacular technologies are referred to rural environments, solving important problematics as scarcity of resources, lack of facilities or low-income dwellings. However, if one of the goals of architecture for the sustainability is to contribute in a good way to the climate change, why not to focus these efforts also on big cities where are produced the most robust impacts? Hence, the starting point of the present research is to identify the possibilities of enhancing earthen material to increase its feasibility as architectural technology for urban projects.

Considering (i)the historical influence of the modern movement, the industrialization and the globalization on developing countries; (ii)the lack of investigations on earthen technology for architecture; (iii)the nature of traditional earthen architecture as a vernacular technology ; (iv)and the nature of a big urban context that is heterogeneous and full of industrialised materials, the first proposal of the present document about the feasibility of an earthen project in a high density city may seem to be incoherent. Nevertheless, the point in common of all those aspects is the actual scenario of climate change, the influence of the cities in sustainability affairs, and the advantages that earthen construction technology can offer for a more sustainable architecture.

On that way, there appears punctual aspects that has to be solved to enable the real use of earthen construction in a city. Which are the limitations of the raw earth technologies and how can they be overcome to include those projects in a city context? There are already regulations that standardize the use of this technology? Which are the weak points of an earthen building and how can be enhanced?

To solve these and further questions, this work is limited to a physical context, hence there can be evaluated real aspects that are not allowing the raw earth techniques to be widely used in urban fabrics. Is chosen the city of Bogotá, capital of Colombia, as urban scenario to hypothesize the use of earthen technology. Is a typical Latin American capital that offer a dramatical complexity considering social, political, economic and cultural aspects. As a city of a developing country, Bogotá has big inequalities that are evident in the city architecture. Millions of people live in self-construct houses that probably are not following constructive regulations. Consequently is notable the extended use of earthen technologies on developing countries as economic solutions that present dignity conditions for the inhabitants.

On the other hand, Colombia has a huge heritage of traditional earthen technologies (Tapia -rammed earth-; Adobe -raw earth bricks-; Bahareque -wood & raw earth-) that, as in different parts of the world, had lost importance and were near to disappear because of the industrial revolution and the modernist movement. Treasuring those techniques and considering a contemporary one (CEB -compressed earth blocks-), the present research is focused on them. To create a complete understanding of these techniques, here is made a description of their designing and construction process. From that is expected to identify weakness and thus propose solutions that can be implemented to increase their availability to be use in Bogotá.

To focus even more the investigation, there are identified limitations that earthen buildings has when are proposed into urban contexts, thus the present research can be focus on one of them. First, considering that Bogota is located in the high seismic region of the Andes, is necessary the use of anti-seismic strategies into the building construction, these can be based on several investigations or regulations. A second obstruction is the restriction of finding the material, as all the surroundings in a city plot are already constructed and the transportation of soil can increase costs and energy consume. This limit the use of the raw earth to peripheral areas where can be easier to find nearest material sources. In addition is evident the ignorance about this technology. Is possible to say that generally architects, engineers, workers, or even the inhabitants have not enough information about earthen buildings and these are widely related to poor constructions that are not "safe" or well seen. Finally, as earth is not a spread material for construction there is a lack of products and solutions offered from the constructive industry (tools, materials or technical solutions to be used in construction site).

In light of above it was early understood the need of an analysis of the seismic-resistant behaviour of the raw earth constructions. Earthen buildings are vulnerable to seismic loads due to three main aspects: the performance of the entire building in relation to the type of structural system which is limited by the lack of tensile and bending strength of the material.

The anti-seismic reinforcements for earthen architecture that are found in literature are organized on three strategies that regards the vulnerabilities of earthen buildings under earthquakes: the understanding of the building as a whole by a building behaviour strategy, a structural strategy to guarantee the box-behaviour, and a load-bearing wall strategy referred to the strength's enhancement of the main structural elements. Under these three main strategies the present research is presented as a compilation and a guide of appropriate construction methods for earthen buildings on the seismic hazard zones of Colombia, with a large focus on the anti-seismic strategies and reinforcement.

Unfortunately, in Colombia there is a lack of regulations for raw earth buildings even on what concern to seismic safety (on new or heritage buildings). The current anti-seismic regulation "Reglamento Colombiano de Construcción Sismo Resistente 2010" (NSR-10) does not present any chapter related to earthen techniques. However, in several Latin American countries there have been developed studies, investigations and even laws that create a framework about the raw earth seismic capacities and the solutions that can be applied to improve the building respond to an earthquake. These are considered as solutions that can be applied in Colombia to construct seismic resistant earthen buildings.

Nevertheless, this work is not the first approach to anti-seismic earth constructions in Colombia. There is a group of architects and engineers that are proposing a new regulation to include earthen buildings in the seismic-resistant construction regulation (NSR-10). The present research is also based on the work of those colleagues, and it is expected this document can be presented as support to the regulation that they are developing. This situation frames the current work into a contemporary and real scenario of our profession.

From the investigation related to load-bearing wall strategy, are identified the "enclosing reinforcements" as an effective opportunity for raw earth buildings. With this identification, the research studied the possibilities to improve earthen plasters that – as the mentioned reinforcements – naturally enclose all the wall elements. In cooperation with Luciana Restuccia from the department of structural, building and geotechnical engineering (DISEG) of Polytechnic of Turin, is considered the use of biochar particles that can be added to the plaster mixture. The investigations carried by Restuccia confirm an enhancement of the mechanical strengths in cementitious composites. In that sense, as starting point for further researches there is proposed an earthen plaster enriched with biochar additive (EPEB) pretending to find an improvement on the mechanical strengths of the plaster and the entire earthen wall under seismic conditions.

Abbreviations:

- Compressed Earth Blocks (**CEB**)
- Base course grid (**BC grid**)
- Phase change material (**PCM**)
- Earthen plaster enriched with biochar (**EPEB**)
- Pontificia Universidad Javeriana, Bogotá (**PUJ**)
- Pontificia Universidad Católica del Perú (**PUCP**)
- Universidad Nacional Autónoma de México (**UNAM**)
- Centre of investigation in materials and civil constructions of Los Andes University (**CIMOC**)

2. RESEARCH CONTEXT

The present chapter expose the reasons that support the development of the current work for the Colombian context considering: the earthen construction technologies as a possibility to the low income population that nowadays lives in informal constructions in Bogotá; the excellent sustainable characteristics of the earth as construction material; its importance as a vernacular architectural, cultural and historical heritage; and the contemporary proposal of a seismic-resistant regulation for earthen buildings in the country.

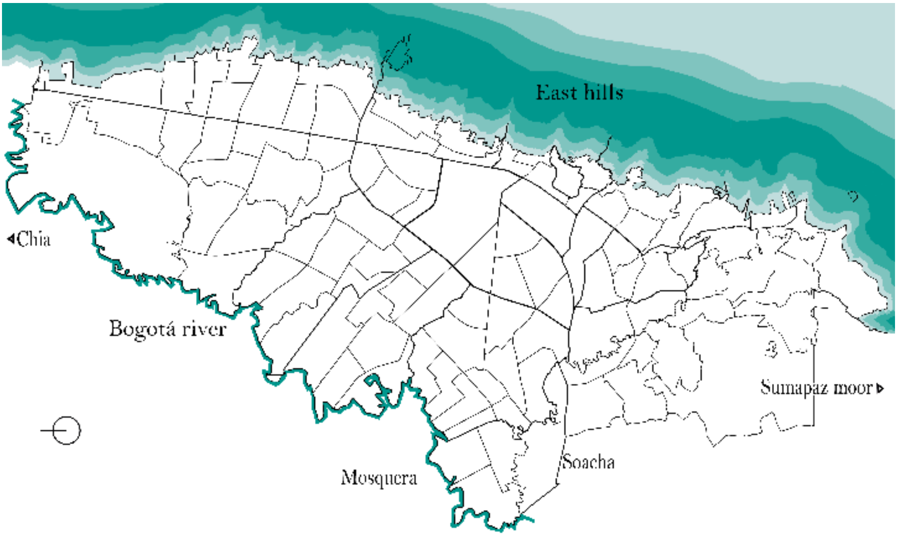
2.1 Bogotá

Located in the centre of Colombia, in the Andes region, Bogotá is at 2640 meters over sea level, has a constant temperature during the year (10-20°C). Geographically is limited by the east hills and the Bogotá river (west of the city) both in a N-S direction. In the south, the urban fabric limits with the bigger moor in the world, the 20th district of the city "Sumapaz". In the north Bogotá is limited by the city of Chia that currently is a suburban city near to be conurbated, as it happened with Soacha and Mosquera in the south-west boundaries (Img. 1).

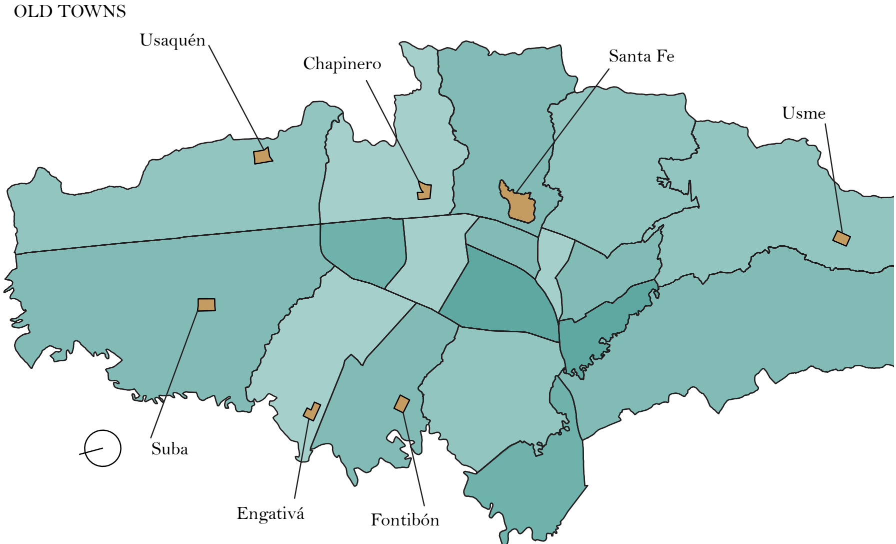
The capital of Colombia is one of the biggest cities in Latin America and the world, has eight million inhabitants with a density around 300 and 100 habitants per hectare (1). During that period in Colombia there were 8'082,033 people forced to leave their houses in rural areas and to go to the big cities as Bogotá, Medellín, Cali, Bucaramanga (2). That phenomena make the city became a real metropolis with several variations on its population regarding cultural, social and economic aspects. In the image 2 is possible to see how the city of Bogotá had grown suffering conurbations with 6 little towns that during the 60's and 70's were going to become districts of the city, today it has in total 20 administrative districts (3). Nowadays in these colonial and historical towns is easy to find examples of earthen buildings that are evidence of the possibility of use that technology in Bogota context.

Historically the city has had several designs and master plans, but the different factor that mark the growing process of the capital did not allow those master plans came to life in a complete way, that is why is possible to understand that a big percent of the urban fabric has not had real planning. It has been constructed by independent developers and – with informal construction – by people that were arriving to different city areas.

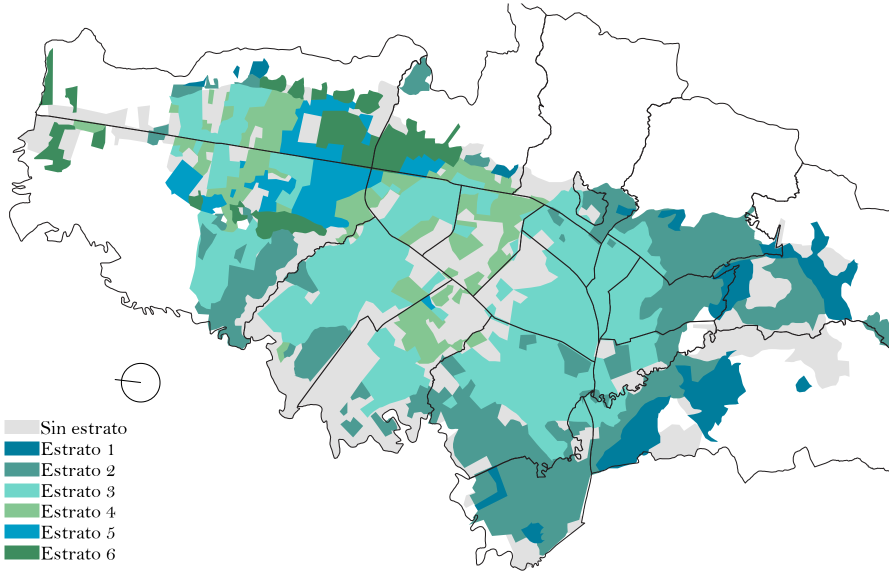
As in many cities of Latin America, in Bogotá is usual to find drastic inequalities: social ones, infrastructure ones, in the public space, and so on. Because of administration issues of the city, it has been used a model that divides the city in 6 "strata" that are used to organize the taxes collection (Img.3). Unfortunately, that administration solution is strongly reflected in the quality of urban spaces and the urban behaviour of the different areas of the city. Mainly, the peripheral areas, south part of the centre and in general the south and west are related to low income people and low urban quality, as centre area and north of the city has good infrastructure, high quality of urban spaces and there is located the high-income population.



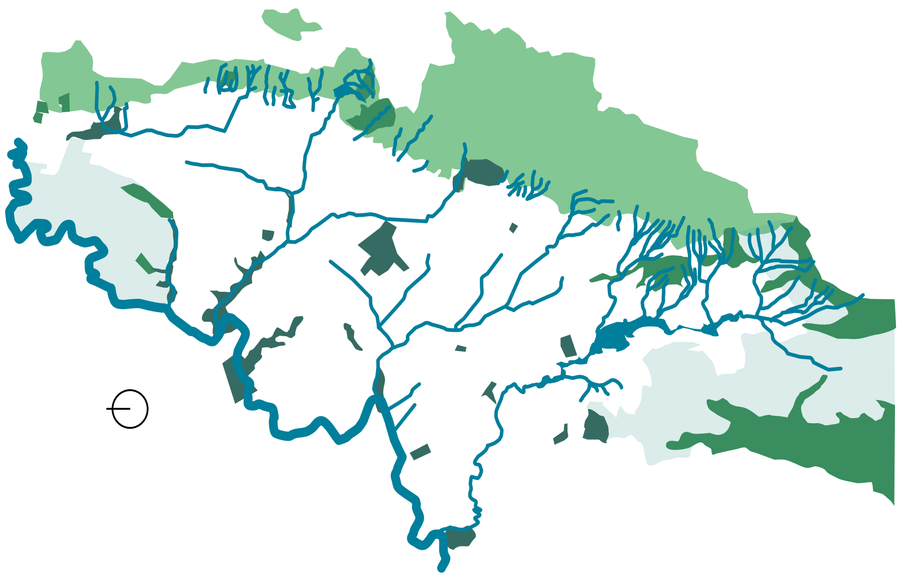
IMG 1. Limits of Bogotá city.



IMG 2. Conurbated towns by the growing process of Bogotá.



IMG 3. Economic strata in Bogotá. Image redrawn from: Secretaria de planeación,2017.



IMG 4. Ecological structure of Bogotá. Image redrawn from: Cámara de comercio de Bogotá,2013.

In coherence to that and the economic input on peripheral areas of the city, the use of earthen techniques can be considered an appropriate solution to construction needs. The same image shows the 1-2-3 strata as majority of the city, there the potential of using raw earth technologies in cities as Bogota.

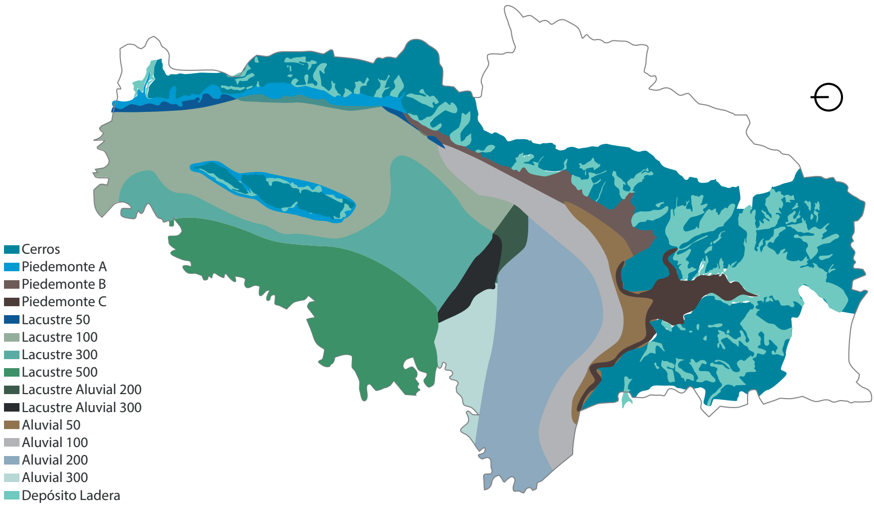
The original territory of the city was really a swamp and that is why the first location of the city was not near to the Bogota river but in a dry area near to the mountains. From the east hills are streams that flows to find the main river, some of those streams create 12 different swamps (Img.4) (4). As consequence of that natural condition of Bogota's territory the soil that is supporting the city nowadays is rich in clay, silt and sand.

That rich water structure of Bogotá has an important influence in the composition of the soil that is currently supporting the city. The soil composition in the lower part of the city, where the water has had influence, can reach 600 meters deep fundamentally of clay, and some strata of sand and organic earths, as it is explained before that layer decrease slowly until it arrives to the east hills, where disappears leaving space to a solid rock as ground composition (5) The law "Decreto N°523" of December 16, 2010 creates a new map with the micro zones of Bogotà according to the ground composition. The emphasis of that law and studies is preventive for earthquakes scenarios, but supply's the aforementioned ground composition in each area of the city (Img.5) (6).

2.2. The raw earth as vernacular constructive technique in Colombia

The vernacular architecture has been internationally defined from different authors as: the architecture "[…] native or unique to a specific place, produced without the need for imported components and process, and possibly built by the individuals who occupy it." (7). Cirvini said that the concept of vernacular implies the consideration of: "a) Building practices are related to popular wisdom, which is transmitted through tradition, with scarcely or no professional intervention during each construction stage. b) Native materials and technologies that fit the local bioclimatic features […] c) These types of building practices are mainly related to rural areas, where the modernization of construction technology has not arrived." (8). Related to the Colombian context it can be also understand as popular architecture "[…] that collected the contributions of the historical social development of Colombia transforming it into urban architectural constructive and ornamental traditions proper of the different regional communities" (9).

It is incorrect to define vernacular architecture just as the finished architectonic object; is preferable to understand it as the local and traditional methods employed to construct a building that, by its architectural typology, is going to respond to the place identity and local culture. The intervention of the inhabitants of the building in a self-construction operation are a fundamental part of vernacular architecture, not only because of the typology, technology and aestheticism of the physical result but also because of the tie that is created during the process between the architectonic object and the community that surrounds it.



IMG 5. Bogotá ground composition. Image redrawn from: El espectador, 2011

In Colombia earthen buildings were widely constructed during the colonial period as they were common techniques and the Spanish invaders used them to establish cities centres and monumental architecture as churches, abbeys or governmental buildings. The heritage department of culture ministry declared that traditional earthen techniques makes up 80% of the national monuments and historic urban centres of Colombia, some notable examples are in Barichara, La Candelaria, Popayán, Salento, Villa de Leyva, Zipaquirá, etc. (10).

According to that the earthen constructive techniques represent an important social knowledge. Hence, the academy community has valued the earthen architecture and started to study and catalogue it to protect the physical, technological and cultural heritage that it represents. The present work is focused on technical aspects that can ensure the well standing of earthen buildings under seismic loads, thus is expected to contribute to the aforementioned protection of earthen architecture as vernacular heritage.

"Nunca nadie ha demostrado que la tierra como material de construcción no sirve o que sus sistemas constructivos son inseguros." (11)

(No one has never proved that the earth as material for construction is not useful or that the earth construction systems are unsafe.)

2.3. Regulations for earthen construction

Considering which are the technical requirements and aspect to propose an earthen building in an urban context it was noted soon the need of a normativity, or any kind of regulation that can suggest how earthen buildings can be constructed on seismic hazard zones. In the punctual case of Bogotá there is not any architectural, structural or even environmental regulation specified to raw earth construction. The actual law of construction in Colombia, specifically the seismic resistant one (Reglamento Colombiano de construcción sismo -resistente NSR-10) does not have any chapter or topic that includes the earthen architecture, even for heritage restoration (10; 12).

In comparison to other materials the regulations related to earthen constructive techniques are limited in the word. During a research related to this topic were identified just 55 documents (laws, regulations, standards) in all the world. From those documents just 21% treat more than one technique (rammed earth, adobe or CEB), and just 26% is referred to adobe or rammed earth, all the others are just for CEB, bahareque technique was not considered during the aforementioned study (13).

Even if (13) confirmed the Peruvian (E.080) and New Zealand (NZS 4297-4299) regulations are the only ones related to seismic zones, in relation to Colombian seismicity can be also interesting the case of Turkish and Italian regulations which are also countries with important seismic hazard. However, those are not focused on anti-seismic issues or are not available on world languages (13).

IMG 6. Social housing projects in Antioquia.
Image taken from: RIVERO et, Al. 2007.

In the Latin America context, the earthen constructions have been studied since the end of the last century, the first investigations were developed by the Pontificia Universidad Católica del Perú (PUCP), the Pontificia Universidad Javeriana de Bogotá (PUJ), and the Universidad Nacional Autónoma de México (UNAM). In the region have been seminaries of seismic-resistant constructions in earth (Seminario Latinoamericano de construcciones sismo-resistentes en tierra), since one in Peru, 1984 (14). These universities and seminaries defined fundamental aspects to create the bases for seismic-resistant solutions and reinforcements the earthen techniques.

Is important to announce the work that has been creating a law proposal to be include in the NSR-10, with the objective to establish, at least, basic parameters to enhance the seismic-resistant safety in the earth buildings. As the main focus of the law proposal is the existent heritage buildings, there are discarded some reinforcement techniques that are not suitable to heritage because of its cultural or historical value, e.g. walls with frescoes (15). However, for the current research most of the reinforcement techniques can be applied to new buildings offering various design possibilities.

The team that is developing that work is conform by architects and engineers from different universities, organizations, associations and offices. Are highlighted Cecilia López from PUJ, Nancy Camacho from the Escuela Taller de Boyacá, the engineer Oscar Medina from the Culture Ministry, and the Colombian association of seismic engineer (Asociación Colombiana de Ingeniería Sísmica) (15-16). In light of above is verified this topic can be considered an important and contemporary issue, there are colleagues that are working deeply in earthen constructions technology. It shows the path that is following the raw earth architecture in Colombia and the future possibilities to this kind of projects.

On the other hand, the only law that is relative to the earthen construction in Colombia is the NTC 5324, "Bloques de suelo cemento para muros y divisiones" (Ground-cement blocks for walls and divisions). Unfortunately the normativity is limited to the production of the CEBs and it has not any recommendation or guideline to the use of them on construction (17). Anyway, it has an important value because it allows the industry to offer CEB as a construction product of the market. As Rivero said, once the government notice the importance of earthen techniques in the popular construction, and if any relative law is developed, then the material production, the industry, commercialisation, the research and proposals, and in general all the construction sector is going to open to earthen material (11).

In Colombia is possible to find ONG's that are working to construct social housing and private projects with earthen techniques e.g. Tierra Viva had construct projects focused on the relation that low-income social groups can have with the earthen architecture. They developed a social dwelling project that completed 250 houses in Vegachí and other 70 in Sonsón, Antioquia (Img. 6) (11). Unfortunately outline information about those projects that surly had an important social and economic impact is not that easy, probably because in real law terms are not regulated as they were supposed to be.

Other distinguished organizations that are working with raw earth are Habit Tierra and PROTerra (the representation of CRATerre in Latin America). PROTerra is related to investigations and researches, they carried the production of manuals for earthen construction (16) that offers recommendations for a well construction of earthen buildings (18), those are also referenced in the present work.

In light of above this document is presented as a structural and constructive manual of anti-seismic reinforcements that can be applied to new constructions made with earthen technologies in Colombia. The importance of the current manual remains on offering seismic resistant solutions to ensuring minimal safety of the inhabitants.

Foto from the author.

3. MAIN EARTHEN TECHNIQUES IN COLOMBIA

Here are going to be shortly described the most widespread earthen techniques that are present in Colombia. Important aspects to be considered during the design and construction phase are described here. General earth buildings constructive methods references can be largely found in (19-28).

3.1 General aspects

The earthen constructive techniques are construction methods that use as principal material earth that is mixed with water. Most of these techniques exist since long time ago, almost 8000 B.C. (23), and have been present in different parts and cultures all around the world.

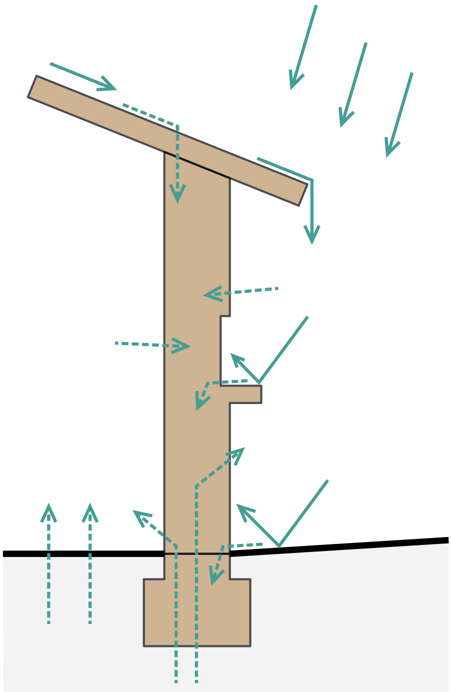
The name given to the earth mixture used for construction is loam (23). To be suitable for building construction the loam should satisfy some characteristics: the organic soil that can be found on superficial ground should never be used; the earth should be composed principally with clay, silt and sand, the proportions of those are going to variate according to each technique; for some techniques there can be also included gravel in a short proportion. When clay is activated by water it works as binder of the other components that conform the matrix.

According to the earth construction manual of CRATerre (20) there are 12 different methods for construct with earth, these are referred to the way loam is worked (pressed, stacked, moulded, hand-shaped, etc.). The variations of each method and between them are related to the geographical location, local resources and the cultural aspects of the population (23).

On the other hand the earthen constructive techniques can be also organized in coherence to the state of hydration of the loam. Moisture provide workability to the earthen material and its proportion into the mix variate in coherence to the way earth is worked (20). On that way is possible to divide the techniques as: the ones that requires a humid loam and the ones that work with loam in a plastic state (28).

From a structural perspective the earthen buildings behaves as load-bearing walls, which means continues walls that carries the loads of the building and transmit them to the supporting ground through the foundation. However, the several earthen techniques can present different structural compositions: monolithic, brickwork, and with an additional structure (20). In any case the main parts of an earthen structure are: the foundations always combined with a base course, over which are constructed the walls (that are the characteristic element of each technique), and the roof that, on several techniques, is construct with other materials as wood.

The earthen techniques are known for their advantages that concern the sustainability of the building. Earth as constructive material has an excellent humidity exchange with the environment, that means it permits to balance the humidity of the internal spaces of the building (23). Its low heat coefficient permits to balance the temperature of internal spaces, especially in locations with high temperature changes during the day (23). Also, the use of earth for construction reduce the energy consume of trans-



IMG 7. Moisture sorces that can affect the earthen building. Image redrawn from: BOLLINI, G. 2013. pg. 17;20.

portation in comparison to concrete. Finally is notable the recyclability of the raw earth, if the building is demolished, the "residual" material is not pollutant and can be reused (23).

Nevertheless, the characteristics of earth as a raw material, make it vulnerable to environmental factors as moisture and biological agents (8; 23; 25), especially if those agents are not considered during the designing and construction of the building.

Additionally, is notable the danger that earthquakes represent to earthen buildings. In Colombia, as a seismic zone, important care should be given to the seismic behaviour of earthen structures and specific strategies should be done on the building to enhance its performance under seismic effects[1].

1 View chapter 4th.

3.1.1. Moisture shelter

Nevertheless, the characteristics of earth as a raw material, make it vulnerable to moisture changes during construction and lifetime of the building. Regarding the construction process, the moisture content, applied during loam production, is going to evaporate during its drying process, provoking a volumetric shrinkage (23). This shrinkage creates cracks that latter can affect the well-standing of the constructed element. To avoid the shrinkage cracks is recommendable to control the drying process avoiding a rapid drying, e.g. adobes should not be dried by direct sunlight but with constant ventilation (21; 25; 29). Concerning the life time of the building, the earthen material remains sensitive to water and humidity. Excessive and punctual moisture influence are also going to be absorbed by the earthen material until it gets saturated. Once the earth material is saturated of moisture, the particles (clay, silt, sand) are going to suffer a debonding effect and loam is going to pass from a solid to a plastic or liquid state (23), thus the constructed element is going to lose its structural stability (28).

The moisture sources that can affect an earthen building are: the rain, that can be spilled from roof and splashed by bouncing on the ground; and the humidity from ground level that can be absolved by capillarity (Img. 7) (28); other sources are also the inhabitants of the building and the internal activities as cooking. In coherence to those moisture sources, earthen buildings should always have shelter strategies on roof, wall base/foundations and the surfaces of walls. Hence the architectonic language of the earthen buildings in rainy contexts usually have big roofs, foundations that came out from the ground level (base courses) and suitable plasters.

3.1.2. Foundations

In coherence to the type of structures that are constructed with earth material, the foundations should be continues to guarantee the support and the reception of loads from the load-bearing walls system. Is clear that all the structural walls should be supported over the continues system of foundations.

It is important to ensure the foundations are going to be supported by good soils, is not appropriate construct foundations over expanding or organic soils (19-20), different geotechnical materials, granular soils and plastic soils (as expanded clays), these are not a good support for the foundations (24). Is preferable make it over rigid soils as rock (20), thus liquefaction effect (soil loss strength under seismic loads) due to high presence of water on the ground can be avoided (19).

Foundations are made with stiffer materials to ensure the support of the totality of loads from the building. Traditionally in Colombia there were used stones of different dimensions, gravel and some binder as clay or lime (8; 27). However, nowadays is more frequent to find buildings with foundation that also include bricks and cement materials (27). Indeed, the use of modern concrete is also an acceptable solution to the foundations of earthen buildings (20).

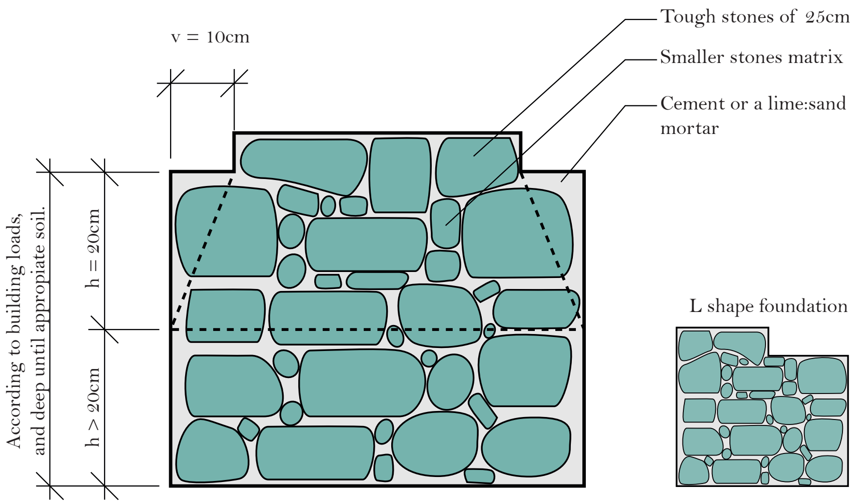
Normally on the Colombian context the foundations for earthen buildings are made with the known "Cimiento Ciclópedo" which is a continues foundation composed of:

- tough stones of 25cm of diameter approximately (29);
- smaller stones that completes the granular composition of the matrix by filling the spaces between the bigger ones (29);
- cement (29) or a lime:sand mortar (27) that act as binder of the stone matrix.
- Is usual that all the stones fill more than the 50% of the volumetric space (27; 29).

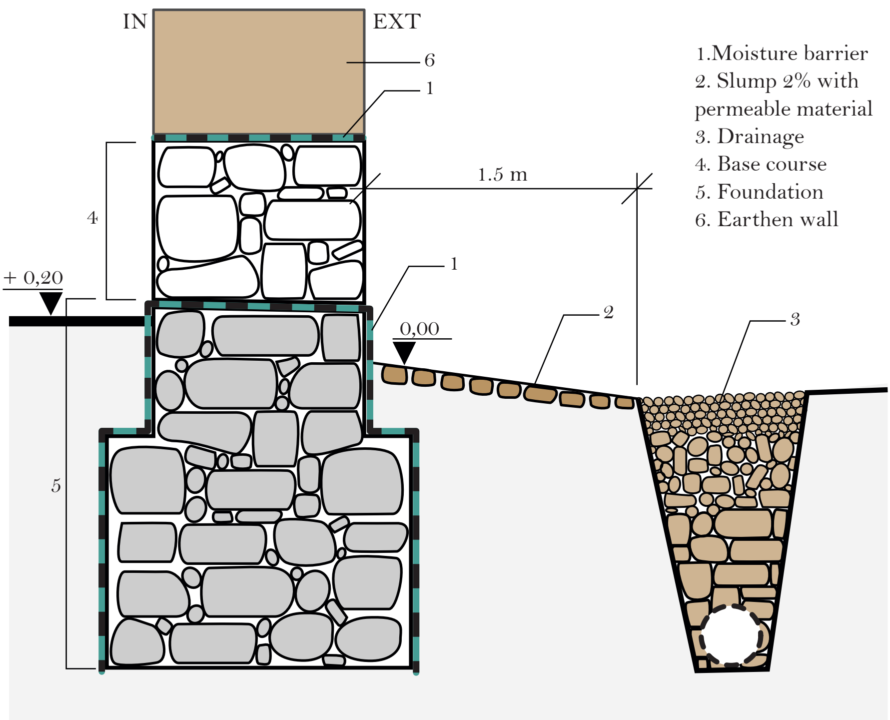
The "Ciclopedo" foundation normally have a L or invert T shape, this guarantees the loads are going to be distributed over larger surface.

The foundation construction begins by the ground levelling and the definition of walls edges on the construction site (29), once it is done there should be grub the continues hole that should be deep until good foundation soil is found (27; 29). Is important to ensure that lateral sides of the hole are straight as they will be the "formwork" of the foundation (29). Later, the filling of the hole should be done by layers of 10cm, pouring stones and cement at the same time. Is important to ensure that the cement reach all the spaces between the stones and that not air spaces remains inside the foundations (29). Just after the entire hole is full – until the ground level – by the aforementioned mix, there should be located some coarse stones (25cm diameter) on the top of the foundation, letting a part of them out of the mix. These are going to join the foundation with the base courses or over-foundations (29). Is possible to see on (Img. 8) how the foundation has already a base to support the base course.

Suggestions of shape, materials, and dimensions for the foundations can be seen on image 8 based on Yamin (27)



IMG 8. "Ciclopedo" foundation: shape, materials, and general dimensions recommendations. Image redrawn from: YAMIN et, Al. 2007. pg. 6. & MINKE, G. 2001. pg. 34..



IMG 9. Foundations and base course strategies against moisture: levels, slope, drainage and moisture barrier. Image redrawn from: HOUBEN et, Al. 1994. pg, 252. & CARAZAS et, Al. 2002. pg,14.

and Minke (30).

The protection of foundation from ground humidity is recommended by some authors (19-20) as buried solutions. Is possible to use moisture barriers located on the sides of the foundation or between the foundation and the base course, so they stop the moisture absorption by capillarity. Is also useful a simple drainage that can be located next to the foundation or with some distance -1.5m - (Img. 9) (20).

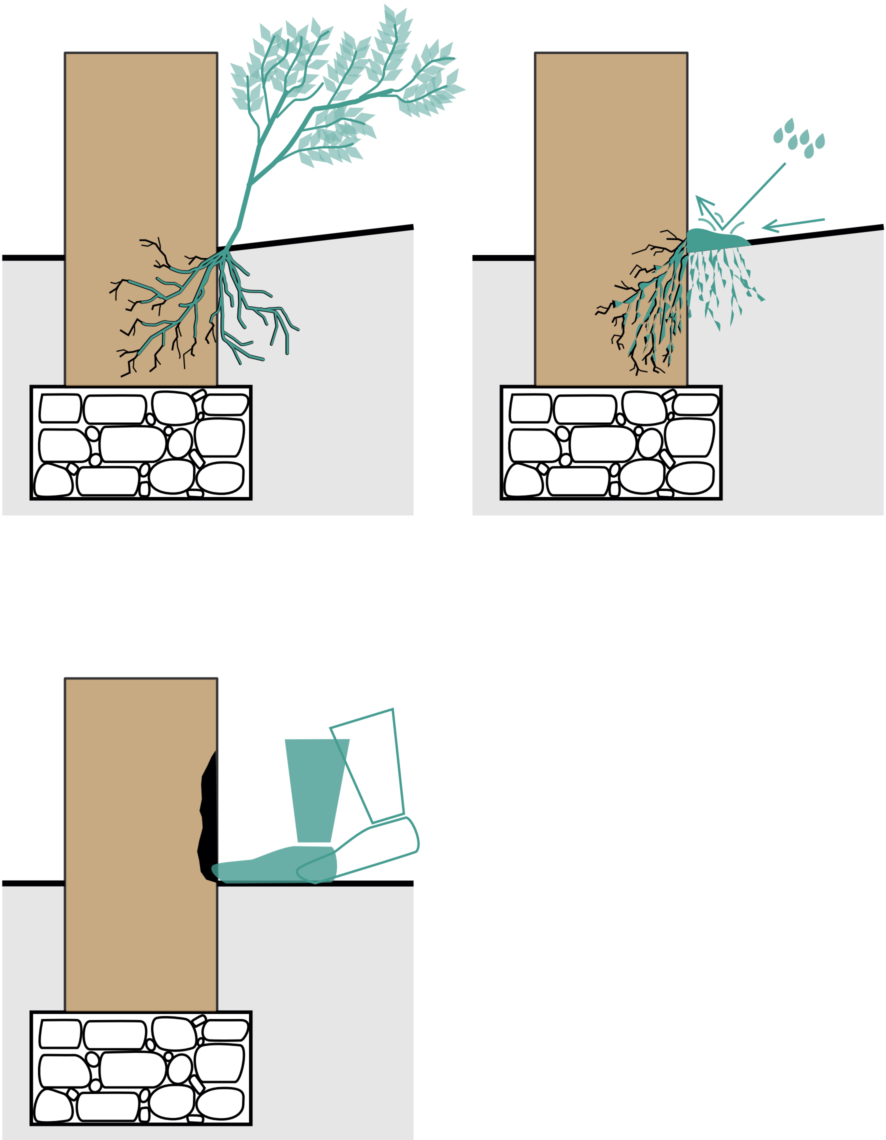
3.1.3. Base courses or over-foundations

Differentiating from other technologies the base for earthen constructions should include a foundation that comes out of the ground level, it can be named "base courses" or "over-foundations". This is going to protect the earthen walls from what can occur at the ground level: hits and impacts caused by humans, animals or any moving element next to the building; vegetal agents that start growing on the base of the wall; or stagnant water and rainfall water splashed by bouncing on the ground (Img. 10) (20). In coherence to that, the base courses should be constructed over all the foundation and under all the earthen walls.

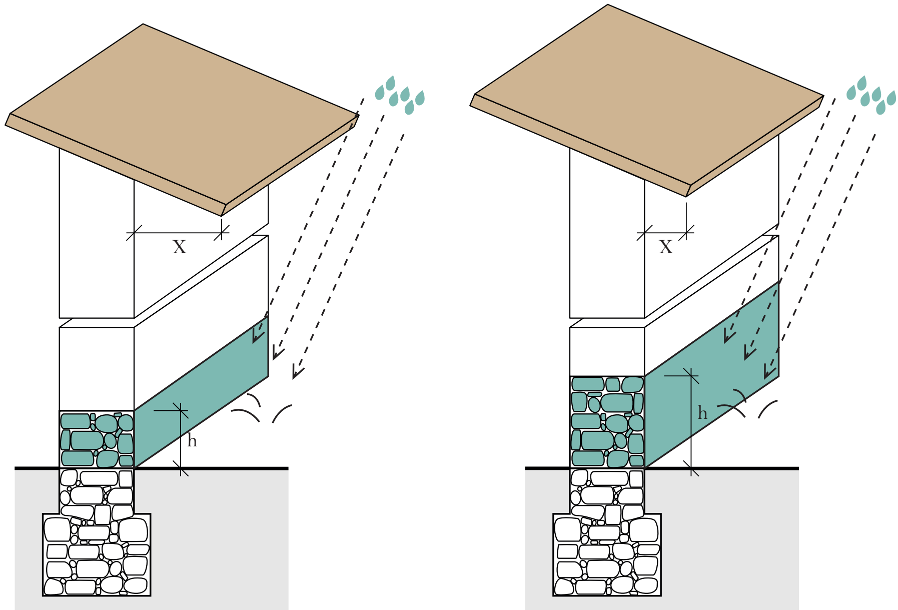
Base courses are made up of the same material of the foundation because they shall be tough enough to support the structural loads of the building and transmit them to the foundations. Nevertheless, the stones used into this mixture can be smaller, 10-15cm of diameter, and should fill 25% of the base course volume (29).

