Learning from vernacular architecture:

translating pre-industrial knowledge in construction into 3d printed earthen housing solutions.

Iaac
Institute for advanced architecture of Catalonia

The first segment, learning from vernacular architecture, compiles traditional earthen architectures from various regions. The second segment, digital analogy, focuses on the integration of traditional examples within 3D printed designs and prototypes developed over the past 9 years within the 3DPA academic program at IAAC.

Acknowledgements

Learning from vernacular architecture is a research and curation project compiling vernacular and 3dprinted projects studied within the 3DPA academic program at IAAC.

Research and curation
Edouard Cabay, Sara Ayoub

3DPA faculty
Alexandre Dubord, Yara Tayoun, Oriol Carrasco, Nestor Beguin, Secil Asfar

Special thanks
3dpa students

Earthen materials have long been employed in vernacular architecture across the globe due to their local availability and abundance, cost-effectiveness, and climatic qualities such as thermal efficiency. Presently, their use has widely been abandoned, replaced by alternative materials with higher mechanical properties and better resistance to intemperies, yet they are high energy-consuming. Earth could play a significant role in constructing with Construction technique and radically lowering buildings' carbon footprint as a response to climate change.

Vernacular architecture

The first part *vernacular architecture* examines various examples of pre-industrial constructions through three key factors: Construction technique, climatic strategy and social structure.

Construction technique: Pre-industrial construction resulted from the use of available materials, and their architecture was often shaped by their limitations.

climatic strategy: diverse housing typologies, construction techniques and details have evolved over time to offer conditioning and protection from weather variations, such as temperature, wind, rain, and light.

Social structure: Geometry can emerge from a community's social culture, such as the courtyard serving as a space for gatherings and social interaction even in continental climates, the same way urban aggregation of houses comes from the need for togetherness.

Vernacular architecture

The first part *vernacular architecture* examines various examples of pre-industral constructions through three key factors: Construction technique, climatic strategy and social structure.

Construction technique: Pre-industrial construction resulted from the use of available materials, and their architecture was often shaped by their limitations.

climatic strategy: diverse housing typologies, construction techniques and details have evolved over time to offer conditioning and protection from weather variations, such as temperature, wind, rain, and light.

Social structure: Geometry can emerge from a community's social culture, such as the courtyard serving as a space for gatherings and social interaction even in continental climates, the same way urban aggregation of houses comes from the need for togetherness.

Construction technique
Pre-industrial construction resulted from the use of available materials, and their architecture was often shaped by their limitations.

Beehive houses

Geography : *Northern Syria and the Beqaa Valley*

Climate : *Mediterranean (hot-dry summers/cool-wet winters).*

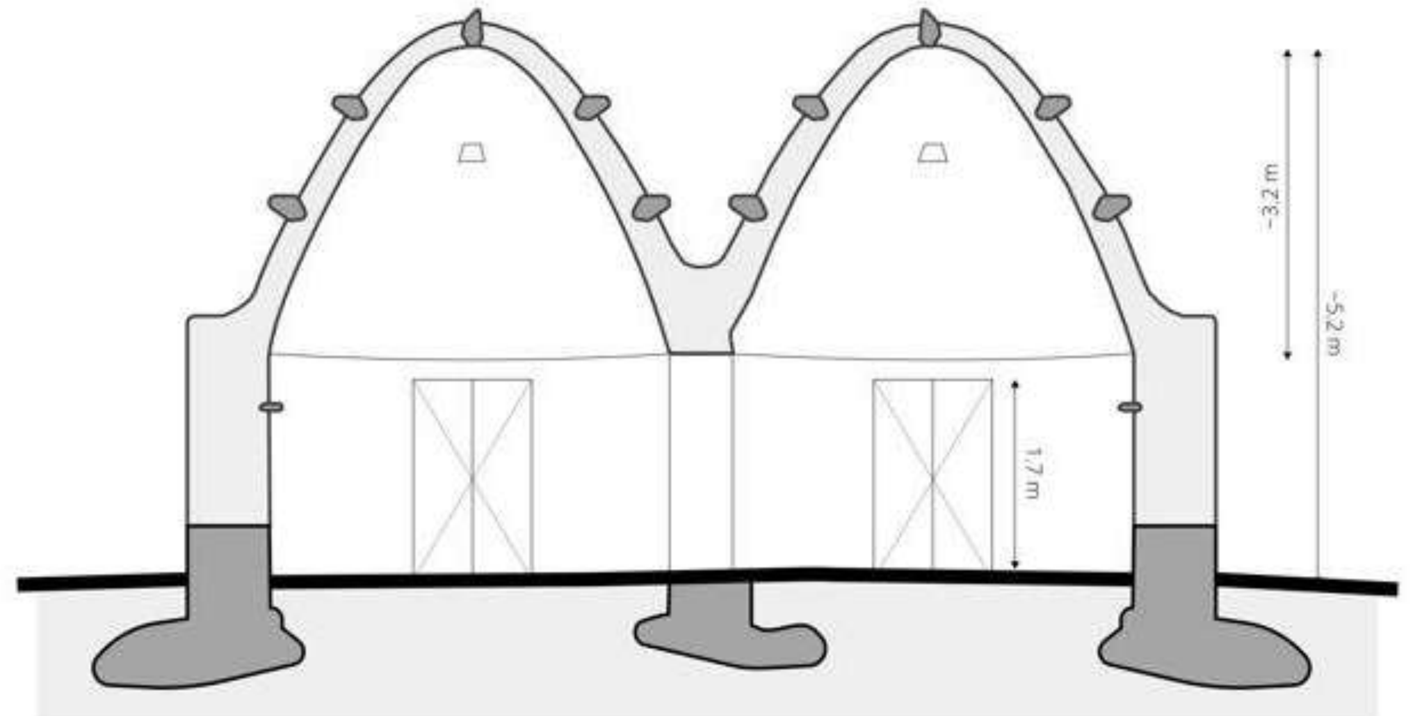
Community : *The dome prototype house in Taanayel*

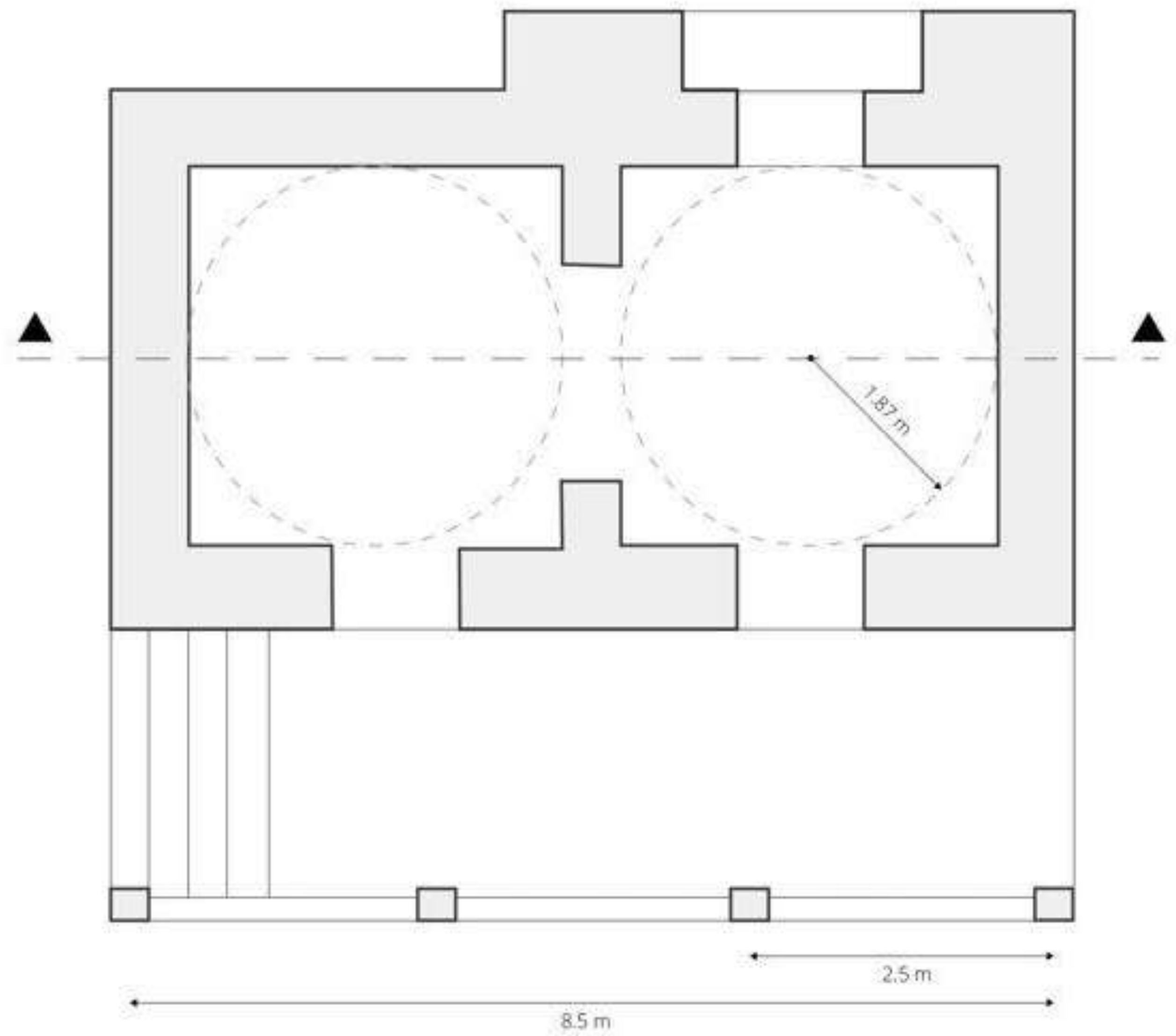
Construction technique: *Sun dried mud bricks + earth coating*

Scale: *Up to 6 meters high*

Period: *5000 millennium bc-Destruction during the current war*

Construction technique: In the north region of Syria, where wood is rare, the cupola of the dome houses was developed for the roofing of houses, instead of using wooden pillars and beams. Some cupolas start from the ground, others start at sixty centimeters or two meters. This choice determines the height of the cupola itself, which when finished, could reach up to three to five meters. In other cases, these cupolas are reduced, and some houses are surmounted by a half-cupola or a flat cupola. The builder makes an opening in the ceiling with a circumference of two meters or a meter and a half, and covered with plant fiber mats, reeds, qasab, or small beams on which he puts straw and clay. Thus, the cupola is truncated from its upper part and replaced by a wooden structure that supports a flat cover.





Research by: Nader Akoum

Drawings by: Nader Akoum

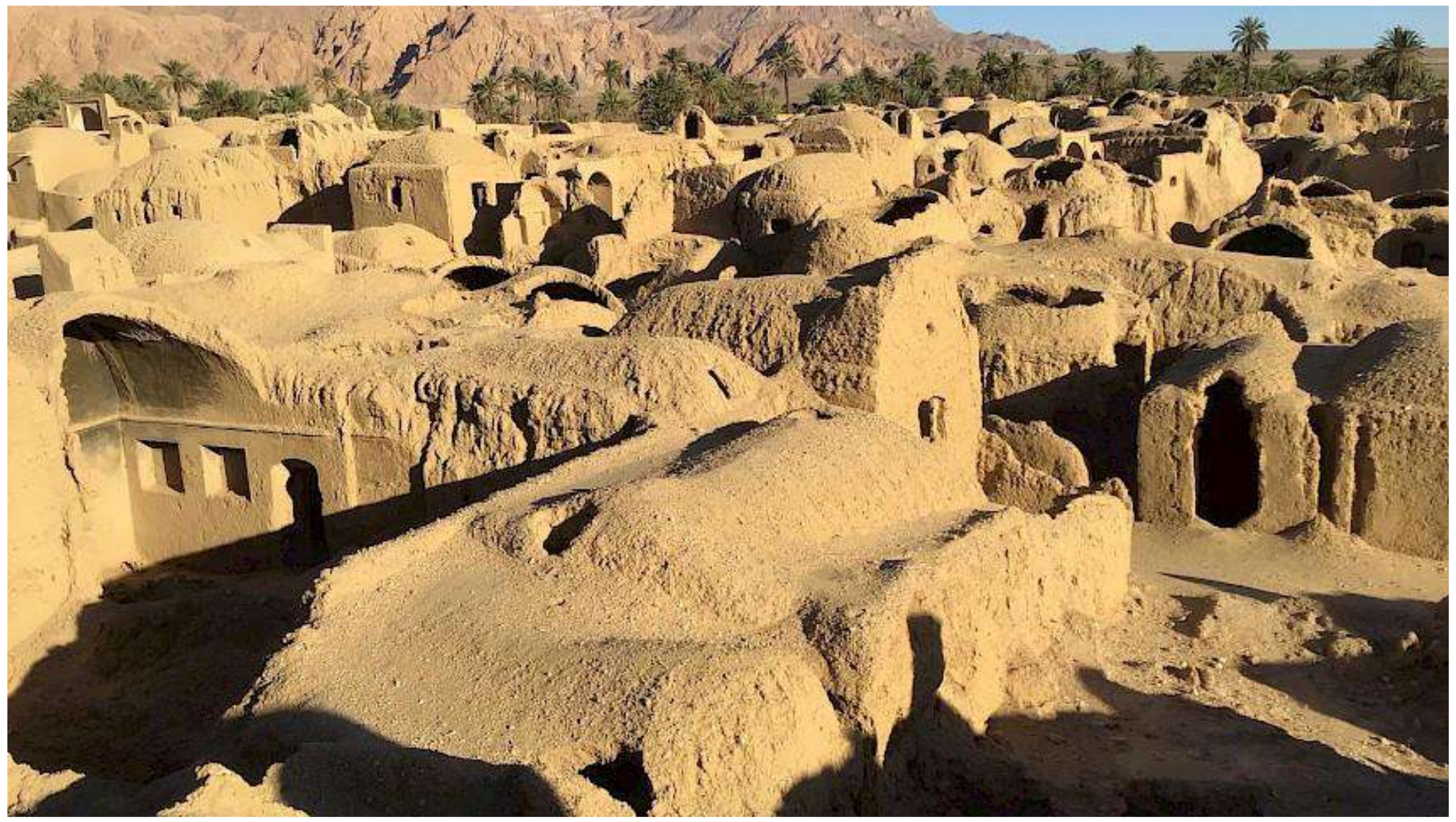
Esfahk village

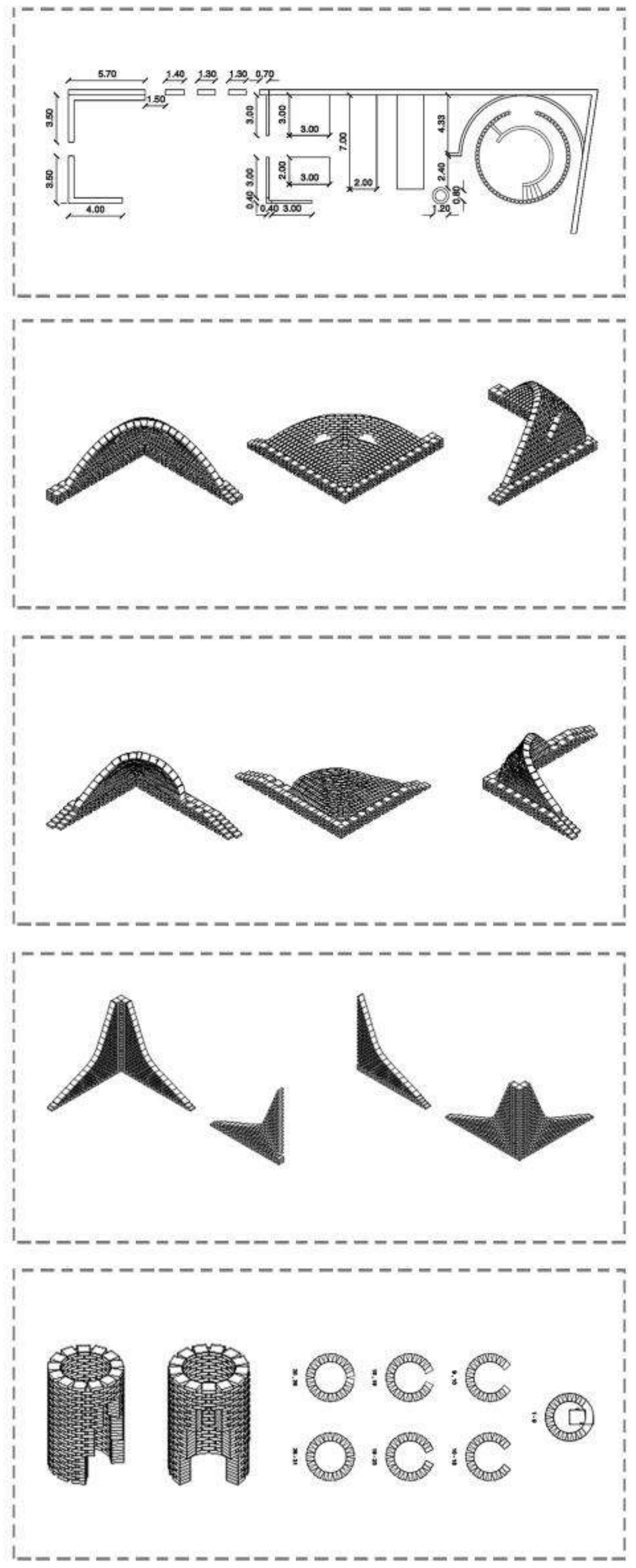
Geography : *Esfahak, South Khorasan, Iran*
Climate : *Dry-Hot*
Community : *Esfahakis*
Building technique: *Earth mud and brick.*
Scale:*Clustered homes-narrow alleys*
Period: *Hisotrical/unknown- post earthquake1978*