Clearly the dimensions of the base course are linked to the thickness of the wall and is going to change depending on the specification of the project. The highness can variate for example: (29-30) recommends 30cm of highness, (21) has suggested there are necessary at least 50cm, but the appropriate parameter to follow is related to the agents that the base course shall assume to protect the earthen wall, e.g. the rainfall patterns of the location in relation to the roof overhang, (Img. 11) (20).

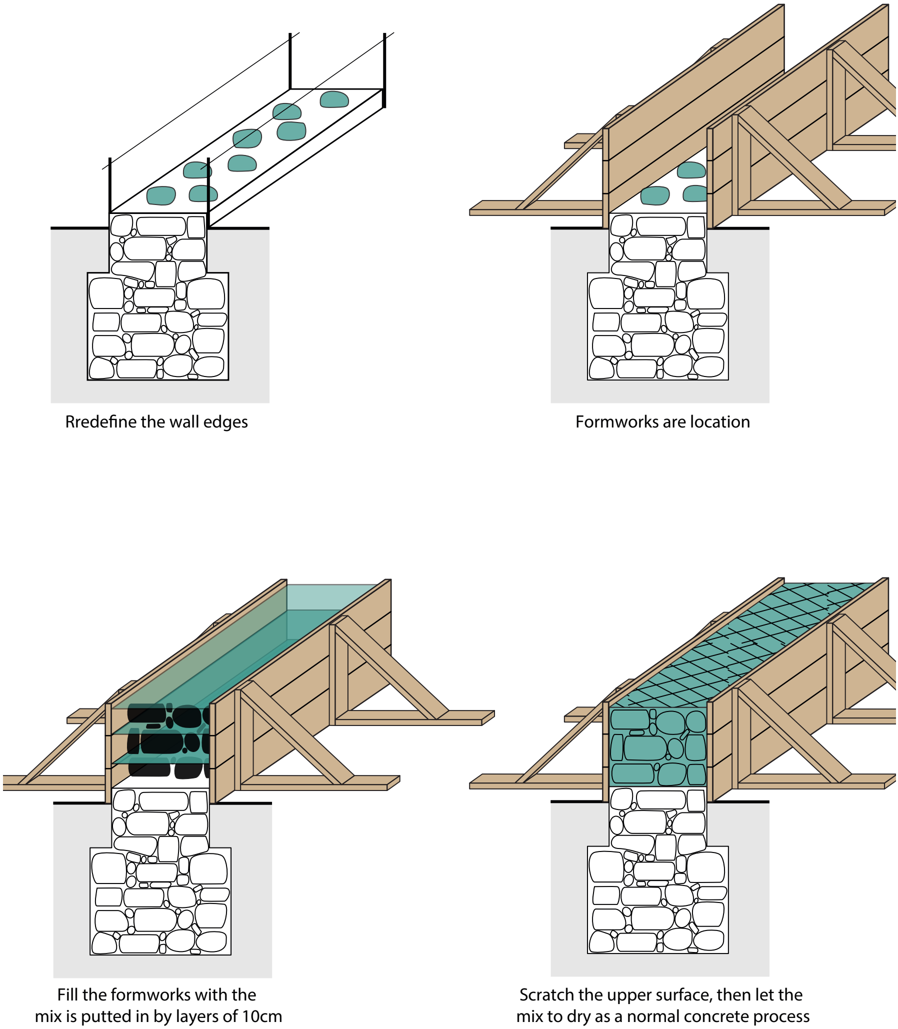
The construction process suggested by Blondet (29) consist on redefine the wall edges over the constructed



IMG10. Dangerous agents for earthen walls on base at ground level. Image redrawn from: HOUBEN et, Al. 1994. pg. 254.



IMG.11 Base course highness in relation to rainfall patterns and roof cantilevers. Image redrawn from: HOUBEN et, Al. 1994. pg. 255.



IMG. 12 Constructive proces of base course. Image redrawn from: BLONDET, M. 2010. pg. 36.

foundations to guarantee the good location and alignment of the walls, after that the formworks are located, and the mix is putted in by layers of 10cm. Once the formwork is full is recommended to scratch the upper surface to improve the junction of the base course with the wall, then let the mix to dry as a normal concrete process[2] (Img. 12).

Concerning the moisture shelters that base courses should have, Houben and Carazas propose simple superficial details that helps the base courses to push out the water. Is useful the construction of a slope of 2% that throws out the water and collect it into a superficial gutter. For this solution the material of the slope should be partially permeable so the humidity from the ground can also go out (20). Another simple solution is to generate a difference between the internal and external ground level that avoid the water to gets in the building and affect well standing of the structure (19). As foundations, the use of moisture barriers as asphalt felt between base course and the wall can stop the moisture absorption by capillarity (20; 29). These solutions are expressed on image 9.

2 For some structural reinforcements is necessary to include junction systems between the base course and the wall, explained to each reinforcement strategy on the chapter 4th

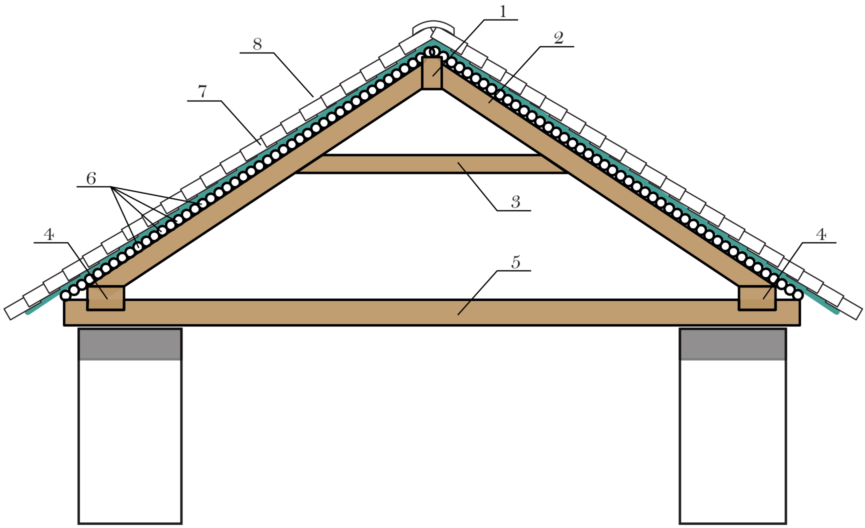
3.1.4. Roof construction

The roof systems used for earthen constructions can be flattened, pitched or with vaults (20; 23; 29). The type of roof of the building is related to the meteorological conditions of the location, thus flattened roofs are not traditionally used on rainy locations.

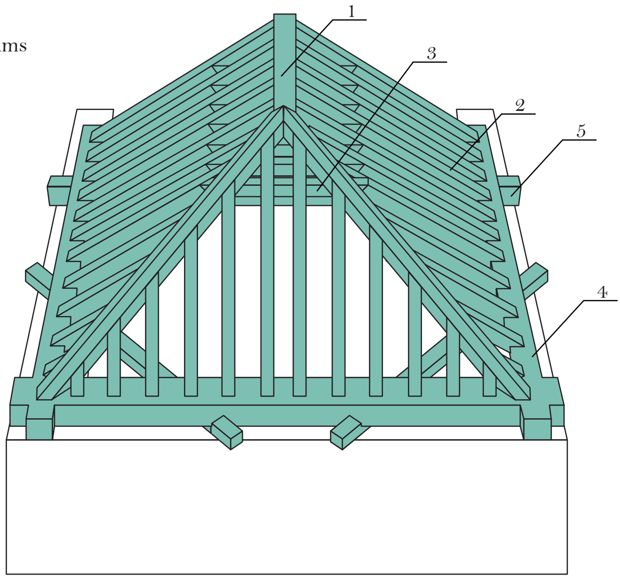
Regarding the flattened and pitched roofs, there is possible the use of loam for their construction, nevertheless in both types of roof is necessary the use of additional elements and materials to supply the structural requirements (20; 23). However, these roofs can be also constructed without loam, instead there are used wood, straw, palm leaves, or even clay tiles (20; 31).

As the principal function of roof is guarantee the protection of the building from rainfall and raining spilling, in the tropical weather of Colombia is usual the use of pitched roofs with important cantilevers that throws out the raining water (27). These pitched roofs can be “gable roofs” with two slopes, or “hipped roofs” with four slops (20).

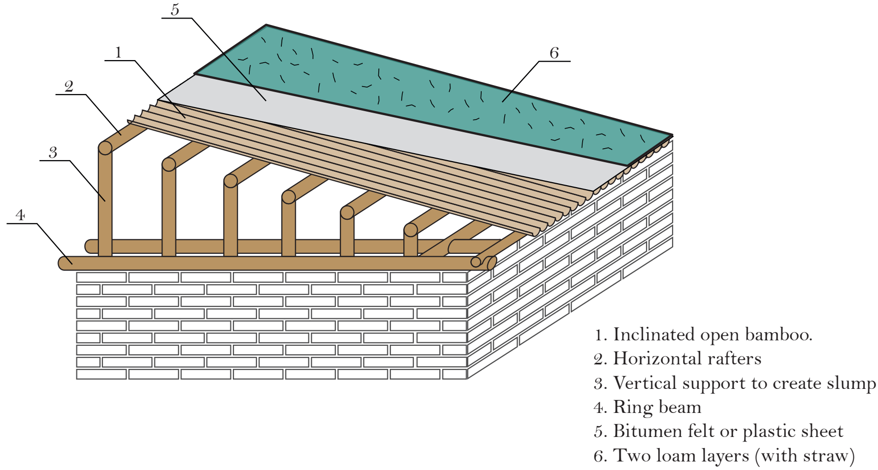
The traditional roof structure used in Colombia is call “Par y nudillo” (25; 27), it can be described as a truss structure that can be seen on image 13. Traditionally this structure is made on sawn or round timber. The structure is composed by a ridgepole beam, two diagonal rafters called “Pares” that are fixed between them by a horizontal collar tie “Nudillo”, and are supported by horizontal beams, the last ones are called “Estribos” and are located parallel to the wall edge. Finally the Estribos rest over tie beams (Tirantes) that assume the thrust from the upper elements and transmit the loads to the load-bearing walls. Over all the aforementioned structure



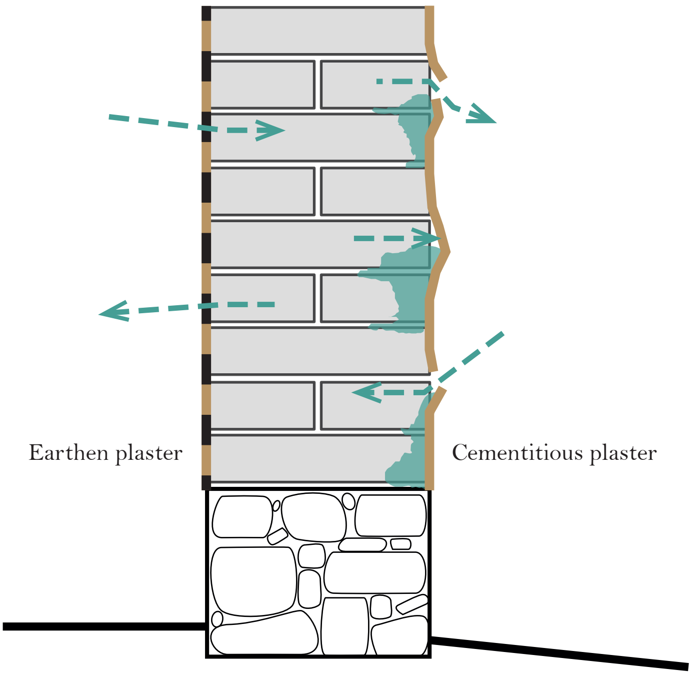
1. Ridgepole beam
2. Pares rafters
3. Nudillo tie
4. Estribos beams
5. Tirantes tie beams
6. Reeds
7. Loam layers
8. Clay ties



IMG 13. Traditional "Par y nudillo" roof strcuture. Image redrawn from: YAMIN et, Al. 2007. pg. 9



IMG 14. Slump roof structure and layering. Image redrawn from: BLONDET, M. 2010. Pg, 51. & HOUBEN et, Al. 1994. Pg,281.



IMG 15. Moisture effect on cementitious plasters Vs. the permeability of earthen plasters. Image of the author.

there are located thinner timbers or reeds, later Yamin describes a layer of loam and finally baked clay tiles (27).

Following contemporary recommendations for roof structures the use of timber or bamboo remains suitable solutions. The constructive manual of Blondet (29) propose the construction of a pitched roof structure conformed by: open bamboo culms over horizontal main beams, the last ones are supported by the ring beam [3]n the lower part and, while the roof slope rise, are supported over vertical elements that are erect over the same ring beam (Img. 11). The rafters and main beams shall be screwed or nailed between them and to the ring beam with 4" nails (29).

The covering of the roof structure described by Blondet is constructed by a surface of wood planks or opened bamboo culms that are nailed to the main beams (29). Over it can be located a waterproof material that avoid water filtration into the building and the earthen walls, there can be used a bitumen felt or plastic sheet. Later there can be construct two layers (2.5cm each) of loam with high quantities of straw (29) as can be seen on image 14. However, for rainy places is preferable the use of materials as clay tiles or metal sheets that offers longer life under moisture, clearly the last covering material shall be also attached to the underneath roof structure (19).

Regarding the sheltering strategies from water on the roof, drainage systems can be included to control the curse of water once it goes out of the roof, always to avoid the sprinkling over the wall surfaces, the water can be collected and conducted to downpipes (20). The waterproofing material should ensure non-filtrations in the entire system (20), especially over the roof junction with walls.

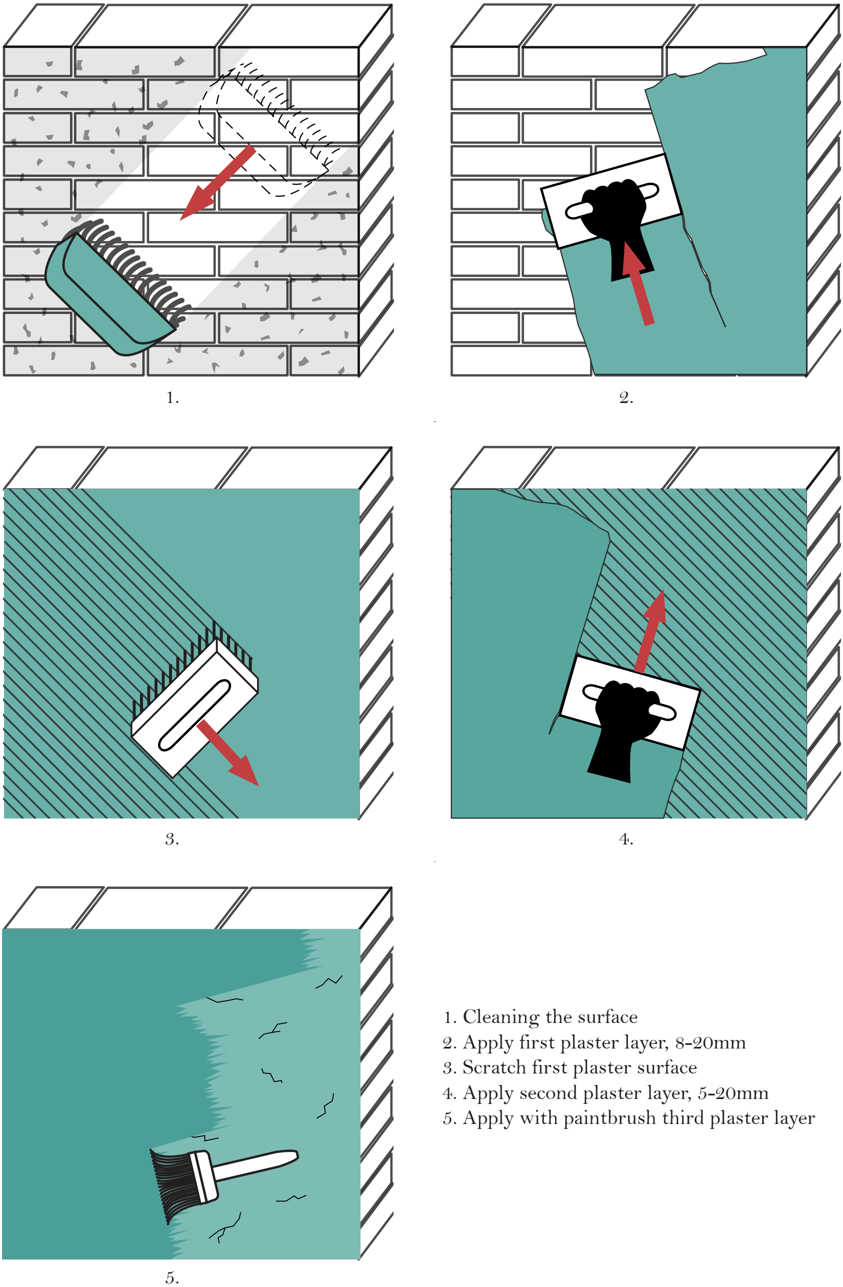
3 Beam constructed over all the load-bearing walls, view chapter 4.4.1.

3.1.5. Plastering

The plaster on earthen technologies is known for coating proposes. The protective effect of plaster is against general environmental factors, not only moisture but also biological agents. Even if earthen buildings shall be protected from moisture, they also need to exchange it in order to regulate its internal humidity (8; 21; 23; 25). This humidity exchange between the wall and the environment is important for it's well standing, so it can maintain a natural equilibrium that dodge the negative effects caused by excessive moisture accumulation or excessive dehydration. Once the wall is able to equilibrate its internal moisture content, it will be able to equilibrate the humidity of internal spaces as well, ensuring the well-known comfort conditions that earthen technologies can offer to architecture.

In light of above the preferable material to plastering an earthen wall is also a loam mix. Some traditional plasters have an addition of vegetal or animal oil, mineral pigments, clay, gypsum or lime (8; 32).

The principal reason to avoid the use of cementitious plasters for earthen buildings is that it has not the same hygrometric properties of loam. Hence the evaporating moisture from the earthen wall is going to be trapped by the cementitious plaster. Moisture



1. Cleaning the surface
2. Apply first plaster layer, 8-20mm
3. Scratch first plaster surface
4. Apply second plaster layer, 5-20mm
5. Apply with paintbrush third plaster layer

IMG 16. Plastering process. Image redrawn from: CARAZAS et, Al. 2002. Pg,19.

is going to be condensed inside the wall provoking the separation of the lamellar junctions of clay weakening the wall stability (33). Additionally, the moisture condensation is going to crack the cementitious plaster, provoking it to blow-out of the wall (Img. 15) (30).

Regarding the rendering process there is important the plaster attachment capacity to the wall surface (34). It is influenced by clay content and the beyond surface conditions (cleanness, roughness, moisture), rougher surfaces, as adobe walls, will improve the attachment of the plaster. To ensure an appropriate plaster-wall bond the earthen substrates can be cleaned, scratched and wetted before plaster application (Img. 16) (23; 35; 36; 37). The use of chicken grids to improve the support of the plaster is also recommended (20; 38).

The plasters can be applied on several layers, indeed is better to apply more than one layer: first one to homogenize the wall surface, second one create the finishing, and third one to cover little cracks that could be presented by shrinkage during the drying phase (19; 20; 29). The first plaster layer is manually applied with a trowel and should have 8-20mm of thickness, once is done is recommended to scratch the surface to improve the attachment of the next layer (19). For this layer Carazas propose a plaster mix of:

- one part of clayey earth,
- two parts of sand,
- and 1/3 part of straw (3cm length).

Second layer – also applied with trowel – can have a thickness between 5-20mm (19; 29). In comparison to the first layer the loam composition usually have one or two more parts of sand (19):

- one part of clayey earth,
- three to four parts of sand,
- and 1/3 part of straw.

Finally, the external layer is applied with a paintbrush, the loam mixture is composed by (29):

- one part of clayey earth,
- one part of fine sand,
- and ½ part of water.

This final layer can be also made with lime: sand or gypsum: sand mixtures (19). Image 16 makes a resume of the plaster application process.

3.2. Tapia

The name for rammed earth (20) in Colombia and in the Latin American context is "tierra apisonada", "tapia pisada" or "tapia".

Rammed earth is a constructive technology that has been used in different parts of the world, it is possible to find this technology since 5000 B.C. (23). The presence of rammed earth constructions in Colombia is widespread, thousands of houses were constructed with this informal constructive technique. Naturally the most important buildings and the most well-conserved ones are the churches and religious buildings made during the colonial period. The doctrine chapel (capilla doctrinera) of Betéitiva and Sáchica (Img. 17 & 18) are examples of buildings constructed principally with "tapia", but there are also many buildings that combine different raw earth techniques (39). In a contemporary approach it is possible to reference rural projects in Barichara where exists several rammed earth buildings. Images 19, 20 and 21 shows the Pinto house of Jesus Moreno (Barichara, 2001), the Caney house designed by Camilo Holguín (Barichara, 2006), as the Supitina house of Lucia Garzón (Subachoque, 2012).

Rammed earth walls are constructed by the compression of a dampened loam into a formwork that is later removed.

Concerning the characteristics of the loam to be used for rammed earth, the granulometric composition of the soil used should be compound with clay, silt, sand and gravel. The clay and lime portions of the loam works as binder, the sand helps to complete a uniform grain size distribution and the gravel increase the compressive strength. Manure has also been used in some traditional buildings (8).

The granulometric distribution of the sub-soils can variate according to the nature of the soil in coherence to the geographic location, however there can be applied general limits to the granulometric curve (20). The comparison made by (40) of several proportions of granulometric composition for rammed earth, suggest that clay and silt should be minimum 20-25% and maximum 30-35%, regarding sand and gravel the lower limit should be 50-55% and maximum 70-75%, considering mass weight. Additionally, it is recommended by Houben maintain the granulometric curve inside the area of the image 22 (20).

Regarding the state of hydration of the loam, the guide for earth construction of CRATerre (20) suggest for rammed earth the use of a humid dry soil or humid moist soil which moisture content can variate form 4-18% (wt%). The liquid limit acceptable can be 25-45% (20), preferable between 30-35% (40). The image 23 express the suggested area for LL in comparison to Plasticity index (20).

As it is confirmed by (40-42) compressive strength of a rammed earth wall can increase as its density increase, according to that the loam used for this technique shall be well compressed so is possible to reach specific densities. Maniatidis suggest reaching 95-98% of the Proctor maximum dry density (40), while Houben (20) specify a range of 90-95% of the same parameter, reaching a bulk density between 1700 - 2200kg/m3.

Regarding the tools used during the construction the formworks are tra-

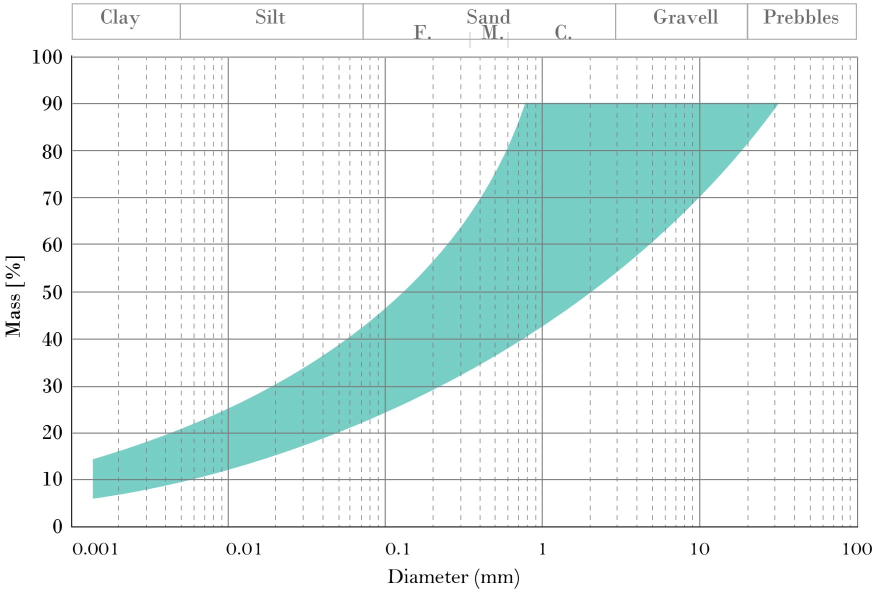
IMG 17. Doctrin chapel of Beteita, Boyacá. Image from: Google street view.

IMG 18. Doctrin chapel of Sáchica, Boyacá. Image from: Google street view.

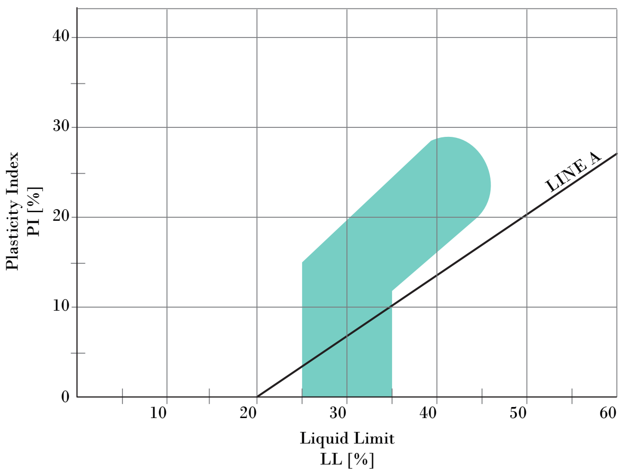
IMG 19. Pinto house, Jesus Moreno. 2001. Image taken from: fundaciontierraviva.org

IMG 20. El Caney house, Camilo Holguín. 2006. Image taken from: arquitecturanativa.org

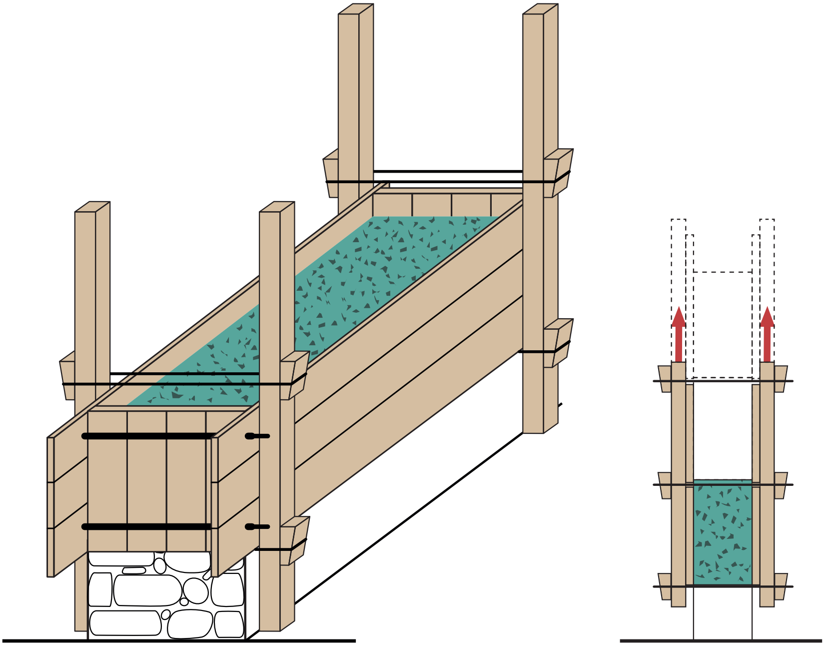
IMG 21. Supinita house, Lucia Garzón. 2012. Image taken from: Arquitectura Lucia Garzèon, 2013.



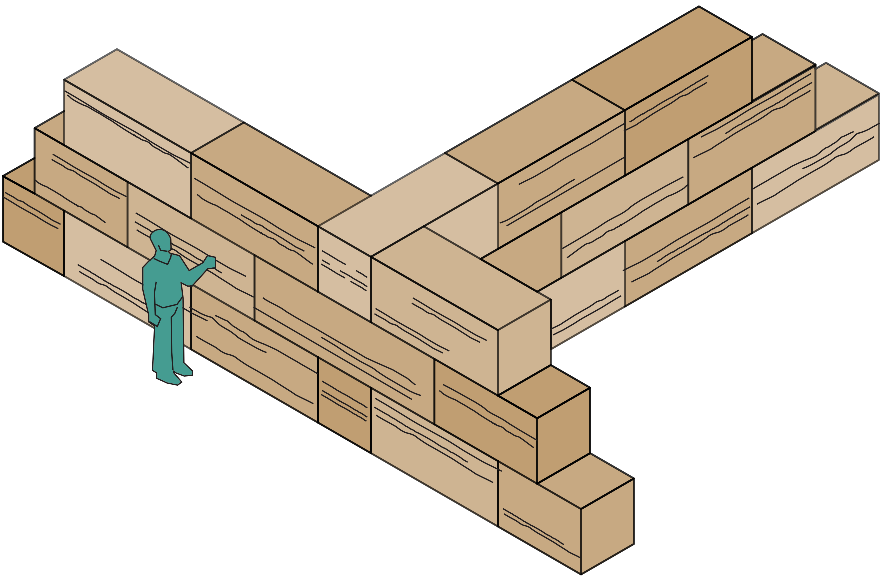
IMG 22. Recommended granulometric curves for rammed earth loam. Image redrawn from: HOUBEN et, Al. 1994. Pg, 112.



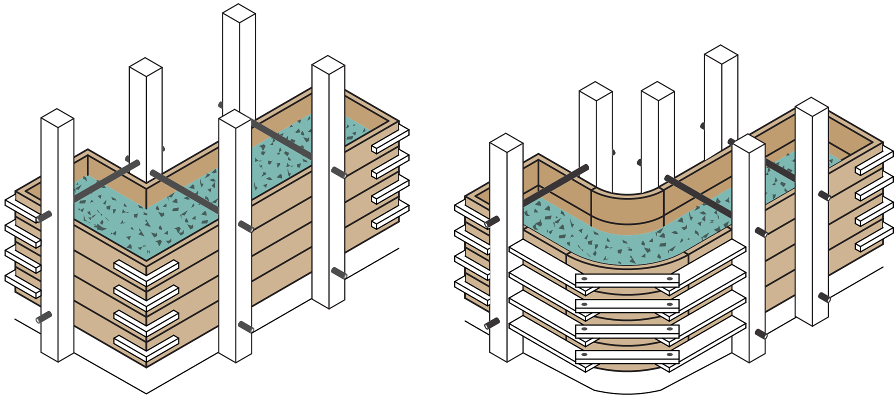
IMG 23. Recommended liquid limit in relation to plasticity index for rammed earth loam. Image redrawn from: HOUBEN et, Al. 1994. Pg, 112.



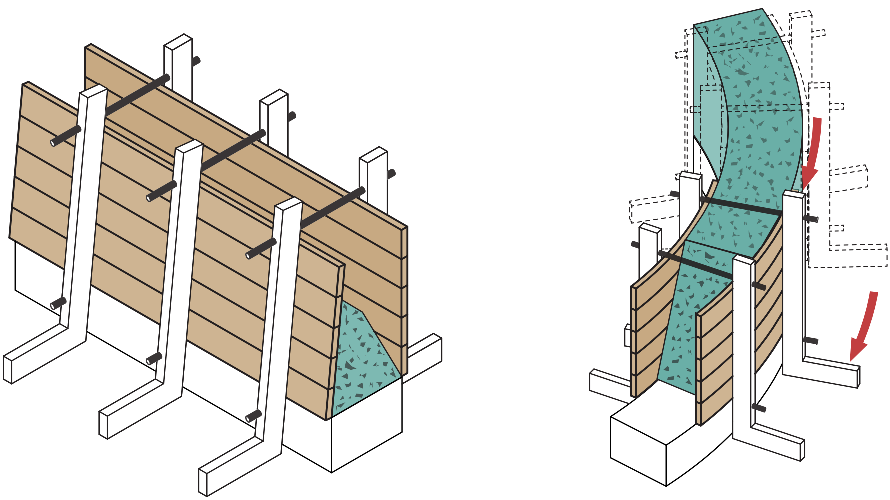
IMG 24. Formwork in timber for rammed earth. Image redrawn from: MINKE, G. 2012. Pg, 51.



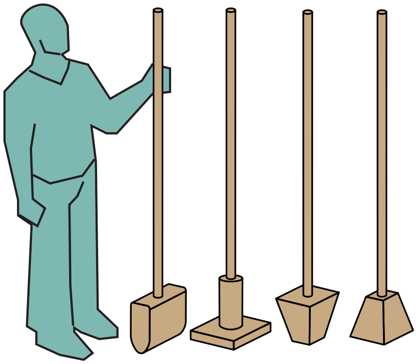
IMG 25. "Brickwork" for rammed earth blocks, T wall intersection. Image redrawn from: YAMIN et, Al. 2007. Pg, 8.



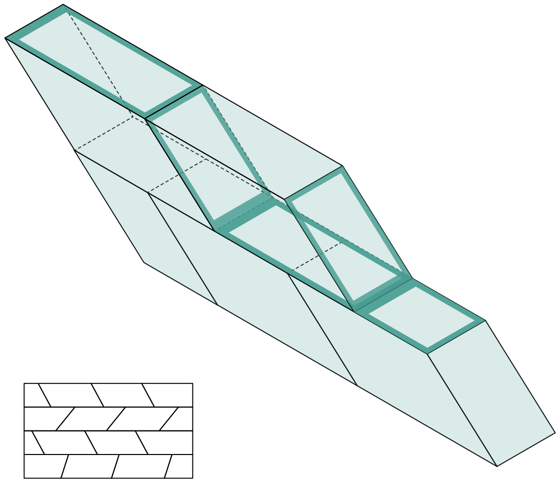
IMG 26. Formwork for rammed earth corners in 90°. Image redrawn from: HOUBEN et, Al. 1994. Pg,209.



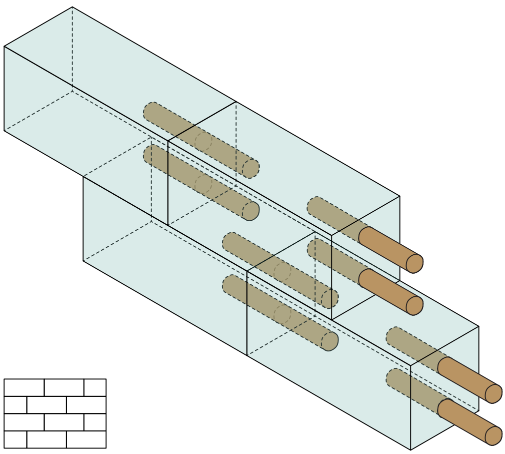
IMG 27. Sloped and curved formworks for rammed earth. Image redrawn from: HOUBEN et, Al. 1994. Pg, 209.



IMG 28. Traditional manual ramms. Image redrawn from: HOUBEN et, Al. 1994. pg. 210.



IMG 29. Rammed earth blocks diagonal junctions with layer of mortar. Image redrawn from: MINKE, G. 2012. Pg, 53.



IMG 30. Rammed earth blocks internal junctions with timber. Image redrawn from: YAMIN et, Al. 2007. Pg, 8.

ditionally made with wood, these are not able to cover all the wall area, therefore to build an entire wall is necessary to move them in vertical and horizontal directions (Img. 24) (20; 23), hence at the end of the process the totality of the wall is going to be composed of several pieces of rammed earth (Img. 25) (27). The two faces of the formwork shall be joined to guarantee that they are not going to separate during the ramming process (23). The formwork should be strong enough to resist the pressure of the earth when it is compacted, (20) propose a resistance of 3000 Pa.

For the construction of corners there can be used formworks as the ones already described or also formworks that create the corner shape as the ones specified by Houben (Img. 26) (20). The use of curved or sloped formworks (Img. 27) is also possible[4] (20). For the case of sloped formworks Houben suggest that both or just the external face of the wall can be battered (20).

However, nowadays is usual to use metal formworks, as those used in a concrete structure, in that case is important to consider that the construction method is different and will implicate different costs (23).

The ramming of loam can be made manually with the help of conical or flatten rams (Img. 28) which weigh can variate from 5-9kg (20). The variation on the head shape of rams is done to achieve corners in the formwork (23), and the material of the rams is traditionally wood or metal (20). The compression can be also done with pneumatic rams that also guarantee a uniform well pressed loam in the entire structure. It also improves the efficiency during the construction, making the process faster and easier for the worker without decreasing the quality of the result (23). If there are going to be used pneumatic rams is recommendable that the tools are able to reach a pressure of 0.5MPa as maximum (20). It is important to highlight that during this ramming process the aforementioned loam density should be achieved, and so an optimal compressive strength of the wall.

The construction of the building is done by the addition of several load-bearing walls, over which a roof or an intermediate floor building can be construct. In concordance with the behaviour of this kind of structural system the supports (walls) shall be continuous, attached between them, and with accurate openings[5]. The thickness of the wall can variate according to loads requirements of the building or local traditions, however approximative suggestion in Colombia is to have more than 50cm (21; 43), and (30) suggest a thickness between 60-100cm.

Concerning the construction process, once the foundations and base courses are finished (chapter 3.1.2-3.1.3) and the loam is prepared, the wall can be constructed. The formworks are located and tied over the base course, gradually the loam is pressed by layers of 10-20cm approximately until fill the entire framework (8). If the framework is a traditional one (Img. 24), once is full, it shall be moved up or to the sides to continue the wall construction. Thus, the wall is made up of "big blocks" of rammed earth that shall be overlapped between them

4 Can be useful for anti-seismic strategies as the control of inertia and the shape of corners, view chapter 4.3.1 and 4.5.3.

5 Openings should follow the parameters given on chapter 4.3.3.

(Img. 25) (27) so, under loads action, they can stay together maintaining the wall unit. To enhance the junction of the wall pieces, Minke (23) suggest the use of incline junctions with the addition of lime mortar between both rammed earth pieces (Img. 29). Other solutions referred to Colombian traditional buildings are exposed by Yamin (Img. 30), on that case the location of internal timbers or bamboo shall be put in the middle of the wall thickness (27).

When the total highness of the wall is reached the construction of the ring beam can be constructed[6], thus over it can be constructed the roof or intermediate floors[7].

6 Ring beam construction should follow the chapter 4.4.1 and 4.4.3.

7 Roof and floors structure should be according to chapters 3.1.4 and 4.4.2.

3.3. Adobe

"Typically, since Spanish times until the beginning of 20th century, building technology was adobe. Gradually it was displaced by brick and concrete structural technology." (8)

The name given to handmade raw earth blocks is Adobe and, as the rammed earth, has extended all around the world since long time ago, in Latin America since 1600 BC (20). The blocks can be made in different presentations and dimensions, but the basic concept works the same in all the buildings: the addition of several blocks conforms a wall and the addition of walls conforms the building.

Nowadays adobe architecture still been used by the people for self-construction buildings in Colombia as is shown by the catalogue of Vernacular Techniques (31). Important heritage adobe buildings in Colombia are the doctrine chapel of Tenjo and the colonial chapel of Sutatausa (Img. 30 & 31). Both buildings were constructed at the beginning of XVII century (44), hence are clear examples of the long constructive tradition that is present in Colombia and the long life that earthen buildings can have.

Concerning the loam production for adobes, Mike (23) propose the following percentage for the granulometric composition: 22% clay, 15% silt, 61% sand and 2% gravel. On the other hand CRATerre (20) propose a limiting area to the adobe granulometric curves, both can be compared on the image 33

The adobe loam mix is worked on its

IMG 31. Doctrine chapel of Tenjo, Cundinamarca. Image from: Google street view.

IMG 32. Doctrine chapel of Sutatausa, Cundinamarca. Image from: Google street view.

plastic state; hence it is damper than the one used for rammed earth. Houben recommends the use of soil on a hydration state of plastic semi-solid paste, semi-soft paste or soft paste, which means a moisture content that can variate from 15-25% (20). Additionally the same authors suggest maintaining the relation of liquid limit and plasticity index inside the area of image 34, with a liquid limit between 30-50%.

Is possible to add manure to improve the plastic properties, also straw that helps to prevent cracks in the blocks and improve tensile strength (8). Once the loam mix is prepared it is recommendable to let it curate during 12 to 48 hours to improve the binding force between its components (21; 23).

The addition of adobe blocks is made with earthen mortar. The mortar is normally made of the same loam, however clay limits of 4-10% (wt%) are recommended by (23). Hydraulic lime and high-hydraulic lime mortars can also be used, these ones present slower drying process than the adobes, hence it reduces the shrinkage cracking and the damages it can produced during the drying of the wall (23). To avoid the shrinkage cracking of the mortar it should satisfy the following recommendations[8]:

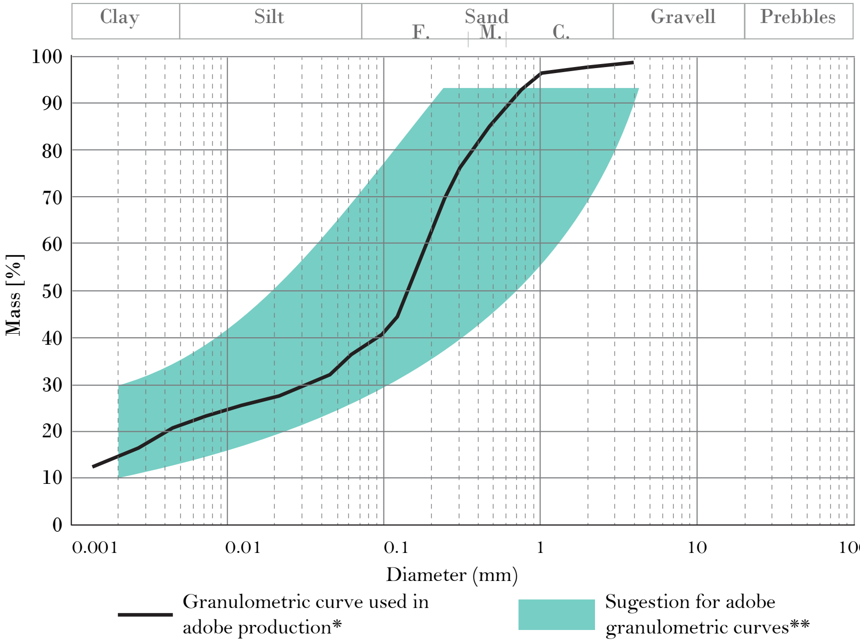
- The humidity of the mortar mixture should not overpass the 20% of the dry mix weight (24);
- The moisture content should be as low as possible without compromising the workability of the mortar (24)
- For the mortar loam the quantity of coarse sand can be slightly increased (23);
- There can be added straw or similar fibres with a fibres:loam proportion of 1:1 or 1:2 (24).
- The use of cement mortar is not the best solution to the current technique (23) as it is stiffer than the adobes and its behaviour under loads is different.

The thickness of the mortar can be between 5-20mm according to regulation E.080 (24), nevertheless Blondet (29) suggest not to overpass a thickness of 10mm intending that thicker mortar can weaken the wall.

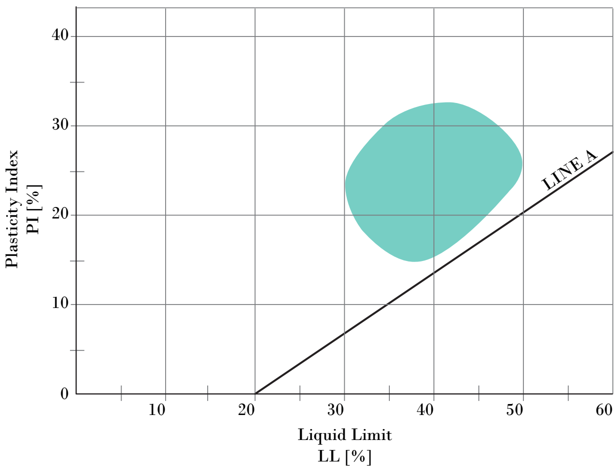
In contrast to the rammed earth the adobes method offers the "pre-fabrication" of the elements, it can be understood as an advantage or also an important aspect to take care of. The production process requires space to create the loam mix, an area to dry the blocks, and -if it is necessary- some space to kip the adobes wile are used. The drying area should be large enough to have all the produced blocks separated one from the others to ensure the natural ventilation. Even if the drying process is called "sun-dried" some authors recommends that the direct sun is not the best solution: elevate temperatures produce fast dehydration that carries to the cracking of the adobes (21; 32). All the spaces for the adobe production and storage should be sheltered from rain and well ventilated.

The loam described above is shaped in moulds that traditionally are made with wood. According to each region of the word the internal dimensions of the moulds can variate: 30-50cm length, 20-25cm width and 6-11cm

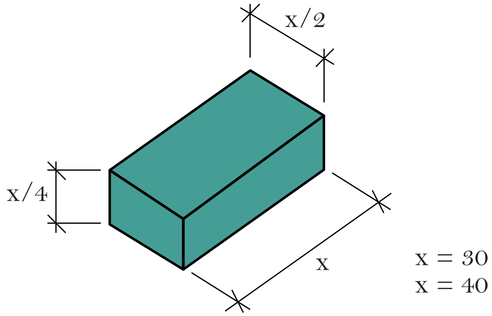
8 The seismic importance of the mortar characteristics and block-mortar bond on blocks masonry is explained on chapter 4.5.6.



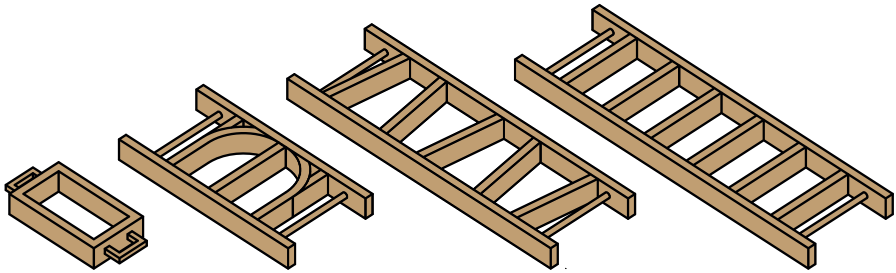
*IMG 33. Recommended granulometric curves for adobe loam. Image redrawn from: *MINKE, G. 2012. Pg, 64. & **HOUBEN et, Al. 1994. Pg, 114.*



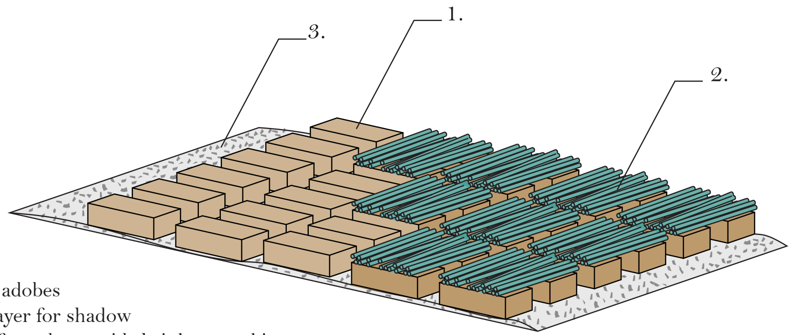
IMG 34. Recommended liquid limit in relation to plasticity index for adobe loam. Image redrawn from: HOUBEN et, Al. 1994. Pg, 114.



IMG 35. Traditional dimensions and proportions of adobes. Image redrawn from: YAMIN et, Al. 2007. pg. 7.

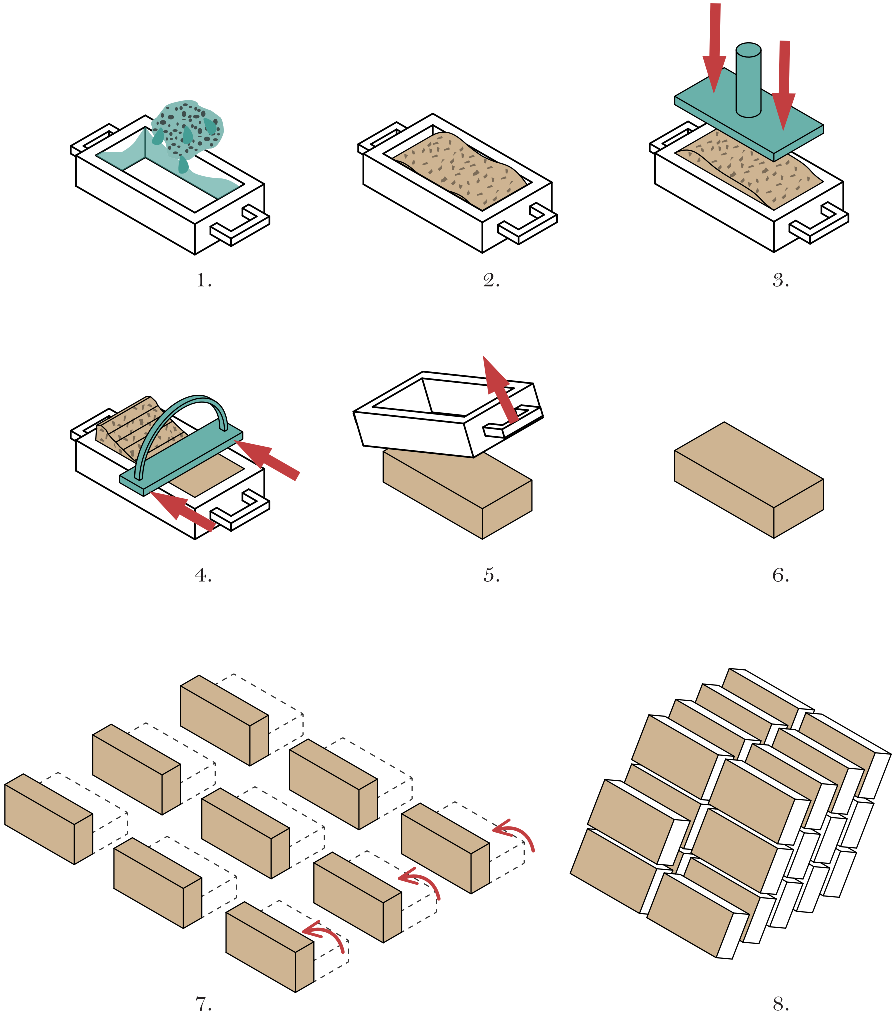


IMG 36. Moulds for adobe production. Image redrawn from: MINKE, G. 2012. Pg, 60.



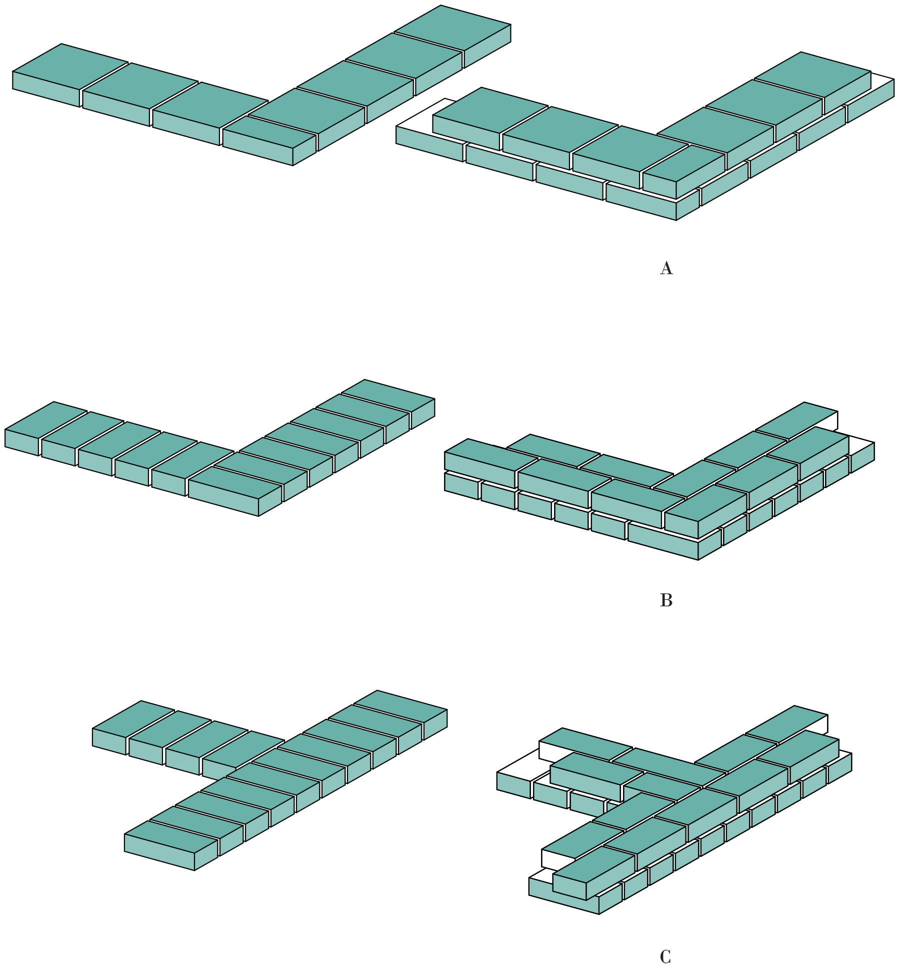
1. Drying adobes
2. Straw layer for shadow
3. Layer of sand to avoid shrinkage craking

IMG 38. Adobe drying strategies. Image of the author, data from: VIÑUALES, G. 2007. Pg, 226. & BLONDET, M. 2010. Pg, 27.



1. Oiling moulds
2. Inserting loam mix
3. Pressing the loam mix
4. Flatting upper face
5. Un-moulding
6. Letting dry for few days
7. Rotating and letting dry
8. Storage

IMG 37. Adobe production process. Image redrawn from: BLONDET, M. 2010.



IMG 39. Brickwork examples for adobe walls. Image redrawn from: HOUBEN et, Al. 1994. Pg, 261.

height (8; 32). The traditional dimensions for the adobe size in Colombia are better define by (27) as 30cm length, 15cm width and 7cm high or similar ones that conserve the proportion of 1:½:¼ (Img. 35). The dimensions the shape of the mould can be changed to produce special pieces for arches or another requirement of the project. Exist several moulds that can create more than one block per time and industrialized machines -Hans Stumpf, 1946- that make the process more efficient (Img. 36) (23).

After producing the loam mixture, the modules are oiled to facilitate the unmolding process (32). The loam is manually put in the moulds and is lightly pressed, as another face of the block the upper part is smoothed, and the mould is taken off to allow the adobes to dry (23), image 37 explain the process. The blocks should remain unmoved for three days approximately, that is why the casting process should be done where the blocks are going to dry. After the first three days the adobes can be rotated permitting the drying process to finish, this is done to guarantee the ventilation of all the adobe faces. Once are dried the blocks can be stored, always protecting them from moisture (23) by ensuring the ventilation between them.

To avoid the shrinkage cracking during the drying process, there are some strategies that can be used (Img. 38): first to let the blocks dry under shadow (21; 29); and second make the blocks over a layer of sand or straw thus the friction with the lower surface caused by shrinkage during drying is diminished and so the cracking (32).

If, after drying, the adobes present cracks or curves on the sides it is not recommendable their use for construction (29), is necessary to have adobes with straight faces.

For the wall construction of the wall it is recommended to soak the blocks during 15-30 seconds before their location on the wall, this ensures a proper bond of mortar and the adobes (24; 29). Adobes brickwork bond is made quite like the normal bricks. According to (8) there are use different kind of patterns to create the adobes fabric inside the wall: header, Flemish or stretcher, anyway the important issue is to ensure the overlapping of the junctions to guarantee the structural behaviour of the wall as a whole system that is composed of several modules. The image 39 represent different brickworks bonds that can be used to construct an adobe wall (20), for sure the chosen brickwork bond should be related to the dimensions of the adobes and the thickness of the wall[9]. Corresponding to the aforementioned Colombian dimensions of adobe blocks the brickwork bonds B & C of the image can be adequate.

From structural point of view is very important to ensure the overlapping of the adobe junctions on walls corners and intersections, thus different walls that converge in the same intersection can maintain their position and behave as a unique element under vertical or seismic loads[10].

Considering the plasticity of the mortar it is recommended to construct adobe walls with a velocity of 1m of highness per day, otherwise the weight can compress the lower layers

9 Recommendations for brickwork construction in relation to seismic effects caused by shear stress are done on chapter 4.5.6.

10 The importance of wall-to-wall junction is larger explained on chapters 4.5.2 and 4.5.3.

provoking different highness decrease long the wall (Img. 40) (32). When the total highness of the wall is reached the construction of the ring beam, roof or intermediate floors can be done, and later plastering should be made[11].

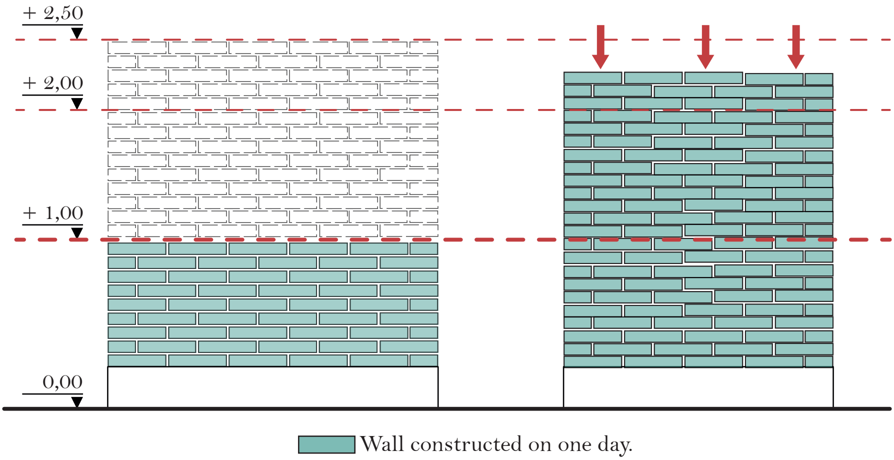
11 For openings, ring beam, roof and floor constructions considered the recommendations of chapters 3.1.4; 4.3.3 – 4.4.3.

3.3.1. Fibres addition to adobe loam mixture

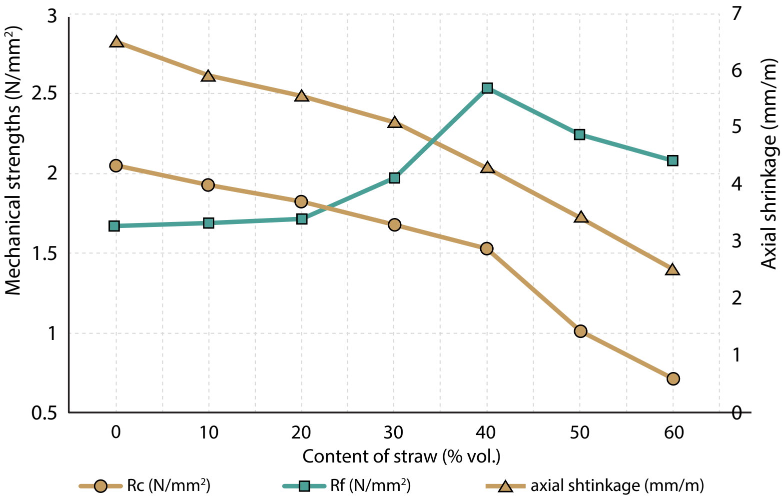
In Colombia the use of fibres in adobe is not widespread in the constructive traditions of the country. However, several investigations (45-46)have been done about additives to the loam mix, principally about the use of straw, and its effect on the adobe structure are already known (prevent cracks in the blocks due to shrinkage when drying). The Peruvian regulation (24) includes straw "or similar fibres" as a "natural additive" for adobes and mortar production, according to the E.080 – and (45-46) – it prevents the cracking (caused by shrinkage) during drying process. Blondet (29) suggested to use straw of 5cm length in a straw:loam ratio of 1:5.

Nevertheless, there have been done some investigations to study the influence of fibres on the mechanical strengths of adobes. With the objective of determine the optimum percentage of the fibres addition to improve the mechanical strengths and thermal capacity of the adobe blocks Catalan (45) have made an investigation on loam mixtures with hemp and straw fibres.

As conclusion it was found an optimum addition of hemp fibres (9-10%) that can enhance the mechanical strength and the thermal conductivity of adobe blocks is if it is more than 10% it provokes a reduction on the compressive strength, in the other hand the tensile strength by bending continue to grow with the addition of fibres. For the straw fibres the optimum percentages are 30- 40%, as it presented the largest increase of flexural strength before the compressive strength decrease sharply (Img. 41). There were not presented drying cracks as the axial shrinkage also de-



IMG 40. Highness decrease caused by excessive load during construction of adobe walls, recommendation of constructing 1m highness per day. Image of the author, data from: VIÑUALES, G. 2007. Pg, 227.



IMG 41. Variation of compressive strength, flexural tensile strength, axial contractions depending of the straw amount in clay mixture. Image redrawn from: CATALAN et, Al.2015

crease with the addition of the fibres (45).

Other investigation has work on the use of pig hair as additive to the adobe blocks, analysing the influence of the amount and length of the fibres on the mechanical-damage of the blocks. The fibres addition was tested with different proportions and lengths. The investigation studied the influence of the aforementioned additives onto the flexural and compressive strengths, and the shrinkage cracking distribution of the adobes (46). It was found an appropriate pig hair addition of 0,5% with 7mm length that can enhance slightly the flexural toughness and the impact strength, clearly, drying shrinkage cracking was reduced. However, the addition of higher quantities or longer fibres produced a decrease on the flexural and compressive strengths of the blocks (46).

From these investigations can be conclude that the use of fibres in adobe can enhance especially the shrinkage cracking but not the tensile strength under seismic loads, and the quantity and length of the fibres are sensitive variables that can also carries negative consequences on flexural and compressive strengths of the blocks.

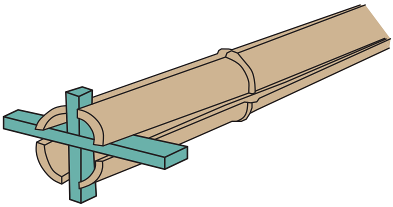
3.4. Bahareque

Another vernacular technique is the daubed earth (20) known as "Bahareque or Quincha" in Latin American countries. As pre-colonial technique, during the colonial period bahareque was considered the constructed method for the poor people; then tapia, adobes, bricks and stones were used to construct the important and rich buildings (11). Is not easy to find important constructions totally made on bahareque, however there are buildings that combine different earthen techniques as the San Calletano church in Confines, Santander. As rammed earth and adobes, in Colombia exist a big amount of informal buildings constructed with bahareque, markedly in the Caribbean region. The bahareque house built by Lucía Garzon in Villa de Leyva is an example this constructive technique (Img. 42).

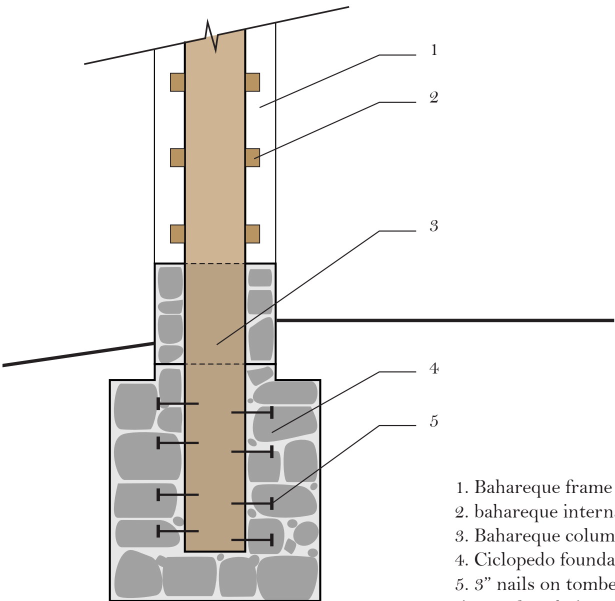
Bahareque is made-up of walls that have a structural grid, usually done with timber or bamboo, this structural structure is covered with a similar loam mix described to the adobes, but in this case, it surly has an addition of straw. As walls are limited by the frame of the wood structure, their thickness is considerable than the adobe or rammed earth walls.

In Colombia traditionally the bahareque is also constructed with guadua or other bamboo spices. For the principal elements of the frame, the entire bamboo culm can be use (19; 23). For the production of thinnest sticks, is necessary a splitting process to open the tubular guadua and obtain linear pieces of wood that are going to be attached to the main structural elements (Img. 43) (19). There is also possible to use smaller bamboo species as "Caña brava" (Gynerium Sagittatum) or "chusque" (Chusquea spp) they are directly joined to the

IMG 42. Bahareque house. Villa de Leyva, Colombia. Image tooken from: GARZÓN. Dialogando con la tierra. [recopil.] Mario Hidrobo. Videoterra 7 | Dialogando con la Tierra. Lucía Garzón. [Video YouTube.]. 29 de Enero de 2015



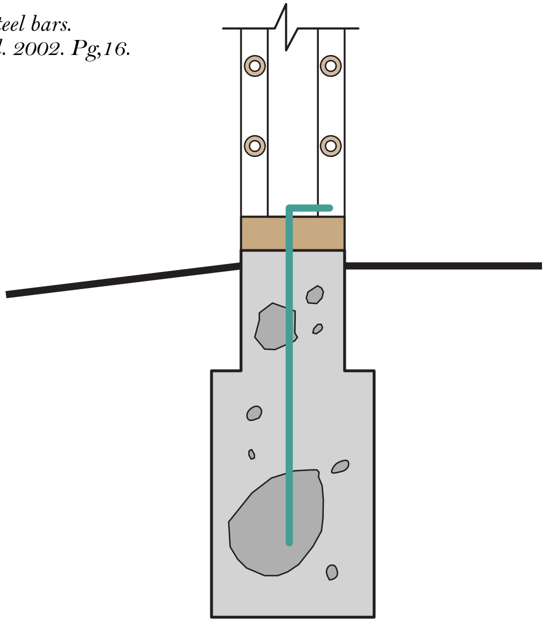
IMG 43. Splitting process for opening bamboo culms.
Image redrawn from: CARAZAS et, Al. 2002. Pg,12.

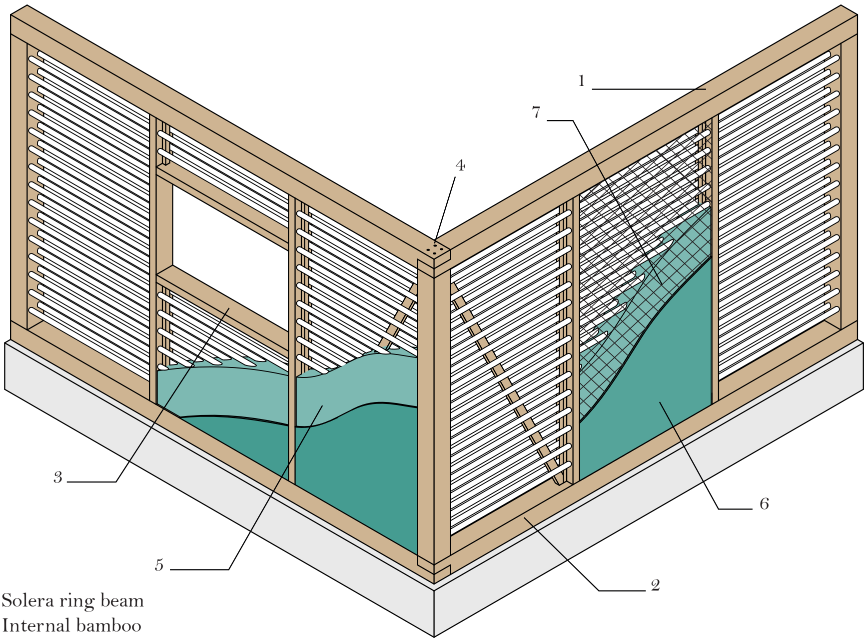


1. Bahareque frame
2. bahareque internal timber elements
3. Bahareque column enbedded in foundati
4. Ciclopedo foundation
5. 3" nails on tomber column to enhance ju
tion to foundation

IMG 44. Junction of bahareque timber structure with Ciclopedo foundation.
Image redrawn from: CARAZAS et, Al. 2002. Pg,14.

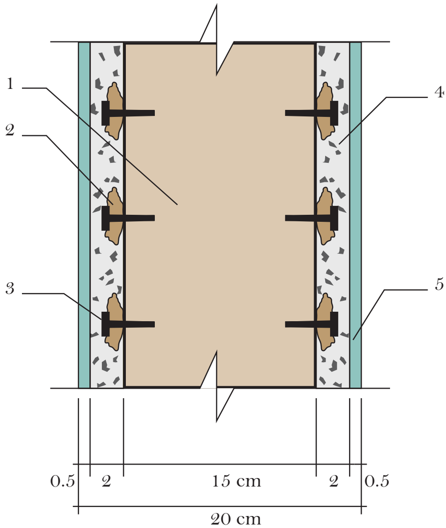
IMG 45. Bahareque foundation with steel bars.
Image redrawn from: CARAZAS et, Al. 2002. Pg,16.





1. Solera ring beam
2. Internal bamboo
3. Window frame, timber
4. Soleras ring beam junction
5. Loam mix
6. Earthen plaster
7. Metal grid for plaster attachment

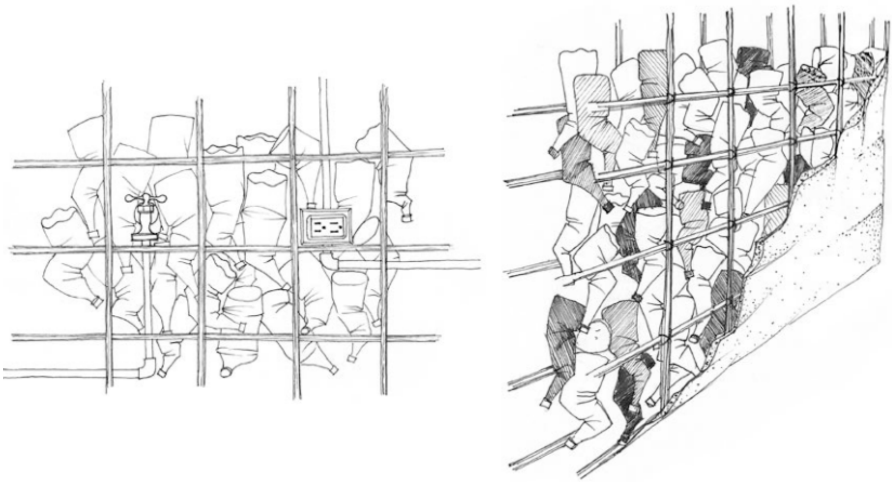
IMG 46. Bahareque frame composition.
Image redrawn from: CARAZAS et, Al. 2002. Pg,16.



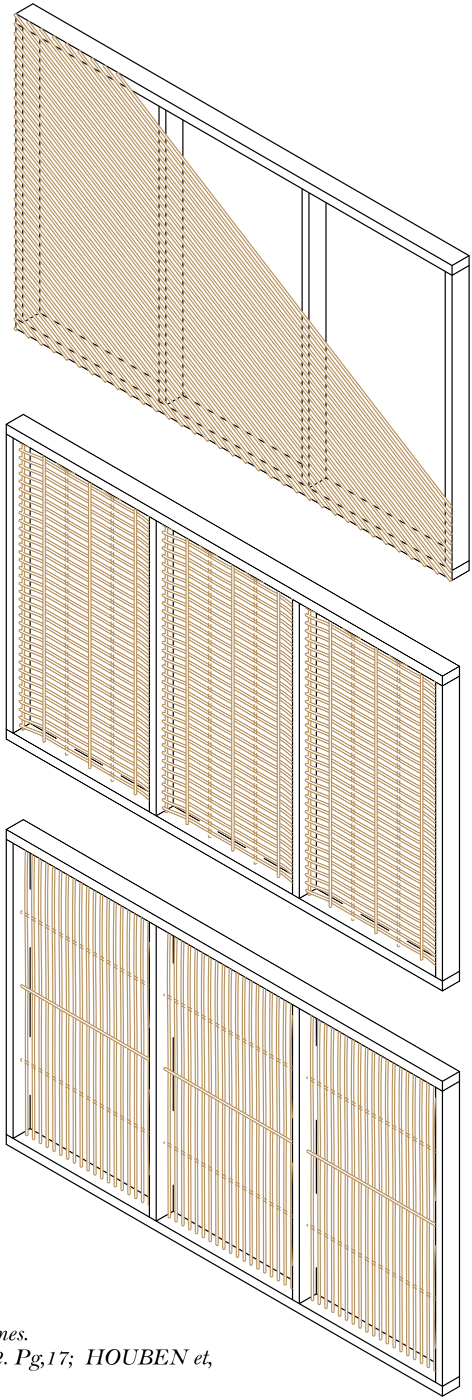
1. Bahareque intermediate structure
2. Horizontal open bamboo
3. Nails
4. Loam infill
5. Clayish plaster

All units expressed in cm

IMG 47. Bahareque wall section. Image redrawn from: CARAZAS et, Al. 2002. Pg,15.



IMG 49. Bahareque wall infiled with PET bottles. Image tooken from: ANZELLINI et, Al. 2016.



IMG 48. Different traditional bahareque frames.
Image redrawn from: CARAZAS et, Al. 2002. Pg,17; HOUBEN et, Al. 1994. Pg, 189. & RIVERA, A. 2013.

principal wood elements (19). If there is going to be used bamboo or timber the selection, production and curating process of the wood can be guided by Carazas (19).

Regarding the bahareque construction process first should be given some specifications concerning the foundations and base courses. Carazas propose the use of the traditional "ciclopedo" foundations (chapter 3.1.2) in which is insert the wooden columns of the bahareque frame (Img. 44), for that case the part of the wood columns that is inserted on the foundations shall have 3" nails partially fixed to improve the junction of the column with the foundation. Other possibility is – wile foundation and base course are been done – insert steel bars that remain partially out of the base courses, the bahareque frame is joined to those bars ensuring the structure-foundation junction (Img. 45) (19).

The wood structure is defined by a rectangular frame that boundaries each wall, timbers on top and bottom are called "Soleras". Inside that frame are vertically located thinner columns that are the secondary level of the structure, these usually have an intermediate distance of 0,80 – 1,20m (19) and should be nailed to soleras (top and bottom). Finally, lighter wood sticks are localised in a horizontal or diagonal position (20; 23; 26) – crisscrossed or just fixed according to traditions and the kind of wood used – to the vertical "columns" that were done before (Img. 46) (19). The section of the wall can be seen on image 47, is notable the wall thickness of 20cm approximately (19; 26). Other compositions of the wooden structures that are exposed by several authors (19; 20; 23; 26) can be seen on image 48.

Once the foundations and the whole wood structure is done, the loam mix – always with a straw additive – is manually put and pressed around the wooden elements, thus the wall is fill until the wood is completely covered (19), is important to guarantee a covering layer of at least 2cm thick over the wood elements (Img. 46) (23). The frame can be uncovered so it can be used to fix the roof structure, doors or windows. Later is possible to do a finishing with lime or clay plaster[12] (19). Sometimes are used metal or plastic grids to improve the adhesion of the finishing to the wall (Img. 46) (20; 23; 38).

There are registrations of bahareque walls that are infilled also with bottles to reduce the amount of loam mix needed (Img. 49) (31).

Is important to note that the opening[13] on bahareque walls should be totally limited by wood boundary that should be attached to the main structure (Img. 46), the internal faces of the opening can be used to fix doors and windows.

Due to the light thickness of the raw earth layer over the wood structure and the dilatations that wood can present, bahareque buildings can easily present cracks and holes that weaken the structure (23), hence frequent maintenance works are required (8) and is recommendable to ensure the isolation from capillarity from ground (20).

When all the walls are erected, the construction of the ring beam can be done, thus over it can be constructed the roof[14].

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12 Plastering should follow the recommendations of chapter 3.1.5

13 Consider also chapter 4.3.3.

14 Follow chapters 4.4.1 & 4.4.3 for ring beam and 3.1.4 for roof construction.

3.5. CEB.

The Compressed Earth Blocks (CEB) are raw earth bricks produced by the compression of a loam mix into a mould, the loam can be previously stabilised with cement or lime. The use of this technology is similar to cooked bricks, the wall brickwork is normally done.

Different from the other techniques described before, the CEB is a new industrialized product, hence is apart from the "vernacular earthen techniques". The projects that can be referenced are all contemporary and are not monumental architecture. However this technique is considered during the present investigation due it contemporary frequent use. In Colombia are several projects that goes from single houses, dwelling or commercial buildings (Img. 50 & 51). For these and other projects, in the country is normal that the CEBs buildings have a main structure in concrete. Principally this is done because of the lack of regulation for this constructive product, the main structure is considered necessary to have safe building. Thus, is normal find projects that mix the CEBs into a non-raw-earth architecture as can be the dwelling Tejar del Rio in Chia, near to Bogotá (Img. 52).

CEBs are used today in many parts of the world and had become a known product in the industry of construction. In Colombia the production of this blocks is regulated by the NTC 5324 regulation standard (17). Important industries of CEBs in Colombia are TierraTEC (47) or Heicon (48), both produce blocks in their own factories or in the construction site, offering the possibility to use local materials. These industries have supply blocks to rural and urban projects

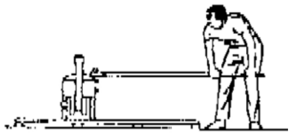
IMG 50. CEB building.
Image taken from:TierraTEC industry. 2018.

IMG 51. CEB house,. Image taken from:TierraTEC industry. 2018.

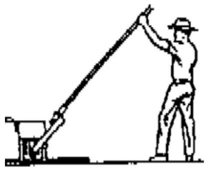
IMG 52. Dwelling Tejar del Rio in Chia, CEB used for construction. Image from the author.

Fill the ram

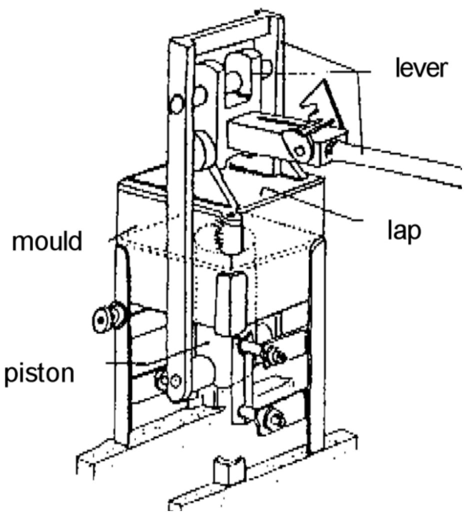
Compact loam



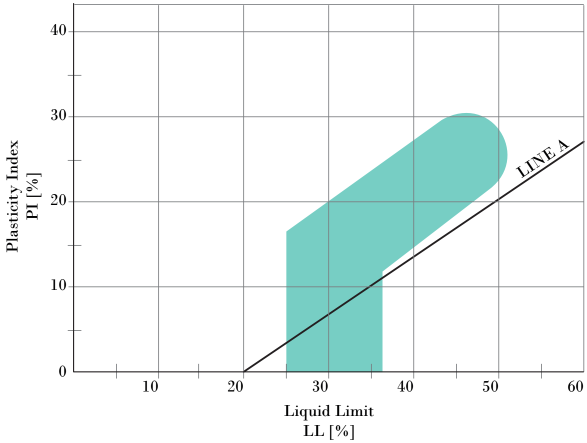
Press completely the loam



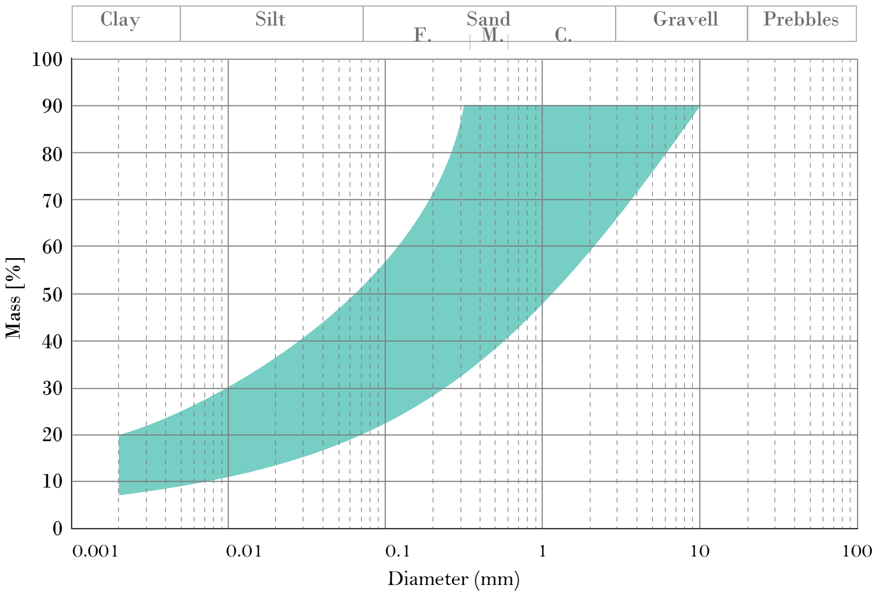
Unmold the CEB block



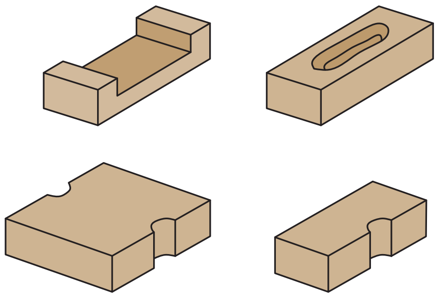
IMG 53. CINVARam. Image tooken from: MINKE, 2012.