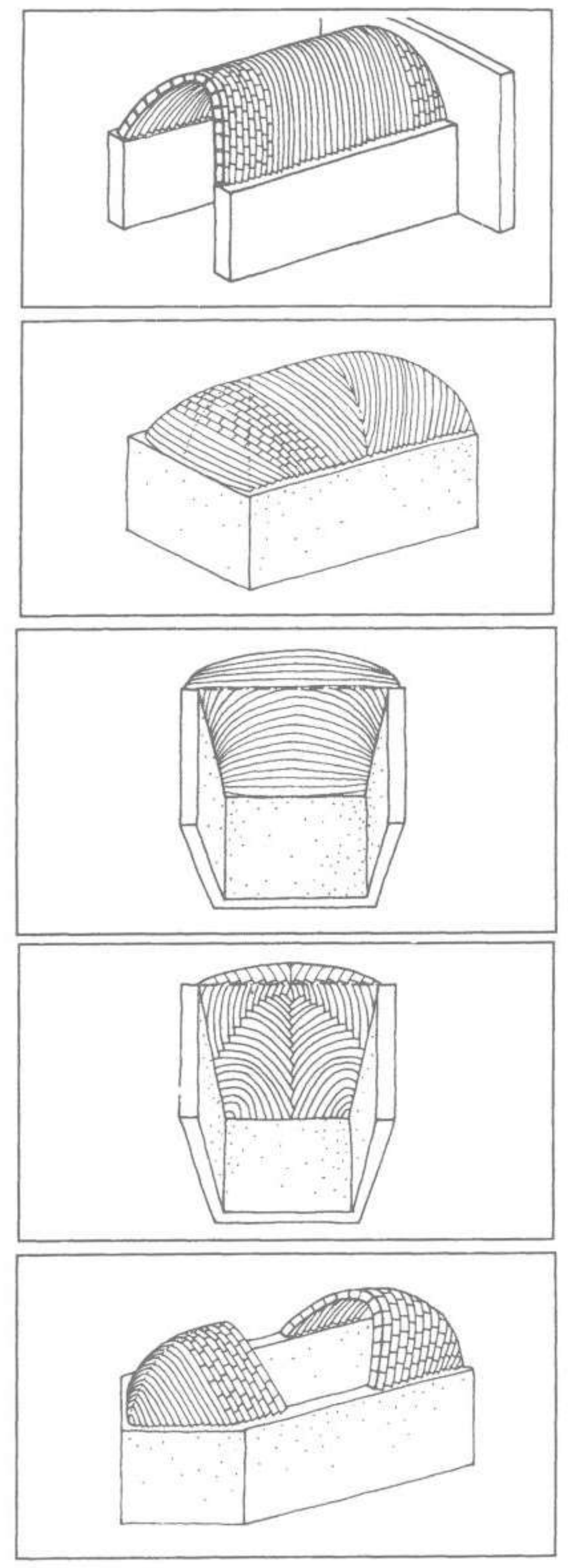
Construction technique: The village is made of two main earth techniques: hand dug-out of cliffs (pre-earthquake) and adobe mud bricks vaulting (post-earthquake). The technique of nubian vaults was used as a solution to build vaulted roofs without any timber framework. Standard mud bricks are laid one after another off of a vertical wall, creating an angled arch that is self-supporting from the beginning of construction.

Social structure: The village was damaged by an earthquake in 1978 and abandoned for 30 years until a group of Esfahakis decided to restore their ruined earthen houses, with the support of architects and old master masons.Today, the old settlement is used both for living and for tourist purposes by the local community in addition to a small research center on earthen architecture established by local architects.

Climatic strategy: The houses are built close to each other in order to provide more safety against rubbery and also more shadow during hot summer days and keep houses warmer during winter.







Espardar Arch

Konbe Arch

Konbe Arch

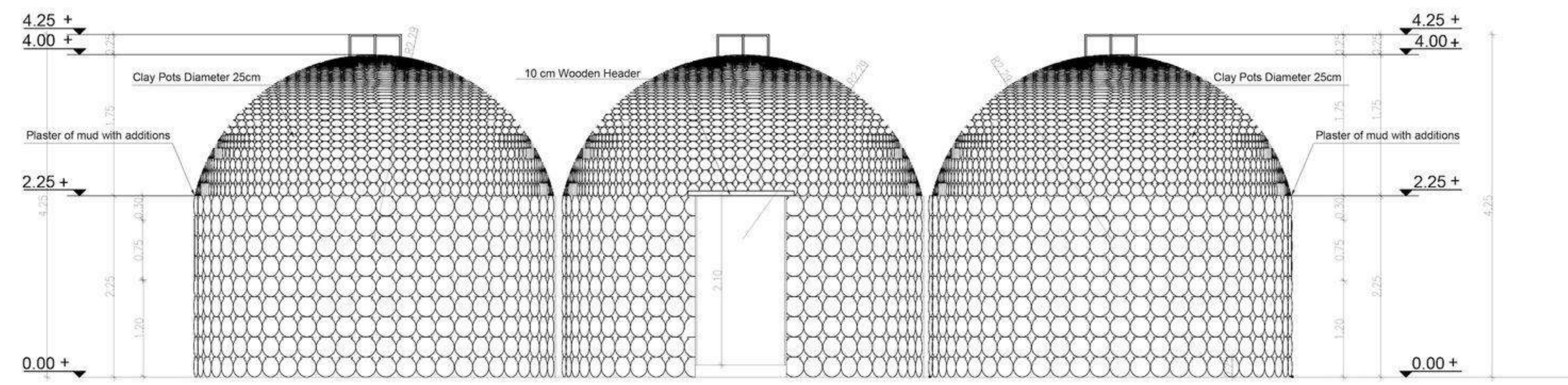
Chahar gardepush Arch

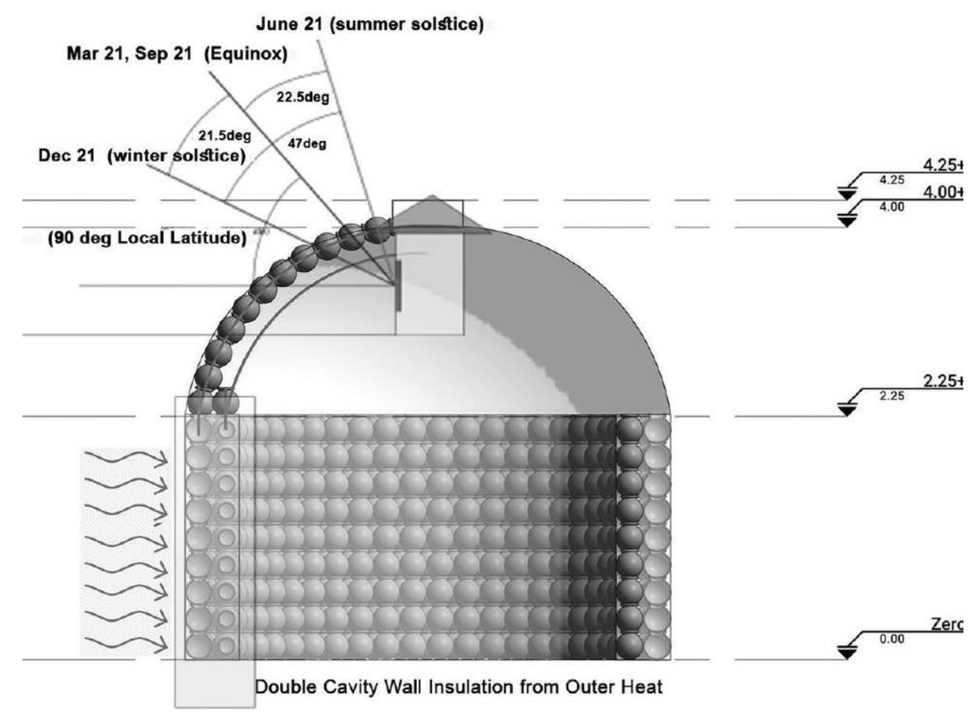
Research by: Ali Salamatian, Nareh Khaloian
Drawings by: Ali Salamatian, Nareh Khaloian

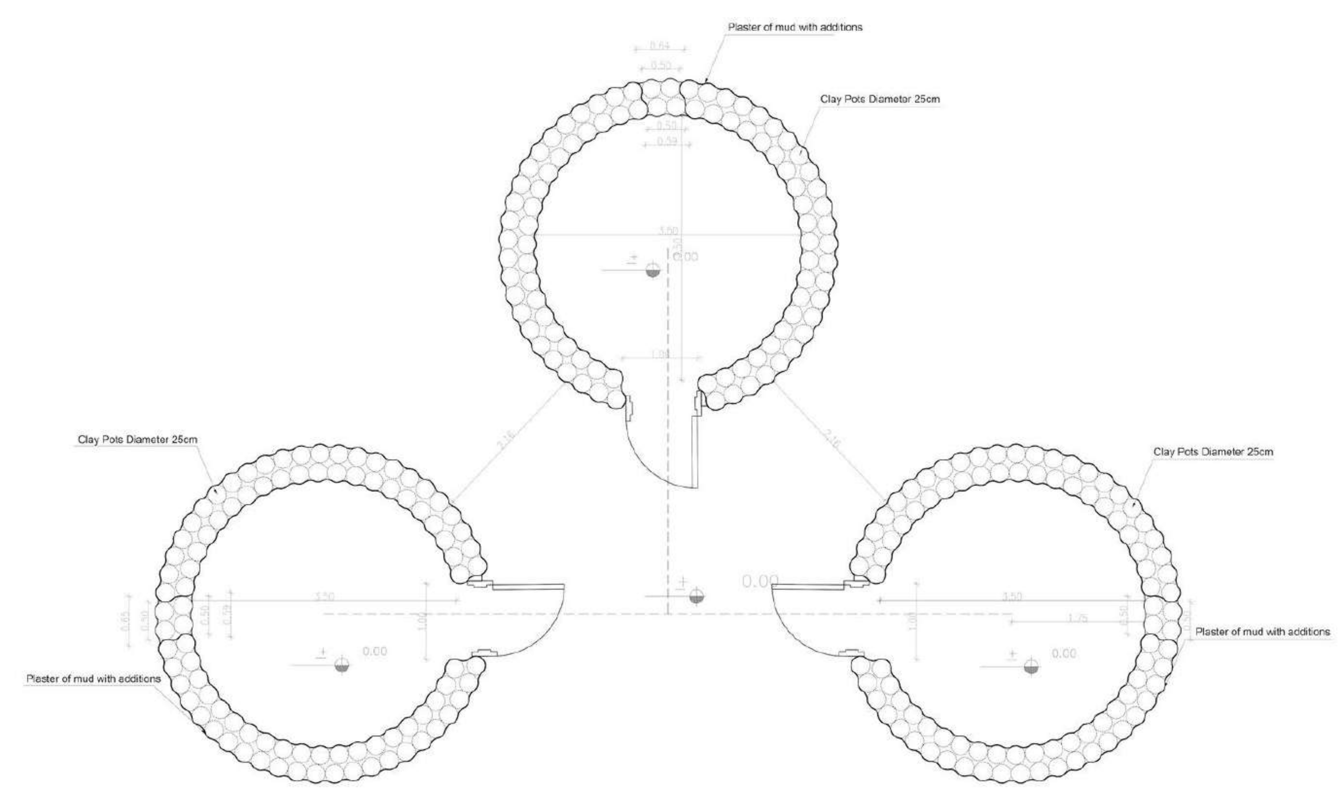
Clay pot

Geography : Al-Nazlah, Fayoum, Egypt
Climate : Dry-Hot
Community : Architect: Hamdy Elstouhy
Technique: Repetitive clay pot, Vault/arch.
Scale: 5m height, 800m²
Period: 2019

Construction technique: El Setouhy used the round terracotta globes produced by the villagers to design and build the workshops, the pots are built by being hammered into their spherical form inside holes in the ground using straw, clay and ash. Once they dry, the pieces are finished on wheel throws to form their rims to the rhythm of the potter, which has become an instinctual process developed over generations. To give the pots and globes their final reddish hue, they're fired at low temperatures that have minimal effects on the environment.







Research by: Deena El-Mahdy
Drawings by: Hamdy Elstouhy, architect

Shibam tower house

***Geography :** Shibam, Hadramawt valley, Yemen*

***Climate :** Dry-Hot*

***Community :** Hadramawt*

***Technique:** Adobe (Mud-bricks)*

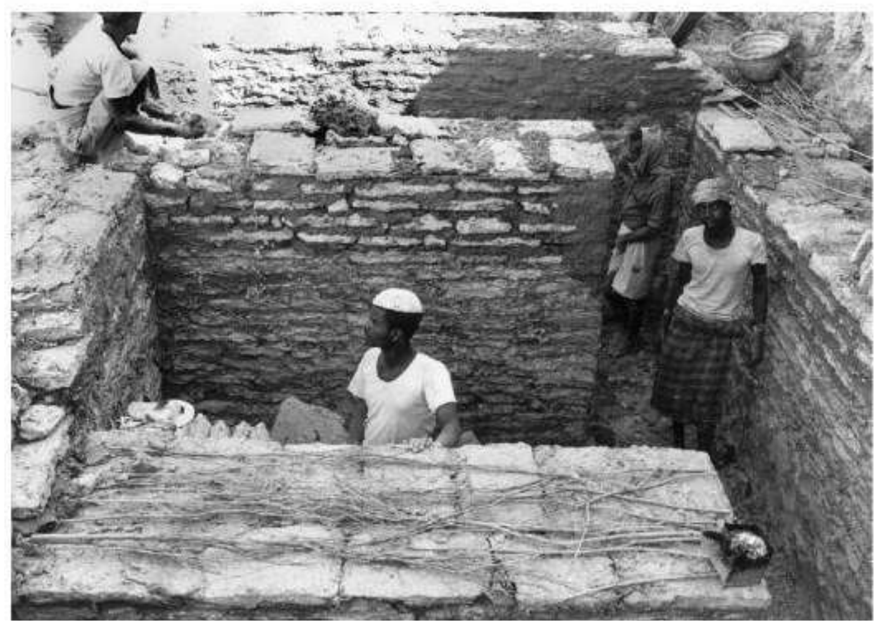
***Scale:** 7 storeys*

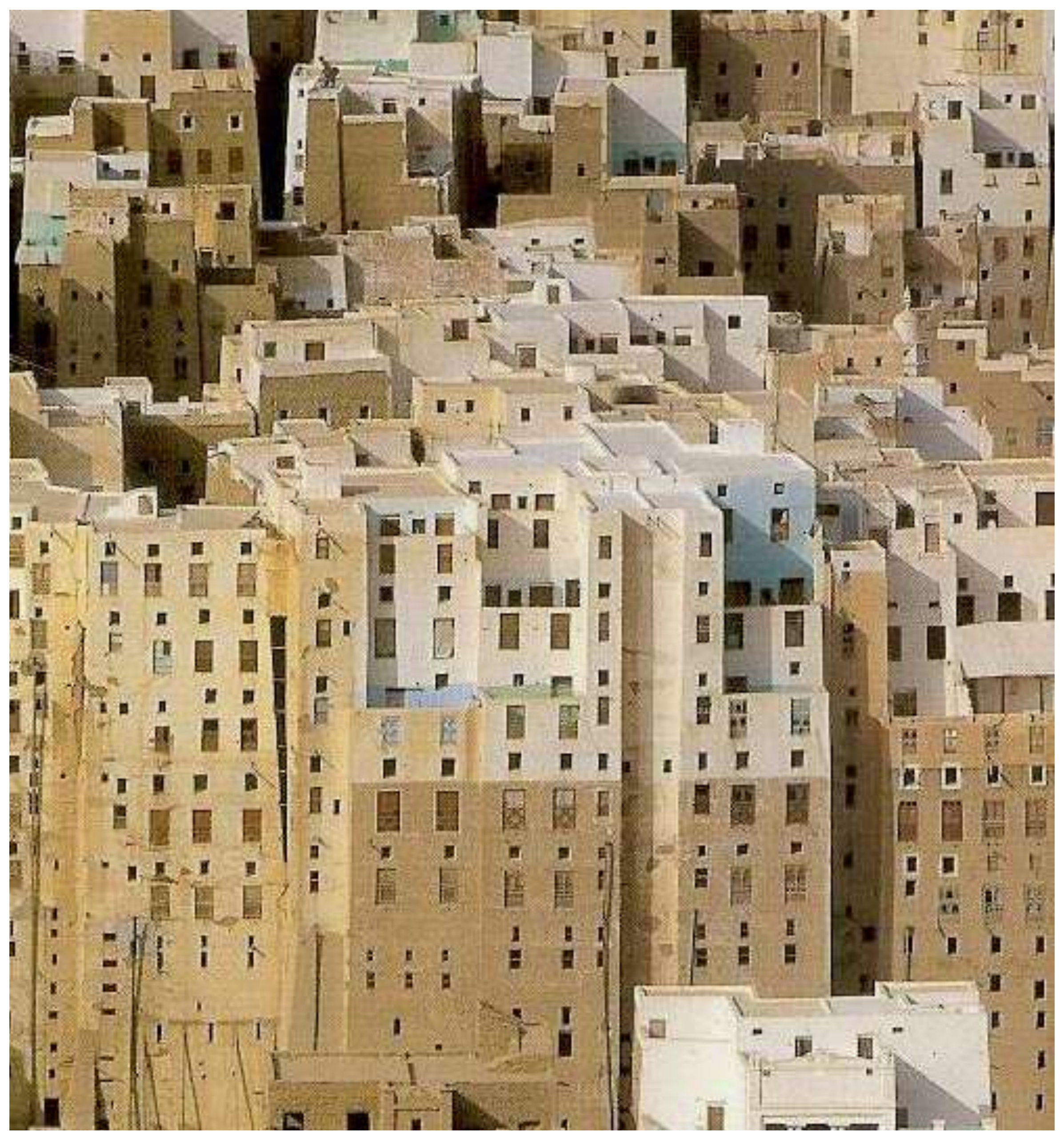
***Period:** 16th century*

Construction technique: Composite building techniques allow to achieve up to 40m in height. No waste material is generated during the entire building process; bricks can remain stored for reuse. Between every five courses of mud brick construction, cut branches are inserted as a chaining. Branches and timbles enable the clamping of the walls

climatic strategy: The morphology of the city and its buildings respond to the necessity to be protected from these attacks.Shibam is built on a rock basement. This basement has let the city to survive the floods of the area.after the massive flood that destroyed the previous settlement in 1532-3.

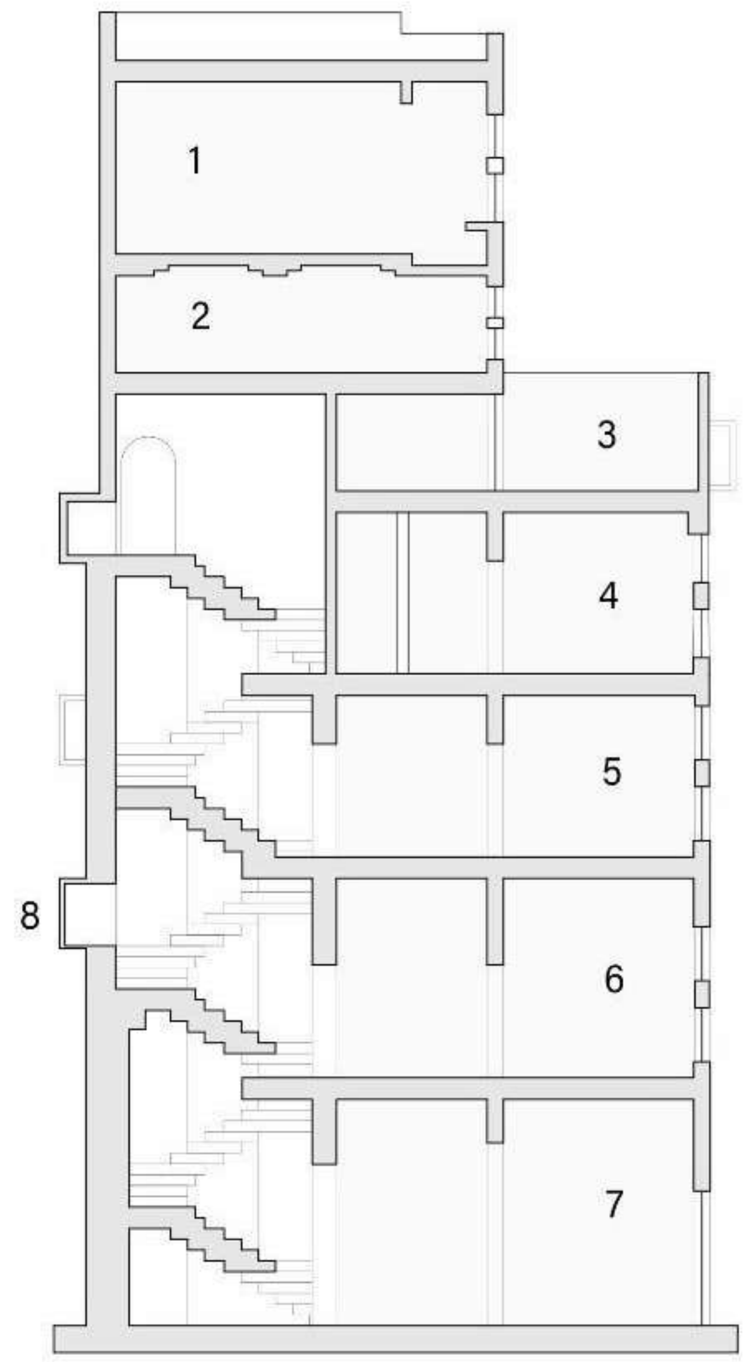
Social structure: Located in irrigated agricultural land, Most of its buildings were built during the XVI century. Shibam has been a rich city due to farming and the trading of spice and incense and this is the reason that city suffered continuous attacks and invasions.



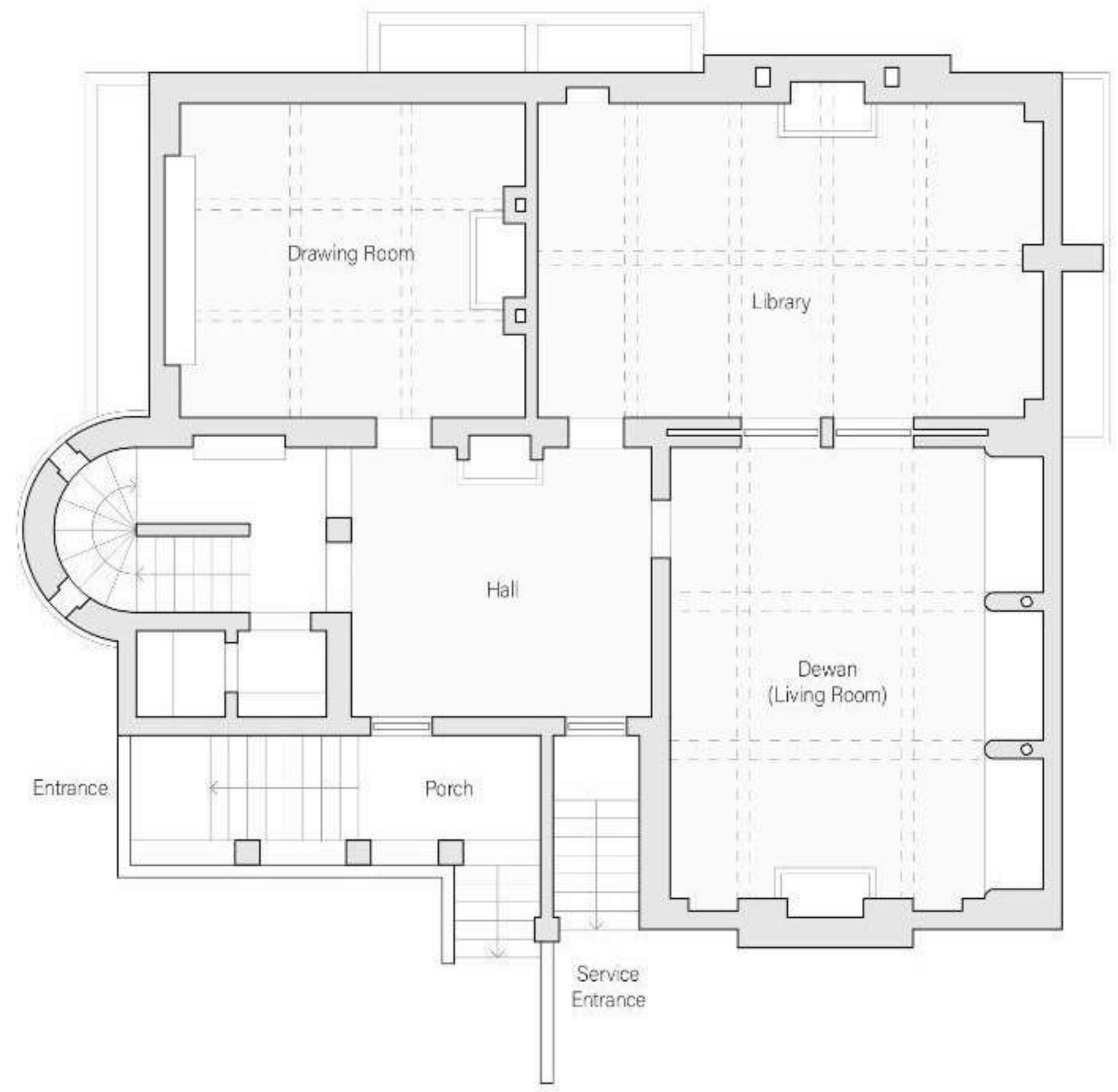


Section Key

1 - Mafraj (Male Living Room)
2 - Women's Room
3 - Terrace
4 - Bedroom
5 - Dewan (Yemeni Majlis)
6 - "Reception Room" and Business
7 - Water well
8 - Mashrabiyah (Window bay)



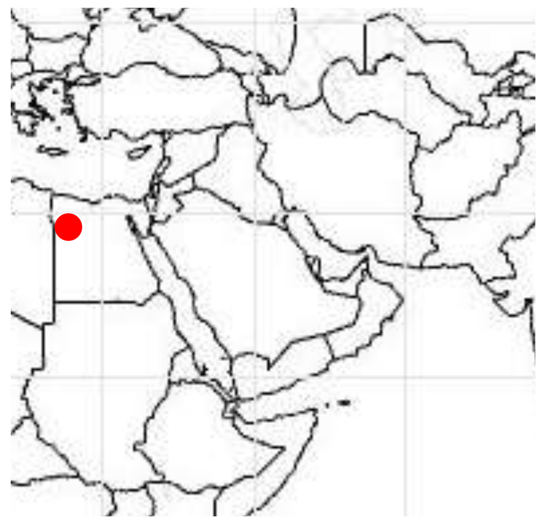
Exemplary Tower House Section (NTS)



Exemplary Tower House Floor Plan (NTS)

Research by: Nawaal Saksouk
Drawings by: ?

Kershef walls



Geography : *Siwa oasis, Egypt*

Climate : *Dry-Hot*

Community :

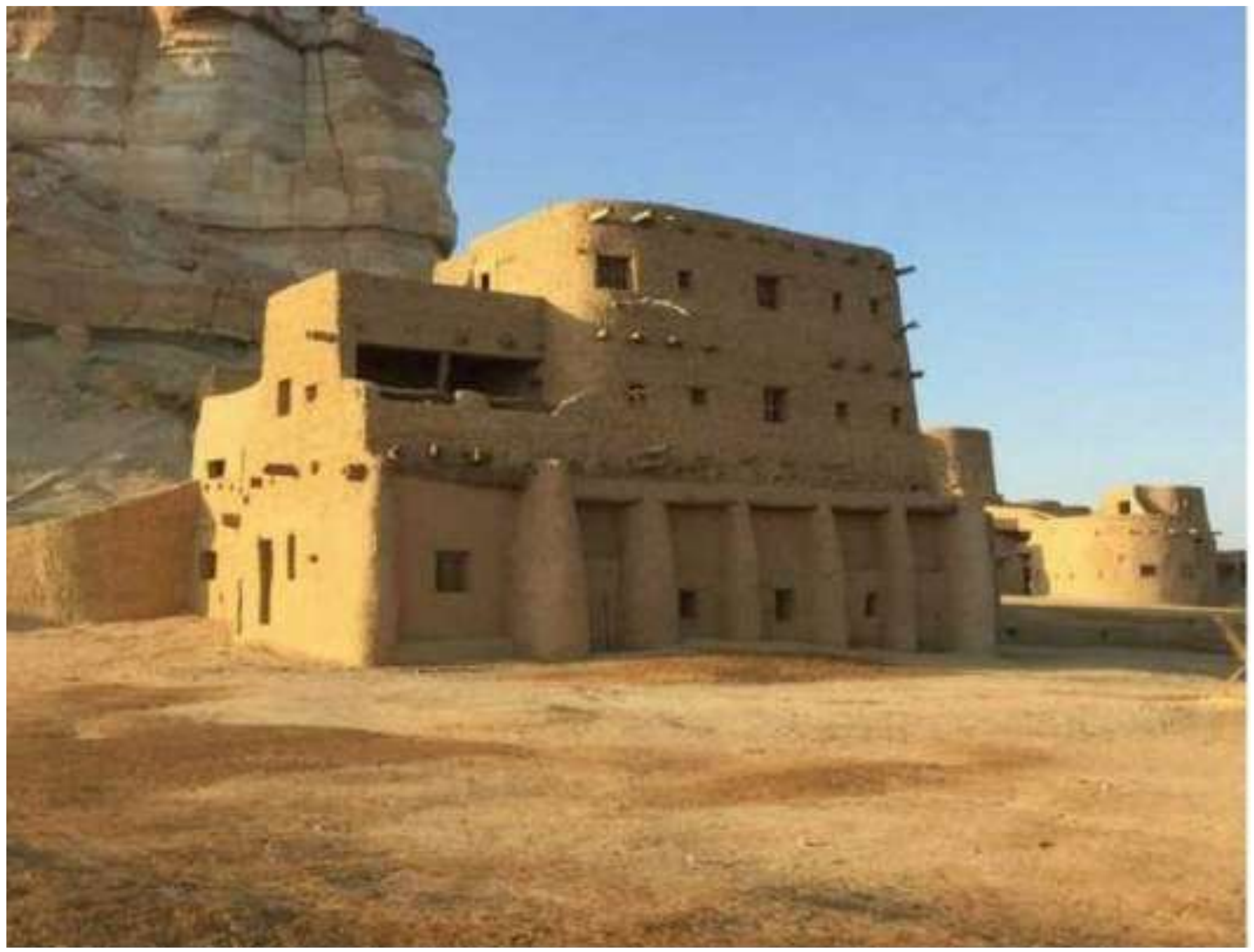
Construction technique: *Earth*

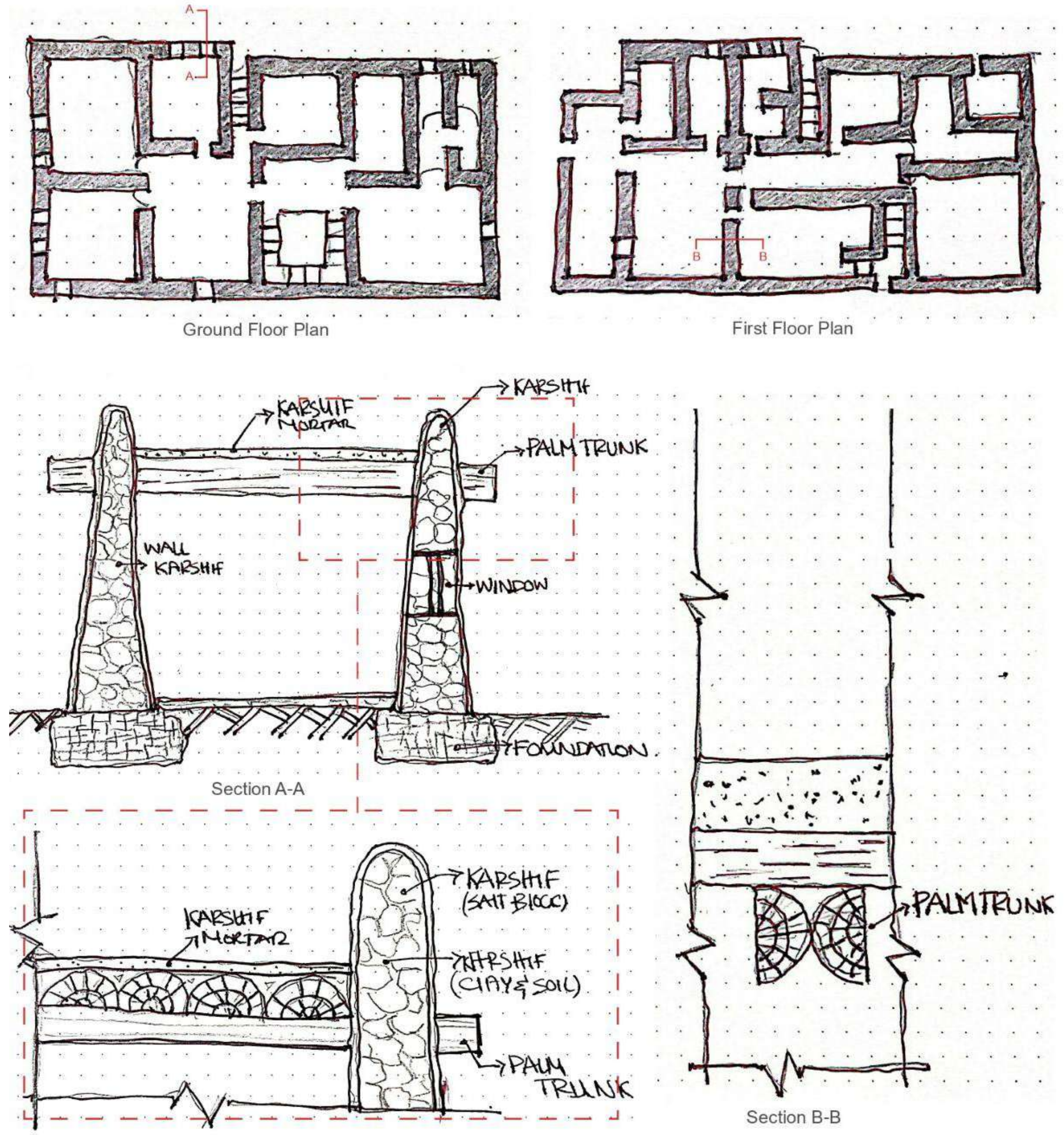
Scale:

Period:

Construction technique: Kershef is an organic mud-brick fortress, built from the local dehydrated mud bricks and is a technique invented in the desert from a mixture of dehydrated salt, clay and sand, around salty lakes in Siwa. The fortress is made with Kershef walls, roofs of palm tree trunks, that is then bonded with 'Tlakh' a fermented mud mix to allow the load-bearing structure to soar that high (minarets).

climatic strategy : The volumetric walls help delay the heat transfer long enough to later release the warmth for the cold Egyptian nights.