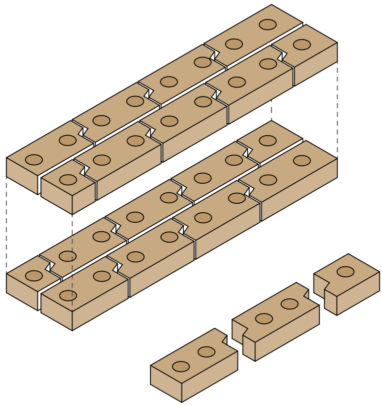
IMG 54. Recommended liquid limit in relation to plasticity index for CEB loam. Image redrawn from: HOUBEN et, Al. 1994. Pg, 116.



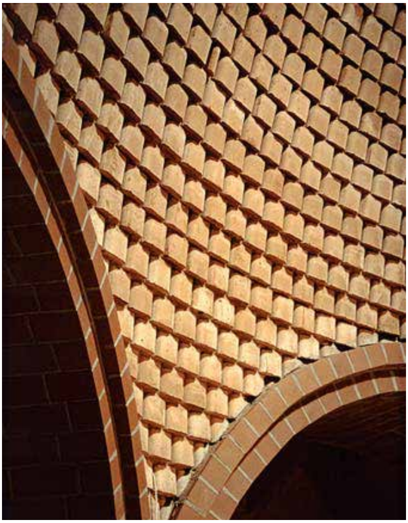
IMG 55. Recommended granulometric curves for CEB loam. Image redrawn from: HOUBEN et, Al. 1994. Pg, 116.



IMG 56. Special shaped CEB blocks. Image redrawn from: HOUBEN et, Al. 1994. Pg, 211.



IMG 57. Interlocking CEB. Image redrawn from: HOUBEN et, Al. 1994. Pg, 211.



IMG 58. Green blocs in a kindergarten in Sorsum, Germany. Image tooken from: MINKE, 2012.

in different regions of the country.

The best known or one of the first process patented in the world to produce the CEBs was created in Colombia in 1952 by the engineer Raul Ramirez (21; 49). Is a manual press that permit to produce up to 200 blocks per day (Img. 53) (23). After that one, numerous manual and mechanical press has been invented to improve the efficiency of the production process.

In coherence to the compressing process that should be done, the loam mix that is used to produce the CEBs is dramatically drier than the one use to produce adobes. Hence, the use of CEBs carries an important reduction of water consumption. Punctually, for the moisture content that CRATerre manual for earthen construction (20) suggest for the production of CEB is between 8-11%, and preferable to maintain the liquid limit and plasticity index of the prepared loam inside the area of the image 54. Regarding the granulometric composition of the loam, the same manual recommends granulometric curves that can be quite similar to the rammed earth loam, with a little reduction of gravel content and a larger range for clay and silt percentage, image 55 show the limits defined by the authors. The proportions for a complete loam mix are proposed by (50) as: sand and gravel 40-70%, clay 15-60% and water 8-12%.

The stabilization of the loam for CEB is normally made with 4-8% (wt%) of cement or lime (23; 50), this is made to increase the mechanical strength and reduce the moisture absorption of the blocks (50), indeed some investigations also show a positive relation between the use of the stabilizer and the resistance of the block to environmental erosions (51).

As the CEBs are pressed in a mould their dimensions can variate – e.g. 14 x 9.5 x 29.5 or 22 x 9.5 x 22cm – (17). CEBs can be done with various shapes (20) as the ones on image 56.

Whit the objective of reduce the costs of mortar, there are produced the “interlocking” CEBs (20; 51). These CEBs, that avoid totally the use of mortar, guarantee the brickwork junctions by their geometry (Img. 57). Interlocking CEBs walls has a unique and uniform material, hence the structural behaviour of the entire wall is also uniform[15].

Another evolution of CEBs brought out the acoustic green blocks[16], these are hollowed moulded and with rounded corners. In the punctual case of a kindergarten in Sorsum, Germany (Img. 58) the blocks are stacked with cut-off junctions improving the reverberation of the sound in the room (23).

Differing from the adobes the compressed earth blocks are ready to be used sooner, even if some authors suggest that CEBs can be used on construction site just after been pressed (23), Bowen (50) and Artega (52) recommends to construct at least 7 days after the production process, however blocks are going to reach their ultimate strength after 28 days from their production. The importance of letting CEBs curate is to ensure the quality of the material and let the blocks reach the required strengths (50).

15 Minke (30) ensure the interlocking CEBs can maintain the stability of the wall under seismic loads preventing failure mechanisms explained on chapter 4.2.

16 Nevertheless, is important to note that the use of normal CEBs for constructing partitions or peripheral walls represent a good thermal and acoustic isolation.

For CEB construction is preferable the use soil:lime mortars (23), the mortars with the same loam composition that is used for the production of CEBs are recommendable (36) as they homogenizes the material and structural behaviour of the entire wall (50). Additionally, Minke specify the quantity of clay for mortars should be between 4-10% (23). Nevertheless, Bowen (50) suggest avoiding particles larger than 3mm in mortar granulometry as they can provoke punctual loads on the block's faces, considering that the same author propose a mortar thickness of 6mm[17]. However, common suggestions for the thickness of mortars are between 1cm (36) to 2cm (23; 53). Regarding the moisture content of mortar it is also recommendable it should be as low as possible, anyway ensuring a proper workability of the mixture[18] (24).

Regarding the construction process, over the foundations and brace course CEBs can be located with a normal masonry brickwork bonds, always maintaining the overlapping of junctions to ensure the stability of the entire wall and the wall-to-wall junction that provides a systemic behaviour of several walls[19]. To guarantee an appropriate bond junction between mortar and CEBs (36; 52; 54) recommended to soak the blocks just before putting them in the wall. Concerning the construction with interlocking CEB, it differs to the normal ones just in the use of mortars, and there should be always construct ring beams and base courses to complete the whole structural system. For plastering is always recommended the use of lime or clayish plasters that allows the humidity exchange through the wall (23).

17 Approximative dimensions, the author refers on inches.

18 The seismic importance of the mortar characteristics and constructive process for blocks masonry is explained on chapter 4.5.6.

19 When the total highness of the wall is reached the construction of the ring beam can be done following the chapter 4.4.1 and 4.4.3, thus over it can be constructed the roof or intermediate floors according to chapters 3.1.4 and 4.4.2. Openings should follow the parameters given on chapter 4.3.3.

Foto from the author.

4. ANTI-SEISMIC STRATEGIES AND REINFORCEMENTS FOR EARTHEN BUILDINGS

“Tenemos que empezar a partir [...] zonas sísmicas y zonas no sísmicas, no se puede hablar de arquitectura en tierra para el mundo” (55)

(We should start dividing [...] seismic zones and no seismic zones, is not possible to talk about earth architecture to the world)

The present chapter is an approach to the main Colombian earthen building techniques from a seismic-resistant point of view. Here are described the possible solutions and reinforcements for improve the application of earthen buildings in urban seismic areas. In consideration of the context and the high exposition to seismic hazards of Colombia, this chapter takes into account Latin American investigations, regulations and manuals that have suggested how to construct anti-seismic buildings – especially houses – and reinforcement to earthen constructions.

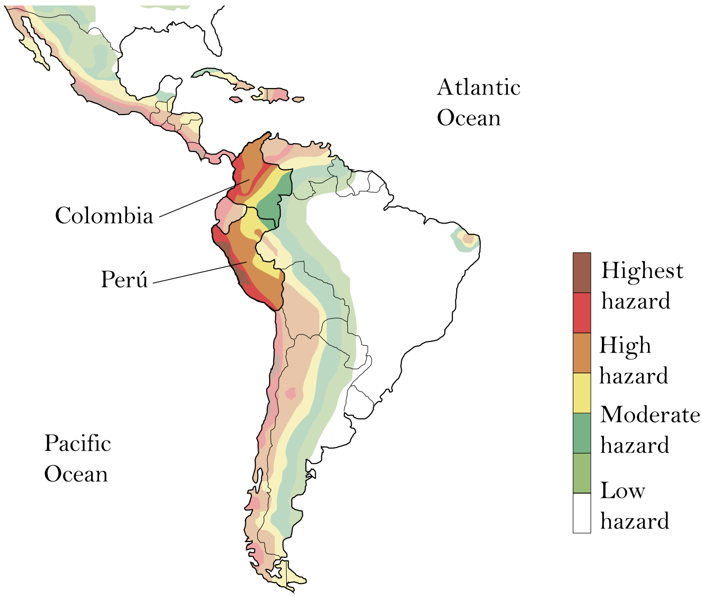
Before the explanation of structural issues of the earthen buildings and considering that the seismicity of each geographical context can change, first there are going to be specified parameters that regards the seismic hazard of Colombia and the surroundings conditions of the building location. Later is going to be done an explanation of the failure mechanism of earthen buildings under seismic loads to understand the importance and functionality of each punctual reinforcement. After that in the present chapter are presented three main strategies that this research identified to enhance earthen buildings performance under seismic loads, the strategies are referred to: the building behaviour as a whole, the systemic “box-behaviour” of the structure, and the performance of the load-bearing walls as principal structural element. For each one of the three strategies correspond punctual recommendations and reinforcements that offer solution to the failure mechanisms of earthen buildings under seismic loads.

4.1. Location: Colombian seismic hazard and surroundings conditions

Apply to: All techniques.

Regarding the location of the building and taking care of seismic hazard there can be defined limitations to the designing of the project and the way it is construct. Two different approaches has been identified: the seismic hazard of the location and the surrounding conditions that can affect the building during an earthquake.

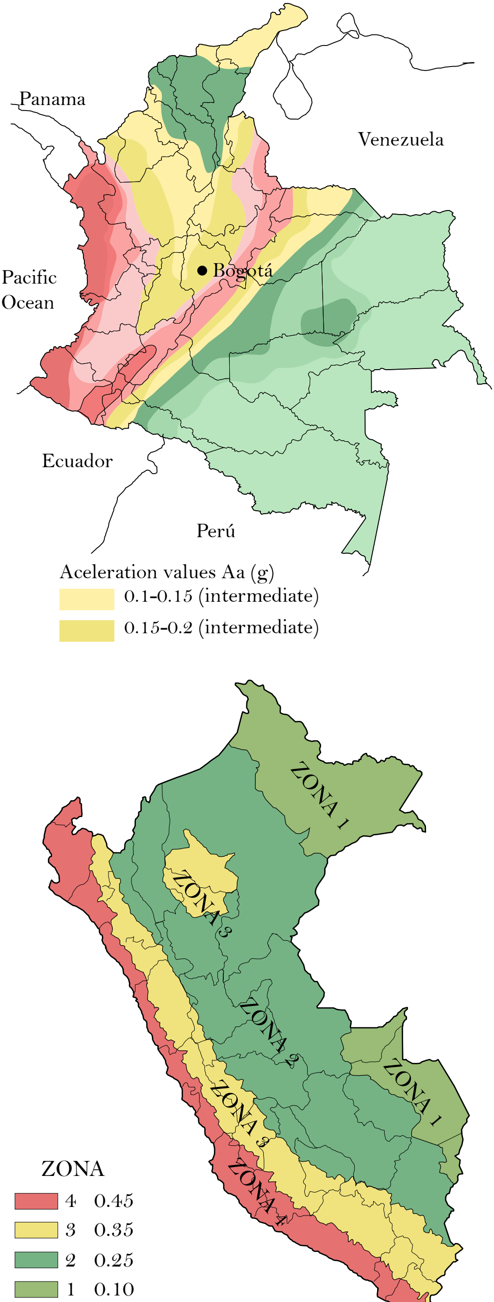
Concerning the seismic hazard, in Colombia it is established by the INGEOMINAS (Instituto Colombiano de Geología y Minería). There was produced a map that identify the accelerations Aa (g) that can be reached during earthquakes on all the national territory, in coherence to those values there are identified three hazard zones: high, intermediate and low. Those seismic hazard zones and acceleration values are similar to nearby



IMG 59. Seismic hazard of Latin America. Image redrawn from: GIARDINI et, Al. 1999. Pg, 1226

Colombia		Peru (E.080)		
Seismic Hazard Zone	Aa (g)	Seismic Hazard Zone	Aa (g)	# levels
Low	0.00-0.05	Zone 1	0.00-.010	2
	0.05-0.075			
	0.075-0.10			
Intermediate	0.10-0.15	Zone 2	0.10-0.25	2
	0.15-0.20			
	0.20-0.25			
High	0.25-0.30	Zone 3	0.25-0.35	1
	0.30-0.35			
	0.35-0.40	Zone 4	0.35-0.45	1

Chart 1. Comparison of seismic hazard zones for Colombia and Peru. In relation there are registered the number of levels allowed by E.080 for reinforced earthen buildings. (24) (54)



IMG 60. Seismic zones of Colombia, (redrawn from INGEOMINAS) & Seismic zones of Peru, (redrawn from Decreto N.080-2016-vivineda. 2016)

countries that are also located over the Andes and near to the geological fault that surround South America in the Pacific Ocean (Img. 59) (56). For example the relation of the seismic zones of Peru and Colombia is notable in the comparison of the image 60, both countries have high, intermediate and low areas, measured by the acceleration Aa (g).

The Peruvian regulation E.080 Diseño y construcción con tierra reforzada" (Design and construction with reinforced earth) (24) established the number of levels that should have earthen reinforced buildings in coherence to the Aa(g) values of each seismic hazard zone. It is possible to construct buildings with reinforced earth techniques of one or two levels (ground and first floor) in seismic zones 1 and 2 with Aa maximum values of 0.10 - 0.25, and buildings with just one level (ground floor) for the seismic zones 3 and 4 were the Aa values are 0.35 - 0.45 (24)

In light of above, the Peruvian law E.080 (24) is useful to establish a limitation to the building highness in relation to the seismic hazard of the location in Colombian territory. Chart 1 shows the comparison of seismic hazard zones, Aa (g) values of Colombia and Peru, and the number of levels permitted by E.080, for each zone.

For example the Colombian seismic hazard map express Bogotá as an intermediate hazard area with an Aa value of 0.1 - 0.2. In relation to the Peruvian law – considering the seismic zone and the Aa(g) acceleration values – in Bogotá is possible to construct buildings with reinforced earth that have two levels.

On the other hand the geographical conditions of the surroundings should be controlled and considered when the earthen project is going to be proposed, thus the building can be protected or distanced from possible ground displacements provoked by the earthquake. The presence of slopes, groundwater, rivers or even contiguous building can represent a risk for the well-sanding of the building.

The following recommendations done by several authors regards principally when the construction is going to be located on slopes:

- Avoid as possible slopes to the building location.
- Distance as possible the building from abrupt slopes (over or down the building).
- Avoid flood zones and areas where have been presented earth avalanches hazard.
- The ground level and bottom level of foundations should be always levelled and flattened, the building cannot be stepped or introduced into the slope terrain.
- There can be constructed breast walls to control the surrounding terrain and diminish the risk of avalanches or loss of supports, these should be located at least 3m from the building perimeter and the use of a ground drainage on the "upper" surroundings is useful to protect the building from water that can come from the slope.

Other considerations concerning the surrounding environment are:

- Avoid areas where groundwater can come out.
- For urban areas is also recommendable to avoid the location of the buildings near to old buildings

in poor conditions that can also present risk of collapse.

(19; 24; 29; 30)

The group of schemes on image 61 explains the aforementioned recommendations.

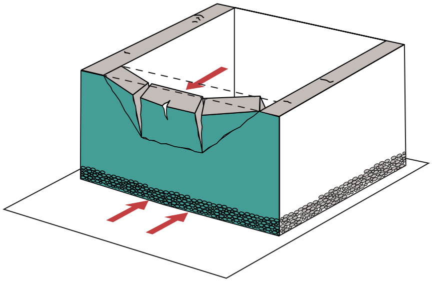
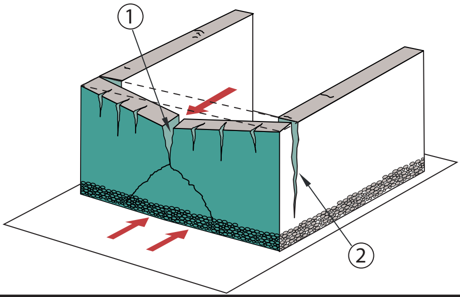
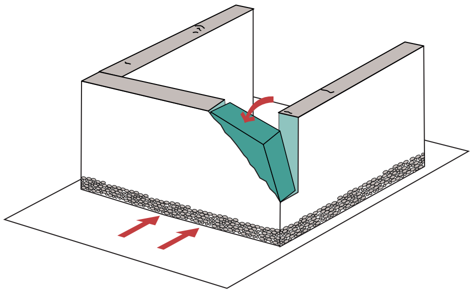
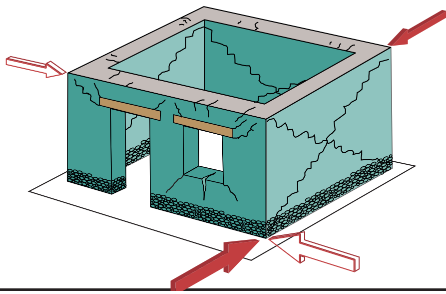
4.2. Failure mechanisms

To understand the importance, reason and functionality of the reinforcements is necessary to explain first why and how the earthen buildings collapse under seismic loads. Yamin (27) and Ortega (58) made an excellent description of the failure mechanisms of earthen buildings, the chart 2 is a reproduction of the work made by the aforementioned authors.

The ductility of a material guarantees its capacity to dissipate energy - through plastic deformation - after reaching the peak load (10; 43), it means is related to the deformation a material can reach without losing its strengths. This parameter is considered an important characteristic for constructive materials used in seismic areas (59). A building with large ductility can retard the failure mechanisms and so the collapse of the structure (43). In other words, it increases the evacuation time of the building before it collapse during an earthquake.

Unfortunately the earth building materials have a brittle mechanical nature, hence the aforementioned ductility is not enough to allow the building to have a post-peak deformation before a sudden collapse.

As it is explained in the chart 2 the failures of earthen buildings during an earthquake are mostly caused by the bending stress generated by horizontal non-axial loads over the walls. The earth building material has low tensile and bending strength; hence the ductile behaviour of the material is limited. These properties are weaker under high inertia forces produced by the weight of the building under earthquake loads, and in absence of a diaphragmatic stiffness (60).

FAULT TYPE	SCHEME
I) Blending effort perpendicular to the wall. Horizontal cracking in the base or in meddle highness and additional vertical cracking. Presented usually in long walls.	
II) Blending effort perpendicular to the wall with vertical cracking in centre area. (1)Diagonal cracking that constitute the fault mechanism and fissuration in the upper part of the wall. (2)Tensile failure of masonry and vertical cracks at the corners.	
III) Out-of-plane failure of corners caused by bending effort perpendicular to the walls with not bounded corners, or corners not well attached to the transversal walls.	
IV) Fault because of shear strength in the wall related to high horizontal loads. In many cases the cracks are related to heavy floors or roofs and are magnified in the openings of doors and windows.	

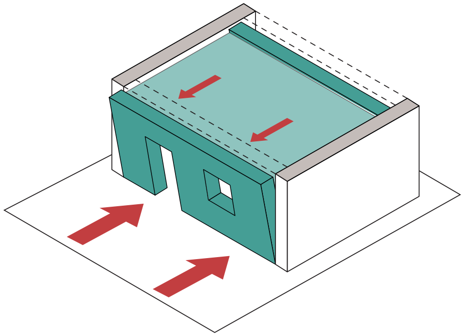
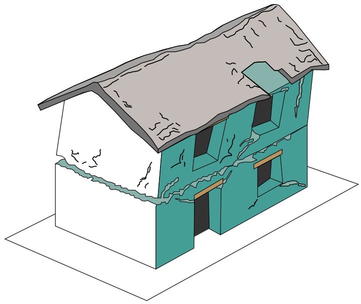
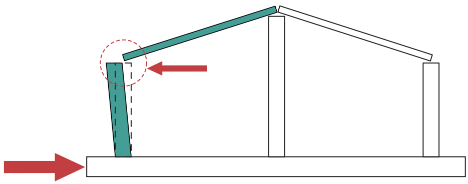
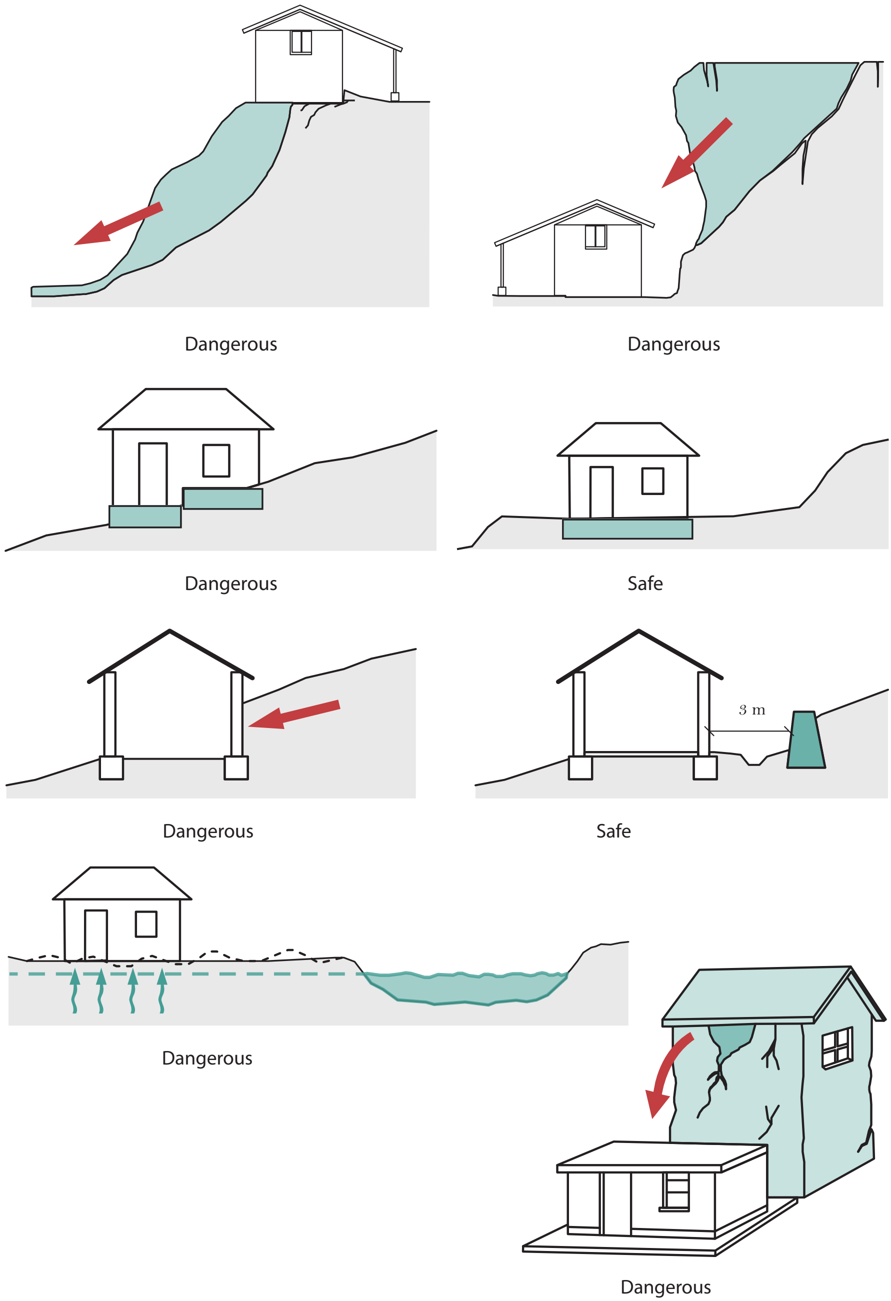
FAULT TYPE	SCHEME
V) No shear transfer connections between perpendicular walls. Shear failure of masonry and vertical crack in the corner. Also caused by inappropriate junction between walls.	
VI) For this fault mechanism the intermediate floor shatters the principal walls in horizontal way, producing the instability of the first floor. Fault caused by wrong connections of ground and first floor walls.	
VII) Fault of the roof to the interior of the house, caused by loss of the supports over the walls. A fault in the upper part of the wall provoke the roof loss its supports. Normal in buildings with heavy roofs.	

Chart 2. Fault types and cracks related to the seismic loads. Reproduced from YAMIN et, Al.2007. Pg, 289. (27) & ORTEGA et, Al. 2017. Pg, 184. (55).



IMG 61. Recommendations for location of the building in coherence to the surroundings. Image redrawn from: CARAZAS et, Al. 2002. Pg,7; BLONDET, M. 2010. Pg, 21. & MINKE, G. 2001. Pg, 8.

In the case a wall is resaving perpendicular loads the mechanism of failure can variate according to the dimensions of the wall and how it is attached to other elements. If the corner junction with contiguous walls is able to support the stress and do not failure, the rocking caused by the acceleration in the upper part of the wall is going to generate a horizontal cracking in the middle of its highness, followed by diagonal cracks that are going to grow until the perpendicular wall's junction chart 2 (I). The failure can be also started by a vertical crack that goes down from the upper part and later diagonal cracks can be also generated. In the case the corners junction is not well constructed, the tensile stress, generated in the wall's intersection, provoke a vertical crack that separate the affected wall from the perpendicular ones, chart 2 (II). The risk of these failures is increased if distance between the perpendicular walls is longer.

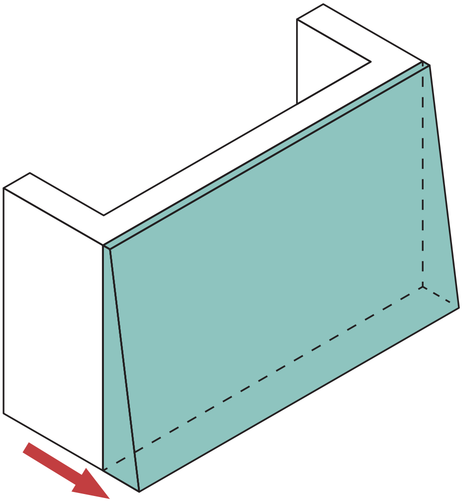
The bending effort can be also localized just in the corner of the building, or the intersection of walls. In that case the corner is going to detach from the walls caused also by diagonal cracks, chart 2 (III).

Additionally to the bending forces, the earthen elements can failure as well by shear stress. In this case the affected wall is going to be located parallel to the direction of the seismic loads. Shear failures are frequently presented in walls with openings as these are weak points of the structure, the length-high ratio and the thickness of the wall can also influence over this failure mechanism. The failure is related to huge shear efforts and low shear strength of the material. It is going to create diagonal or "X" cracking over the entire wall (58), chart 2 (IV).

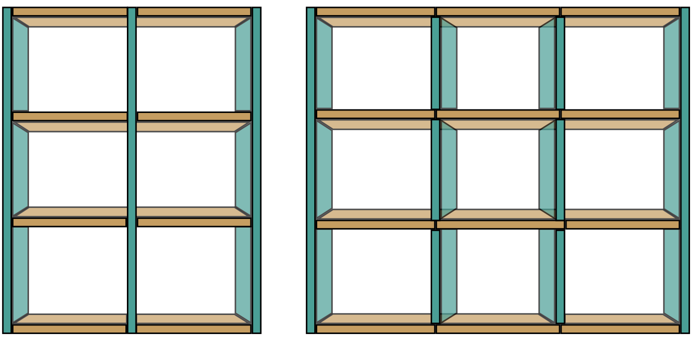
The shear stress can also generate mechanisms of failure in the corners of the building. The failure is presented as a vertical crack that divides the walls, the one that is perpendicular to the loads can collapse because of its detachment from the structural system. The risk of this failure to be presented is increased by the absence of rigid diaphragms and poor wall-to-wall junctions (58), chart 2 (V).

Due to the main failure mechanisms (previously mentioned) other failures can be presented in the entire building. In the case the building has more than one level, the intermediate floors generate horizontal thrusts over the walls provoking cracks on them, thus the stability of the upper level is lost, and the collapse is presented (27; 30), chart 2 (VI).

The failure of the roof can be presented when its support – over the earthen wall – is affected, chart 2 (VII) (30). Yamin (27) reported that this failure is usually presented on buildings with heavy roofs, wrong junction of roof-wall structures, and in old buildings that present an important degradation state.



IMG 62. Thickening of walls on ground floor. Image redrawn from: ORTEGA et, Al. 2017. Pg, 13.



IMG 63. Wall distribution on architectural design.

4.3. Building behaviour strategy

Due the large magnitude of seismic loads and their influence over the entire building, it is necessary to understand the building as a whole in order to optimize its behaviour as a unit under seismic loads. The building mass and shape, as well as the location, distribution and orientation of the structural elements, can influence the performance of the entire building during earthquakes, the appropriate management of those parameters can enhance the response of the structure and would be especially useful in the case of using inelastic materials as earth.

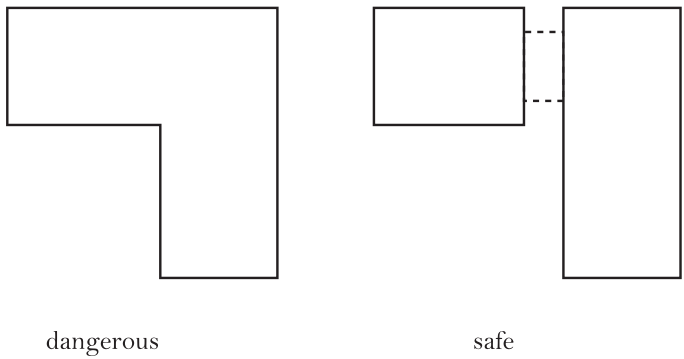
The recommendations and parameters proposed under this strategy offer solutions that are referred to the architectonic conception of the building and aims to safeguard its behaviour as a whole.

4.3.1. Control the seismic inertia loads

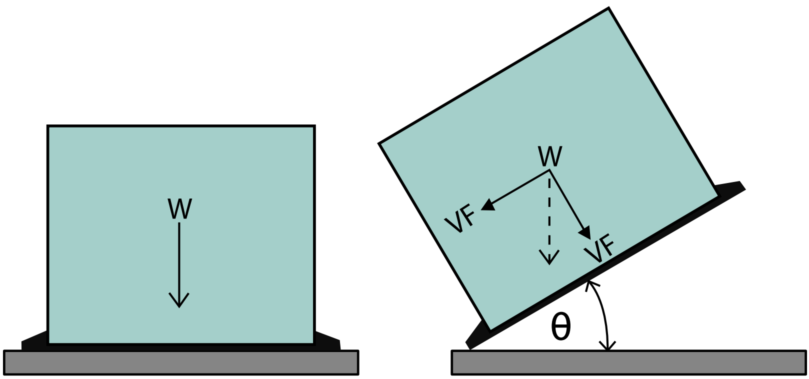
Apply to: All techniques.

It was noticed that the big mass of earthen buildings can be an important problem producing high inertia in respond to horizontal forces of an earthquake (14). This increased inertia raises the tensile and shear stress that earthen walls are going to suffer. As the inertia is dependent on the weight of the building, the weight reduction of the structural elements can help to control the building inertia. That means to construct upper levels with lighter materials, reducing the thickness of the walls as growing in highness and opt for light roofs and floor structures (10; 58).

On image 62 is possible to see the thickening of ground-floor walls as a strategy to equilibrate the building mass by lowering its centre of gravity (58). As the section area of the wall is increased, the resistance to out-of-plane loads also increase, and the failures by bending cracks can be diminished. This can be conceived as a reinforcement for the slenderness ratio defined on the section 4.3.2.



IMG 64.General plant recomendations avoiding "L" plant shapes. Image redrawn from: MINKE, G. 2001.



IMG 65. Concept scheme of the static testing. Image redrawn from: SAMALI et, Al. 2011.

4.3.2. General plants configurations and dimensions

Apply to: Especially to Adobe and Rammed Earth techniques.

As the seismic loads can arrive to the building by any direction, the shape, proportions, disposition or design of the structural elements can highly influence the building mechanical resistance to seismic stresses. Loads should be distributed into the entire structural system avoiding its concentration as peak loads in specific points.

In order to distribute the loads into the entire load-bearing walls structural system, it is important to ensure an equilibrate plan distribution of walls. That means the architectural design should be compact using typological and distributive schemes with equilibrated proportions on X, Y, Z axis. A typological scheme for the wall's distribution can be seen on image 63 (14; 21; 26).

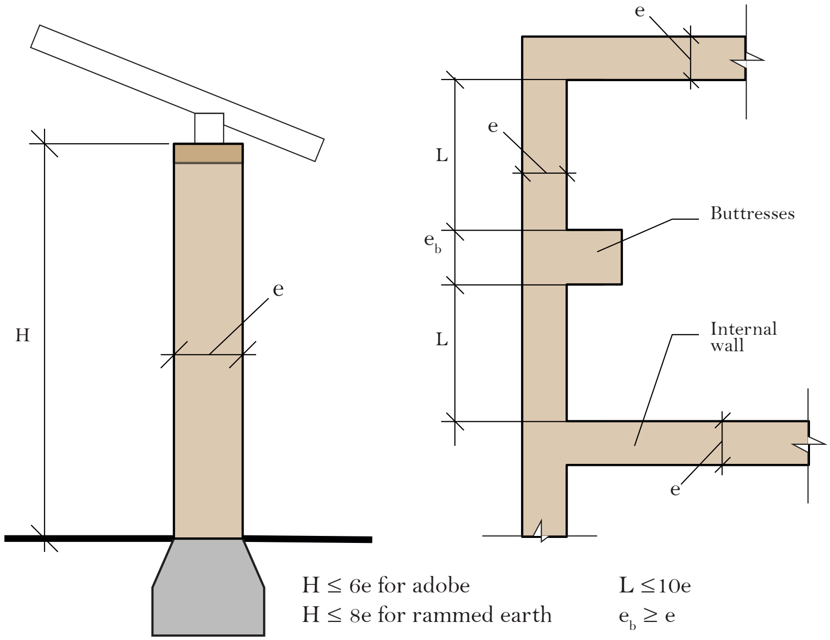
There are pointed out general plant designs that reduce the dramatic damages that can suffer the corners of the building. Avoid "L" shapes in the general plant or dividing the structure in a way the parts of the building can oscillate independently one from the other (30) can decrease corners failures as vertical cracks caused by tensile stress or the out-of-plane failure, caused by bending efforts (Img. 64).

Some authors propose the use of circular plant shape to avoid weak corners (30). There was found a study that analyse the performance of a square Vs. a circular plant shape building. In the University of Technology of Sidney were constructed two 1:3 scale adobe models (one with square and one with circular plant shape), both constructed with the same loam mixture. The models were placed in a tilt table to create a constant acceleration perpendicular to the walls (Img. 65). The circular scheme demonstrated better performances: the horizontal force at the first shear crack was 1.73 KN and at the complete failure was 2.02 KN; in comparison to the square scheme that presented the first shear crack under 1.45 KN and a complete failure under 1.78 KN. Just as is explained on chart 2 (II), the failure of the square model started with a vertical tensile cracking on corners that carries the separation of the frontal wall from the rest of the model, thus provoking a complete collapse (61).

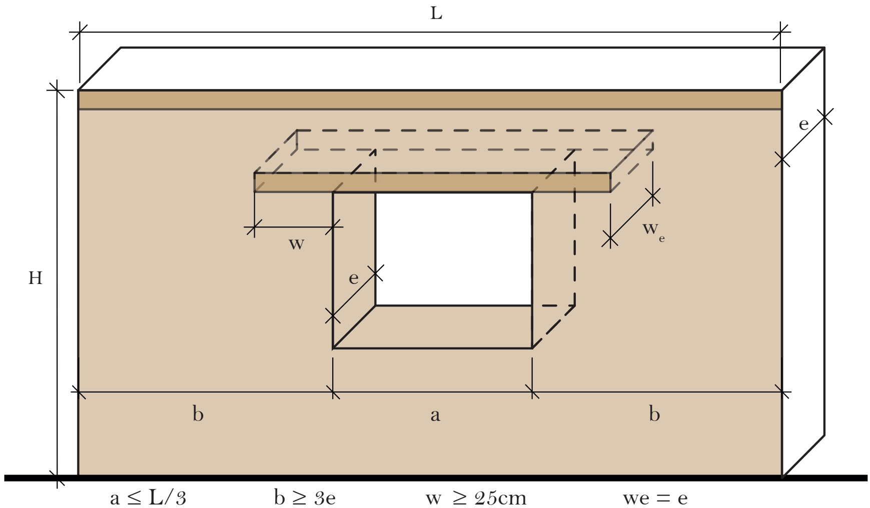
Regarding the dimensions of the building and the structural elements, on adobe and rammed earth constructions the slenderness of walls should be controlled, in order to decrease the risk of failure by bending efforts on walls and corners, and to maintain a significant wall section able to support shear stress. According to that, the first dimension established should be the thickness (**e**) of the wall in relation to the highness (**H**); that measure will be a reference to define all the other general dimensions. However, the thickness (**e**) of the wall is going to variate according to the loads that the walls should carry and to the building technology[1]. For example adobe walls thickness is related to the dimensions of the blocks and the brickwork bond used. However, the E.080 (24) suggest the wall should be thicker than 40cm for anti-seismic buildings.

Nevertheless, the recommendation for adobe walls is that the high:thick ratio should be minimum 1:6 (wall thickness $\mathbf{e} \geq \mathbf{H/6}$) (29). For rammed earth walls the slenderness ratio is

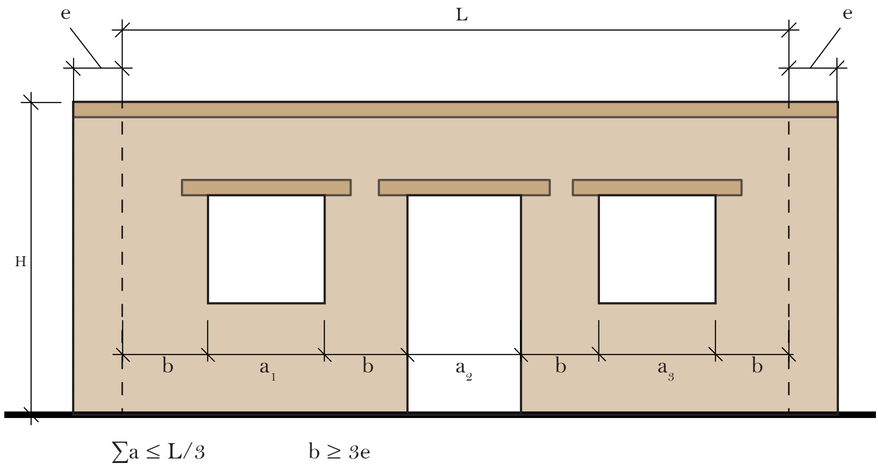
1 Dimensions of constructive elements and walls for each technique are on the relative chapters (3.2 - 3.5)



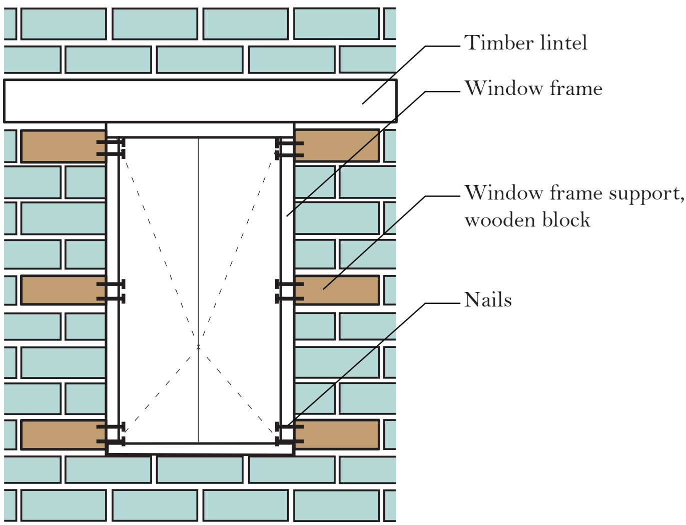
IMG 66. Limits for wall highness Vs. wall thickness & distance between tow load-bearing walls Vs. wall thickness. Image of the author, data reference from (BLONDET, M. 2010; MINKE, G. 2001; RIVERA, A. 2013; HOUBEN et, Al. 1994. & Minvivienda Peru, 2017.)