Ground Floor Plan

First Floor Plan

Section A-A

Section B-B

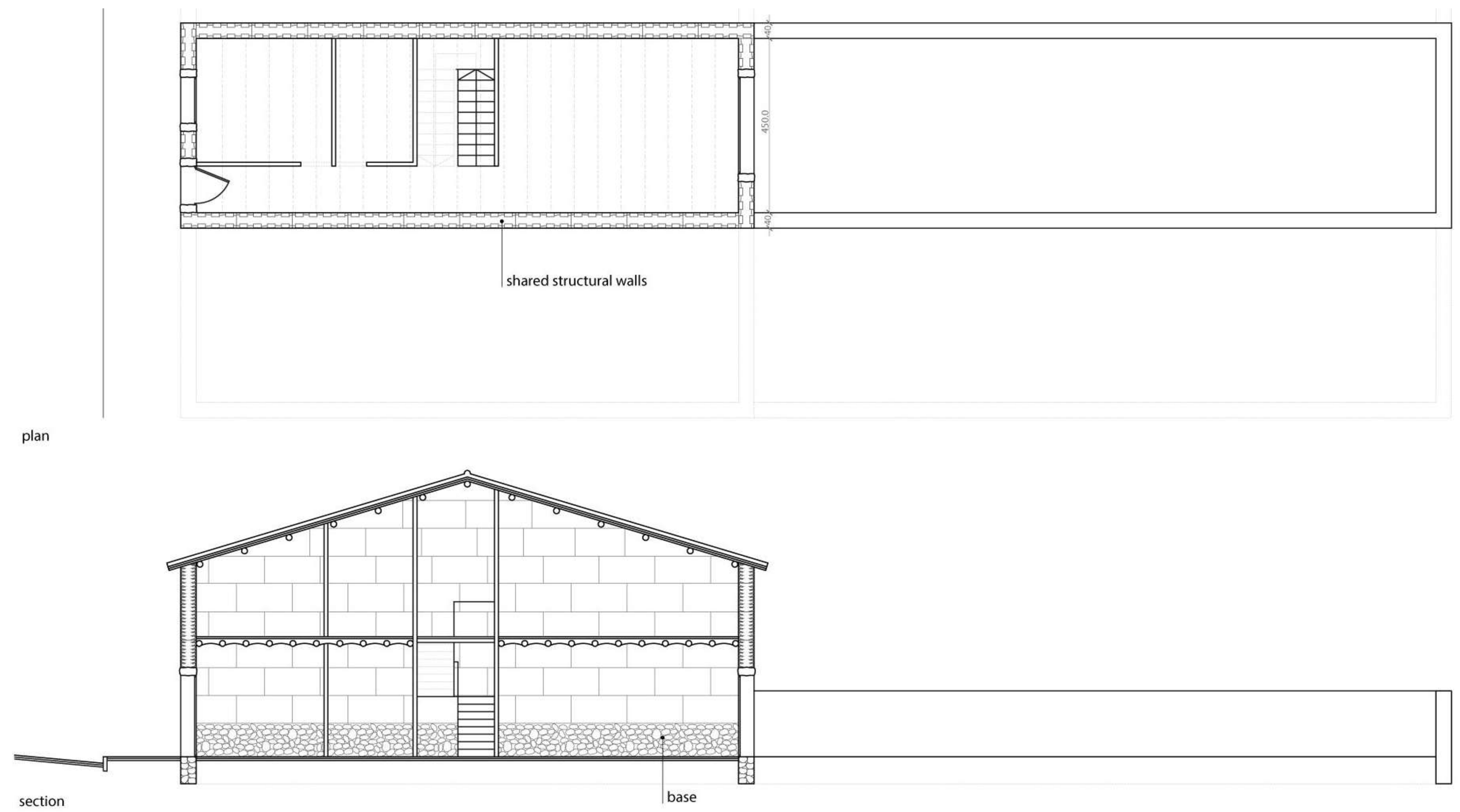
MARINA NASSIF

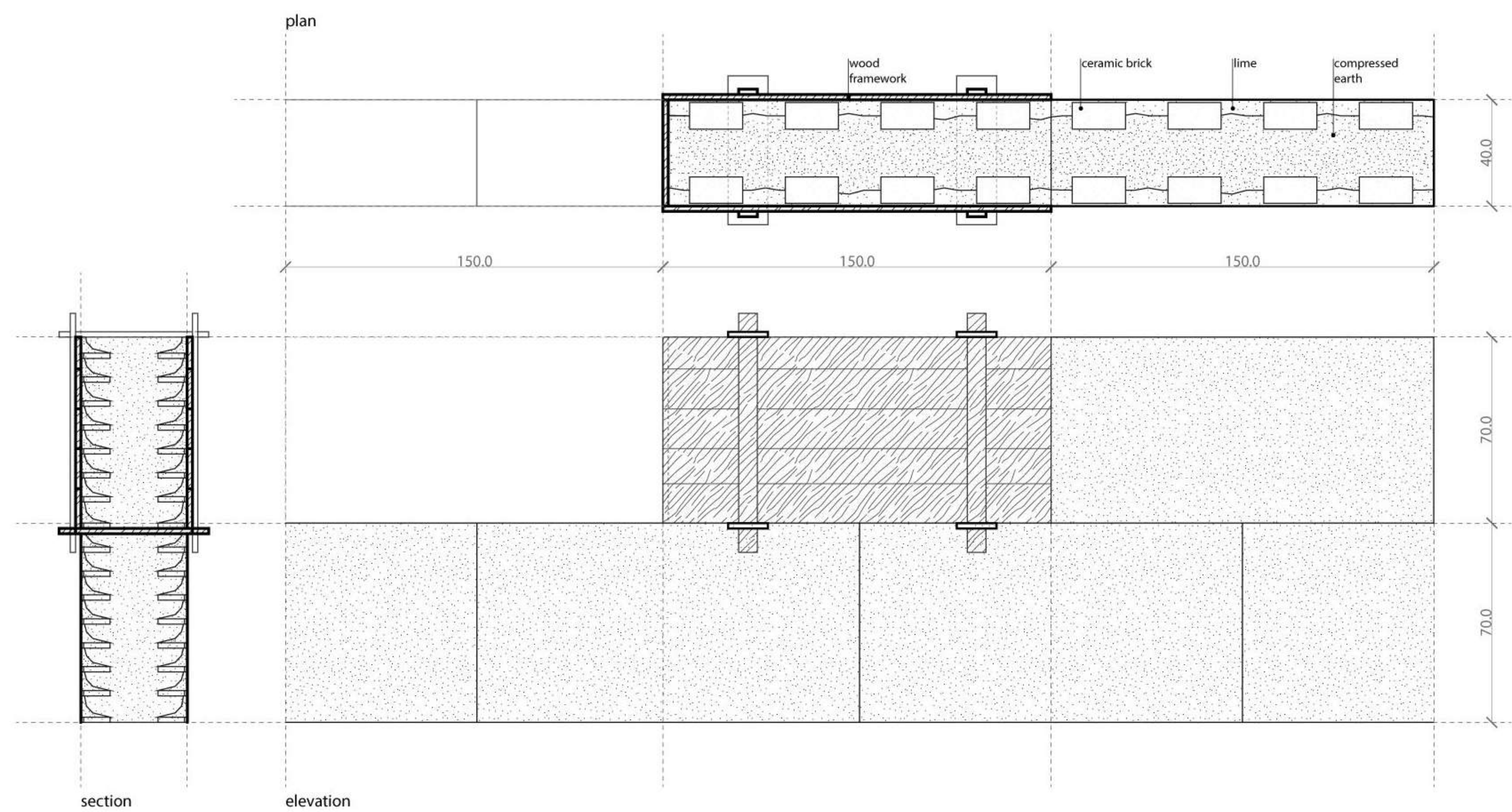
Research by: Marina Nassif, Deena El Mahdy
Drawings by: Marina Nassif, Deena El Mahdy

TAPIA

Geography :
Climate : Mediterranean
Community : Architect ?
Construction technique: Tapies (rammed earth) wood
Scale:
Period:

Construction technique: rammed earth structural wall - **"mur de tapia"**: *Walls made of building units of earth fulfilled formwork*



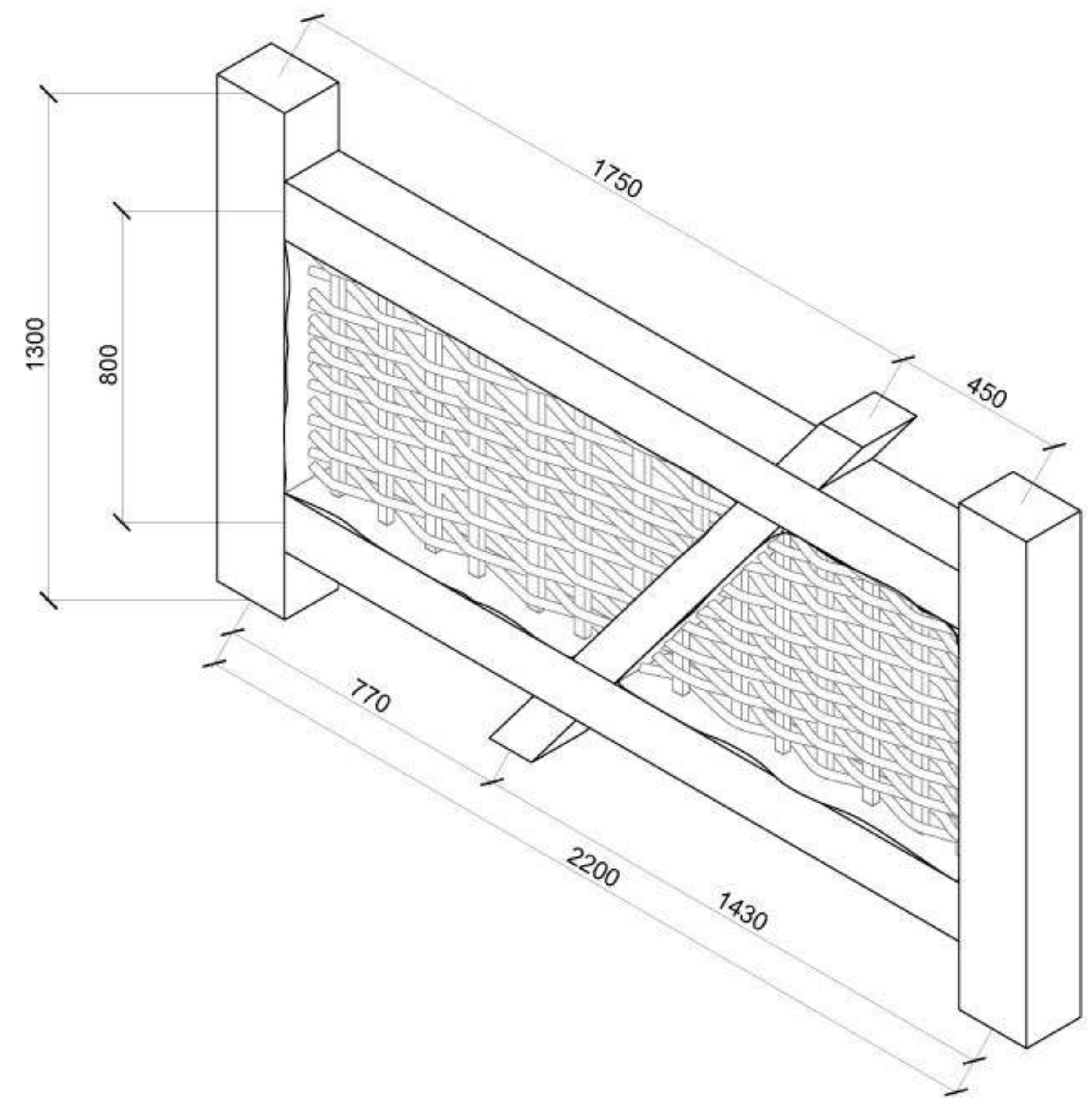


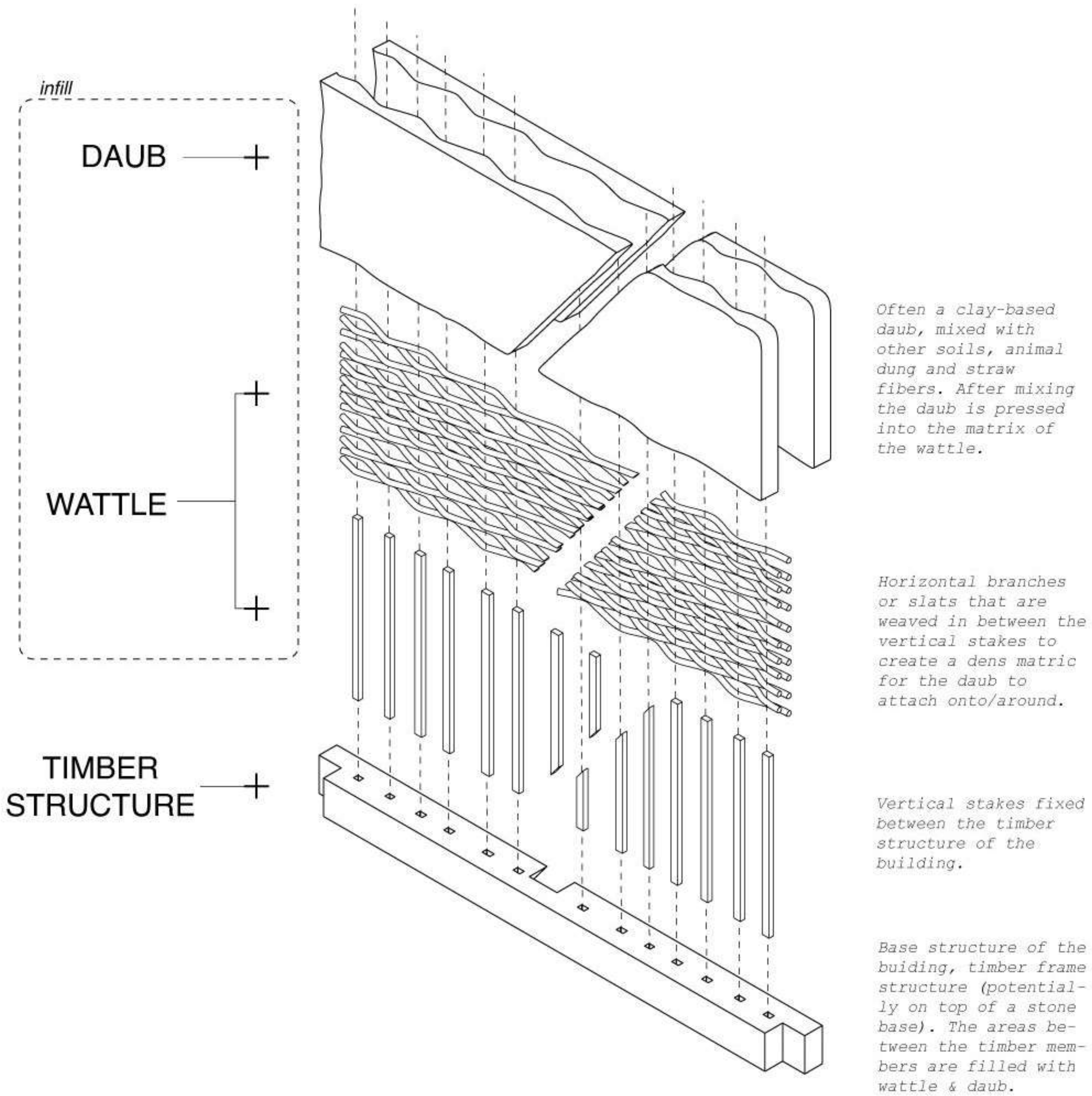
Research by: Marta Navarro
Drawings by: Marta Navarro

La Maison Espagnole

Geography :*Grupont, Belgium*
Climate : *maritime climate*
Community :
Construction technique: *Wattle and Daub technique*
Scale: *4 stories*
Period:*16th century*

Construction technique: Abundance of wood (southern part of Belgium), clay-rich soils & low cost resulted in the development of the building technique in Belgium (and the rest of Central-Europe). Wattle and Daub technique was at its height during the Middle Ages and was used until the beginning of the 19th century.