IMG 67. Distance for lintels overlapping with walls & lintels thickness. Image of the author, data reference from (BLONDET, M. 2010; MINKE, G. 2001; RIVERA, A. 2013; HOUBEN et, Al. 1994. & Minvivienda Peru, 2017.)



IMG 68. Limits for openings dimension and location . Image of the author, data reference from (BLONDET, M. 2010; MINKE, G. 2001; RIVERA, A. 2013; HOUBEN et, Al. 1994. & Minvivienda Peru, 2017.)



IMG 69. Window frame supports. Image redrawn from: HOUBEN et, Al. 1994. Pg, 269.

suggested by Minke (30) as 1:8 (wall thickness **e ≥ H/8**)

The distance between two load-bearing walls (**L**) is limited by Blondet (29), the author suggests that **L** distance should be shorter than **10e**. This consideration should be considered also valid for the distance between buttresses or walls supplying the same reinforcement[2].

Regarding the highness of the building[3] is going to be defined by the highness of the walls (**H**) in relation to the wall thickness (**e**) as: **H ≤ 6e** for adobe, and **H ≤ 8e** for rammed earth.

Image 66 resume the limits for dimensions.

Dimensions for buttresses, openings, opening location and foundations are going to be specify on the corresponding reinforcement chapters 4.5.2; 4.3.3 and 3.1.2 respectively.

2 View perpendicular reinforcements & buttresses (chapter 4.5.2)

3 Number of levels is specified by E.080 in relation to Aa(g) values, view chapter 4.1.

4.3.3. Openings

Apply to: Especially to Adobe and Rammed Earth techniques.

Openings in load-bearing walls represent a weak point for the structure, even if seismic loads are not considered. The vertical loads of the building are supported by the walls, however, the reduction in the area of the walls by the openings represent a deviation of the load path, thus reducing the load-bearing capacity .

It is always necessary to include lintels as to ensure the vertical load distribution to the sides of the opening. The upper loads are going to generate bending stress in the in the middle of the opening, lintels should supply the required bending strength, that is why is usual the use of timber[4]. Some authors recommend the location of the openings in way their upper side match with a ring beam, on this way the ring beam behaves also as lintel of the opening (21; 26; 30; 58). The limitation of the openings dimension is principally related to the bending strength and highness of the lintel. The lintels should be embedded enough (**w ≥ 25cm** (20)) on the wall and should cover the entire thickness of the wall to guarantee the aforementioned structural requirements (Img. 67) (26).

Due to the reduction of the section area of the entire wall, caused by the presence of openings, the walls suffer a reduction of their shear strength, hence the dimensions of openings should be limited. In case shear stress is passing through the opening the lintel also reinforce the upper corners of the opening, decreasing the

4 For lintels is also not recommendable the use of concrete as it is explained on the section 4.5.1.

failure risk by concentration of peak loads. As well, doors or windows distribution and position can debilitate the structure. If openings are located near to corners the risk of a detachment of the corner by shear stress is increased (21; 25; 26; 29; 30).

In light of above the following parameters should be carry out for opening dimensions and distribution:

- The length of the opening (**a**) or the sum of all openings length $\sum$**a** located on the same wall should not exceed 1/3 of the wall length (**L**): **a** $\leq$ **L/3**.
- The distance **b** between openings and between opening and corners should be at least three time the wall thickness (**3e**), it is not recommended to have shorter distances than 1.2-1.0m.

(20; 21; 24; 26; 29; 30)

Image 68 explains the aforementioned dimensions.

Additionally to the recommendations suggested above, to prevent cracking on earthen walls, caused by the frequent use of doors/ windows, Houben (20) makes the punctual suggestion of use, as fixing frames, wooden elements embedded into the earthen material (Img. 69).

4.4. Box-behaviour: diaphragmatic strategy

To ensure a systemic behaviour of earthen structure and guarantee the structural elements (load-bearing walls, floors and roofs) to work jointly under seismic loads, some elements connection is needed. This connection should ensure the distribution of horizontal loads into all the load-bearing walls; thus the concentration of stress over single elements can be avoided, and the loads can be transmitted to foundations and to the ground. The aforementioned systemic performance of the structure is known as "box-behaviour" and pretend to maintain the structural elements working together.

The reinforcements of this strategy supply principally the "box-behaviour" of the entire structure, however can contribute to the performance of the single load-bearing wall and the distribution of punctual vertical loads over the whole wall's length.

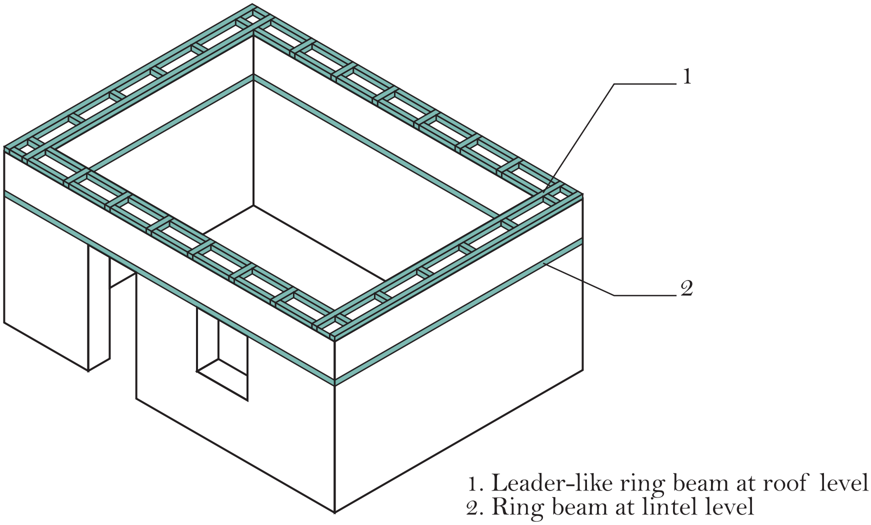
4.4.1. Ring, bond or collar beams

Apply to: All techniques.

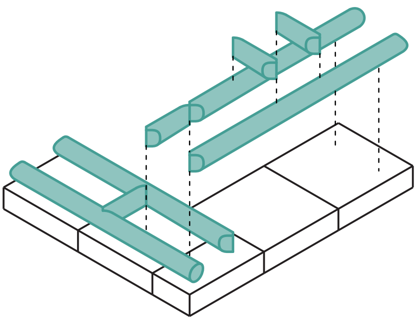
The ring beam is basically a beam of different but suitable material[5] located over all the earthen walls of the building. Is the principal constructive element that is going to ensure the conjunct work of the load-bearing walls as a structural system, it also transmit – in an appropriate way – the loads from upper roof or floor to the earthen wall.

During an earthquake this beam dis-

5 View chapter 4.5.1.



IMG 70. Leader-like ring beam in two different locations. Both are appropiate. Image redrawn from: ORTEGA et, Al. 2017. Pg, 8.



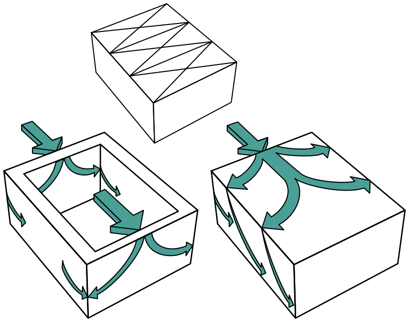
IMG 71. Bamboo unions for ring beam. Image redrawn from: BLONDET, M. 2010. Pg, 45.

tributes the horizontal loads into all the walls of the building (perpendicular and parallel to the load direction), at the same time the ring beam behaves as shear transfer connection of perpendicular walls that is able to control the failure by shear vertical cracks on corners and intersections. On that way it enhances the "box-behaviour" of the building (58) and also help in preventing upper structures failure. Additionally, as the ring beam is located over the walls, it increase the bending strength of the wall on its upper part, thus the mechanisms of failure referred to bending stress cracks are also diminished.

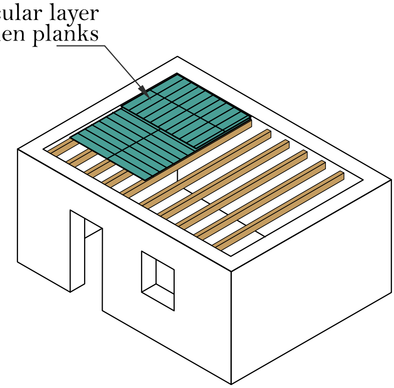
In rammed earth and adobe structures the ring beams are traditionally construct with two timbers, both localised over the wall element. Each timber goes on one side of the wall (internal and external) and are joined together by perpendicular wood sticks that conform a "leader-like" structure seated over all the walls (Img. 70) (27; 58). This type of ring beam overlay the entire wall thickness ensuring a longer surface for load transmission between both elements. Additionally, in the case of an adobe wall with multiple brickwork courses on thickness the leather-like ring beam can also help to maintain them together (58).

The junctions between the wooden elements that conform the ring beam should be always done by half of the wood, ensuring the restriction of movement in all directions. This restriction should be also done for junctions of bamboo ring beams (Img. 71) (29). If the timber used has rectangular section, there is recommendable to use elements of 8x8 cm, for circular wood or bamboo the diameter should be at least 10cm (29).

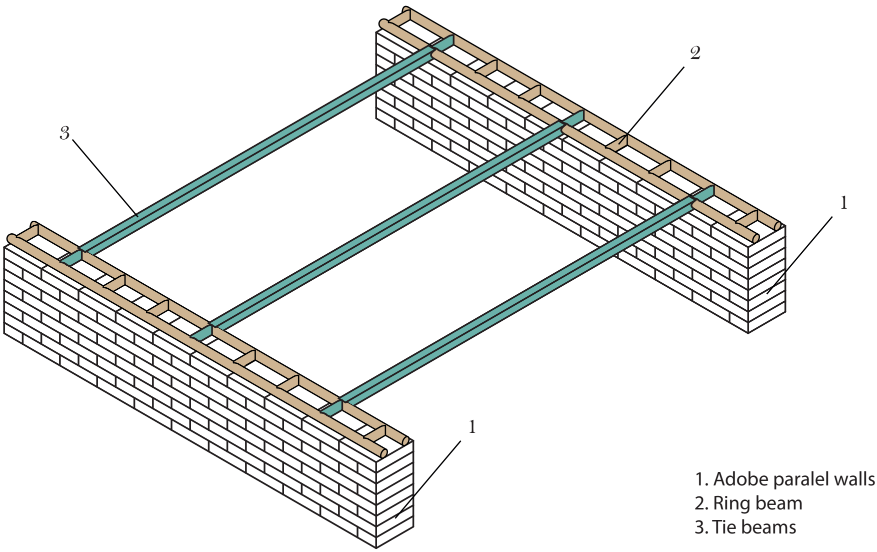
For the case of CEB and Bahareque buildings the ring beam is always located on the upper part of the walls and is preferable it covers the entire wall thickness. Punctually the Bahareque ring beam is the upper timber of the bahareque frame call "Solera" (Img. 46) (19). To make the reinforcement effective the different frames of the bahareque should be well joined one to other by the "soleras" ring beams.



IMG 72. Performance of and distribution of loads by diaphragmatic reinforcement. Image redrawn from: MICHELS, TL. 2015.



IMG 73. Diaphragma made of perpendicular layers of wooden planks. Image redrawn from: ORTEGA et, Al. 2017



IMG 74. Tie beams reinforcements on restauration work church of Kuño, Tambo, Peru. Image redrawn from: KARANIKOLOUDIS. 2018. Pg, 8.

4.4.2. Diaphragms: rigid roofs and upper floors

Apply to: All techniques.

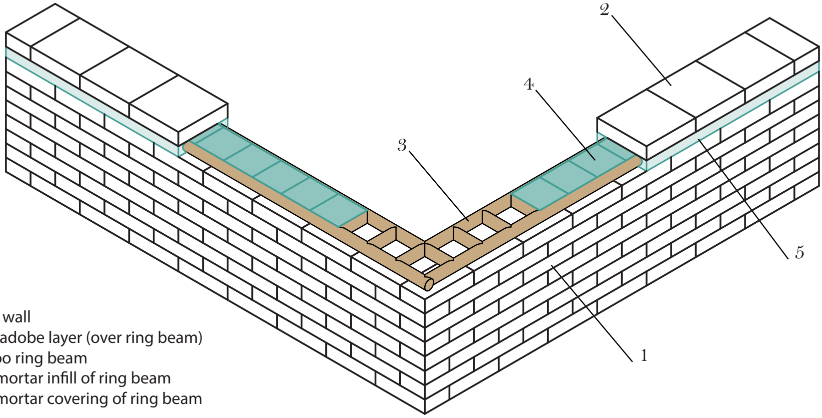
Strengthening the function of ring beam, the construction of a structural horizontal diaphragm can improve the performance of the building during the seismic scenario by distributing the horizontal loads into all the load-bearing walls. The performance of this reinforcement system is schematized by (62) on image 72. Based on laboratory tests with earthquake shake table, the UNAM suggested the how use of rigid diaphragms can enhance the flexion and ductility of the walls (14), meanwhile investigations by PUCP also ensured the effectiveness of this reinforcement strategy to stabilize the whole earthen structural system (42).

The diaphragmatic strengthening can be reached by the construction of rigid roof and/or floor structures, properly fixed to the ring beam. On the image 73 Ortega explain how perpendicular layers of wooden planks can guarantee a diaphragm sufficiently rigid (58).

The traditional material of this reinforcement is naturally wood. Roof and intermediate floor timber structures usually lying on the ring beam (27; 58). Nowadays, some restorations works have also used steel bars (58). Several authors suggest the use of floors with concrete or rammed earth layers (10; 20; 27), nevertheless these solutions should be carefully used due the elevated mass that represent and the horizontal thrust that can provoke on the walls[6].

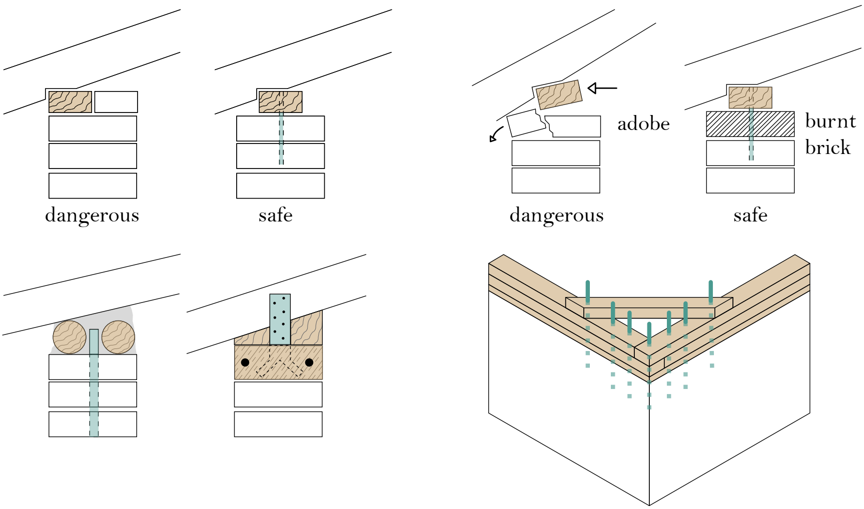
An example of diaphragmatic reinforcements for earthen buildings is the restauration work of the Church of Kuño Tambo (Peru). In this case one of the used reinforcements were parallel tie beams connecting two parallel long walls, allowing both walls to assume together the perpendicular loads, hence the entire structure is strengthened (Img. 74) (60).

6 View chapter 4.5.1.

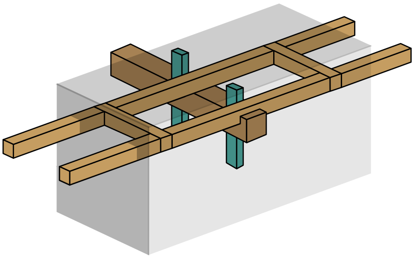


1. Adobe wall
2. Upper adobe layer (over ring beam)
3. Bamboo ring beam
4. Loam mortar infill of ring beam
5. Loam mortar covering of ring beam

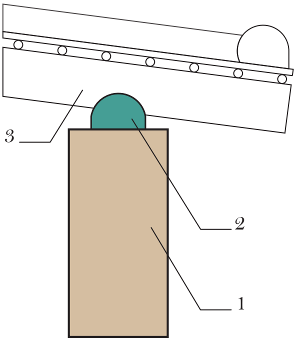
IMG 75. Filling ring beam with loam mortar & corner junction of bamboo ring beam. Image redrawn from: MINKE, G. 2001. Pg, 35. & BLONDET, M. 2010. Pg, 45.



IMG 76. Ring beam and roof support detail. Image redrawn from: MINKE, G. 2001. Pg, 35

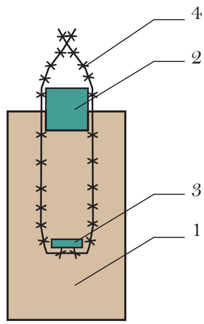


IMG 77. Tie rafters, ring beam and wall junction. Image redrawn from: KARANI-KOLOUDIS. 2018. Pg, 8.



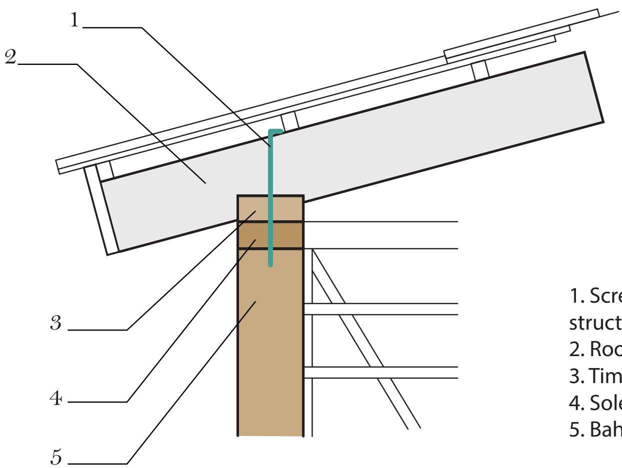
1. Rammed earth wall
2. Timber ring beam
3. Roof structure

IMG 78. IMG 75. Ring beam simply located over rammed earth wall. Image redrawn from: HOUBEN et, Al. 1994. Pg, 281.



1. Rammed earth wall
2. Timber ring beam
3. Internal timber support for wire
4. Metal wire attachment of the ring beam

IMG 79. Ring beam attached to rammed earth wall with metal wire. Image redrawn from: MINKE, G. 2001. Pg,35.



1. Screw for junction of roof structure and solera ring beam
2. Roof rafter
3. Timber support of roof rafter
4. Solera ring beam
5. Bahareque frame

IMG 80. Roof - Wall junction for bahareque. Image redrawn from: CARAZAS et, Al. 2002. Pg,18.

4.4.3. Ring beam junctions: diaphragm-ring beam-wall

Apply to: All techniques.

As the ring beam is the intermediate element among the upper structure (roof or floor) and the load-bearing walls, is important to build carefully its connections with walls and roof (14). If those connections are well done the ring beam is going to be able to:

- distribute punctual loads from the floor beams into the walls, preventing effort concentration over the earthen material;
- guarantee the diaphragmatic load transmission explained before;
- maintain both structures together, receiving the loading stress from walls and the roof at the same time;
- preventing the wall to be broken by the thrust from the upper structure (27);
- ensure the effectivity of other internal or external reinforcements[7].

Traditionally it has been assumed that the friction of the ring beam – loaded with the upper structure – over the earthen wall is enough to guarantee the beam-wall junction (58), however filling or covering the ring beam with loam mix is recommendable as basic junction strategy (29), these can be seen for a leather-like ring beam on image 75. Nevertheless there exist several solutions to enhance that junction (19; 20; 27; 30; 60).

As the junctions of timber elements that conform the ring beam, all the junctions with other wooden structures should restrict the movement of the joined parts in all directions, as it was explained on image 71, chapter 4.4.1.

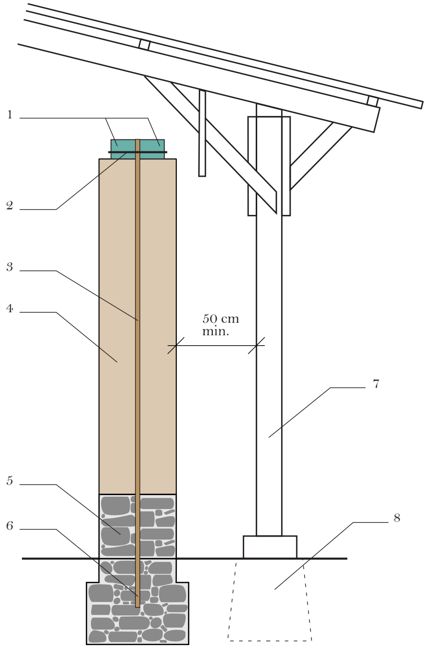
Regarding the junctions with roof structures, Minke (30) makes some suggestions for adobe walls. Due to the concentration of stress on this specific junction, the objective is also to protect the upper layer of adobes, while an appropriate support of the roof structure over the wall is supplied (Img. 76). Other solution for roof-adobe wall junction was made during the work done by Karanikoloudis on the church of Kuño Tambo (Peru). The connection of the tie beams to the walls was made by the ring beam with an additional vertical timber anchors inside the wall (Img. 77) (60).

For rammed earth the roof structure is equally fixed to the ring beam which rest simply over the wall (Img. 78) it can be also attached with metal wire inside the wall (Img. 79) (30), the last solution requires the location of the internal wood and wire before ramming the last layers of the wall. For the case of bahareque, the roof structure is directly supported and fixed to the "solera" of timber frame by screws (Img 80).

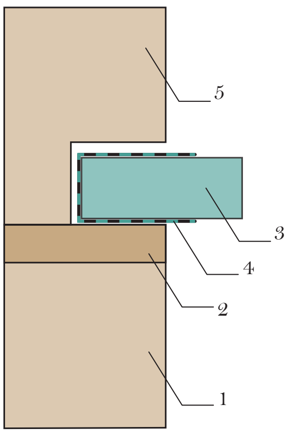
To avoid this demanding junction (roof-walls) and reduce the possibility of a roof failure, different design also has been tested, in which the roof is supported by independent columns, in this way both structures can oscillate independently during the earthquake (30). For sure, in this case is important to guarantee enough distance between the pillars of the roof structure and the earthen walls, thus during the earthquake both can have independent oscillations avoid-

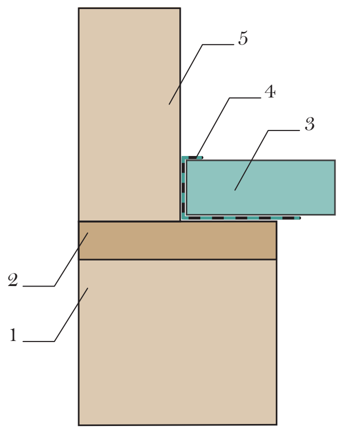
7 These reinforcements are explained in the corresponding chapters 4.5.4 and 4.5.5.

1. Ring beam
2. Nails, junction internal bamboo and ring beam
3. Internal bamboo reinforcement
4. Rammed earth wall
5. Base course
6. Bamabo reinforcement enbeded in foundation
7. Independent structure for the roof
8. Independent foundation



IMG 81. Independent roof structure and internal bamboo reinforcement. Image redrawn from: MINKE, G. 2001. Pg, 39.





1. Rammed earth wall (ground floor)
2. Timber ring beam
3. Floor beam
4. Water-repellent protection
5. Rammed earth wall (1^{st} floor)

IMG 82. Floor support over ring beam by introduction of the beam into the wall. Image redrawn from: HOUBEN et, Al. 1994. Pg, 277.

IMG 83. Floor support over ring beam by reduction of the wall thickness. Image redrawn from: MINKE, G. 2001. Pg,227.

ing the transmission of loads from one to other and dodging the risk of crashing between them. Minke (30) suggest separate both structures by 0,50m, nevertheless the distance should be calculated according to the performance of the chosen materials under horizontal loads (Img. 81).

Concerning the junctions with intermediate floors, some suggested solutions are shown on image 82, where the floor structure gets into the wall to reach the ring beam, Houben recommend ensure a separation between the timber beams and the earthen material, thus cracking on the wall provoked by the vibration of floor structure can be avoid. As well, to protect the timber from moisture, is suggested the use of bitumen felt or a water-repellent protection. Other possible solution is shown on image 83 where the wall section is reduced in the upper level, and part of the ring beam remains out to support the floor structure (20; 27).

4.5. Enhancing load-bearing wall strength

In coherence to the load-bearing wall structure this strategy is focused on the punctual enhancement of the principal structural elements (earthen walls). Due the low tensile, bending and shear strengths of earth as constructive material, it is advantageous to enhance those strengths in the structural element to improve its performance under seismic loads. The proposed strategy do not enhance the mechanical strengths of earth as a construction material but supply additional strengths to the load-bearing walls.

To supply the missing strengths there can be used additional structural elements that work together with the load-bearing walls (buttresses, corner braces) or the use of suitable materials (timber, bamboo, synthetic grids) into the load-bearing wall composition.

4.5.1. Avoid stiffer materials

Apply to: All techniques.

Stiffer materials have larger strengths than earth, hence their resistance to loads stress is also larger. This means that under seismic loads the failure of structural elements constructed with stiffer materials is going to be presented latter than the earthen walls failure. However, all the building parts is going to be subjected to oscillation caused by the earthquake. According to the mechanical properties of each material the oscillations of structural elements with different materials are going to be different. Consequently, during the seismic phenomena the stiffer parts of the structure are going to maintain their integrity for a longer period while they are rocking inside (and against) the earthen structure (62). This effect provoke transmission of larger forces into the earthen walls that can generate failures on the wall and on the junction between both materials (62). That is why, even if is possible to find buildings with reinforcements (e.g. ring beams or lintels) made of concrete, it can carry negative effects during an earthquake.

Regarding the use of cement into the loam mixture, there should be considered the different thermal behaviour of cement in comparison to the loam one. According to Minke (23), a heavy loam mixture can present a coefficient of linear expansion among 0.0043 – 0.0052 mm/m*K, for a sandy mud mortar can be 0.007 mm/m*K, which is lower in comparison to a strong cement mortar: 0.01 mm/m*K. In a loam mixture with overlay addition of cement, the volumetric expansion of cement particles inside loam matrix can provoke cracks that compromise the structural stability of the wall.

Other notable reason to avoid the use of cement in loam mixtures (specially plasters) is the incompatible hygrometric properties of both, and its consequences regarding the natural moisture exchange of earthen walls[8].

8 The effect of cementitious plasters regarding the moisture exchange of earthen walls are explained on chapter 3.1.5.

4.5.2. Perpendicular reinforcement and buttresses

Apply to: Adobe, Rammed Earth and CEB techniques.

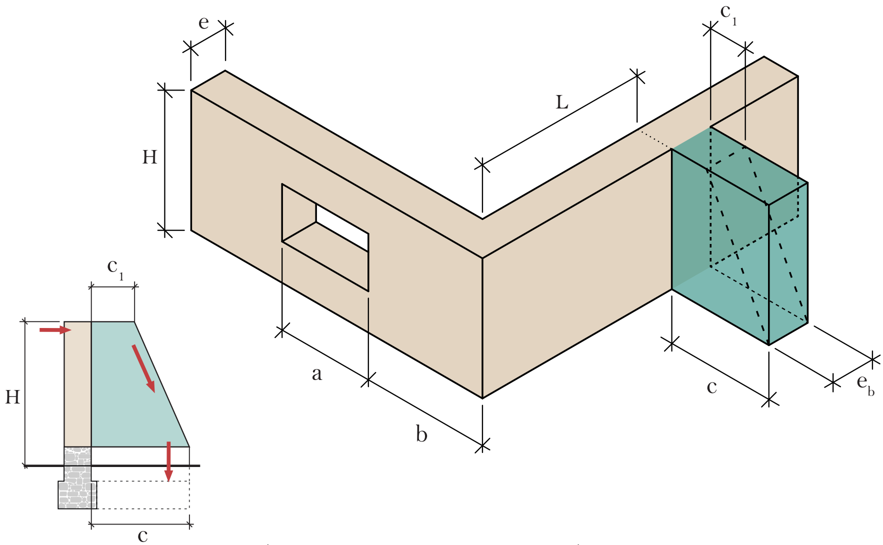
The use of buttresses was well known since long time ago and can be seen in traditional earthen and not earthen masonry (58; 60). Nevertheless, the use of them as appropriate constructive methods for earthen buildings has been diminished probably because of the abandonment of earthen technologies and the loss of the popular constructive knowledge.

Perpendicular reinforcements can decrease the bending moment in the middle of long walls by transferring, in diagonal direction, the horizontal loads (perpendicular to the wall) to the foundations (30). Hence, the wall failure by horizontal and diagonal bending cracks are dodged (14). This type of reinforcement can consequently also prevent what is considered one of the most dangerous mechanism of failure: when the upper floor or roof lost its support on the affected wall and suddenly collapse (27).

The perpendicular reinforcements can be constructed as buttresses or literally as perpendicular walls that are part of the architectural design conforming "L, T, U" shapes in plant view. In both cases, to reduce the bending moment of the reinforced wall, long distances among the perpendicular elements[9] should be avoided (30).

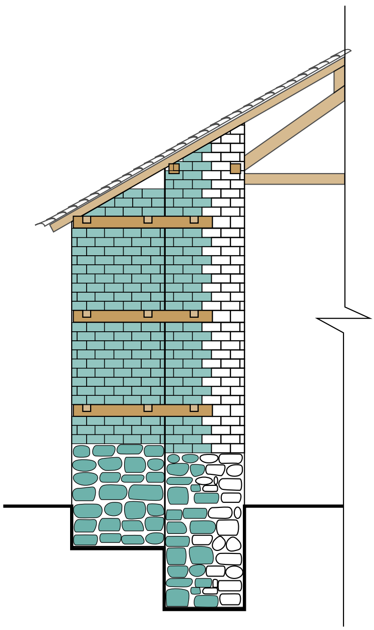
Regarding the dimensions of the buttresses, some limitations should be considered to ensure the stability of the element and its effectiveness as structural reinforcement, some of

9 This is also related to the distances among load-bearing walls explained on chapter 4.3.2.

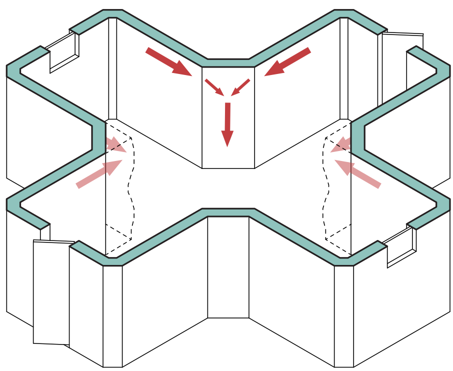


$\frac{1}{3} H \leq c \leq \frac{3}{4} H$ $c_1 \geq c/3$ $e_b \geq e$

IMG 84. Recommendation for buttresses dimensions. Image of the author, data reference from (MINKE, G. 2001. & Minvivienda Peru, 2017.)



IMG 85. Internal timber keys between buttresses and wall. Imagre redrawn from KARANIKOLOUDIS et, Al. 2018. Pg.8.



IMG 86. Rounded corners scheme. Image redrawn from: MINKE, G. 2001. Pg, 17.

these parameters are related to the thickness and highness of the wall[10]:

- The thickness $\mathbf{e}_b$ of the buttresses should be at least equal to the wall thickness **e** (24).
- The length of the buttresses c should be among **¾ H** and **¼ H** to ensure the reinforcement is long enough to transfer the loads diagonally but not too much to be vulnerable to perpendicular loads (30).
- In the case the buttress has a slope the upper length $\mathbf{c}_1$ should be at least **c/3** (24).

Image 84 describes the aforementioned distance limits.

The material of this reinforcement should be the same of the reinforced wall to ensure the same performance under the seismic loads. As well, the foundations and base courses of both elements should be aligned at the beginning of the earthen material.

In the case of using buttresses as reinforcement, is important to ensure their junction with the main wall, if it is not done the rocking of both elements (buttresses and wall) can be independent provoking more damages to the structure (58). The use of internal timber keys located through the buttresses into the wall can be a solution to guarantee the junction (Img. 85) (60). In the case of an adobe or CEB building the brickwork bonds of wall corners and intersections[11] contributes also to an appropriate junction of buttresses as structural reinforcements.

10 Chapter 4.3.2.

11 Described on the 3th chapter.

4.5.3. Corner reinforcements: braces and shape

Apply to: Adobe, Rammed Earth and Bahareque techniques.

Due the corner weakness of earthen buildings caused by bending and shear stress concentration, there can be used two strategies to reinforce wall corners: increase the section of the earthen corner or supply the aforementioned strengths by an additional material.

Variating the shape of the corners and intersection is a solution that can be used on adobe and rammed earth techniques. It reduce the risk of failure by increasing the section of the corner, thus the concentration of stress on the perpendicular wall's angle is reduced (Img. 86) (30).

This can be easily made on rammed earth constructions by the use of rounded or especial shape formworks for corners[12], as the ones proposed by Houben (20). For adobe walls the special shape corner can be construct with the use of special shape blocks or characteristic brickwork bonds.

On the other hand, the missing strengths in corners can be supplied by reinforcements with additional materials. Called corner braces or corner keys, these timber reinforcements pretend to maintain the wall-to-wall junction together during an earthquake. Transferring shear stress between the walls and assuming the bending ones, the corner braces reduce the bending and shear failure of the corners. Additionally, if the reinforced corner cracks, corner braces continue been efficient, in that case the braces can keep the cracked walls together and thus the ductility

12 View Tapia chapter 3.2.

of the system is ensured during the after-peak phase (58).

The corner braces, traditionally of timber, are localized diagonally to the corner, creating a triangle shape (plant view). To guarantee the appropriate connection with the wall, there should be used also timber struts perpendicular to the main one, these struts limit the movement of the reinforcement through the walls (58). Other possible configuration is embedding the timber inside the wall intersection, following the angle of the walls (58). If it is done for adobe walls is important matching the timber with the brickwork bonds of the walls to ensure the junction between both.

There can be construct more than one corner brace in the same wall-to-wall intersection on different highness of the corner, even matching with the ring beam[13].

The image 87 shows how corner braces can be localized in the corner of walls, while image 88 show the detailing for the junction with adobe brickwork.

In the case of bahareque the corner braces are not widely spread, however their use can enhance the bahareque strengths under seismic loads.

To construct them is necessary its coordinated position and junction with the "solera" ring beam as it is the structural part of the wall. If the corner braces do not match with a structural part of the bahareque frame they are not going to transmit properly the loads and are not going to have any structural performance. If the corner brace is attached to the bahareque filling structure, under loads stress, this is going to failure and the reinforcement is not going to be effective. Regarding the direction of the braces, hence they can enhance the normal perpendicular junction of the "soleras" ring beams they will work better for bahareque structures if they are located creating a triangle in plant view[14] (Img. 89).

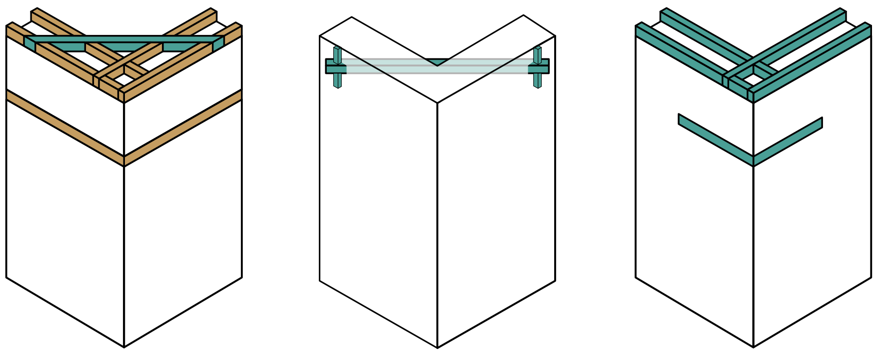
Naturally the preferable material is also timber or bamboo according to the material of the bahareque frames.

Carazas (19) suggested other braces for bahareque corners, in this case the reinforcement is made in vertical plan of the wall. The use of diagonal timber elements located inside the corner bahareque frames[15] can transfer the bending stress of the corner to the foundations. These braces can also be seen on image 89.

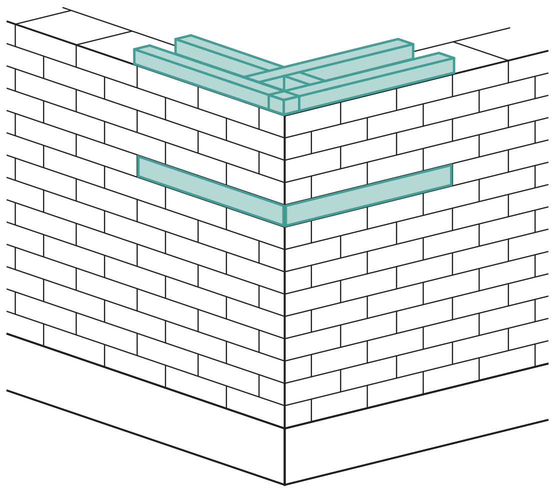
13 On that case all the timber elements (ring beam and braces) should be joined between them ensuring the restrictions specified on chapters 4.4.1 and 4.4.3.

14 The junction of several "soleras" ring beams is explained on bahareque chapter 3.4.

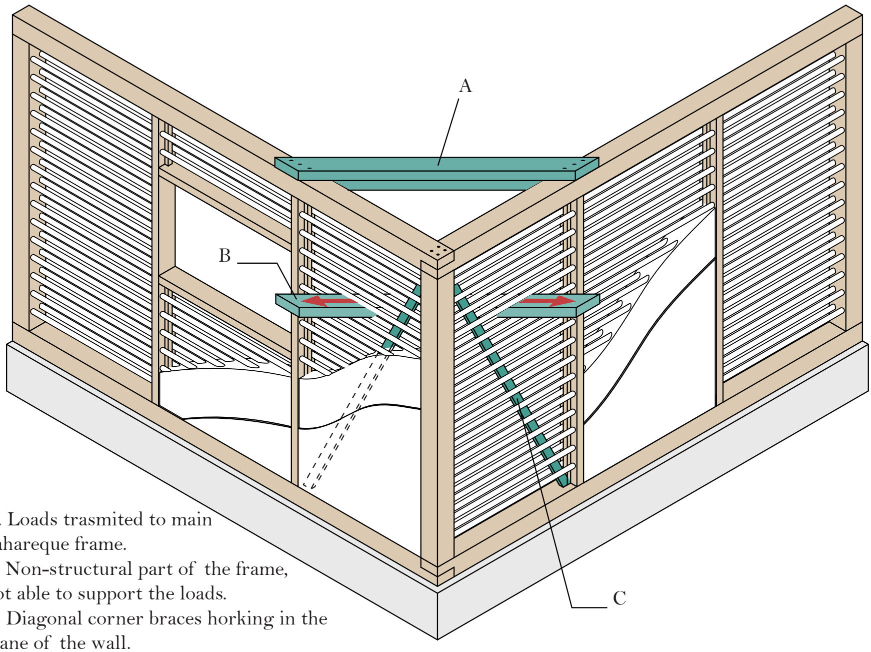
15 View also bahareque reinforcements on chapter 4.5.4.



IMG 87. Corner braces on corners. Image redrawn from: ORTEGA et, Al. 2017. Pg, 7.

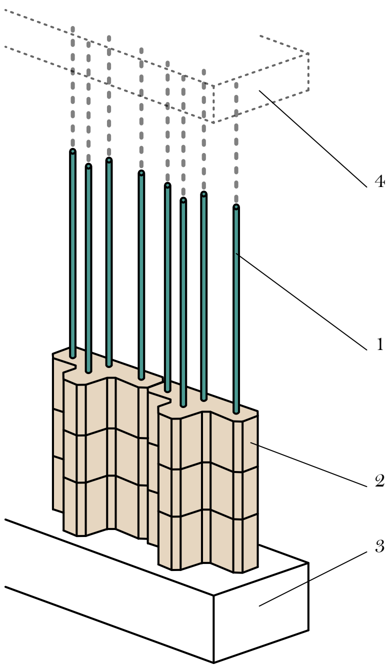


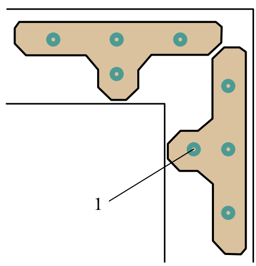
IMG 88. Corner braces in adobe wall brikwork. Image based on: ORTEGA et, Al. 2017. Pg, 189.