Research by: jett
Drawings by: jett

Iaac

Haus Stöcker

Geography *:rural region of Detmold.*

Climate : *maritime climate*

Community :

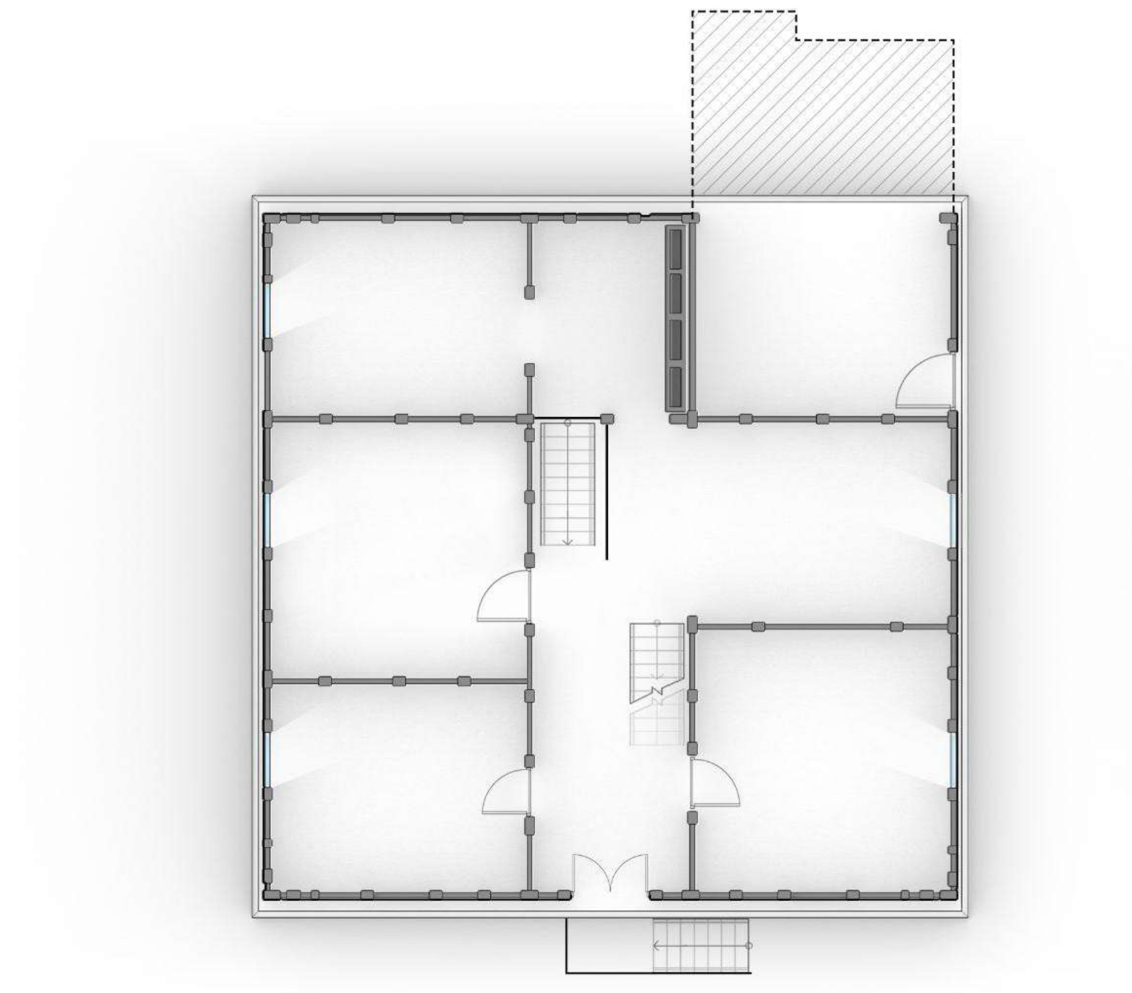
Construction technique: *Wattle and Daub technique*

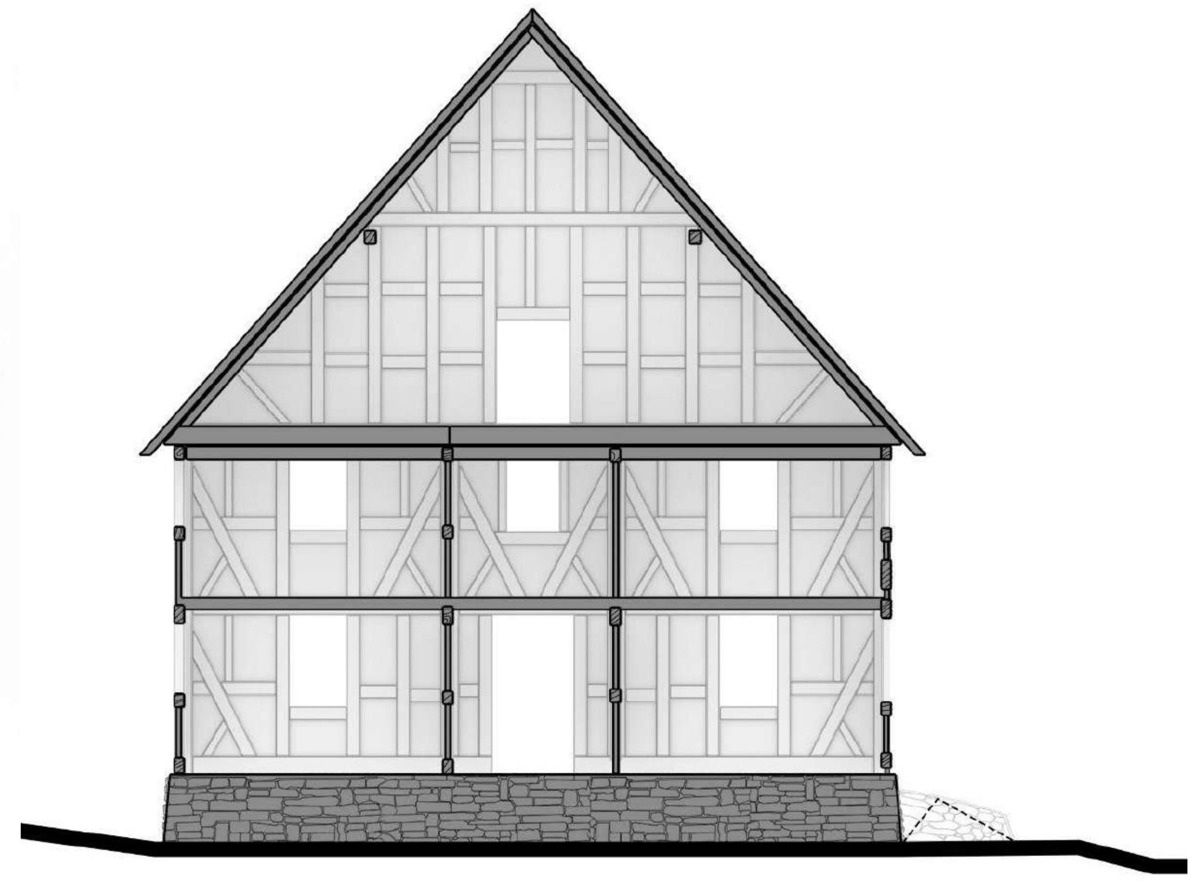
Scale: *4 stories*

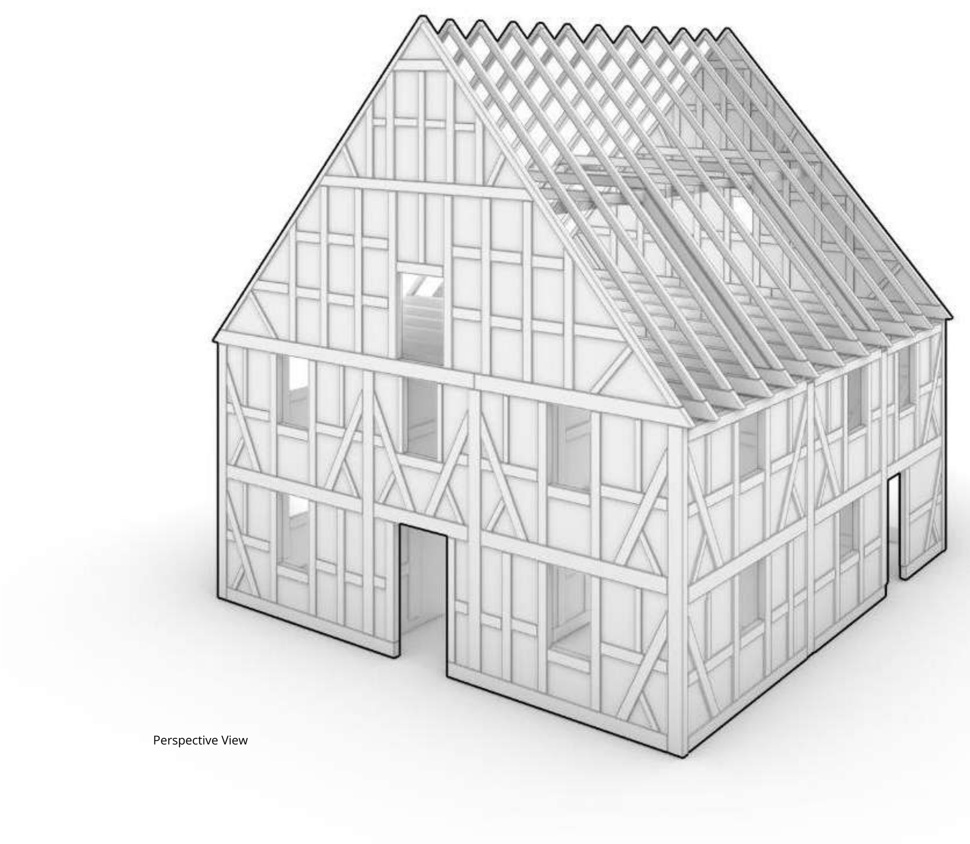
Period:1797

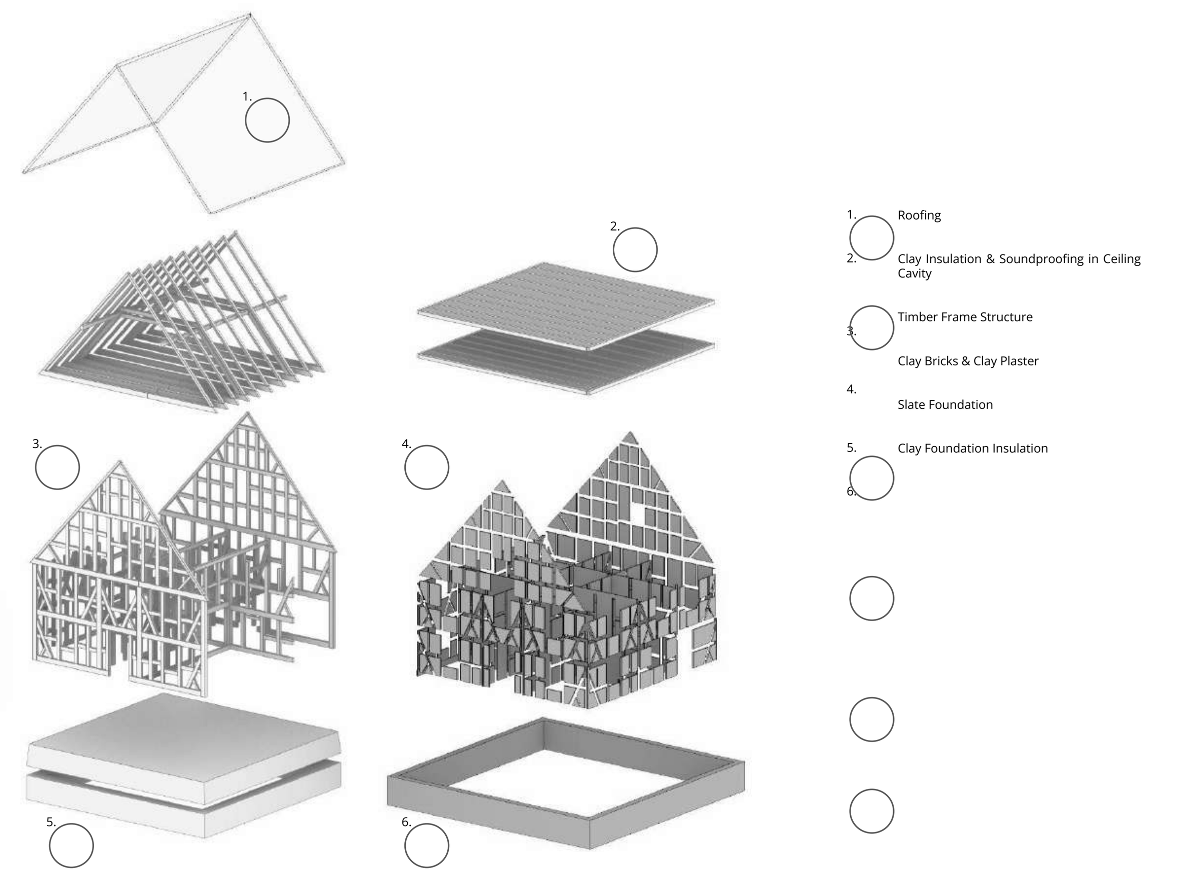
Construction technique: The house is a traditional Westphalian house, standing completely on a high rubble stone base and was thus better protected from soil moisture. Today it is a museum showcasing the architecture of the region.

In 2017 the open-air museum started preparations for the construction of Haus Stöcker at its new location. The individual timbers of the framework were sifted through and laid out wall by wall. The numbering plans that were created during dismantling in 1963 helped us with this.









Research by: H.Benz
Drawings by: H.Benz

Bahareque wall

Geography :_Many parts of Latin America._

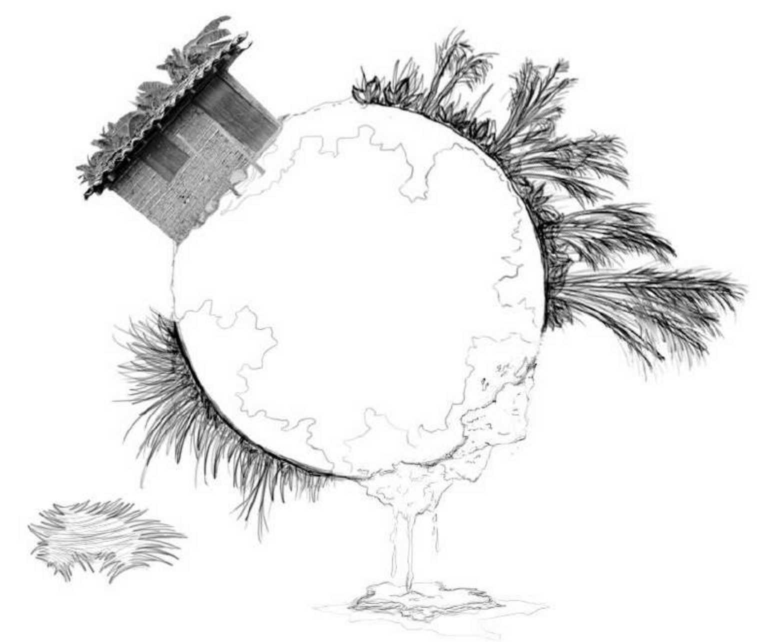
Climate : _Tropical_

Community : _Mexico, Colombia_

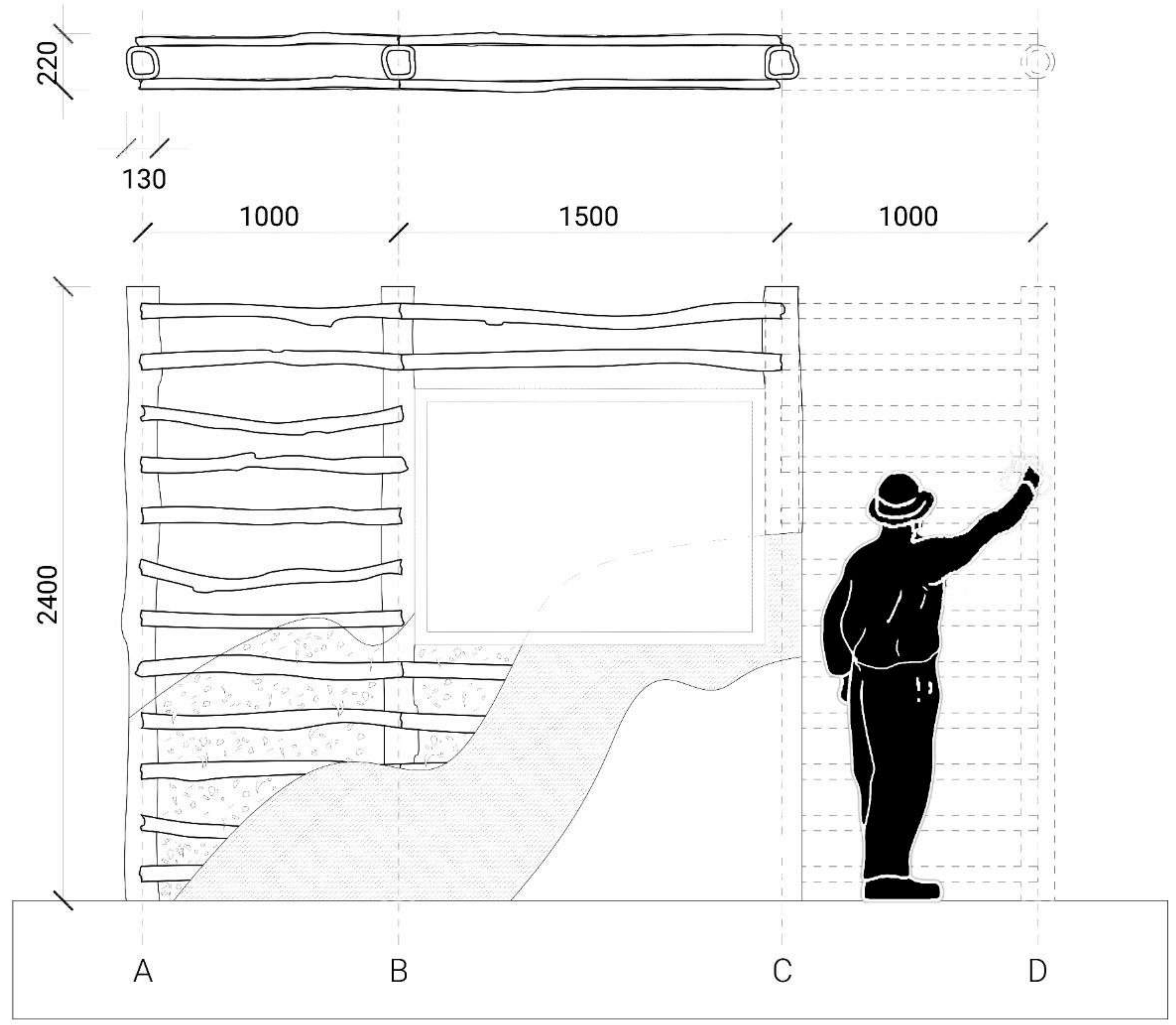
Construction technique: _Bamboo, daub_

Scale:_-_

Period: _Pre-Columbian_



Construction technique: Bahareque, also spelled bareque is a traditional building technique used in the construction of housing for indigenous peoples in south america. The constructions are developed using a system of interwoven sticks or reeds, with a covering of mud, similar to the systems of wattle and clay structures seen in Europe.