A. Loads trasmited to main bahareque frame.
B. Non-structural part of the frame, not able to support the loads.
C. Diagonal corner braces horking in the plane of the wall.

IMG 89.Corner braces location for bahareque structure. Image redrawn from: CARAZAS et, Al. 2002.





1. Internal bamboo reinforcement.
2. “T” shape rammed earth piers.
3. Base course.
4. Ring beam.

IMG 90. Internal bambo reinforcement in rammed earth walls. Image redrawn from: MINKE, G. 2001. Pg, 20-21. & HOUBEN et, Al. 1994. pg, 201.

4.5.4. Internal reinforcements

As the mechanical characteristics of earth as building material are low tensile and bending strength, in some cases could be helpful to combine the loam mixture with other suitable materials, as wood, that can supply these strengths. Here are reported some opportunities to strengthen earthen load-bearing structures.

Internal bars

Apply to: Adobe, CEB and Rammed Earth techniques.

This reinforcement consist on localizing vertical bars inside the earthen walls. Steel bars are generally used for CEB, wile for adobe and rammed earth walls are preferable bamboo culms. However, the use of internal bamboos reinforcement into rammed earth walls still been debated as it can carry constructive complications that can weaken the wall strengths.

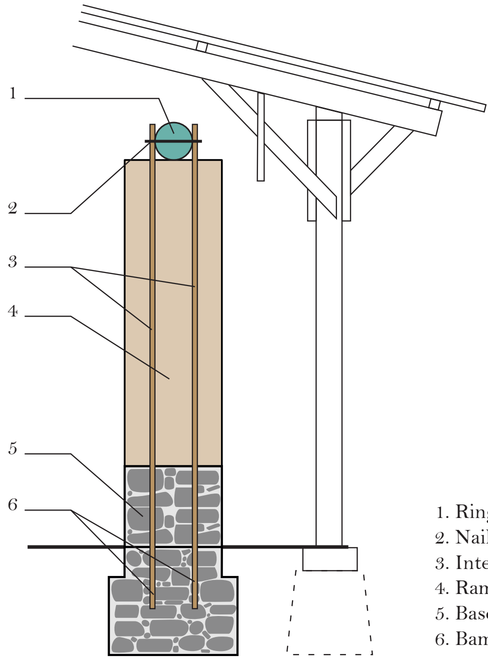
An example of internal bamboo for rammed earth is done by (20; 30) where the wall consist on several "T" shape modules of rammed earth located next to each other

over the same base course and under the same ring beam, each module has four internal bamboo culms that attaches it to the base course and the ring beam (Img. 90). However, Lopéz also suggested the use of these internal bamboo culms in traditional rammed earth walls (15; 21). For adobe technique this solution was tested and approved by Peruvian regulation (24) and, after that, it was used for over 2000 dwelling projects in 2010 (42).

The internal bars contribute to control the bending stress of the wall when is horizontally loaded in a perpendicular direction. It was found that, if this reinforcement is also attaching the corners of the walls, the failures of corners by bending and shear cracking can be avoided. The experiments in earthquake shake table of the PUCP shown that the reinforcements prevent the separation of the walls, keeping the wall box together (42).

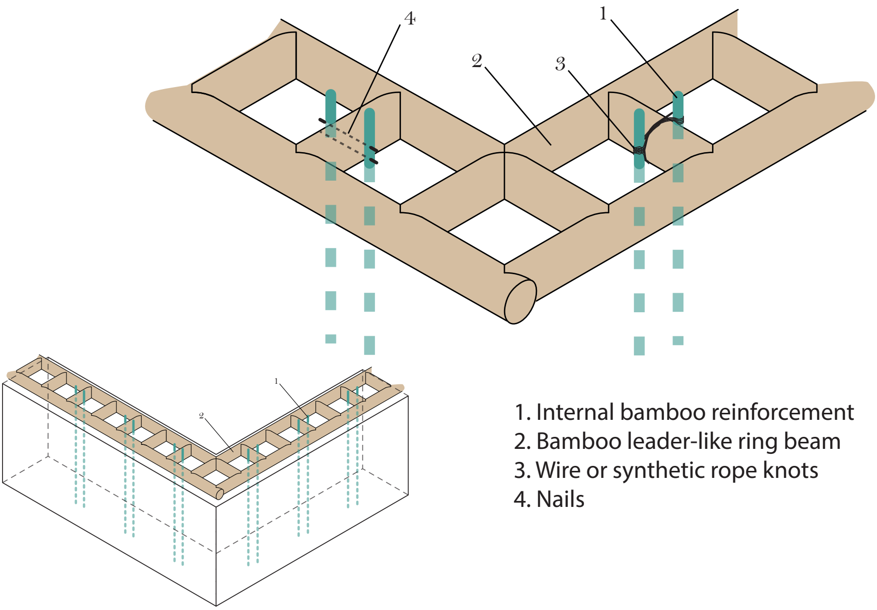
For the appropriate construction of this reinforcement are used bamboo spices with short diameter of 25mm as "caña carrizo" (Arundo donax) (24; 29) can be also used Chusquea Celeou (30). It is mandatory the bamboos are well joined to the foundation and the ring beam, to ensure the real effectiveness and the structural system behaviour (24); hence they should go into the base course and, if is possible, into the foundation. A clear example is the proposal of low-cost housing by the university of Santiago de Chile in 2001 (30), on image 81 is shown the foundation detailing for the aforementioned project.

Regarding the construction process in rammed earth, first the bamboo culms should be located vertically and fixed to the base course. Then the whole wall can be rammed traditionally, controlling the vertical position of the bamboo reinforcements during the ramming of each loam layer. The ramming should be carefully done around the bamboo culms but should ensure the proper compaction of the loam. Finally, after completing the entire ramming of the wall, the bamboos should remain partially out on the upper part of the wall, thus can be attached to the ring beam. The last junction can be seen on the image 81 for the same Chilean project where the bamboos are trapped between the



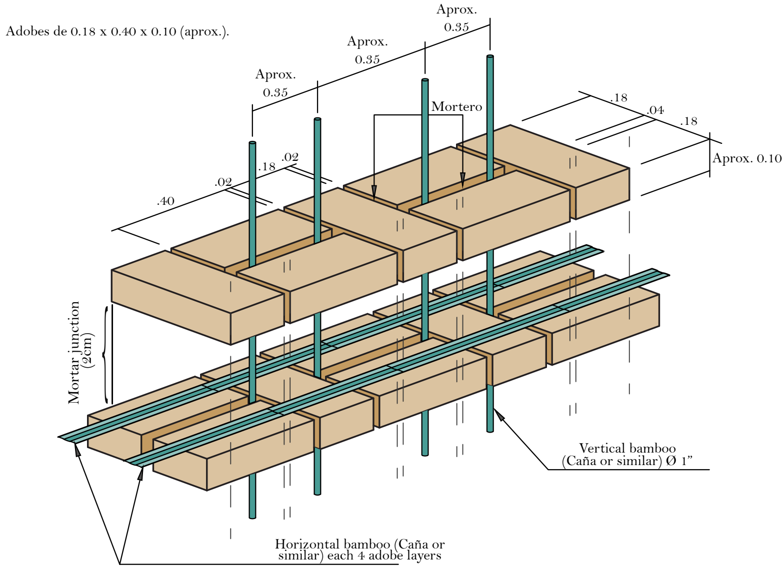
1. Ring beam
2. Nails, junction internal bamboo and ring beam
3. Internal bamboo reinforcement
4. Rammed earth wall
5. Base course
6. Bamabo reinforcement enbeded in foundation

IMG 91. Internal bamboo reinforcement with central ring beam. Image redrawn from: MINKE, G. 2001. Pg, 19.

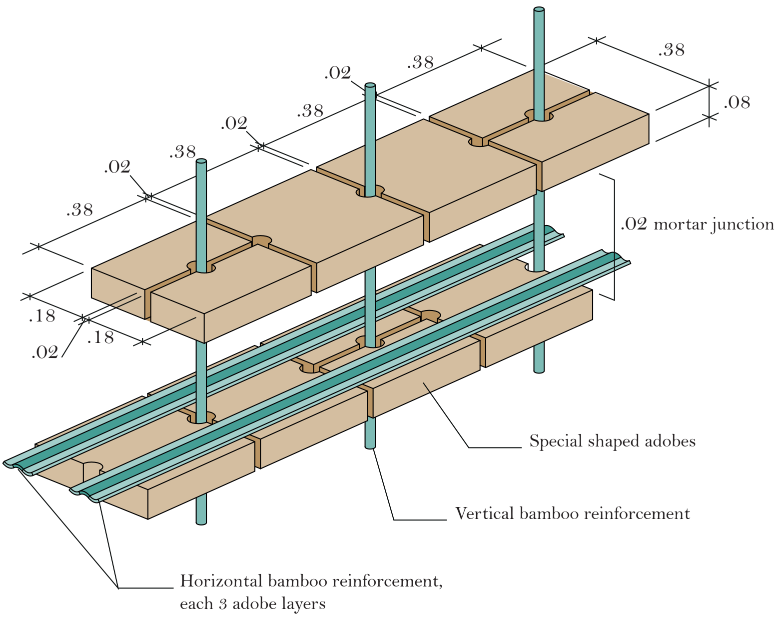


1. Internal bamboo reinforcement
2. Bamboo leader-like ring beam
3. Wire or synthetic rope knots
4. Nails

IMG 92. Internal bamboo reinforcement attached to leader-like ring beam.



IMG 93. Adobe wall composition reinforced with internal bamboo and special shaped adobes. Image redrawn from: E. 080, Peru. 2016. Pg, 10.



IMG 94. Adobe wall composition reinforced with internal bamboo and special shaped adobes. Image redrawn from: E. 080, Peru. 2016. Pg, 10.

ring beam timbers. Other possible junction is localizing one central ring beam timber to which are tied the bamboos on each side (Img. 91) (30). In the case the ring beam has a leader-like structure the bamboos culms can be also attached to the perpendicular elements of the beam (Img. 92). The junction to the ring beam can be done by nailing or tying the bamboo culms with wire knots (29) or synthetic ropes as nylon following the recommendations made on E.080 regulation (24), anyhow the junction should restrict the movement of the pieces under the horizontal loads.

Due to the aforementioned process and considering the bamboo culms are located since the beginning of construction, Minke and López clarify that the use internal bamboo reinforcements provoke complications during the construction process of rammed earth buildings (15; 30). The presence of the bamboos do not permit the appropriate ramming of the surrounding loam; therefore the wall is not going to reach the required density and its optimal compressive strength.

Considering the use of internal bamboo reinforcement for adobe structures, the internal elements can be located among normal adobes – inside the block-mortar junction –, or there can be also used adobes with special sides that optimize the space for the bamboos (20; 24), the difference can be seen on images 93 and 94. The use of horizontal bamboos inside the adobe brickwork can also enhance the ductile capacity of the walls and thus avoid the bending failures, indeed E.080 regulation (24) ensures that the correct internal reinforcement for adobe structures should be done in both directions.

According to the Peruvian regulation, in an adobe wall the location of the vertical bamboos should be in the middle of the wall thickness each 45cm. The horizontal ones should be located each four adobe layers and matching with upper and lower side of the openings. For each layer of horizontal reinforcement there should be two bamboo culms, one on each side of the wall (24). For the vertical reinforcement tubular bamboos culms are used, for the horizontal ones is recommendable to open the bamboo culms by splitting process, is important not to damage the rods (24). As the same of rammed earth the internal bamboos should be joined to foundations and ring beam, additional junctions should be done between vertical and horizontal bamboos, however the junction materials can be the same.

Image 93 shows the aforementioned dimensions and location of the reinforcement. For the reinforcement on image 94 there are used adobes that increase the space for bamboo location, this wall composition became thinner (38cm) due the dimensions of the adobes, is notable that for the E.080 regulation is the only exception to construct adobe walls thinner than 40cm (24).

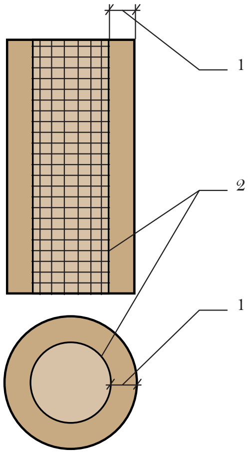
Regarding the application of the internal bars' reinforcement to CEB technique it can be done if there are used hollow blocks. According to Minke this reinforcement is made (when the wall is been construct) filling the CEBs holes with steel bar or bamboo culm and cement:sand mix (30; 52). Clearly, the reinforcements should be also attached to ring beam and base courses thus it is able to support the bending stress.

Reinforcement embedded in adobe blocks

Apply to: Adobe techniques.

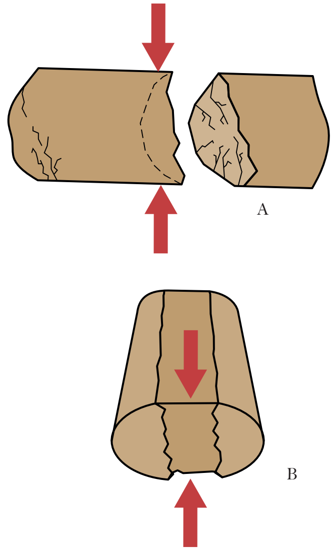
A different reinforcement solution was proposed to adobe technology, in this case the reinforcement is proposed to be embedded in the adobe blocks (63). A Malaysian research tested adobe cylindrical specimens reinforced with kenaf fibres and wire meshes (Img. 95). The specimens were tested under uniaxial compressive strength test and tensile splitting test. From the experimentation it was found an increase on the compressive strength of the reinforced specimens, three time higher than the unreinforced (63). Even if the tensile strength does not increase significantly, the mechanism of failure of the specimens change drastically from a "sudden brittle failure" to a "ductile one" the comparison of the failure can be seen on image 96. The ductility reached by the reinforced specimens was also displayed by a linear post-peak behaviour on stress-strain curves with a continuous post-cracking hardening (63).

However, for the proposal of an internal mesh reinforcement in the adobe blocks is required more investigation, especially with blocks and wallet specimens (not cylindrical ones). Additionally, it will be necessary to solve the production process of adobe blocks with an internal wire mesh.



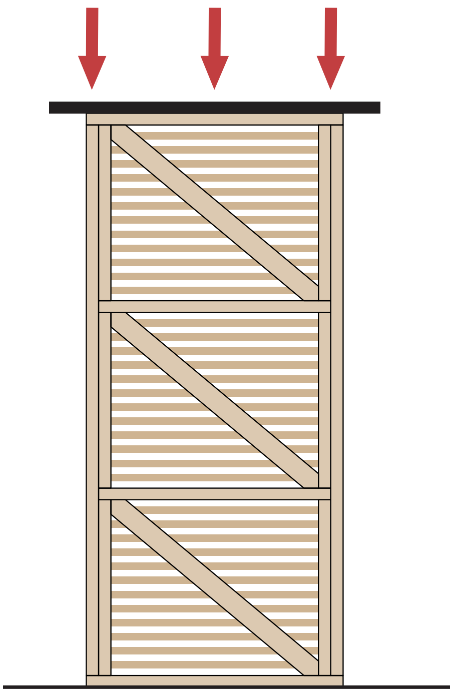
1. Clear cover
2. Wiremesh reinforcement

IMG 95. Cilindrical adobe specimens reinforced with wiremesh. Image redrawn from: JOKIO et, Al. 2018. Pg,385.



A. Specimen without reinforcement
B. Specimen with reinforcement

IMG 96. Failure comparison under tensile splitting. Image redrawn from: JOKIO et, Al. 2018. Pg,388.



IMG 97. Reinforced bahareque panel tested under vertical loads. Structure and test developed by the reference. Image redrawn from: VACACELA, N. 2015. Pg, 53;57.

Bahareque reinforcement

Apply to: Bahareque techniques.

Some authors describe the bahareque as a good system for seismic locations, the lighter structure improve the ductility of the building during an earthquake, however the maintenance of the elements requires significant works to guarantee the wholeness of the building (8; 30). In concordance to that the architect, restauration expert and professor of the PUJ, Cecilia Lopez ensure that bahareque is the most feasible technique to introduce in Colombian construction regulations, due the existence of an internal wood structure in the walls (15).

Reinforcing a bahareque structure means to reinforce the wooden structural frames of the walls. Traditionally there is included a diagonal timber inside the frames (19). These reinforcements works in the axial direction of the wall, hence Carazas propose the specific use of this solution in bahareque frames of walls corners and intersections[16], to reinforce the entire system more than the single wall.

During a thesis work of the University Estatal de Cuenca, Ecuador there were tested internal "V" diagonal reinforcement in wood into prefabricated bahareque frames. The structural behaviour of the panels was not tested on earthquake shake table, the thesis was limited to the support of vertical loads. Nevertheless, the author – supported by the engineer Patricio Cavallos – proved that the use of such "V" reinforcement can improve the load-carrying capacity of each panel in more than 500% (Img. 97). Finally, the study ensures that if the roof is less than 100Kg/m2 the distance between loaded walls can be 8m (38).

16 View chapter 4.5.3.

4.5.5. Enclosing reinforcements

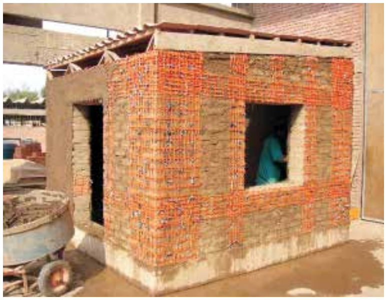
As the internal reinforcements the enclosing ones pretend to create compound structural element just as concrete, where the cement is resisting the compress forces and the steel the tensile ones. The PUCP has tested wood sticks, natural and synthetic ropes, PVC pipes, rib laths and plastic grids searching the most suitable combination that can enhance the tensile strength of earthen buildings (42).

This group of reinforcements was proposed and has been tested for rammed earth and adobe structures (new and existing ones), punctually the geogrids and synthetic ropes are permitted by the E.080 regulation (24).

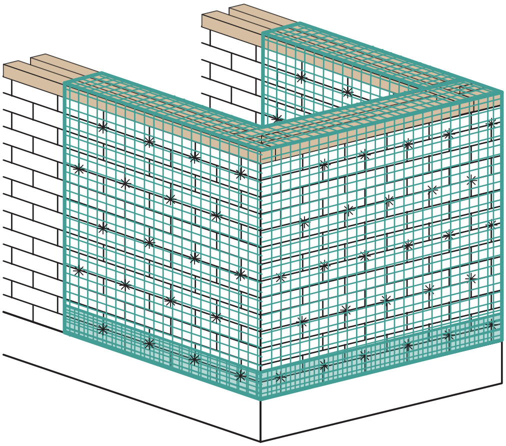
Plastic geogrids and synthetic ropes

Apply to: Adobe techniques.

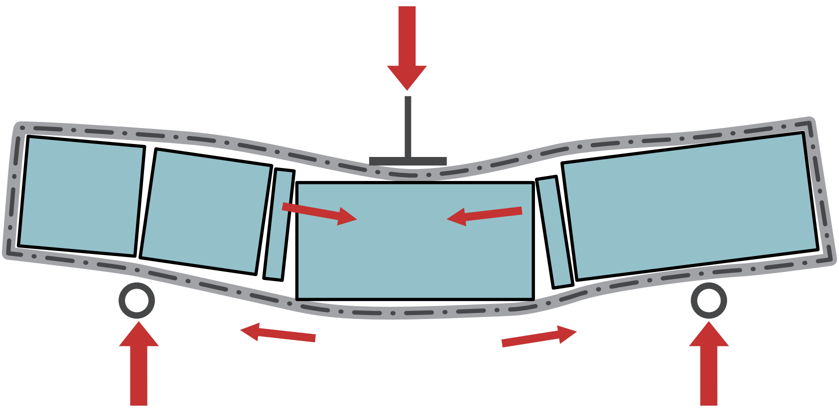
The external reinforcement of earthen walls with plastic geogrid and with a grid made-up of synthetic ropes were the most important contributions to earthen reinforcements that the PUCP has done. Basically, both work in the same way, the purpose of the rope grid was done to reduce costs and guarantee that more people were able to construct the reinforcement in their houses. The strategy is to enclose the wall with a tensile resistant material that is going to keep the earthen material together in case of tensile stress. That is why the reinforcement should surround all the faces of the wall including the internal

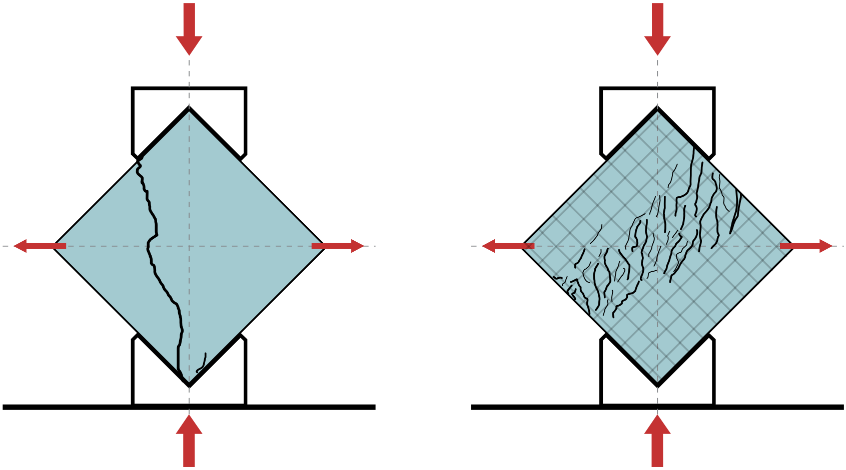
IMG 97. Plastic grid reinforcement lab test. Images tooken from: BLONDET et, Al. 2011.



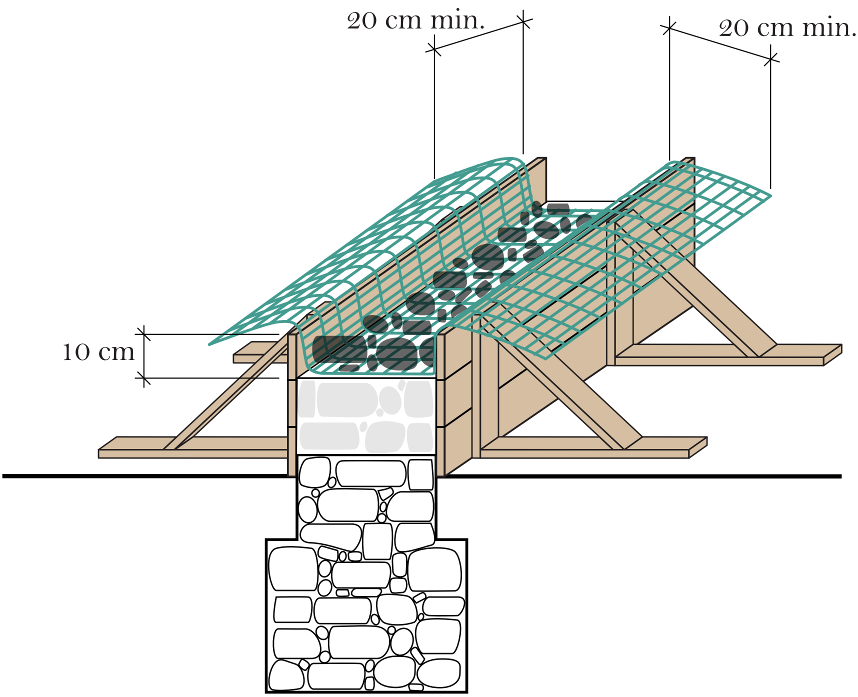
IMG 99. Plastic grid reinforcement. Image redrawn from: BLONDET M. 2010



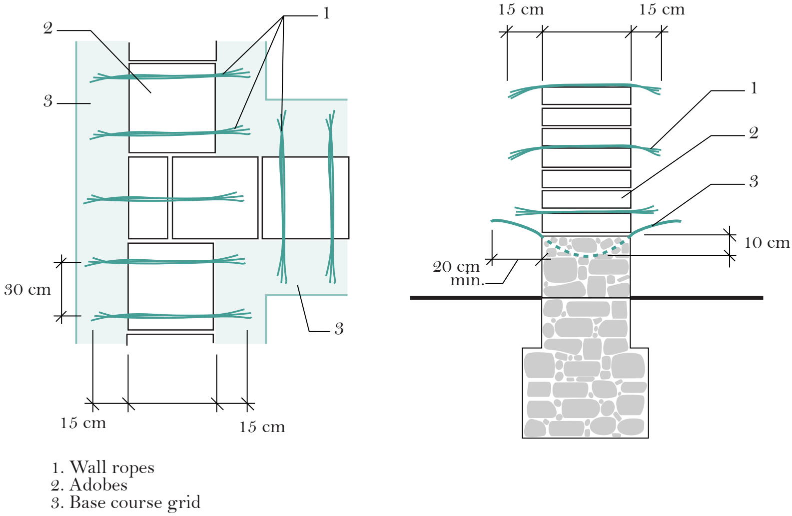
IMG 100. Scheme of Adobe bricks kinematics and geogrid bending effect. Image redrawn from INVERNIZZI et, Al. 2017.



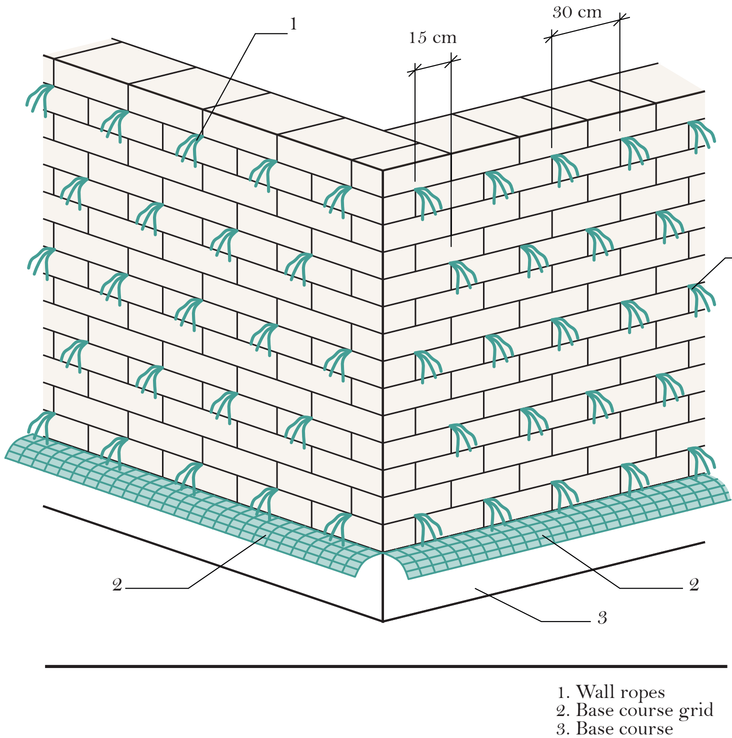
IMG 101. Dominant vertical splitting crack in unreinforced walls (a); smeared diagonal shear cracks in reinforced wall (b). Image redrawn from: INVERNIZZI et, Al. 2017.



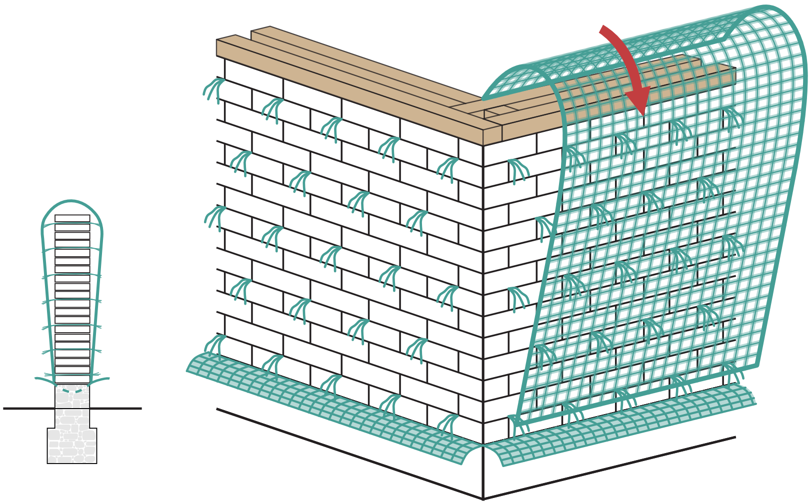
IMG 102. Location of the BC grid during the foundation of the Base Course. Image redrawn from: BLONDET, M. 2010. pg. 37.



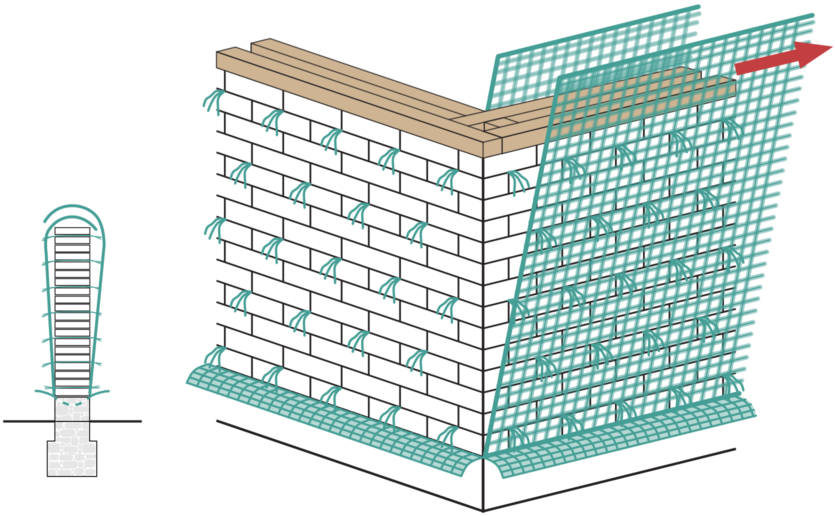
IMG 103.Wall ropes and BC grid location in adobe brickwork. Image redrawn from: BLONDET, M. 2010. Pg, 42.



IMG 104. Distribution of the wall ropes into the brikwork of the adobe wall. Image redrawn from: BLONDET, M. 2010. Pg, 43.

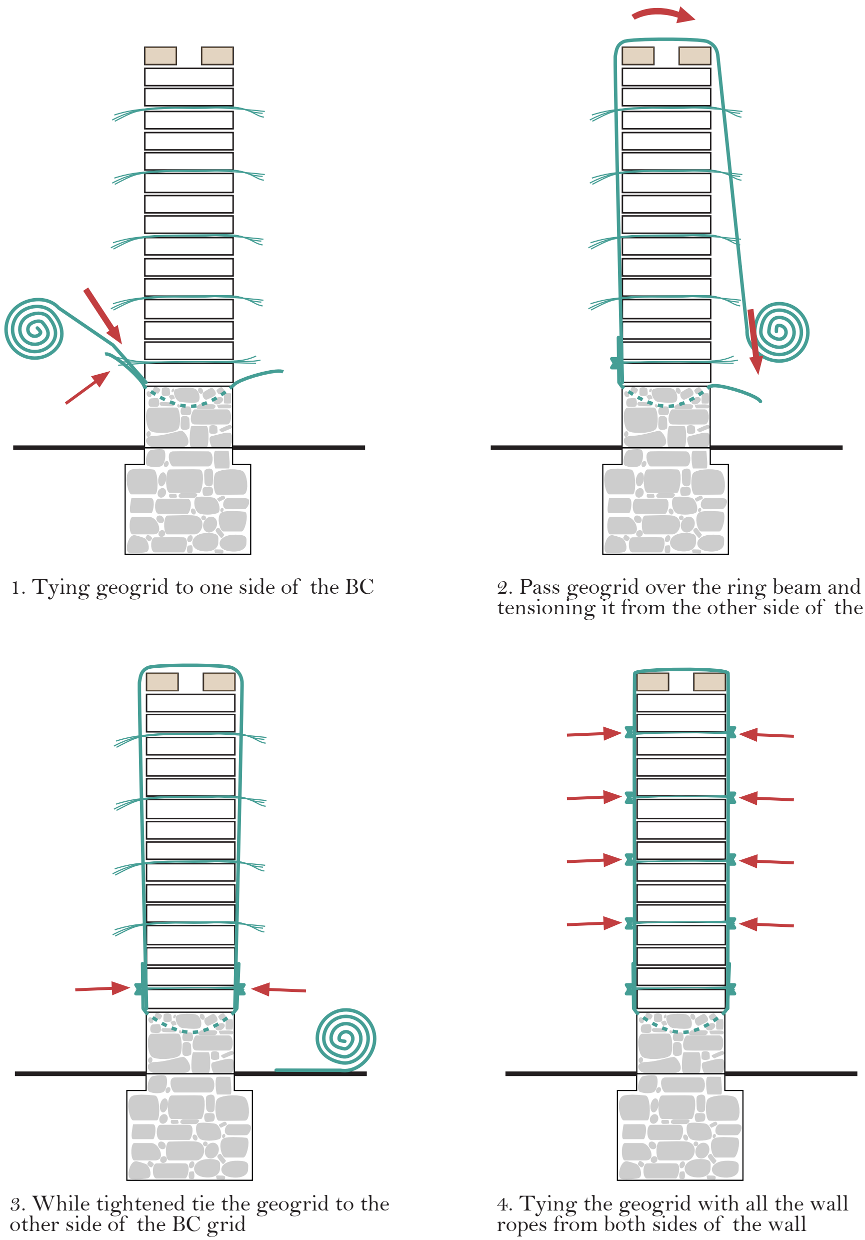


Geogrid passing over the ring beam frome one side of the base course to the other.



Geogrid covering just one face of the wall, high enough to overlap over the ring beam.

IMG 105. Location of the geogrid over the walls. Image redrawn from: BLONDET, M. 2010. Pg, 46.



IMG 106. Proposed process for tying the geogrid to the BC grid and the wall ropes.

faces of the openings (Img. 98 & 99).

The behaviour of compound wall under horizontal non-axial loads can be schematized in the image 100. The image shows in section a geogrid reinforced adobe wall during a three-point bending test done by (64). The geogrid tensile strength is working to control the flexural crack caused by the maximum moment section located below the loading point. The investigation specifies that the reinforcement "redistribute the stress" and "brace" the wall, keeping it together as a single el element (64). As expected, the internal adobe blocks get separated between them, during those separations the authors identified the activation of frictional dissipation of energy. That is why authors expected an enhancement of non-axial behaviour of the walls caused by horizontal loads (64).

The image 101, that is the typical scheme of a diagonal tension test, explains also the working mechanism of these reinforcements. If the wall is constructed just with brittle earthen material it is going to fault by a vertical crack caused by the tensile stress produced in horizontal edge. If it is a reinforced wall the additional materials are going to assume the tensile stress and the cracking is going to be presented in a diagonal direction, thus increasing the tensile capacity of the tested element (64).

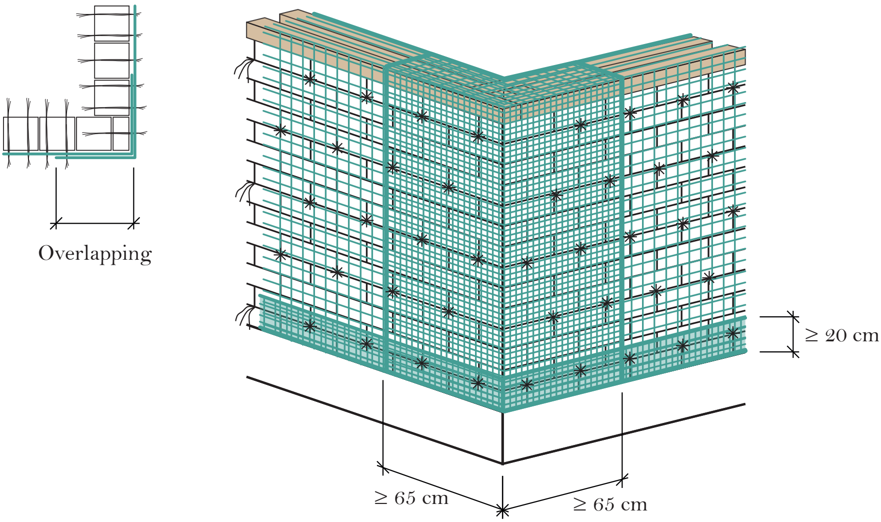
For the construction of geogrid reinforcements on adobe walls, several authors (24; 29; 42; 64) made specific recommendations that should be considered:

As it was already explained the reinforcement should surround all the faces of the wall, including the internal faces of the openings. The geogrids should be attached to ring beam and base course to guarantee its functionality with the entire structural system. Additionally, it should be fixed through the wall and covered by a plaster that is going to control the cracking and increase the ductility of the wall (29; 42). According to Invernizzi (64) the geogrid used for the reinforcement can be:

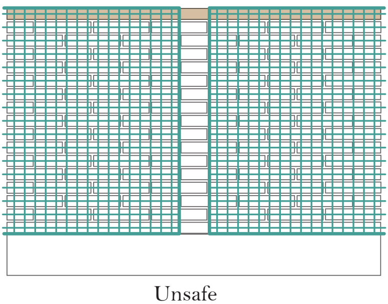
- coarse polymeric resin net (Tenax 3D Grid S);
- fiberglass net (Alpeadria textile Alrter GTS 31), reinforced with a spider web inside the main mesh;
- or polymeric resin net (Alpeadria Textil Arter AG 50-50), also reinforced with a spider web inside the main mesh.

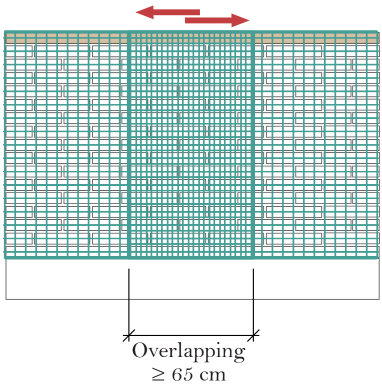
The construction process starts with the junction of the enclosing geogrid with the foundations, it should be done during the foundation construction, before start constructing the earthen wall. When the formwork of the base course is been fill is necessary to put a strip of geogrid before finishing the filling. This geogrid strip is going to be call base course grid (BC grid) and should be embedded at least 10cm under the top of the base course, the BC grid should be sufficiently long (40cm more than wall thickness approx.) to be tied to the geogrid that is going to enclose the entire wall (Img. 102) (29).

During the construction of the wall there should be located ropes that pass through it, these ropes (here named wall ropes) are going to tie the enclosing geogrid to the wall surfaces. Blondet (29) recommends the location of the wall ropes starting over the first layer of adobes: once the base course is ready a layer of mortar (1cm) is applied, the first layers of adobe is located and then groups of 4



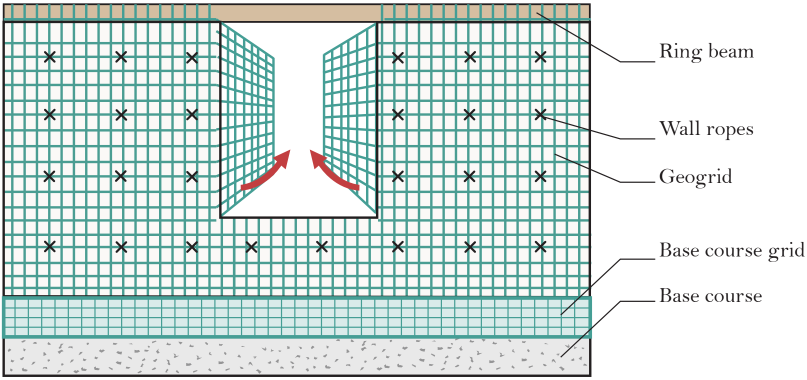
A. Overlapping of geogrids on corners



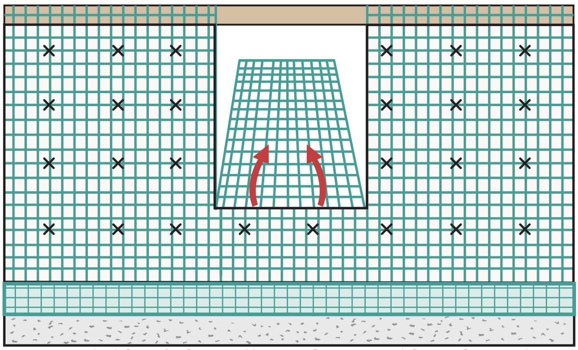


B. Overlapping of geogrid onfacade

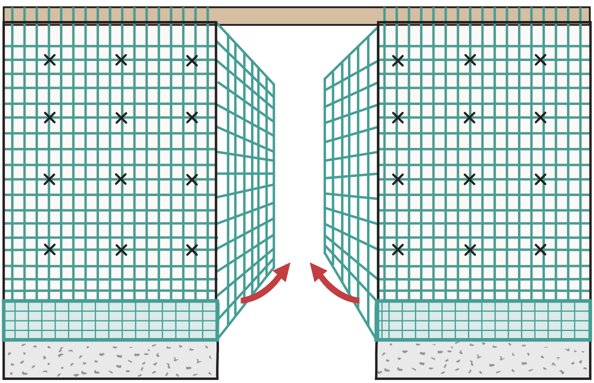
IMG 107. Overlapping of geogrid. Image redrawn from: BLONDET, M. 2010. Pg, 47.



1. External side of the wall: cut the geogrid by half in vertical axis allowing the grid to turn as window and cover the vertical surfaces of the opening.

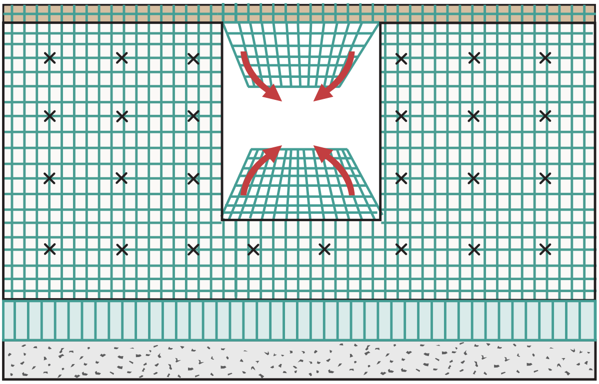


2. Internal side of the wall: cut the geogrid on the perimeter except the down side, so it can turn down into the opening.



For doors the proces is like the external face of the windows, cut the geogrid by half in vertical axis allowing the grid to turn as window and cover the vertical surfaces of the opening.

IMG 108. Cutting the geogrid reinforcement on the openings. Image redrawn from: BLONDET, M. 2010. Pg, 48.



IMG 109. Proposal for covering lintel with geogrid reinforcement. Image based on: BLONDET, M. 2010.

Wall No	Reinforce-ment	Material	Vertical load (kN)	Angle (°)	Overload (kN)	Effect
1	None	Adobe	50	71	0.0	Collapsed
2	None	Adobe	20	66	0.0	Collapsed
3	None	Tapia	50	90	2.0	Collapsed
4	None	Tapia	20	90	25	Collapsed
5	Timber	Adobe	50	90	32	Cracked without collapse
6	Timber	Adobe	20	90	32	Cracked without collapse
7	Timber	Tapia	50	90	42	Cracked without collapse
8	Timber	Tapia	20	90	58	Cracked without collapse
9	Timber	Adobe	50	90	45	Cracked without collapse
10	Rib lath	Adobe	50	90	43	Cracked without collapse
11	Rib lath	Adobe	20	90	28	Cracked without collapse
12	Timber	Tapia	50	90	53	Cracked without collapse
13	Timber	Tapia	20	90	30	Cracked without collapse
14	Rib lath	Tapia	20	90	23	Cracked without collapse

IMG 110. Perpendicuar load test in reinforced and not reinforced walls. Remake from: YAMIN et, Al. 2007.

ropes are located each 30cm in a perpendicular direction to the main wall edge. The wall ropes should be long enough to have 15cm free on each side of the wall, just as image 103 shows. The construction of the wall continues with the adobe bonds at half distances, tree more layers of blocks can be constructed before putting again wall ropes, in other words the wall ropes should be every tree layers of adobes (29). Is possible to overlap the location of wall ropes on one layer in relation to the one below for 15cm (29), with this overlapping the position of tying points on the area of the wall is going to be more distributed enhancing the geogrid attachment to the wall (Img. 104).

The wall should be constructed following the aforementioned recommendations until it reaches its total highness, later the ring beam can be constructed[17]. Then is possible to put the entire geogrid that is going to enclose all the wall, first is important to clean the wall surfaces, take off impurities or residual pieces of dry loam. To ensure the total covering of the wall the geogrid can be located from the external side of the walls starting on the base course, passing over the ring beam, and finishing on the internal side of the base course (29). Other process can begin covering just one face of the wall ensuring that the geogrid is higher than the wall, so the excess of grid can pass over the ring beam and be tied on the opposite side of the wall, clearly the same process should be done for the second face of the wall so both geogrids are going to be overlapped over the ring beam (29). Image 105 makes the comparison of both options.

17 Ring beam construction should follow the parameters established on the relative chapters (4.4.1 and 4.4.3).

When the geogrid is located is important to ensure that is as near as possible to the wall surface, it should be tense (29). A possible process can be first tying the grid just to one side of the BC grid, pass it over the wall and ring beam, then it can be tensioned and tightened from the other side of the wall, and finally can be tied to the wall with the wall ropes (Img. 106).

Is recommendable to reduce as possible the number of junctions between two different pieces of geogrid as they waken the reinforcement. However, when the junction is necessary, both pieces of geogrid should be always overlapped and tied between them and to the wall ropes (Img, 107):

- Geogrid to BC grid, should use the entire BC grid length (20cm on each side of the wall) to overlap both grids.
- Geogrids on corners should have an overlapping of 65cm and is important to tie both extremes to the wall ropes.

Once the entire wall is covered with the geogrid it is necessary to cut the geogrid on the openings. The cutting should ensure the possibility to cover the internal faces of openings with the same grid. In coherence to that, Blondet (29) suggest the geogrid of one side of the wall (external) should be cut by half in vertical axis allowing the grid to turn as window and cover the vertical surfaces of the opening; the geogrid on the other face of the wall (internal) should be cut on its perimeter except the down side, so it can turn down into the opening (Img. 108). Clearly the overlapping of this opening grids should be also tied to the wall ropes (29).

The covering of the lintel with the geogrid is not defined by Blondet or

IMG 111. Wood grid reinforcement laboratory test. Image tooken from: YAMIN et, Al. 2007.

IMG 112. Wood grid reinforcement laboratory test. Image tooken from: DOMÍNGUEZ *et, Al. 2013.*

E.080, nevertheless in consideration to the behaviour of the reinforcement here it is recommended. On that case the geogrid of one side should be cut by half in horizontal way to permit one part to cover the windowsill and the other half cover the lintel as is explained on image 109.

After finishing the geogrid reinforcement the construction process can continue with the roof construction and so on. Is important to be careful with the geogrid during the construction of other parts of the building, avoiding damaging it. Later the reinforced walls should be covered with earthen plaster following the process described on chapter 3.1.5.

Timber grids

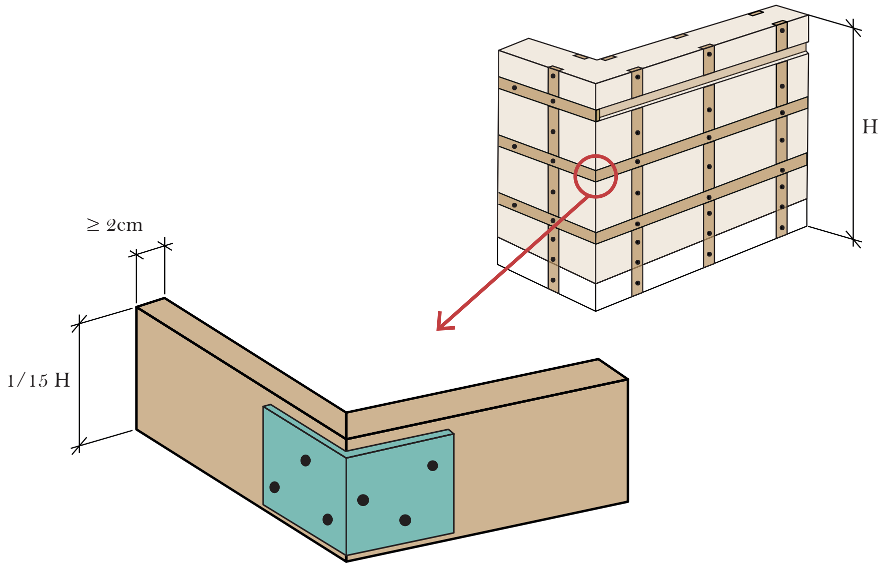
Apply to: Adobe and Rammed Earth techniques.

As "innovative" solution in Colombia it has been also tested an enclosing grid reinforcement but, in this case, the grid was made with wood strips. The investigations have shown the efficiency of timber grid reinforcement as it enhances the ductility of the wall and the energy dissipation, hence the system provides a collapse mechanism that is acceptable and safer to the inhabitants of the building (10; 43).

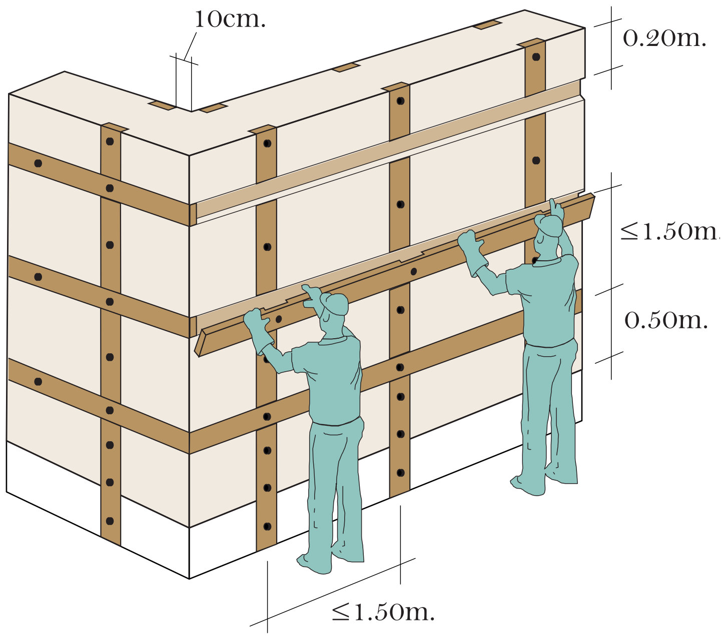
The CIMOC of Los Andes University of Bogotá has developed laboratory tests in real scale walls and houses models in scale 1:5 without and with timber grid reinforcements. The reinforcement in the tested walls improves the displacement until a 400% and the shear strength in 100% (27). Additionally, the test of walls under perpendicular loads show how the reinforced walls did not fall (Img. 110). For the case of the adobe house models the building resistance in earthquake shake table increased in 270% and the capacity of deformation and the elastic range was multiplied by 4,4 (Img. 111) (27).

A civil engineer thesis of the PUJ tested the timber grid reinforcements in a model of the chapel of Suesca, Colombia. The models were built in scale 1:50, one just with rammed earth and the other with timber grid reinforcement, the roof structure was also made in timber and over it, the loads were located. Both models were tested in an earthquake shake table. The conclusions of the experiment were positive to the reinforced model as it guaranteed the stability of the building thanks to the enhanced connection between the walls, making them work as a single system. The reinforcement elements have controlled the displacement of the building during the seismic phenomena (Img. 112) (65). Is important to note that the tested building on Domínguez (65) research – a chapel – has long walls without any perpendicular buttress to stabilize them, hence the excellent performance of the timber grid reinforcement was demonstrated. It supply enough bending strength avoiding bending cracks on the walls and corners and shear cracks on wall-to-wall connections. The research was focused on a rammed earth building and the authors recommend performing similar ones with adobe buildings (65).

Following the recommendations of Ruiz (10) and Yamin (27), for the construction of the timber grids reinforcement, the grid should cover internal and external faces of the wall, the timber used should be at least type



IMG 113. Dimension suggestions for timber elements of the timber grid reinforcement. Image from the author, data from: RIVERA et, Al. 2012.



IMG 114. Wood grid reinforcement. Image redrawn from: LÓPEZ, 2018 & YAMIN et, Al. 2007.

"ES4" cording to the NSR-10 (10). The timber width can be calculated as the 1/15 of the wall highness **H**, and never shorter than 20cm. The thickness is preferable to be at least 2cm (Img. 113) (10). Regarding the distribution of timbers over the wall, both grids should match between them on both faces of the wall and should follow the next lengths.

Horizontal timbers:

from bottom the first timber should be 50cm over the base course;

- the distance between horizontal timbers cannot exceed 1.5m;
- and the last timber should be 20cm below the ring beam.

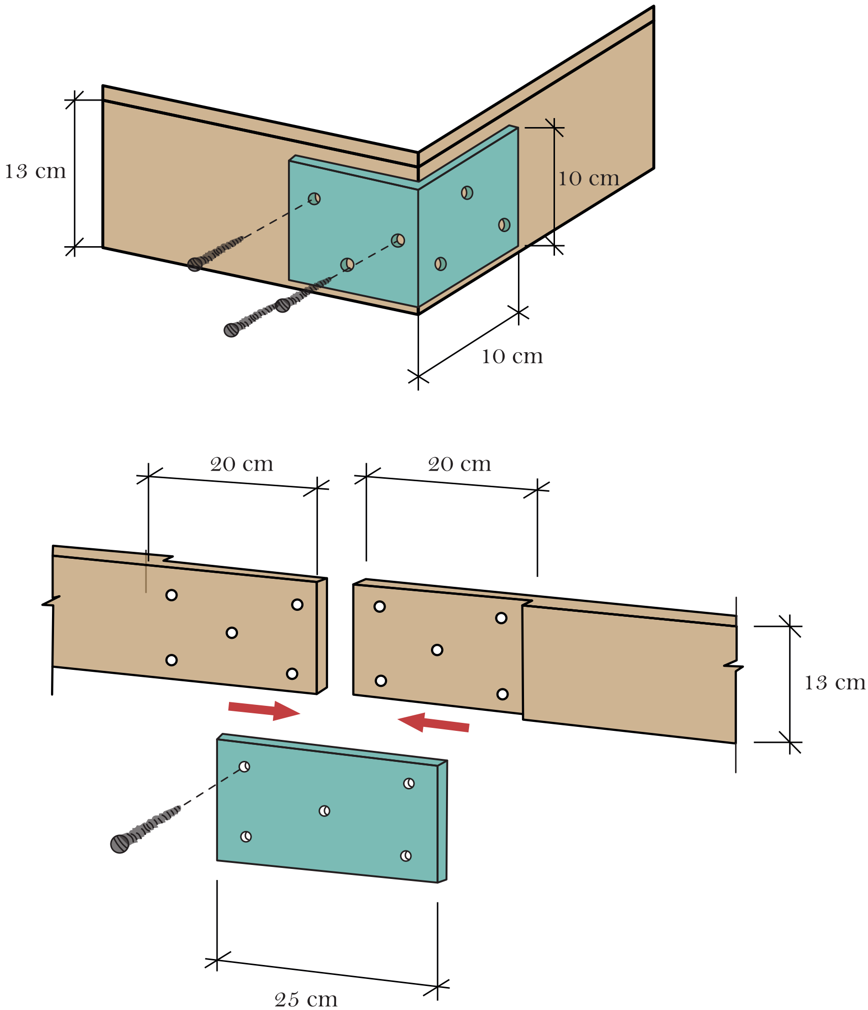
The vertical timbers should:

- be located 10cm apart of internal corners and wall intersection;
- the distance between they cannot either overpass 1.5m;
- vertical timbers are going to be localized matching with the sides of all openings (Img. 114).

The timber strips have to be attached to the wall by bolts of ¼" that are located through the wall each 50cm and on the timber intersections. When vertical timbers (internal and external) reach a ring beam they should be attached through the ring beam with the aforementioned bolts, same process should be done with the base course (10). Additionally the wood grid is going to be joined to the wall surface each 15cm by nails, this increase and ensures the contact surface of both materials – wood and raw earth – (43). Timber junctions on corners should be done with metal plates that should cover at least ¾ of the timber width, the plates thickness should be larger than ¼" (10). However, Yamin (27) recommended specific measures for timber and metal plates, those measures are registered on image 115

Some authors suggest opening the space for timbers on the wall surface, also opening the holes to bolts junctions before fixing the timber grid (27). Nevertheless, that should be done carefully (measures control) to guarantee the holes on the wall are going to match with the holes on timber grid. For the bolt holes on rammed earth buildings (10) suggest filling them with mortar to avoid weaken the wall.

After finishing the location of the timber grid reinforcement the construction process can continue normally and on finial phases the reinforced walls should be covered with plaster as is described on chapter 3.1.5.



IMG 115. Metal plates and timber dimensions for timber grid junctions. Image redrawn from: YAMIN et, Al. 2007. Pg, 6.

Rib lath grids

Apply to: Adobe and Rammed Earth techniques.

Complementing the Peruvian research of PUCP, in Colombia were also done tests with reinforcements of rib lath grid and lime plaster located on the important parts of the structure. The reinforcement creates a pattern of "beams and columns" over the face of the wall, these enclosing elements should match with corners and the openings (vertical & horizontal) (43), and should be also located on both faces of the walls (10).

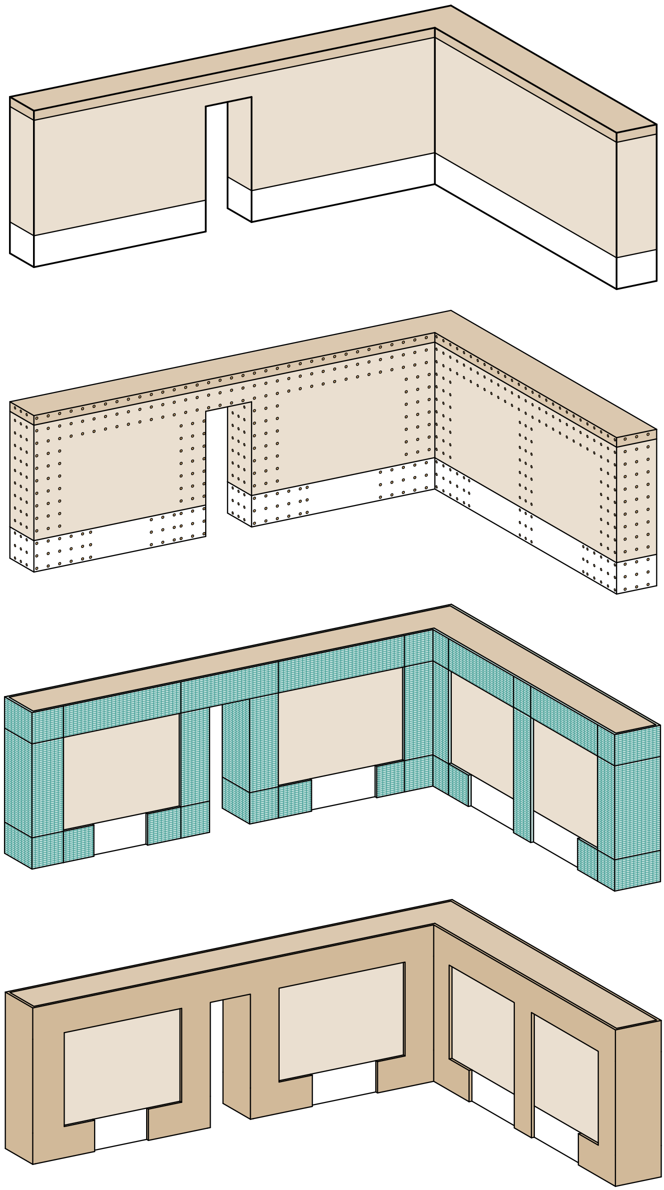
On earthquake shake table an adobe house on scale 1:5 reinforced with rib lath grids was tested (43). The reinforcement showed to enhance the ductility and the dispersed energy of the structure. The building models suffered a sudden unexpected collapse, which represent an extreme danger for the building inhabitants (43).

For the construction of this reinforcement the rib laths should be localize over the wall faces creating the "beams and columns" pattern described above. The grids of both wall faces are attached by 8mm wire that pass through the wall each 20cm on vertical and horizontal directions (10; 27). For this reinforcement is also necessary fill the holes of the supports with lime:sand mortar, Ruiz suggest a proportion of 1:2. Finally the rib laths are covered with lime plaster. The entire process for the construction of the rib lath reinforcement can be seen on image 116 and 117.

Even if the aforementioned authors do not specify the junction of the rib lath to ring beam and base course, is assumed it should be done to ensure the effective performance of the reinforcement under seismic loads.

Steel bars

In other investigation of the PUJ it was proposed the use of steel bars to pre-compress the walls. The objective was to avoid the cracking that can be produced by shear strength, that is why tensors were localized in vertical and horizontal direction and should run around the whole wall perimeter (Img. 118) (10). However the architect Cecilia López, who has investigated the most that solution, has confirmed by experimental tests these reinforcements were unsuccessful because, with time, the steel bars lost the appropriate tension and the system became once again unsafe, hence the use of this reinforcement should be avoided (15).



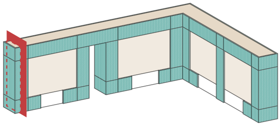
1. Adobe or rammed earth walls with normal ring beam and base course

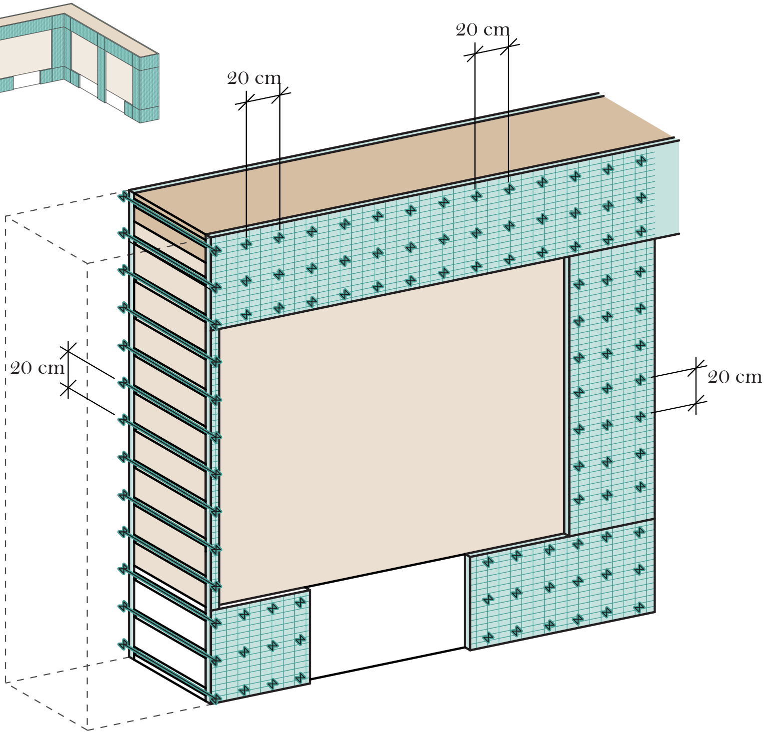
2. Perforate the wall each 20cm for the attachment of the rib lath

3. Localize the rib lath creating beams & columns patterns that match with corners and openings. Tie it with 8mm wire that passes through the holes

4. Plaster the rib lath with lime plaster.

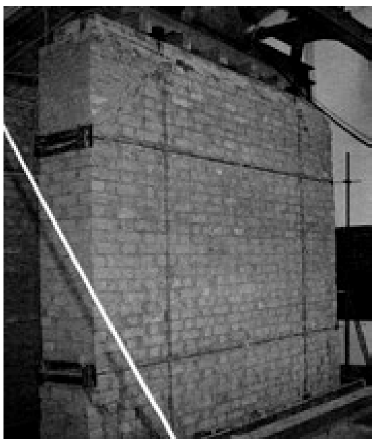
IMG 116. Constructive process for rib lath grid reinforcement. Image of the author, data from: YAMIN et, Al. 2007. Pg, 5 & RUIZ et, Al. 2012. Pg,10.



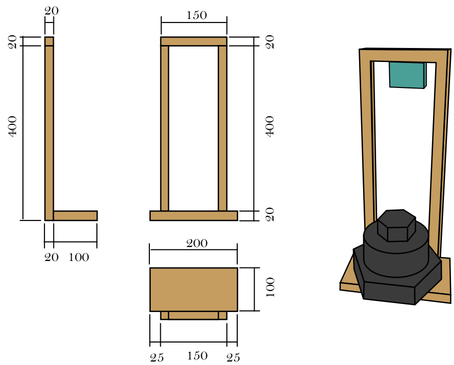


3. Tie it with 8mm wire that passes through the holes in the wall

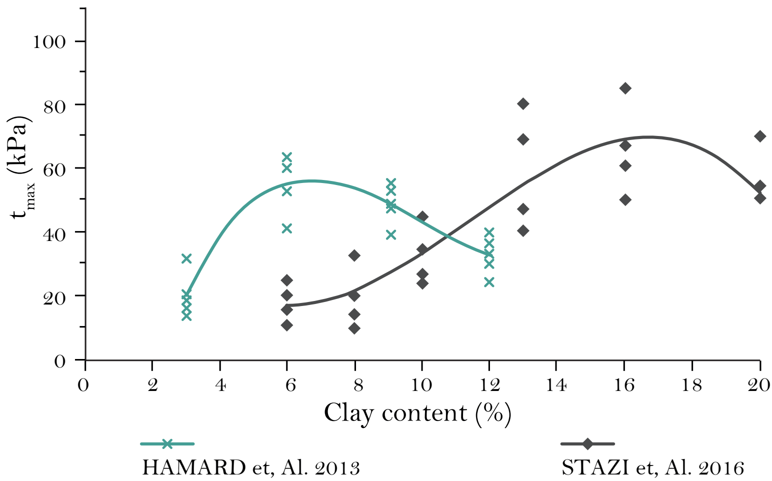
IMG 117. Detail of attaching the rib lath grid. Image redrawn from: YAMIN et, Al. 2007. Pg, 5 & RUIZ et, Al. 2012. Pg,10.



IMG 118. Metal bars reinforcement. Image tooken from: LÓPEZ et, Al. 2007.



IMG 119. Shear test loading divice example, 400mm high, 150mm large and 20mm thick. Image reproduced from: HAMARD et, Al. 2013.



IMG 120. Shear strength Vs. clay content on plaslters applied over rammed earth walls. Image redrawn from: HAMARD et, Al. 2013. Pg, 114 & STAZI et, Al. 2016. Pg, 33.

Plaster: wall enclosing element by default

In coherence to the coating function of plaster[18], it is the component (of the wall layering) that is normally enclosing the entire wall. Hence, it can be considered into the "enclosing reinforcements" as a possible improver of the wall strengths under seismic loads (42).

As other components of the wall, the plaster have mechanicals strengths that make it able to support load stress (34; 35; 53; 66). If the plaster strengths were large enough, under horizontal seismic loads, it could contain the internal components of the wall, decreasing the risk of fault. To make the plaster behave as anti-seismic "enclosing reinforcement" would be necessary it:

- has enough tensile and compressive strength, to support bending and shear stress from horizontal loads;
- has enough adhesion to the wall surface, to ensure it conjunct performance with the reinforced wall;
- has not shrinkage cracks that can weaken it.

With these characteristics the plaster would be able to strengthen the load-bearing wall. Nevertheless, the traditional earthen plasters are not designed to support external loads, their mechanical and physical characteristics are limited to the coating proposes and its appropriate attachment to the underlying surface.

To understand how the earthen plasters can be enhanced to become an "enclosing reinforcement" for load-bearing walls, here are reported guidelines from some investigations that have studied, among others, the mechanical strengths of earthen compatible plasters. These investigations have tested modifications on the clayey plaster mixture (34-35) and the use of several clays as additive for lime plaster (53).

In the matter of the structural performance, the references care about two parameters of the earthen plasters that are related to the aforementioned requirements for plasters as "enclosing reinforcement": first the effect of clay into the plaster shrinkage (with the problems that shrinkage carries), and second the plaster attachment capacity to the wall surface.

Regarding the plaster's shrinkage, it can weaken the plaster itself by cracking and the plaster-wall interface inducing the plaster to blow-out and fall from the wall (34). To avoid the shrinkage cracking, is recommended control the clay content in the loam mix (35). Plasters with more clay percentage have higher bending strength, which can be useful for anti-seismic proposes, nevertheless this strengthening of plaster produces an increase on its shrinkage and consequently the plaster-wall interface is weakened (34). Additionally to control the shrinkage cracking, there can be added natural fibres as straw, sisal or hemp chaff, these can also enhance the workability of the mix but has not a significant influence on the plaster strengths (34).

Concerning the attachment capacity of the plaster to the wall surface, Hamard (34) developed an investigation to study the shear strength of the plaster applied to different wall surfaces (rammed earth and cob). The

18 The importance of plaster for earthen walls is explained on chapter 3.1.5.

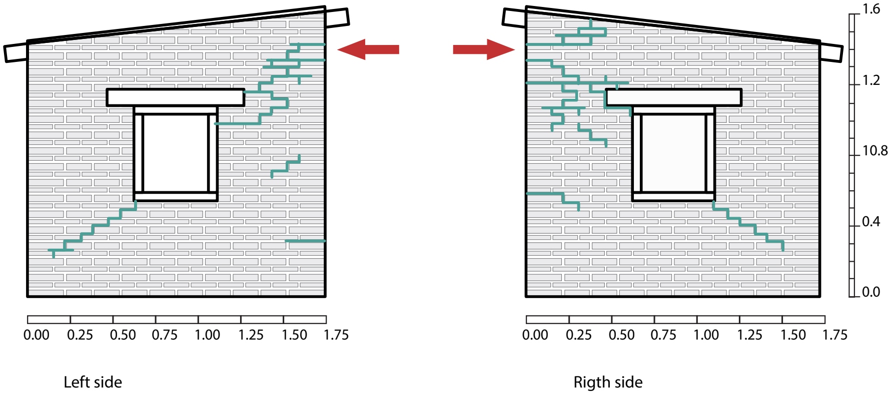
shear strength was tested by the use of the device shown on image 119. According to the investigation of (34), it is clear that the clay content in plaster loam mixture can rise its shear strength: an increase from 0 to 6% of clay content represented a growth of the plaster shear strength, however beyond 6% the shear strengths decreased (Img. 120) (34). During a similar investigation, Stazi (35), identified the same behaviour with some variations on the clay percentage (Img. 120). In this case the authors suggested that the decrease of the plaster shear strength, after an increased clay content, is provoked by the increased shrinkage that clay content also carries (35). However, the plaster with the lowest clay content (8%) of the (35) investigation has reported enough shear strength (19 kPa) to guarantee its attachment to the wall surface[19] (35).

The addition of several clay minerals to lime:sand plaster was tested by Andrejkoviková (53). Four types of mortars were analysed as renders of adobe walls: the basic plaster was composed by lime:sand, each one of the other three plasters mixtures had a replacement of lime by:

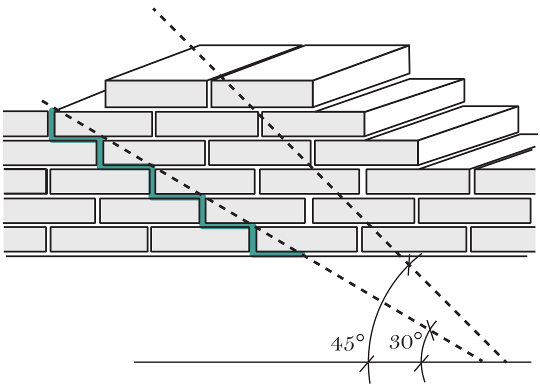
- 5% of bentonite clay,
- 20% of metakaolin clay,
- 5% of bentonite and 20% of metakaolin clays (53).

The addition of bentonite does not present any important change on the flexural strength of the plaster (53). On the other hand, the of metakaolin addition provoked an improvement in the compressive strength at early curing age and a higher adhesion strength at later curing ages. These results are useful if the plaster is considered for an "enclosing reinforcement", however, there is not reported the shrinkage performance of the plaster mixture. As conclusions the authors recommend the use of plasters wit 5% of bentonite as the most appropriate one to be used as render for adobe buildings (53). Nevertheless, this suggestion is done valuing more the coating than the structural properties of the plasters because for that plaster mixture were not registered important enhancements for its adhesion to the background, its tensile or flexural strengths.

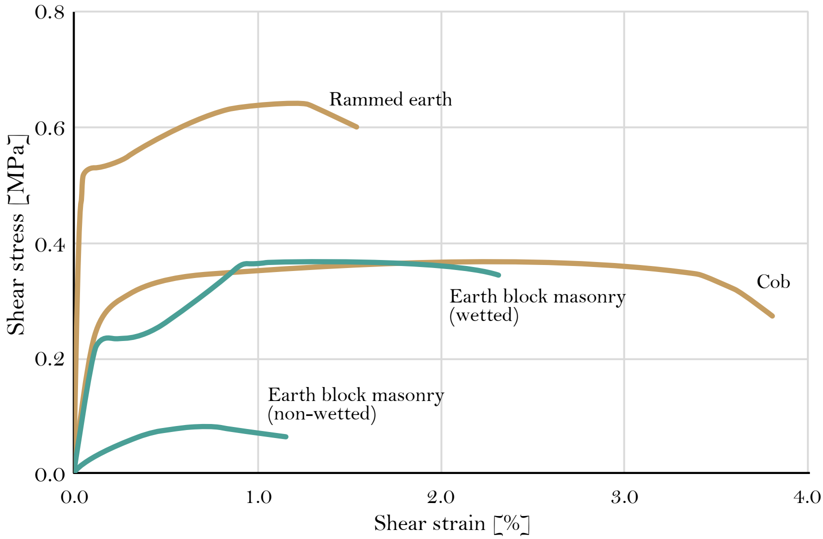
19 The influence of the beyond surface conditions (cleanness, roughness, moisture) on plaster attachment are also valid here. The correspondent explication is done in chapter 3.1.5.



IMG121. Crack pattern recorded after subjecting the model structure to monotonously increasing horizontal loading test. side walls. Image reproduced from: ILLAMPAS et, Al. 2014.



IMG122. Brickwork against "X" shear cracking. Image redrawn from: HOUBEN et, Al. 1994. pg, 319.



IMG 123. Typical stress-strain curves of earth block masonry, rammed earth and cob. Comparison of behaviour of the three basic techniques under digonal compression. Image redrawn from: MICCOLI et, Al. 2014.

4.5.6. Block-mortar junctions

Apply to: CEB and adobe techniques.

The CEB and adobe walls, as masonry composed of several blocks, have a weakness under seismic loads: all the blocks should be attached (normally by mortar) to make them remain together, thus the wall can behave as a unique structural element able to support bending and shear stresses from horizontal loads. Hence mortars should be carefully managed to control the behaviour of the wall during seismic activity.

Regarding the interaction of the block-mortar junction on CEB walls, Arthega (52) and Walker (54) found the difference between the compressive strength of the blocks and the bond strength in block-mortar junction can influence the behaviour of the entire wall. The authors suggested that the more similar are both strengths (block and block-mortar bond), the wall strength will be enhanced, given the uniformity of its materials. From the specific investigation of (54), is suggested to increase mortar strength up to the strength value of the block, but never to overpass the block strength, thus the block and mortar strengths remains similar and compatible (54).

Regarding the structural behaviour of adobe buildings a Cyprus investigation have tested an adobe building model in a scale 1:2 under monotonic lateral loading test (67). The research identified two main causes of the cracks presented during the monotonic lateral loading test:

- low bonding capacity between adobe blocks and the mortar, that reduce the tensile strength of the entire masonry;
- and the lack of a ring beam[20].

The authors found the block-mortar junction as a weak point of the masonry based on the cracks pattern presented in these junctions and not in the blocks (67). Image 121 shows the aforementioned cracks caused by the shear stress provoked by the axial load over those walls.

This brittle performance of the block-mortar junction was also reported for adobe during a comparison study between rammed earth, cob and adobe, under axial and diagonal compression, and shear tests (37). In most of the cases, the failure of adobe wallets was presented in mortar-block interface, hence the contact and interaction between both elements was identified as an important characteristic for the structural performance of the wall (37).

To enhance the block-mortar interaction there can be implemented two strategies: use a brickwork bond that is not "aligned" to the load's direction; and to control the moisture content of the blocks when the wall is been constructed.

Regarding the brickwork bonds Houben (20) recommend choosing patterns that differentiate from the characteristic "X" cracking caused by shear stress (Img. 122), the author suggest this can reduce the cracking effect on mortar junctions that was reported by (67) on image 121. Nevertheless, to conform a brickwork bond that avoid the "X" cracking is complicated as the cracking pattern cannot be predicted exactly and the walls and blocks dimensions variate depending on the project and location.

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20 The function of ring beams is explained on chapter 4.4.1.

On the other hand, according to Walker (36), an aspect that can influence the toughness of the block-mortar junction is the moisture of the blocks when the wall is been build. If blocks are dry the water content of the mortar is going to be rapidly absorb by the block, avoiding an appropriate adhesion (36) and probably causing shrinkage cracks during drying. If the blocks are "very wet" the mortar is going to "float" over the block, also avoiding a proper adhesion (36). Therefore, the adobe wallets for the tests done by Miccoli (37), were constructed with pre-wetted and dry blocks expecting different behaviours. For the diagonal compression test the wallets constructed with pre-wetted blocks showed two to three times higher shear strength values, between 0.25MPa and 0.40MPa (Img. 123) (37).

In concordance to the aforementioned studies, the recommendations done for constructive process of adobe and CEB techniques should be carefully follow as they also can enhance the bonding capacity of mortar-block interface, preventing failures of walls by bending and shear cracking. Here are reported the most important parameters to follow during the construction process:

- The moisture content of the mortar mix cannot overpass the 20% of the dry mix weight (24).
- The moisture content should be as low as possible without compromising the workability of the mortar (24).
- The blocks should be soaked during 15-30 seconds before their location on the wall (24; 29).
- The mortar should contain fibres to prevent shrinkage cracking[21] (23).
- The mortar mix should be similar to the composition of the blocks loam and the mechanical strengths of both should be tested to guarantee their compatibility.

21 Following the recommendations described on chapter 3.3

Foto from the author.

5. TECHNOLOGICAL INNOVATION: ENCLOSING PLASTER REINFORCEMENT

In concordance to the load-bearing walls enhancement strategy explained on the chapter before, the present research have focused on the enclosing reinforcement group, as those have been investigated, approved and used in a similar seismic zone to Colombia (Peru), (24; 29; 42). Additionally, those reinforcements have demonstrated by laboratory tests that are able to enhance the structural performance of earthen walls under bending, tensile and shear stress produced by horizontal axial and non-axial loads (27; 42; 64). Indeed, it is clear the structural strategy of these enclosing reinforcements that supply – with suitable materials – the tensile strength that earthen material has not, hence create a compound structural element that is able to support compressive and tensile stress. Focused on this specific group of anti-seismic reinforcements for earthen buildings, is expected propose a possible solution that carries a technological innovation for earthen construction field and that can encourage future research for anti-seismic earthen technologies.

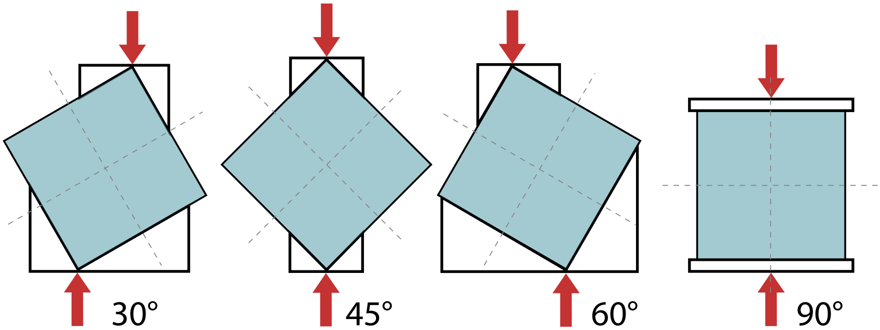
For all the enclosing reinforcements is suggested the additional materials used shall be covered and attached to the wall by a clay or lime plaster [1] but plaster is not mentioned by the authors (27; 42; 64) as the principal element of the reinforcements. Nevertheless, understanding the plasters as the evident enclosing element of the wall, guides this research to inquire the possibility of enhancing the earthen plaster itself.

Searching for an enhancement of the earthen plasters' strengths, there are considered similar reinforcement proposals referred to several types of plasters, with the objective of find strategies to apply into earthen plasters technologies. On that path, there are considered the positives results that are coming out from researches on cementitious composites with addition of biochar microparticles.