Research by: Juliana Rodríguez Torres
Drawings by: Juliana Rodríguez Torres

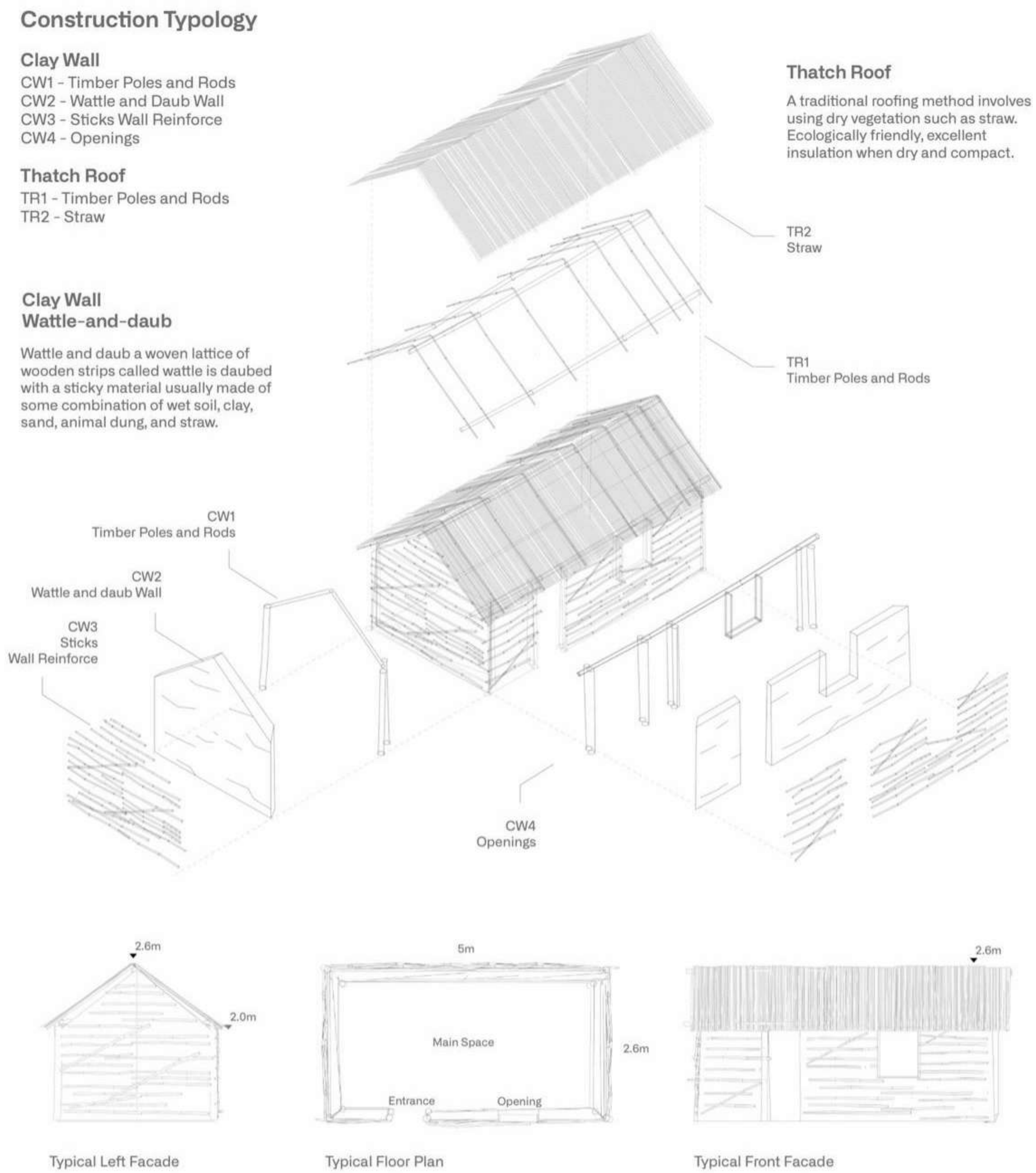
El Rancho

Geography : Uruguay
Climate : Humid subtropical climate
Community :
Construction technique: *Woof sticks, clay, straw*
Scale: 3m
Period: -

Construction technique: composed of local clay and chopped straw compacted into wall formworks. Its population has rich amount of descendants from European countries such as Portugal, Spain, and Italy. With that context El Rancho appears as a mix of imported expertise mixed with Construction technique, mainly wood sticks, clay, and straw.

Social structure: Ranchos are largely used for housing, including other programs such as rural schools.

↥ Pictures of one of the latest isolated Ranchos in rural areas of Uruguay.



Research by: Francisco Magnone Rienzi
Drawings by: Francisco Magnone Rienzi

Dai houses

Geography : *Dai Dehong prefecture, China*

Climate : *subtropical*

Community : *Dai ethnic group*

Construction technique: *Hybrid: Earth, Wood*

Scale: *varies*

Period: *10th century*

Construction technique: Dai buildings entail the mixed use of materials to optimize their performance, with **earth** for flooring, external walls, **wood** used for posts, beams, roof structures and internal wall partitions.

Climatic strategy: While earth has thermal properties, wood is an ideal material for structural frameworks and spatial partitioning. Its tensile strength helps to support earthen walls, during storms or earthquakes.

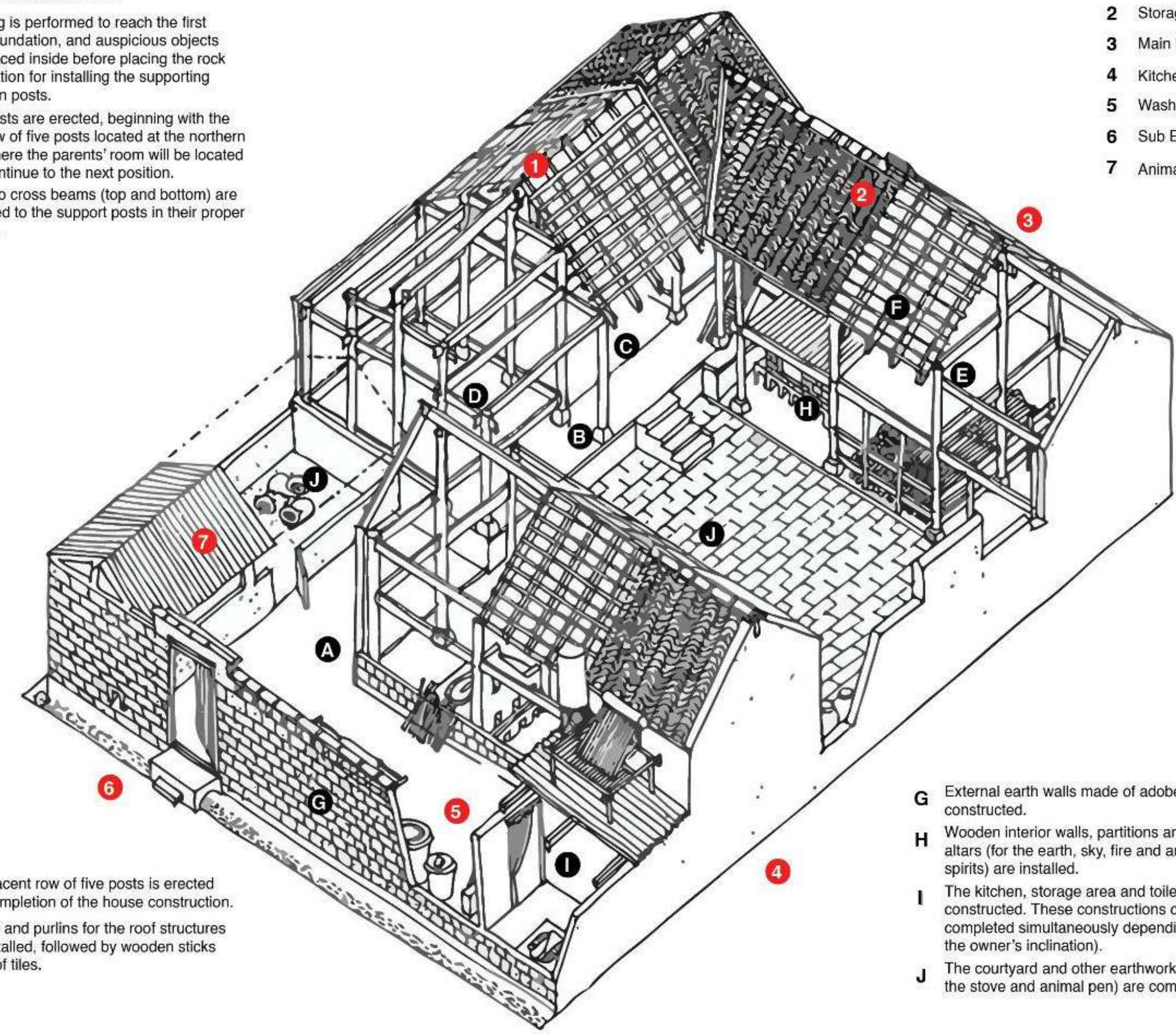
A Site planning is completed, and the land is filled to the desired level.

B Digging is performed to reach the first rock foundation, and auspicious objects are placed inside before placing the rock foundation for installing the supporting wooden posts.

C The posts are erected, beginning with the first row of five posts located at the northern end where the parents' room will be located and continue to the next position.

D The two cross beams (top and bottom) are attached to the support posts in their proper places.

1 Main House
2 Storage
3 Main Entrance
4 Kitchen
5 Washing area + Toilet
6 Sub Entrance
7 Animal Pen



E An adjacent row of five posts is erected until completion of the house construction.

F Rafters and purlins for the roof structures are installed, followed by wooden sticks and roof tiles.

G External earth walls made of adobe are constructed.

H Wooden interior walls, partitions and house altars (for the earth, sky, fire and ancestral spirits) are installed.

I The kitchen, storage area and toilet are constructed. These constructions can be completed simultaneously depending on the owner's inclination).

J The courtyard and other earthworks (i.e., the stove and animal pen) are completed.

Research by: ?

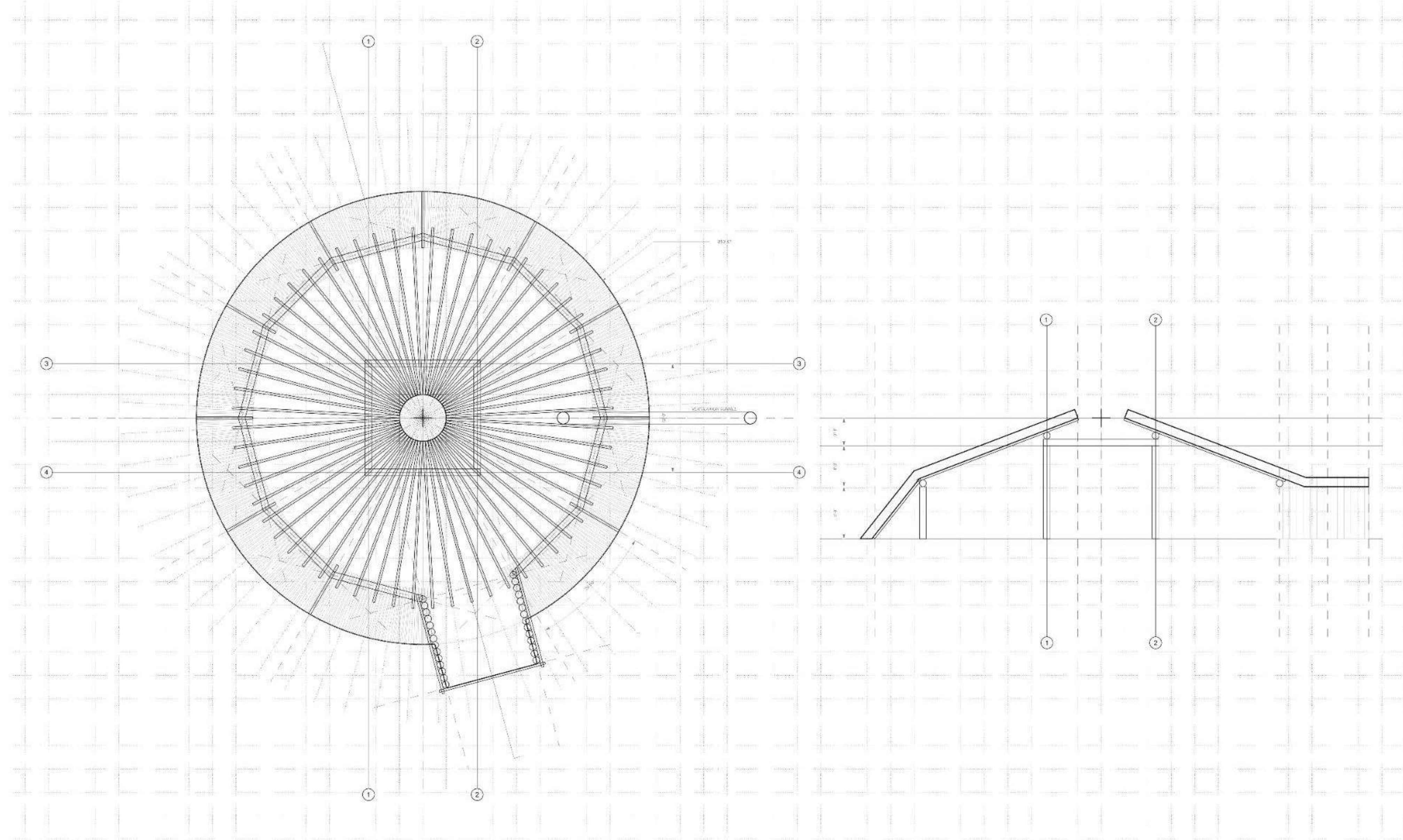
Drawing by: YEAR 2022

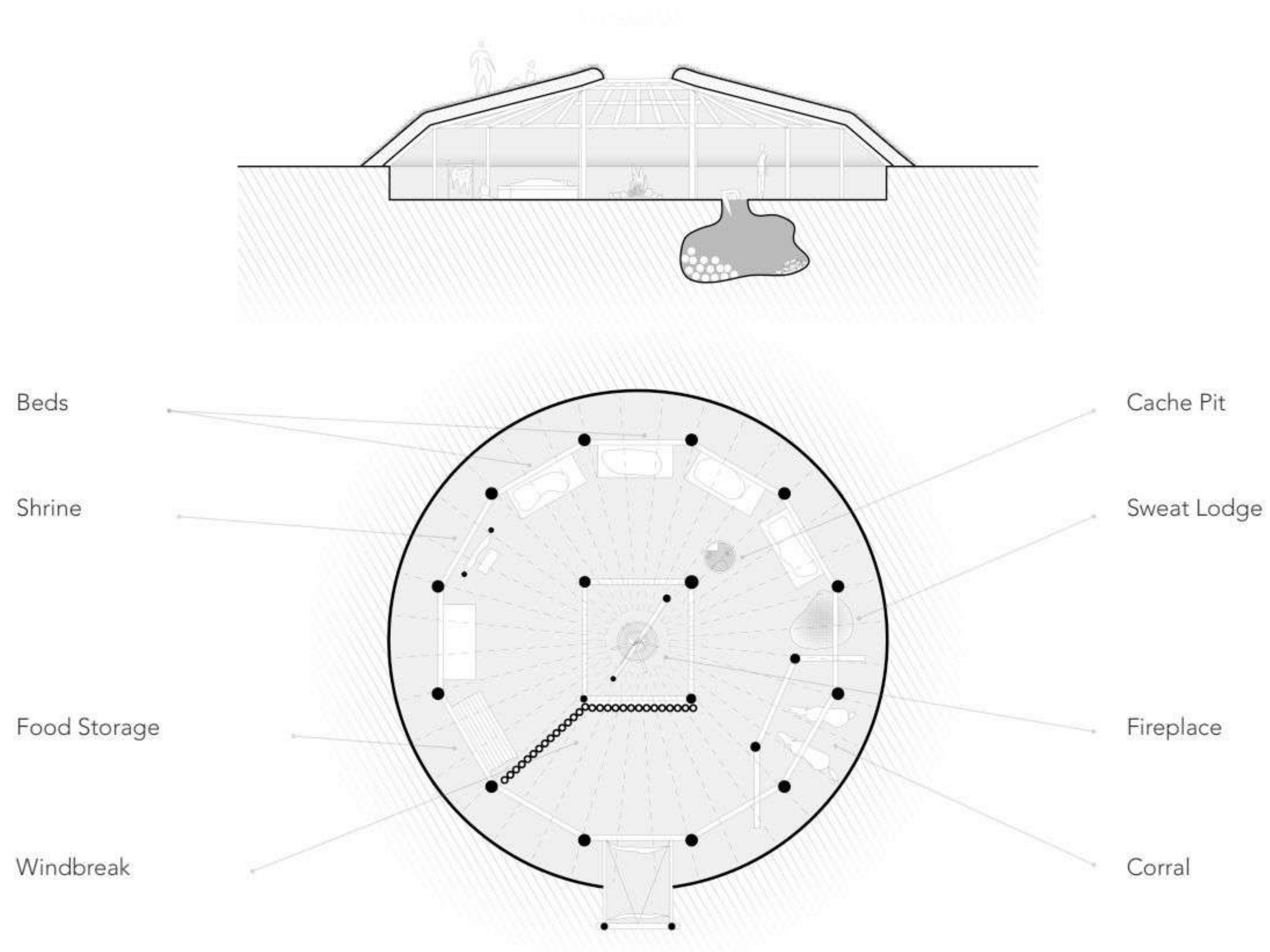
Earth Lodge

Geography :*North america*
Climate : *Continental - cold*
Community : *Pawnee, Native americans*
Construction technique: *Willow branches, grass, sod, earth*
Scale:*120m²*
Period: *Pre-Columbian 1400s to the late 1800s*

Construction technique: These structures are constructed by digging a shallow pit and then building a dome-shaped or circular structure using a framework of wooden poles covered with earth, grass, and sometimes hides. Earth lodges vary in size and construction materials depending on the tribe and the specific region they inhabit. They are used for various purposes, including housing, ceremonial gatherings, and storage.

An earth lodge is a distinctive type of timber-frame house built from the early 1400s to the late 1800s by a dozen different Indigenous nations on the Great Plains. These massive circular structures, often encompassing 1,500 square feet or more, featured four large support posts arranged around a central fireplace. The walls were formed by a ring of shorter posts and rafters were laid between the center posts and the wall posts. The resulting wooden shell or framework was then covered with successive layers of willow branches, a matting of prairie grass, and finally sod or earth.





Research by: Nestor Beguin, Michelle Bezik
Drawings by: Nestor Beguin, Michelle Bezik

Thanal house

***Geography :** Tiruvannamalai, Tamil Nadu, India*

***Climate :** semi-arid*

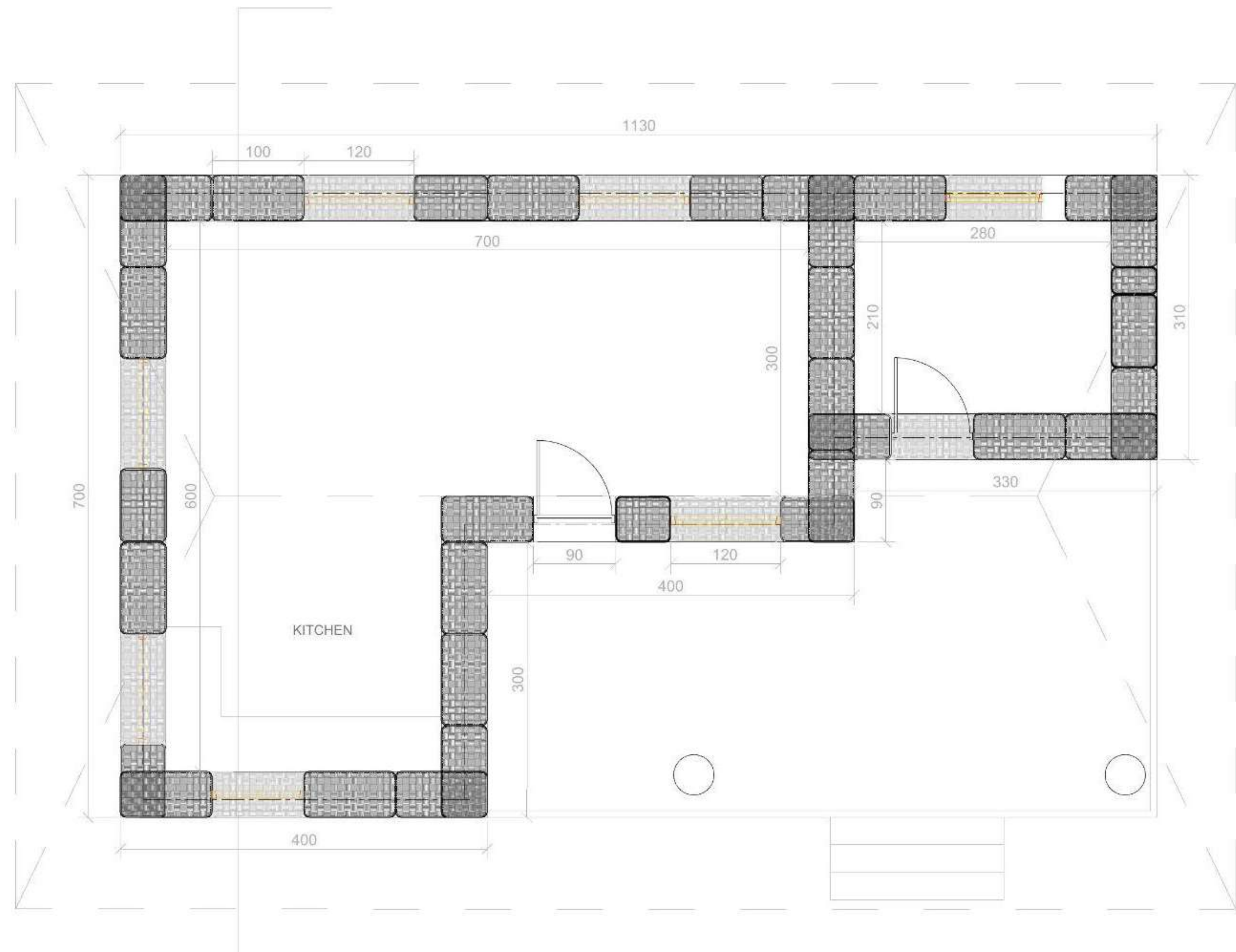
***Community :** Thanal collective*

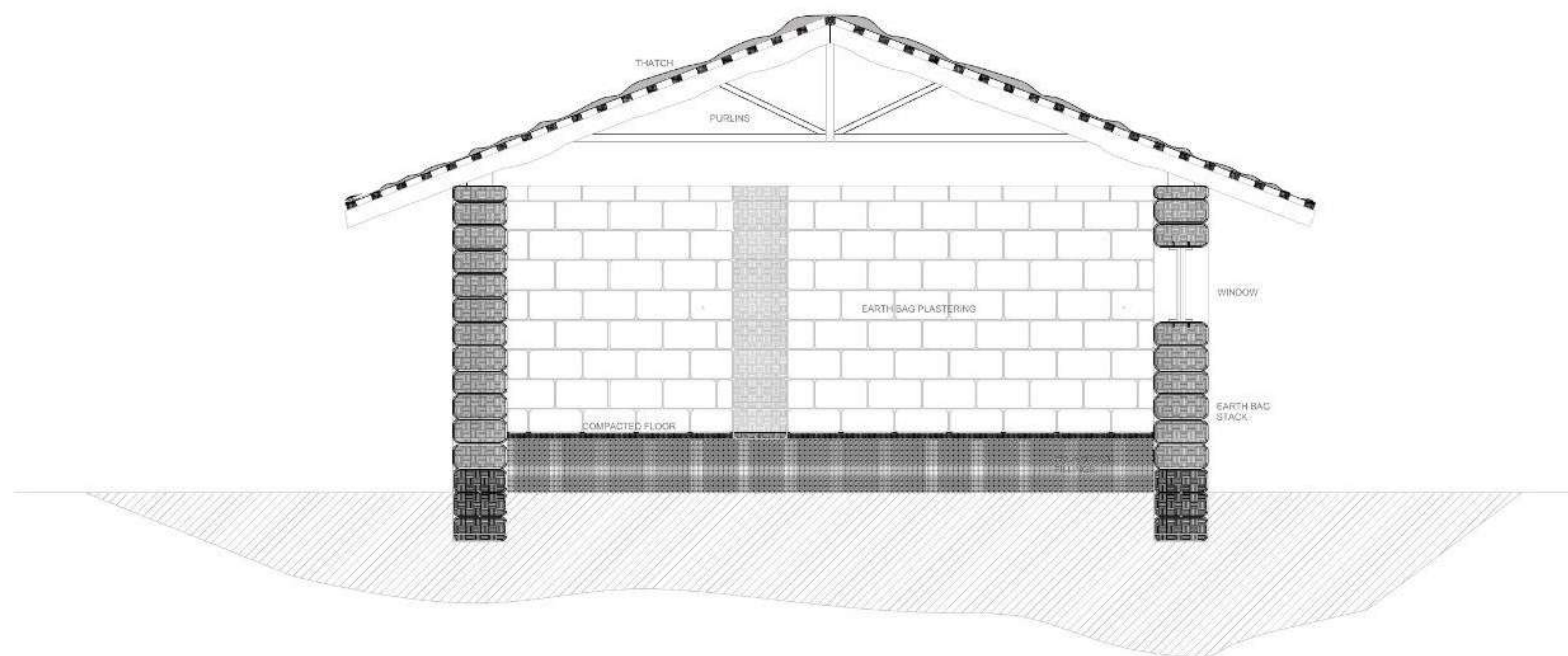
***Construction technique:** Earthen bags, bamboo, palm, terracotta tile*

***Scale:** units*

***Period:** 2011*

Construction technique: Earthen bag construction is an initiative by a cooperative called Thanal, using locally sourced used jute bags and used wooden joineries. After 45 cm soil excavation and compaction for foundation. Earthbags are stacked and bonded with mud and natural bonding mixtures. Roof is then made of bamboo/ palm/coconut wood and layered with thatch or terracotta tile. The walls are plastered with mud and for an extended roof coconut trunk is used as a column. The Interior planning is mostly open or with minimal partitions and internal temp is well regulated. The basement is treated to avoid termite issue and its coped to avoid water soaking





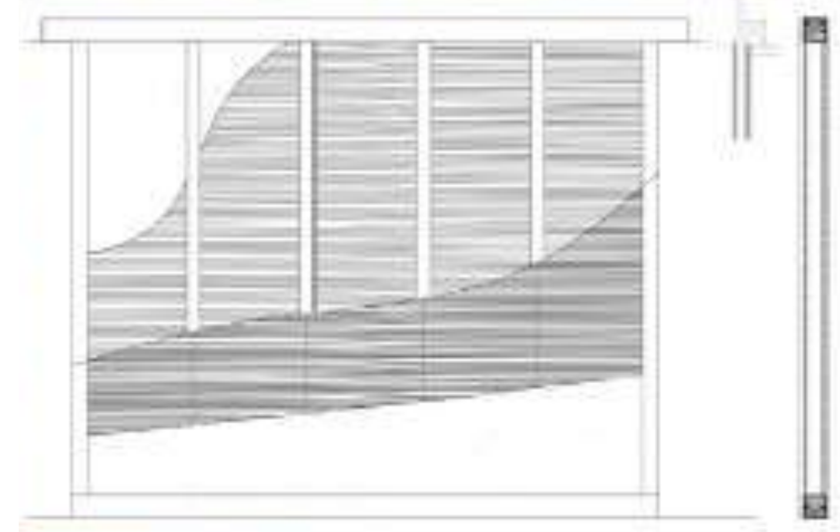
Research by: Kingsley Claudin
Drawings by: Kingsley Claudin

Magoulitsa traditional house

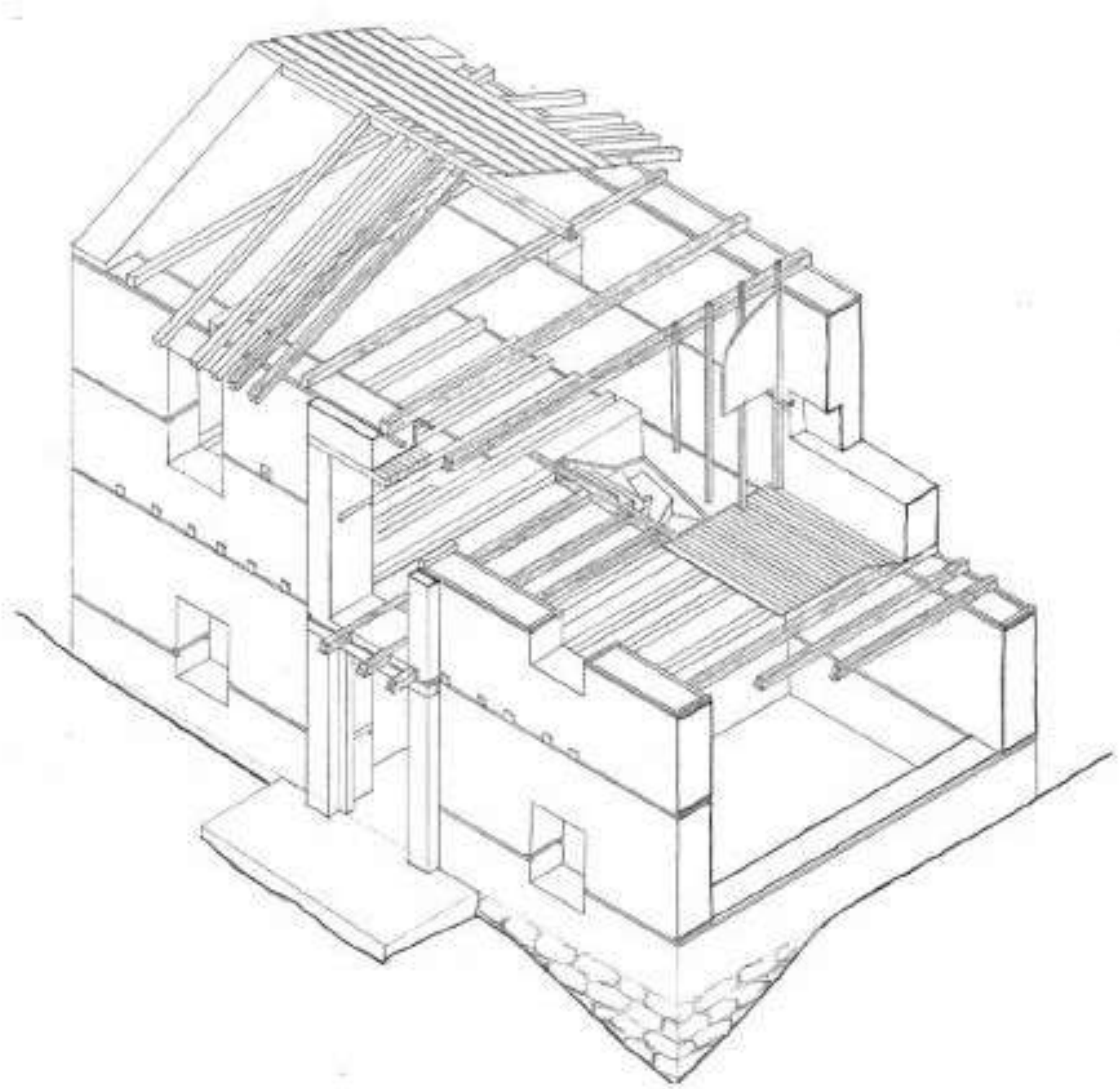
Geography : *karditsa,Thessaly, Mouzaki, Greece*
Climate : *Mediterranean*
Community : *-*
Construction technique: *Adobe, wood*
Scale: *2 stories, courtyard house*
Period: *1788*

Construction technique: Magoulitsa (the small hill) is a settlement with many underground and surface waters. During the 19th century it had a lot of running but also stagnant water (marshes), which made the subsoil moist, so that the production of mud bricks became easy, but also the place was fertile.

Elevation, Marietta Kaltsa



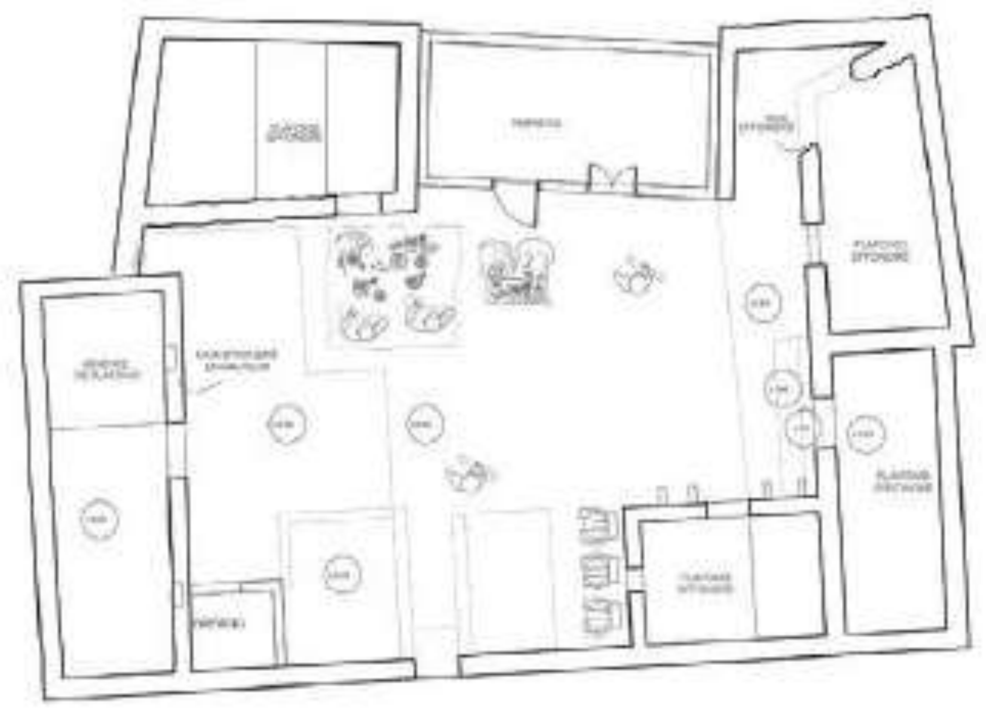
Wall detail : wood ties, Marietta Kaltsa



Research by: Marietta Kaltsa
Drawings by: ?