From a technological point of view, biochar is reporting an improvement on flexural strength and ductility of cementitious composites, hence is questioned its compatibility with earthen technologies. From a sustainable point of view, biochar has advantages as reduction of CO2 and embodied energy of the construction material (68) and, as its raw material are organic wastes, it contributes to close life cycles of other production lines as food industry. Additionally, biochar production is feasible in a country with important agriculture production as Colombia, indeed nowadays in the country there are present industries that produce biochar (69). Regarding economical aspects is notable the cost-effective benefits that biochar has (68; 70) due the origin of its raw material.

In light of above there was studied the feasibility of produce and test under seismic loads an earthen plaster enriched with biochar additive (EPEB). Here is proposed a possible procedure for an experimental investigation of EPEB applied over adobe

1 Specifications and suitability of plasters to earthen walls is explained on chapter 3.1.5.



IMG 124. Compression tests to wallets under different angles. Image redrawn from: BASARAN et, Al. 2013. Pg, 4.

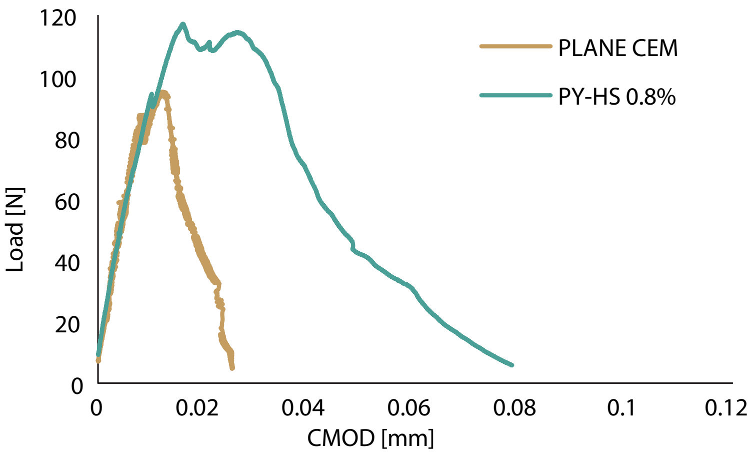
Lateral compression strength tests on masonry specimens.

	Without plaster [MPa]	With plaster [MPa]	plaster [%]
f	1.89	2.41	+27.5
σ	0.20	0.43	---
CV	11%	18%	---
f_k	1.58	2.01	---
E	2863	4597	+37.7

Diagonal compression strength tests on masonry specimens.

	Without plaster [MPa]	With plaster [MPa]	plaster [%]
f_t	0.256	0.358	+39.9
σ	0.044	0.060	---
CV	17%	17%	---
f_{tk}	0.207	0.298	---
G	795	892	+12.2

IMG 125. Comparison of lateral and diagonal compessive strength on plastered and unplastered wallets. Image redrawn rom: MORANDI et, Al. 2016. Pg, 8.



IMG 126. Load CMOD curve, results for TPB test. Image redrawn from: RESTUCCIA et, Al. 2016.

walls. Those procedures are proposed as starting point for future investigations that can contribute to the technological field of earthen architecture.

5.1. Plaster reinforcements

In order to find different solutions to enhance the mechanical strengths of earthen plasters – especially tensile and flexural ones – the research range was opened to include enhancement strategies of generic plasters, searching one that could be applicable to an earthen plaster. The majority of the investigations on structural reinforcement for plasters are focused on their performance over infill walls. Nevertheless, during an earthquake, this type of walls suffer the same bending and shear stress due the horizontal loads (71-73).

Similar to the reinforcements for earthen technologies, on several plasters have been tested geogrids embedded in plaster (74-75) and fibres addition to the mixture (72-73). The objective of such solutions is also to supply tensile, bending and shear strength to the masonry by the plaster in order to avoid failure mechanisms as bending or shear cracking of the wall[2].

Concerning the reinforcements of generic plasters with geogrids, there are also described as "coated or confined" reinforcements that makes the masonry a "composite material" (74) able to support different forces (compressive and tensile). The objective of such reinforcement is to distribute the masses and avoid the stress concentration (74). Just as it has been demonstrated for earthen walls the geogrids reinforcements present an optimal cooperation with brittle masonry under seismic loads (74). According to (71; 74), this reinforce can offer:

- higher displacement of energy,
- increase on the shear strength of the wall,
- control of shear "X" cracks,
- "fail-safe" mechanism of failure,
- and better out-of-plane behaviour.

For the reinforced plasters with fibres the materials used are normally polypropylene, steel fibres (73), "Carbon Fibre reinforced Polymer" or "Fibre Reinforced Cementitious Matrix" as existent solutions to apply on plasters[3] (72).

To increase the strength, stiffness and ductility of the masonry walls, Basaran (73) tested the reinforced plasters over 1:2 scaled brick wallets applying vertical loads at different angles (Img. 124). The load carrying capacity under diagonal tensile test of the plaster-reinforced wallets presented a shear strength and deformation of almost the double in comparison to the un-reinforced ones (73). Morandi (72) proposed, among others, fibre-reinforced plaster as a structural element that can control the horizontal flexural strength of infill masonry. The contribution of the plaster was notoriously for the diagonal shear tests over simple wallets with an increase of almost 40% of the diagonal compressive strength, and around 12% of the elastic modulus (Img. 125) (72).

2 View failure mechanisms on chapter 4.2.

3 Unfortunately the research do not specify which specific fibres were used to the reinforced plaster.

5.2. Biochar as a possibility

With the objective of increase the anti-seismic capacity of cement mortars and plasters, recent researches have been testing the use of micro inert biochar additive into cementitious composites (68; 70). The strategy is always to supply tensile strengths to the masonry by the plaster/mortar, in order to control the cracking caused by bending and shear stress.

As micro inert there has been tested biochar produced by pyrolysis of bamboo (70) or hazelnut shells (68), the latter has been chosen according to the elevated presence of carbon, which make the carbonized particles stronger in comparison to the cement matrix, additionally the low amount of impurities, offers an adequate performance in the mixture (68).

From the investigation of Restuccia (68) and Ahmad (70) was highlighted the flexural strength improvement on cementitious composites with an addition of biochar. In the case of cementitious composites enriched with hazelnut biochar, Restuccia found a maximum increment of the fracture energy required of 130% with a biochar addition of 0.8% (wt%) (68). Whereas, the addition of 0.08% of bamboo biochar present a 20% of increase of the flexural strength (70). In both cases it was noted that the deformation after the first crack is bigger for the specimens that are enriched with biochar, converting the brittle performance of cementitious material into a more ductile behaviour (Img. 126) (68; 70).

Furthermore there was also demonstrated that, as biochar is made of stronger micro-particles, these particles have the capacity of deviating the micro-cracks path in the cement matrix making them more "tortuous" (68). According to Ahmad (70) the micro-cracking deviation compromise more material during the failure, thus energy required to arrive to the failure is bigger and an improvement of the post-peak performance is presented.

5.2.1. Biochar in Colombia

The production of biochar in Colombia is just beginning, nevertheless in the country there is already an industry that is producing it (69) and there have been done some investigations referred to its potential use for the optimization of cultivations soils in Colombia (76-77).

In relation to the biochar raw materials used in some investigations, traditional and important industries from which can possibly be supplied raw material for biochar production in Colombia are agriculture products as rice (76), caña (bamboo spice) (70), or even oil palm (77), there can also be considered wastes from coffee or cocoa industries. As an example of biochar production in the country, the company Biochar Colombia nowadays is working with organic wastes from municipal, industrial and domestic origin (69). Nevertheless the raw material sources of Biochar Colombia seams not to be so selective, which would be necessary to specify the characteristics of the micro inert biochar particles for EPEB production.

As it was noted the production of biochar (independently of the its use) carries the transformation of wastes into a useful product, thus it contribute to enclose life cycles reducing the amount of waste production from alimentary industries. The Colombian planning department (Departamento de Planeación Nacional- DPN) established for 2018 it was necessary to transform more than 20% of the agroindustrial wastes into usable materials for other fields as construction or energy, however the objective of DPN has not been reached (78) and, from sustainable point of view, there should be done efforts to reach it.

Is important to note biochar is a new product just getting some space in the market, hence will be needed develop investigation, education and propagation of its use in construction materials and other applications, highlighting its advantages from a sustainable perspective.

5.3. Biochar reinforcement for adobe walls plasters

Under the logic of the enclosing reinforcements for earthen walls and in concordance to the solutions that have been exposed in the present chapter, for the Colombian seismic hazard zones there can be proposed an anti-seismic reinforcement for earthen walls by the application of earthen plaster enriched with biochar additive (EPEB).

Considering the importance of adobe as earthen constructive technique and its compatibility to the reinforcement proposed, the following reasons suggest adobe walls as appropriate to study the EPEB reinforcement. First of all, as the EPEB proposal is done under the enclosing reinforcements for earthen structures, the possible techniques to be tested are those that have presented optimal behaviour with this reinforcement solution: rammed earth and adobe structures (27; 42; 64). Indeed, some of these reinforcements have been approved by the Peruvian regulation E.080 (24) to adobe structures. Additionally, these earthen techniques are the most spread in Colombia and the world (8; 21; 23; 25), that is why their research field is larger than other earthen techniques offering more information to base the testing procedures for a new technology as EPEB. Furthermore, in concordance to the adhesion capacity of earthen plasters to the wall surface[4], adobe walls offer a rough surface that guarantee a better plaster attachment (34-35), thus the effectiveness of EPEB can be easily ana-

4 The adhesion capacity of earthen plasters over the wall surface is explained on plaster sections of chapters 4.5.5 and 3.1.5.

lysed. Finally the block composition of adobe walls allows to understand the effects of a reinforced plaster into the wall structural behaviour as it has been done on similar investigations with infill brick walls (71-73).

5.4. Experimental procedure proposed

The EPEB proposal is characterized by combining two different technologies that seem to have not been combined before (biochar and clayish plasters), hence is necessary to define the effects of biochar into a clayish plaster, searching for an improvement of the mechanical strengths, as the results of biochar additive in cementitious composites. To scientifically confirm the mechanical behaviour of EPEB as anti-seismic reinforcement over adobe walls, here are proposed laboratory tests that permit to analyse the stresses that load-bearing walls can suffer under seismic loads.

With the cooperation of Luciana Restuccia from the DISEG department of Polytechnic of Turin, is proposed to test EPEB reinforced adobe wallet specimens under axial compressive test, and diagonal shear test to evaluate their compressive and tensile strength. These tests are referenced to similar investigations (34; 35; 37; 53; 66; 72; 73), due to their efficiency to proof the seismic behaviour of a single load-bearing wall, when is not possible to construct an entire building model. For the development of the experimental research is necessary the construction of the specimens reinforced with EPEB, the test execution, and the analysis of the results.

<u>Materials and specimens</u>

Regarding the materials (adobes, mortars and plasters) and the construction process of the specimens, these should have the characteristics and follow the constructive methods (traditional or widely used) of real adobe constructions. This should be done to ensure the compatibility of the laboratory results to real cases. Therefore is necessary the materials chosen are similar as possible to the case of study: adobe buildings in Colombian seismic hazard zones[5]. Annex 1 includes specifications of products that are proposed. Even if these are produced in Italy, their selection was done pretending to maintain similarity to the traditions of Colombian adobe technique.

For the production of the EPEB plaster, is important to highlight the recommendation done by Stazi (35) which regards the use of additives, normally produced for different technologies, into an earthen one: the additive quantity shall be related to the binder content of the mix (clay content for earthen plasters), hence if (e.g.) the additive percentage into the mixture should be equivalent to 5% of cement content of the plaster, for an earthen plaster the additive content should be 5% of the clay content. Nevertheless, scientific approach indicates that if the additive have not been studied before on earthen technologies, different contents should be tested to define the optimal content that supplies the better enhancement. Anyhow, it is necessary to specify the mechanical and physical characteristics of the EPEB plasters produced.

Is proposed the construction[6] of six reinforced adobe wallets: three for axial compression test and three for diagonal shear test. According to the specimen's dimensions established by UNI EN 1052-1 (79) and ASTM-E 519 (80), and considering the use of adobe blocks from Terragena (Annex 1), the wallets shall have the following dimensions:

- Length of 131.5 cm
- Highness of 138.7 cm
- Thickness of 14 cm

These dimensions can be reached by using mortar thickness of 1.3 cm and plastering one face of the wallet with a plaster thickness of 2 cm.

The adobe wallet specimens, already plastered with the optimal EPEB mixture, shall have a curating period of at least 7 days, however are preferable 28 days to ensure the materials reach optimal strengths (36; 46; 54; 68; 70), nevertheless (81) suggest the curating period shall be long enough to ensure the specimens reach their moisture equilibrium. The environmental conditions for the curating period shall be controlled and maintained on 20-24° C with a relative humidity of 50% (37; 46; 82).

Tests execution

As first procedure in laboratory is necessary to produce several EPEB mixtures with different percentages of biochar additive to establish the mechanical and physical characteristics: shrinkage, workability, Atterberg limits, moisture absorption, compressive and flexural strengths, and adhesive strength to adobe surface. For sure these characteristics shall be also tested for a normal clayish plaster in order to compare the EPEB mixtures.

5 All the recommendations that are referred for the production and construction of adobe and earthen plasters given on the present document can be followed to ensure the most similar conditions of the tested wallets and a real adobe building constructed in Colombia.

6 Recommendations for adobe walls constructions are made on chapters 3.3 and 4.5.6.

The following are referred to the characterization test of the EPEB plasters:

- EN 933-1:2012 Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. (83)
- EN 1015-6: 1998 Methods of test for mortar for masonry - Part 6: Determination of bulk density of fresh mortars. (84)
- EN 1015-3:1999 part 3: Determination of consistence of fresh mortar (by flow table). (85)
- ISO / TS 17892-12 Geotechnical investigation and testing — Laboratory testing of soil — Part 12: Determination of Atterberg limits. (86)
- EN 1015-10/A1 Part 10: Determination of dry bulk density of hardened mortar. (87)
- EN 14146 Natural stone test methods - Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency). (88)
- EN 1015-11 Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar. (89)
- EN 16302 Conservation of cultural heritage – Test methods – Measurement of water absorption by pipe method. (90)
- EN 16322 Conservation of Cultural Heritage – Test methods – Determination of drying properties. (91)

For a Colombian context the investigation of Yamin (27) suggested the use of NTC 4017 regulation to develop the compressive and flexural test of the specimens. (NTC 4017. Métodos para muestreo y ensayos de unidades de mampostería y otros productos de arcilla: Resistencia a la compresión y a la flexión de piezas individuales)

For establish the consistency of the EPEB plasters is recommendable the execution of flow table test (EN 1015-3), however Gomes suggest modifying the water content of the mixture to obtain a flow table result between 160-176mm which have presented excellent workability (82).

Considering the recommendations done by (34), the adhesive capacity of the plaster to the beyond surface can be tested as shear strength by using the device illustrated in image 119. However, for establish the adhesive strength of the plaster Anderjkovicová (53) suggest following the procedures of EN 1015-12 standard. During the phase of characterization of several EPEB plasters, this test can be done to each EPEB mixture proposed over a single adobe block. Considering the optimal plaster attachment over adobe walls, is expected that the adhesion capacity of the plaster will increase for its application over the wallet specimens.

For drying shrinkage test are normally used specimens of 40x40x160 mm. Traditionally is measured linear shrinkage, nevertheless according to (82) is recommendable to control the volumetric shrinkage of the specimens as it was reported as more significant and sensible shrinkage values. (82) suggested to calculate an average of the shrinkage in all the axis of the specimen.

Once obtained and compared the characteristics of several EPEB plasters, one mixture composition should be chosen as optimal to test it over the adobe wallets. In coherence to plaster section of chapter 4.5.5 the optimal EPEB plaster should present the highest tensile and compressive strength, the better adhesion capacity to the wall surface, and the less drying shrinkage cracks that can weaken it. However characteristics as moisture absorption shall be considered to confirm the feasibility of EPEB as plaster for a real earthen building.

The experimentation shall continue with the plastering procedure of adobe wallets with the optimal EPEB plaster and the curating period under the aforementioned conditions.

For the development of the axial compressive and diagonal shear of masonry wallets the next standards can be followed:

- EN 1052-1: 2001. Metodi di prova per muratura. Determinazione della resistenza a compressione. (79)
- ASTM E519/E519M-15. Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages. (64; 80)

Concerning the procedure of the diagonal shear test, (27; 42; 52; 64) suggested to have special attention to the wallets supports, the load transmission should be as vertical as possible and the concentration of loads on the end of the support should be avoided. The location of the wallets on the supports shall be carefully, due to the brittle nature of earth as construction material the wallets can failure just with their own weight.

In the same way (27) have suggested to develop the axial compression test of the wallets following the Colombian regulations NTC 3495 and NTC 3495.

Regarding the analysis of the results they can be compared to investigations of other enclosing reinforcements for earthen technology as can be (18; 27; 42; 64).

6. CONCLUSIONS

From a sustainable approach to architecture is questioned the feasibility of earthen projects in a dense urban context. The starting point of the present research took into account the well-known advantages that earth has as construction material: low embodied energy of the material, recyclability, low cost, healthier spaces, acoustic and thermal isolation, valuable architectonic traditions, etc. On the other hand, is also considered the huge contribution of cities into climate change, contamination and energy consumption. Hence, expecting this constructive technology can decrease the impact of buildings and cities on climate change, are studied the key factors to make earthen architecture suitable for urban contexts. This research is limited to the city of Bogotá, Colombia, the analysed variables and solutions proposed are in coherence to this specific context.

Regarding the geographical, social, economic and architectural conditions of Bogotá, there can be viable and appropriate the use of earthen constructions. The socio-economic conditions of the city generate contrast between high- and low-income population, this contrast is viewable when several urban and architectural environments are compared in the city. Low-income population is representative in Bogota's demography and is generally localized on peripheral areas where large number of dwellings are self-constructed and public buildings are required. Without excluding its viability in high-income zones, the low-cost and the traditional "self-construction" process of earth architecture, makes of it a tool to offer dwellings or facilities construction that would be useful in low-income areas of the city.

Considering the socio-economic distribution of population in Bogotá and in coherence to the availability of soil sources, the feasibility of earthen buildings in urban context is raised in peripheral areas where soil can be easily managed or nearest find. For the case of Bogotá this suggestion is also supported by the fact that peripheral areas, located far away from the eastern hills (west of the city), present larger layers of clayish and sandy soil which is useful for earthen construction.

In Bogotá, as in all Colombian territory, exist a large earth building heritage, 80% of monuments and historic urban centres of the country are earth constructions. Traditional earthen techniques for construction are tapia, adobe and bahareque. Nevertheless, this large tradition is no longer spread due to the presence of standardized materials from the construction industry. The decreased use of earthen techniques represent not only a decrease of physical heritage but also losses of social knowledge. Consequently nowadays inhabitants, constructors or even architects, have a lack of information about earthen buildings and these are normally related to poor, unsafe or bad seen constructions.

According to that the use of these |traditional techniques, or contemporary earthen techniques as CEB, for iconic buildings would be an adequate strategy to diffuse the advantages of earth as constructive material and to increase its acceptance in the population. Regarding this issue is notable the work of CEB industries and earth-constructive organizations and architects that are diffusing the use of earth architecture in Colombia, independently of the project budget, client or requirements.

However the aforementioned proposals of iconic (or not) earthen buildings cannot be possible without an official and recognized regulation that support these constructions in Colombia. The actual construction codes of the country do not include as constructive material earth, mud or loam. The lack of regulations decrease the feasibility of developing such projects, the industry, construction, research and education sectors surely would be largely opened to earthen construction with the support of regulations, otherwise private or public sector will not have assurance to work with this material.

Hence this research suggest the formulation of an earthen constructive regulation for Colombia which can be based on the proposal that is developing a Colombian team headed by architects and engineers from universities as PUJ, Los Andes or Nacional; independent organizations as the Escuela Taller de Boyacá; and official entities as the Culture Ministry and the Colombian association of seismic engineer. Additionally as guidelines for a possible regulation, there are highlighted the Peruvian E. 080 regulation and the investigations done by PUCP and UNAM, which are referred to the correct construction of earthen buildings in similar contexts to Colombia.

Earthen construction, as any other technology, has specific parameters and procedures to care of. Appropriate construction methods have been documented by several authors (10) (19) (20) (24) (27) (28) (30) (42), these documentations normally aimed the correct use of earth as constructive material according to laboratory researches and traditional procedures for each technique. To prose earthen buildings is necessary to follow those procedures as they can enhance the life-time and well-sanding of the building.

Nevertheless, earth as construction material has low tensile strength, hence is vulnerable to tensile, bending and shear stress produced by seismic loads. However, there exist several solutions to improve the behaviour of earthen buildings in seismic hazard locations, some of these solutions are part of the traditional construction, others are contemporary and combines modern materials and technologies with earthen one. In light of above, and considering the seismic hazard of Colombia, the proposal of earthen buildings into the urban context of Bogotá shall also care about structural and anti-seismic aspects.

Therefore the present research makes a compilation of several anti-seismic solutions for earthen buildings. These solutions are organized under three main strategies that were identified to enhance the performance of earthen buildings during earthquakes. The first strategy is referred to the building behaviour as a whole under seismic loads, this strategy concern the architectural design of the building and how the entire building is conceived and shaped. The second strategy regards the conjunct work of all the structural elements of the building (horizontal and vertical ones), ensuring the "box-behaviour" of the whole structure. Finally the third strategy is to enhance the load-bearing wall performance itself as principal structural element of earthen buildings. This strategy consist on provide, to the structural wall, the missing tensile, bending and shear strengths of the earthen material.

The three aforementioned strategies are not independent and should be applied together to the projection and construction of earthen buildings. This does not mean that a single project shall contain all the reinforcements explained on the present document, but earthen structures should be proposed taking care of the three strategies.

On chart 3 are presented the three anti-seismic strategies for earthen buildings and the punctual solutions or reinforcements, for the last ones there are listed the suitable material that can be used, the earthen technique to which can be applied, and failure mechanisms that can dodge. Additionally is exposed if the specific reinforcement is supported by the Peruvian regulation E.080 (24) and, in concordance to López, if it is been studied for a future Colombian regulation (15).

Under the third strategy that regards the load-bearing wall strengthening and considering the performance of the enclosing reinforcements, there is proposed a specific reinforcement to the plaster loam mix. The proposal is based on the structural enhancement of generic plasters and the positive effect of biochar additive onto the mechanical strengths of cementitious composites. Is expected that an earthen plaster enriched with biochar additive (EPEB) would be able to increase its tensile strength and thus contribute to contain the earthen material of the walls under bending and shear stress. This proposal combines two technologies that seem to have not been combined before, hence the EPEB effectivity is unknown and it is necessary to develop laboratory test to determine the clayish plasters behaviour in presence of biochar micro inert particles. Moreover, if the combination of these technologies has positive results, it should be necessary to establish the optimal quantity of biochar additive that would produce the best strength enhancement, without compromising other characteristics required for earthen plastering.

Develop the experimental investigation of EPEB on adobe wallets can contribute with a new and different reinforcement solution that could be able to enhance the anti-seismic performance of earthen constructive technologies. There is recommended to continue the experimental investigation of EPEB with the same or similar procedures as the ones proposed on chapter 5th.

According to some constructive manuals, researches and regulations the use of earthen constructive technologies is viable and safe in seismic hazard locations. Nevertheless, the construction shall consider the anti-seismic strategies by making use of the specific parameters and punctual reinforcements described on this document.

Additionally, considering the Colombian earthen tradition and the proposal that is been done for a new earthen construction regulation in Colombia, there would be feasible to construct anti-seismic earthen buildings in urban and seismic zones of the country, always under the aforementioned limitations.

Strategy & *Objective*		**Reinforcement or solution**	**Additional material**	**Applicable to raw earth techniques**
Building behaviour strategy *Entire building conception*		Control seismic inertia		All
		Plant configuration and proportions		All
		Opening location and dimensions		All
Box-behaviour: diaphragmatic strategy *Systemic structure performance*		Ring beam	Timber or bamboo	All
		Diaphragms	Timber	All
		Ring beam junctions	Timber or bamboo	All
Enhancing Load-bearing wall strengths *Behaviour of principal structural elements*		Avoid stiffer materials	Concrete	All
		Buttresses and perpendicular walls		Specially to adobe and rammed earth
		Corner braces & shape	Timber or steel bars	Adobe, Rammed earth and Bahareque
		Block-mortar junction		Adobe and CEB
	Internal reinforcements	Internal bars	Bamboo culms Steel bars	Adobe, CEB and rammed earth
	Internal reinforcements	Diagonal timber in "V"	Timber or Bamboo	Bahareque
	Internal reinforcements	Embedded wire mesh	Steel wire mesh	Adobe
	Enclosing reinforcements	Rope grid	Synthetic ropes	Adobe
	Enclosing reinforcements	Plastic geogrid	Plastic grids	Adobe
	Enclosing reinforcements	Timber grid	Timber	Adobe and rammed earth
	Enclosing reinforcements	Rib lath grid	Metal rib lath	Adobe and rammed earth

** Consequently is also prevented the roof failure by losing its support over the walls.*
*** Reinforcements and solutions that are studied by the team that is proposing the new Colombian regulation for earthen construction.*

Chart 3. Anti-seismic strategies with the corresponding solutions and reinforcements.

Controled failure mechanism	Regulation support	Regulation support
All	No	(10; 14; 58)
Bending and shear cracks on corners and walls intersection	**E.080 / Developing (COL)	(14; 21; 24; 26; 30; 61)
Shear "X" cracks on walls	**E.080 / Developing (COL)	(21; 24; 25; 26; 29; 30; 58)
*Bending cracks on walls; shear, tensile and bending cracks on corners; loss of roof supports; shatter of walls by intermediate floors	**E.080 / Developing (COL)	(24; 27; 30; 58)
*Bending cracks on walls; shear, tensile and bending cracks on corners; loss of roof supports	E.080	(14; 24; 27; 42; 58; 60)
Loss of roof supports; shatter of walls by intermediate floors	E.080	(14; 24; 27; 30; 58)
*Shatter of walls by intermediate floors or roof	No	(33; 62)
*Bending cracks on walls	E.080	(14; 21; 24; 27; 30; 58; 60)
*Bending and shear cracks on corners and walls intersection	No	(58)
*Shear and bending cracks on walls; shear, tensile ande bending cracks on corners	No	(36; 37; 54; 67)
*Bending and shear cracks on walls; shear, tensile and bending cracks on corners;	No E.080 (for adobe)	Rammed earth: (15; 30) Adobe: (42; 24) CEB: (52; 30; 20)
"Shear cracks on walls"	**No / Developing (COL)	(15; 19; 38)
Bendig cracks on walls, provides ductility to the material	No	(63)
*Bending cracks on walls; tensile and bending cracks on corners	**E.080 / Developing (COL)	(29; 42)
	**E.080 / Developing (COL)	(29; 42; 64)
	** Developing (COL)	(10; 27; 43; 65)
Bending cracks on walls; shear, tensile and bending cracks on corners (sudden colapse)	No	(43)

7. ANNEX

The annex present data sheets of the materials proposed for the experimental research on earthen plasters enriched with biochar (EPEB). Even if the products are produced in Italy, the selection of the following was made in consideration of the materials' characteristics for adobe construction in Colombia.

Products from several industries were also analysed, are highlighted:

- Terragena.
- Terra Cruda. Representation of Argilus in Italy.
- Ton Group.
- Matteo Brioni.

TERRAGENA SB2

- intonaco di fondo a base di argilla cruda -

Composizione:

- sabbia calcarea in curva granulometrica 0 – 2 mm ed argilla selezionata
- (esente da leganti idraulici e sostanze di origine sintetica)

Campi d'impiego:
Viene utilizzato a spessore sopra laterizio cotto, cemento cellulare, cemento armato ruvido, mattone crudo della linea Later di Terragena .

Essendo un intonaco naturale di argilla si aggrappa al supporto meccanicamente, per cui necessita di un fondo sufficientemente poroso e ruvido come può essere il laterizio cotto, il mattone crudo fatto a mano, l'arella portaintonaco. Nel caso di supporti difficili quali cemento armato vibrato è indispensabile eseguire una mano di rinzaffo, oppure per le superfici in legno applicare l'arella portaintonaco Terragena. Per applicazioni su mattoni crudi consultare le schede tecniche relative.

Applicazione e lavorazione:
Mescolare il prodotto in betoniera o impastatrice aggiungendo acqua fino ad ottenere la consistenza desiderata, lasciar riposare per 30 minuti quindi rimescolare. Il prodotto si applica a mano o con apposita intonacatrice da premiscelato (Tipo PFT G4) per uno spessore massimo di 1,5-2 cm ogni mano, le sovrapposizioni si effettuano sempre su intonaco asciutto.
Dopo l'ultima mano, quando l'intonaco è ancora molle è buona norma applicare la rete di iuta Terragena per dare maggiore elasticità e resistenza all'intonaco. Per la posa in opera di quest'ultima consultare le schede tecniche specifiche.
Nelle superfici non assorbenti come il cemento armato è bene procedere con la stesura dell'intonaco con strati non superiori ai 5-6mm per evitare distacchi o eccessivi ritiri.
<u>Terragena SB2 va applicato sempre su supporto precedentemente inumidito.</u>

Indicazioni:
La fase di asciugatura dell'intonaco comporta la perdita d'acqua che potrebbe causare dei cavilli, i quali, a livello strutturale, non compromettono le caratteristiche tecniche del prodotto.
Non applicare su supporti che temono l'umidità o i sali di risalita.
Il prodotto si applica a temperature comprese tra i 5 e i 25°C, evitare l'asciugatura rapida del prodotto.

Dati tecnici:
Consumo: circa 15-16 Kg al metro quadrato per cm di spessore.
Confezioni: disponibile in sacchi da 25 Kg e big bags da 1500kg. Conservare al riparo dall'acqua.
Conformità UNI EN 998.

Peso specifico	1500 kg/mc
Lambda	0,59 W/m °K
Consumo	14-15 kg/mq x cm ca.

TERRAGENA ADOBE

- mattoni in argilla fatti a mano -

Composizione:

- argilla selezionata
- (esente da leganti idraulici e sostanze di origine chimica)

Campi d'impiego:

E' un mattone non cotto particolarmente adatto per la realizzazione di muri divisori o contropareti interne a vista. Particolarmente indicato per il controllo dell'umidità dell'aria negli ambienti, per l'isolamento acustico ed elettromagnetico.

Massa	3,6 Kg/cad
Massa della parete spessore 12 cm	240 kg/mq
Fonoassorbenza spessore 6 cm Rw (teorico):	42 dB
Massa della parete spessore 6 cm	119 kg/mq
Fonoassorbenza spessore 12 cm Rw(teorico):	48 dB

Applicazione e lavorazione:

Il mattoni vengono forniti in bancali che devono rimanere in luogo asciutto e al riparo della luce solare.

Solo nel momento della posa il mattone va immerso nell'acqua per 2 o 3 secondi e posato con malta certificata da muratura.

TIPOLOGIA DI POSA	CONSUMO DI MALTA	QUANTITÀ
Spessore muro 12 cm	42kg/mq	55 mattoni/mq
Spessore muro 6 cm	12kg/mq	30 mattoni/mq

Indicazioni:

È un mattone in argilla pura fatto a mano, appositamente studiato per muri facciavista interni.

A causa della resistenza meccanica ridotta rispetto all'argilla cotta, i mattoni possono presentare qualche lieve difetto dovuto al trasporto e al confezionamento.

Non applicare su muri che temono fortemente l'umidità e in vicinanza d'acqua.

Confezioni e misure:

Misure : 25 x 12 x 6 cm.

Disponibile in bancali da 352 pezzi.

Si conserva in luogo fresco per diversi mesi e lontano dall'acqua diretta.

[terragena]

Terragena
Sede: Via Giotto 41
45100 Rovigo (RO)
Tel. +39 0425 494085

PRIMAT *passione e competenza nel recupero*
Via per Muzzano, 23 13897 Occhieppo Inferiore (BI)
tel 015-2593919 fax 015-2595238
info@primatsrl.it www.primatsrl.com

TORCHIS

INTONACO PER ALTI SPESSORI

Il luogo di produzione dell'intonaco ARGILUS si trova a 300 mt dalle cave di argilla.
Le nostre terre sono al 100% ecologiche, riciclabili e riutilizzabili.

Utilizzo (torchis)
TORCHIS è pronto all'uso, a base di argilla pura, ideale per intonaci ad alto spessore nel restauro di vecchi edifici o per case di paglia.

Composizione
Terra argillosa (cava GILLAIZEAU), sabbia di fiume, paglia d'orzo.

Proprietà fisiche
Peso specifico in opera = 900-1100 kg/m3
Conduttività termica λ = 0.40-0.50 W/mC°
Calore specifico = 0.80 kj/kg C° circa
Capacità termica = 300-350 Wh/m3 C° circa
Umidità di equilibrio = 2.5% sul secco circa
Classe di resistenza al fuoco = M0

Confezioni
Sacchi di carta da 25 kg o big bag da 1000 kg

Consumo (quantità reali su supporto planare)
25 kg/mq/20 mm di spessore

Miscela di acqua per un sacco da 25 kg
- L'intonaco TORCHIS deve essere miscelato con un miscelatore o con betoniera. La quantità di acqua da aggiungere è di 8-9 litri per ogni sacco da 25 kg.
- Tempi di miscela: 3-5 minuti
- Lasciar riposare la miscela per 10-20 minuti in modo che l'argilla assorba correttamente l'umidità. Dopo questo intervallo di tempo, sarà necessario aggiungere una piccola quantità di acqua in modo da ottenere l'omogeneità specifica per un'applicazione di qualità

Supporti di applicazione
L'INTONACO TORCHIS può essere applicato su numerosi supporti quali:
- Vecchie murature
- Murature in pietra, terra battuta, terra cruda, mattoni pieni e paramano…
- Muri in balle di fieno, stuoie di canna (cannicciato)…
- Altri tipi di supporto: consultare il nostro servizio tecnico

I supporti devono essere puliti, solidi e resistenti. Dovranno essere anche leggermente umidi prima dell'applicazione di questo intonaco in modo da favorire l'aggrappo.
Tutti i residui di pittura, di intonaci sfarinanti o carta da parati devono essere rimossi.
Un supporto che presenta umidità da risalita o salnitro rischia di deteriorare o macchiare l'intonaco.

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MALTA DI ARGILLA

MORTIER D'ARGILE

Il luogo di produzione dell'intonaco ARGILUS si trova a 300 mt dalle cave di argilla.
Le nostre terre sono estratte con grande cura e con mezzi nostri.
L'intero processo di fabbricazione è assicurato dalla società Argilus.

PRONTO ALL'USO

Utilizzo
La Malta di Argilla ARGILUS è un prodotto pronto all'uso destinato all'utilizzo dei Mattoni in Terra Cruda. Si applica solo all'interno.

Qualità
La Malta di Argilla ARGILUS ha come qualità principale la sua composizione naturale. La sua applicazione è molto semplice e alla portata di tutti.

Composizione
Argilla extra-fine asciugata, macinata e setacciata (Cave ARGILUS), sabbia 0/1 e 0/4.

Confezioni / Consumo
Sacchi di carta da 25 kg / 1 sacco da 25 kg = 1 mq circa (per giunti di 1 cm massimo)

Preparazione / Applicazione
La Malta di Argilla ARGILUS serve esclusivamente all'utilizzo dei Mattoni in Terra Cruda. Si prepara con un miscelatore o con una betoniera e si applica con una semplice cazzuola.
ATTENZIONE: bisogna rispettare scrupolosamente le quantità di acqua da aggiungere (6-7 litri circa per un sacco da 25 kg) e non si devono assolutamente bagnare i Mattoni in Terra Cruda.
Al fine di realizzare un'applicazione di qualità dei Mattoni in Terra Cruda, si consiglia di suddividere l'applicazione in 2 passaggi:
1) Realizzazione di un muro in Mattoni in Terra Cruda con la Malta
2) Una volta che il muro è asciutto, stilatura dei giunti con una "sac à poche" o una cazzuola a lingua di gatto (con la stessa malta)

Per evitare un cedimento del giunto ai piedi del muro, l'applicatore dovrà rispettare un'altezza massima di 1,5 metri/giorno.

TEMPI DI ASCIUGATURA: definitiva dopo circa 72 ore.

SE NON SI RISPETTANO QUESTE INDICAZIONI, IL PRODUTTORE, NON POTRA' IN ALCUN CASO ESSERE MESSO IN CAUSA

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MATTONI IN TERRA CRUDA

Brique de terre crue

Il luogo di produzione dell'intonaco ARGILUS si trova a 300 mt dalle cave di argilla.
Le nostre terre sono estratte con grande cura e con mezzi nostri.

Formati disponibili
Nella gamma ARGILUS sono disponibili due modelli:
6x11x22 – 70 pezzi/mq – 2.2 kg/pezzo o **9x15x30 – 35 pezzi/mq – 9 kg/pezzo**

Utilizzo
I MATTONI IN TERRA CRUDA ARGILUS sono realizzati a partire da argilla pura e calce (circa 5%). Possono servire a diverse applicazioni. ARGILUS ha sempre privilegiato una produzione dei suoi mattoni con una stabilizzazione a calce per evitare risalite di umidità troppo importanti dei muri di tramezzo e un rapido degrado dovuto al rigonfiamento dei muri stessi.
ATTENZIONE: ***i Mattoni in Terra Cruda ARGITECH sono mattoni pieni. Il supporto di applicazione deve avere una buona resistenza e stabilità. Generalmente, i mattoni sono posati su un supporto preesistente in calcestruzzo. Per un'applicazione senza supporti, consultare il produttore.***

Realizzazioni
Tipi di realizzazioni possibili con i Mattoni in Terra Cruda:
- Riempimento di murature con strutture lignee e intonaco in argilla
- Muri portanti (in alcune condizioni – consultare il produttore)
- Muri ad inerzia termica (per accumulare calore – dietro una stufa a legna ad esempio)
- Muri di tramezzo
- Muri antisismici

La malta per i mattoni è fornita da ARGILUS (vedi scheda tecnica). Questa malta serve solo per l'utilizzo dei Mattoni in Terra Cruda ARGILUS. Si confeziona in sacchi da 25 kg ed è pronto all'uso.

Confezioni e precauzioni di stoccaggio
I Mattoni in Terra Cruda vengono imballati in bancali (9x15x30 – 120 pezzi/bancale – 6x11x22 – 400 pezzi/bancale). I mattoni sono imballati e protetti con del cartone. Devono essere stoccati obbligatoriamente all'asciutto e su bancale.

Applicazione
L'applicazione dei Mattoni in Terra Cruda rispetta le tecniche dell'edilizia tradizionale. Tuttavia, i Mattoni in Terra Cruda ARGILUS devono essere tenuti all'asciutto. Per evitare un cedimento dei giunti ai piedi del muro, l'applicatore dovrà rispettare un'altezza massima di 1,5 metri/giorno. I giunti dovranno essere di 8-12 mm di spessore.

DIMENSIONI IN CM	**6X11X22**	**9X15X30**
MASSA VOLUMICA	2,0 KG/DM3	2,0 KG/DM3
PESO MEDIO a umidità ambientale normale	2,2 kg ca.	9 kg ca.
QUANTITA' al mq	70	35
CALORE SPECIFICO	900 J/kg C°	900 J/kg C°
CONDUTTIVITA' TERMICA	1-1,2 w./mC°	1-1,2 w./mC°
RESISTENZA alla compressione (materiali asciutti)	30 BAR ca.	30 BAR ca.
VARIAZIONE DEL PESO In funzione dell'umidità	+/- 0,4% asciutto	+/- 0,4% asciutto
RESISTENZA AL FUOCO	M0	M0
PERMEABILITA' (MU) Resistenza alla diffusione del vapore acqueo	10	10

STUDIO SULLA DIFFUSIVITA' TERMICA DEI MATTONI IN TERRA CRUDA, MATTONI PIENI IN TERRA COTTA e ABETE

DESCRIZIONE	LAMBDA (in W/M.C°)	MASSA VOLUMICA (in kg/dm3)	CALORE SPECIFICO (J/kg C°)	DIFFUSIVITA' (in mq/H)	OSSERVAZIONI
Mattoni in Terra Cruda	1.10	2000	900	0,000363	TERRA CRUDA
Mattoni pieni 6x11x22 in Terra Cotta	0.84	2000	1030	0,0018	TERRA COTTA
Abete	0.36	450	420	0,00686	LEGNO

La diffusività dei Mattoni in Terra Cruda è di 2,2 x 10-3 mq/h
Più la diffusività è bassa, più il calore impiega tempo per attraversare lo spessore del materiale (sfasamento importante tra il momento in cui il calore arriva su un lato del muro e il momento in cui raggiunge il lato opposto).
Questa caratteristica è dunque importante per la costruzione di cappotti e/o di muri a inerzia termica.

NB: il nostro servizio tecnico è a vostra disposizione per qualsiasi informazione al n. 015-2593919.

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