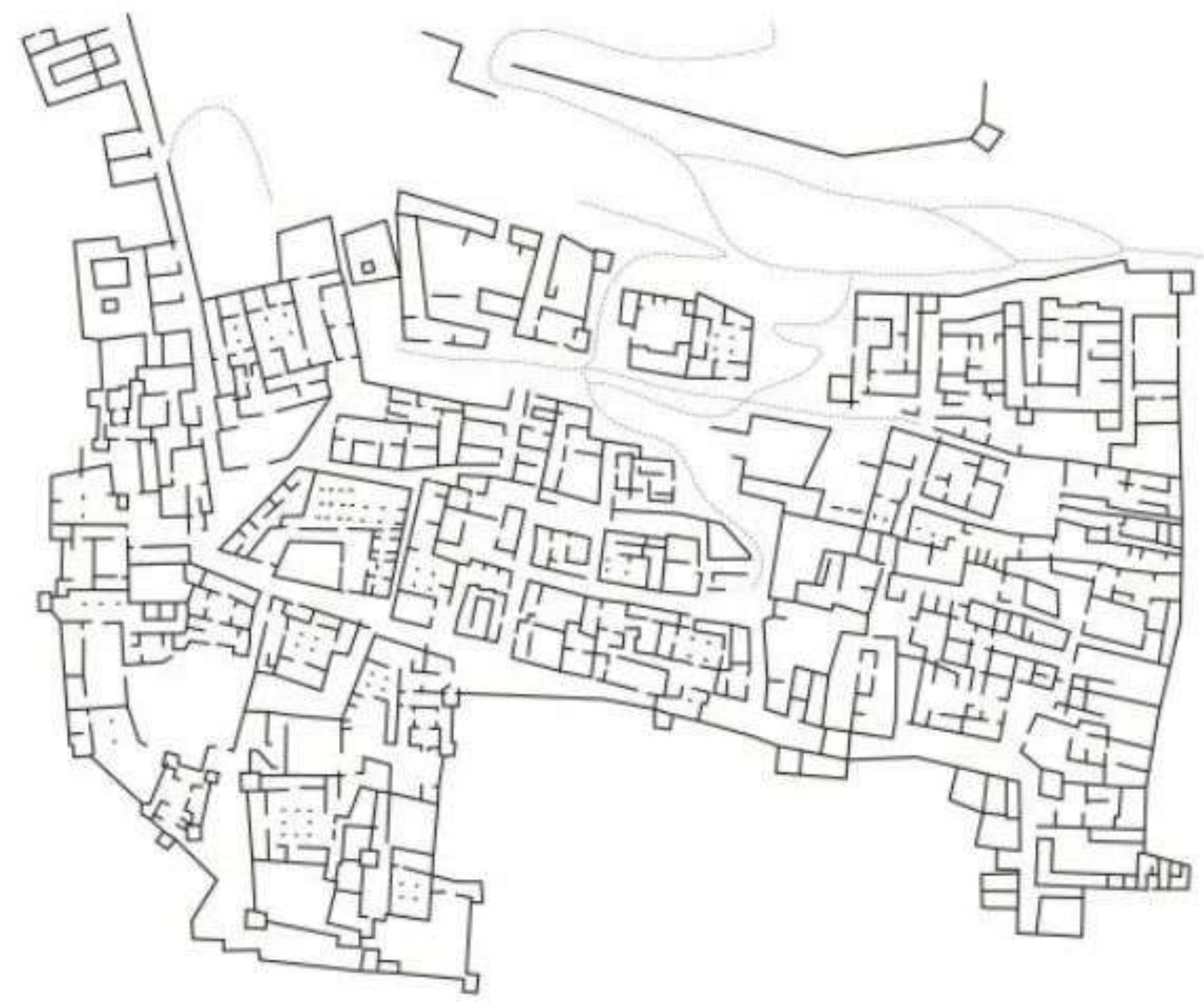
Ksar Ait Ben-Haddou

***Geography :** Atlas Mountains, Ouarzazate, Morocco.*
***Climate :** Dry-Hot*
***Community :** Amazigh*
***Technique:** Rammed earth-adobe*
***Scale**:3 ha, 6m height*
***Period:** 17th century*



Construction technique: It is the most known example of a ksar in southern Morocco. It is a complex of rammed earth buildings, with some parts of adobe (upper parts) and stone foundations. Earth has also been used to make floors, terraces and ceilings. The houses are up to 15 meters high with their corner turrets decorated with adobe masonry bounded in such a way that delicate geometric patterns can be obtained.

climatic strategy: Given the arid climate of the region, water management was crucial. The architecture includes features such as cisterns and underground tunnels (qanats) to collect and distribute water from nearby sources such as rivers or wells.

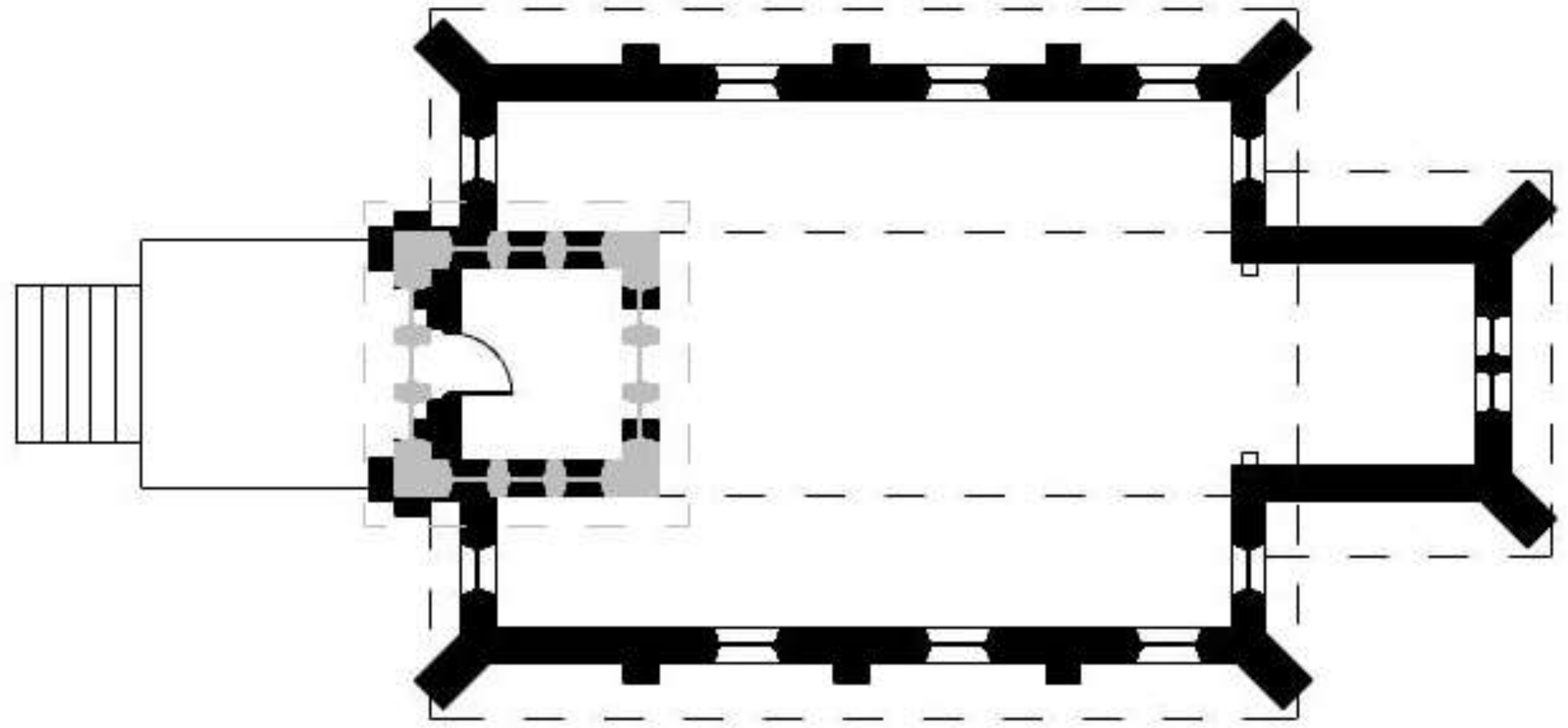


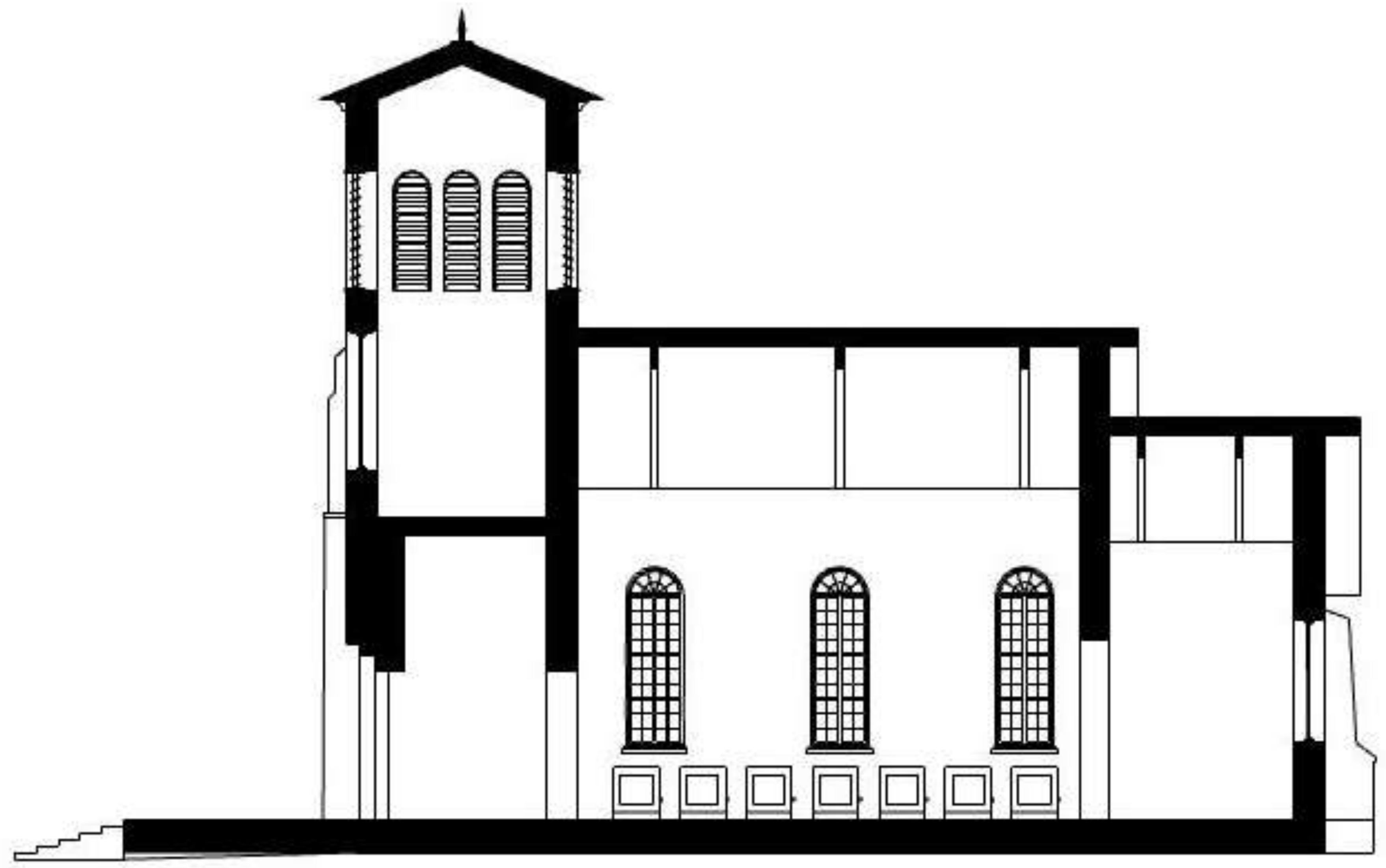
Research by: Sara Ayoub
Drawings by: Sara Ayoub

St. Thomas Anglican Church

Geography : *Shanty Bay, Ontario, Canada*
Climate : *humid continental climate*
Community : *Architect ?*
Construction technique: *Rammed earth*
Scale: *6m (nave)*
Period: *1838 and 1841*

Construction technique: composed of local clay and chopped straw compacted into wall formworks. When dry, the rammed earth walls are covered in plaster and then paint or siding to protect it from the elements. The church is constructed in a simple Romanesque style, partly resulting from the formal limitations of the construction material.





Research by: Mark Francis
Drawings by: ?

climatic strategy
Diverse housing typologies, construction techniques and details have evolved over time to offer conditioning and protection from weather variations, such as temperature, wind, rain, and light.

Harran Beehive Houses

Geography : *Northern Syria and the Beqaa Valley*

Climate : *Mediterranean (hot-dry summers/cool-wet winters).*

Community : *The dome prototype house in Taanayel*

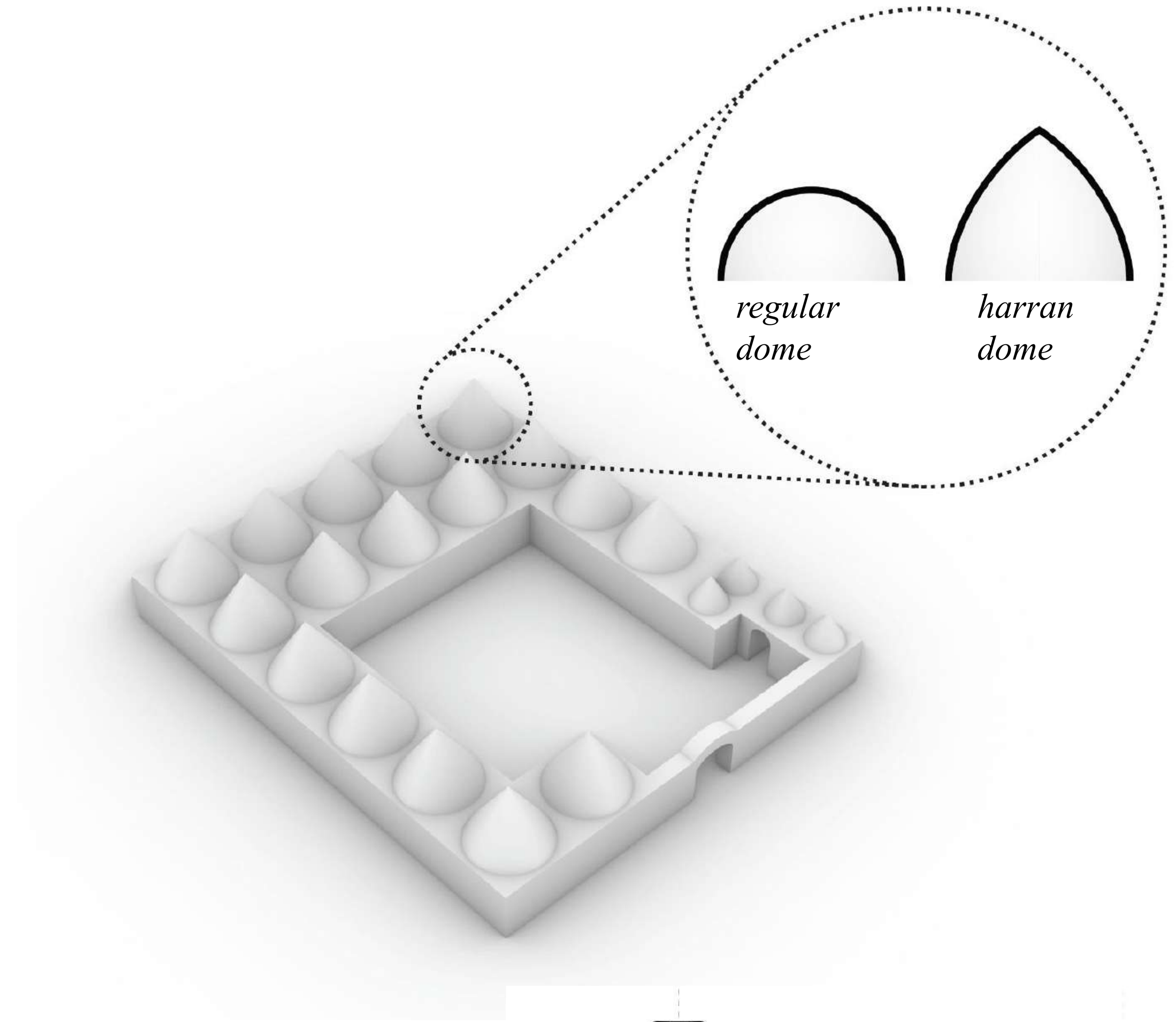
Construction technique: *Sun dried mud bricks + earth coating*

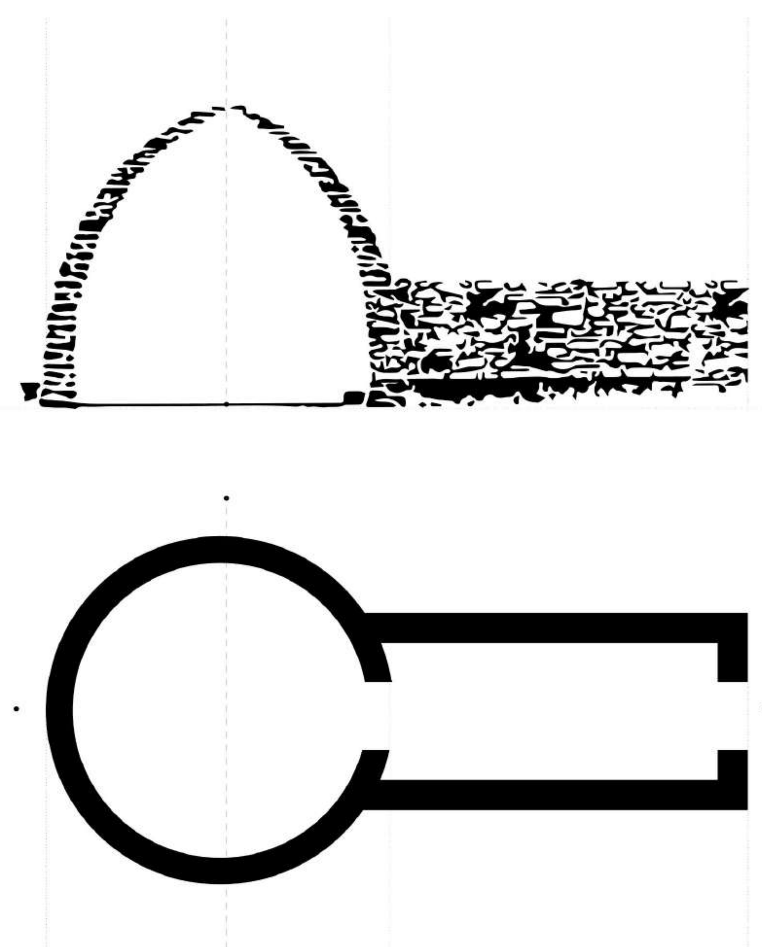
Scale: *Up to 6 meters high*

Period:*5000 millennium bc-Destruction during the current war*

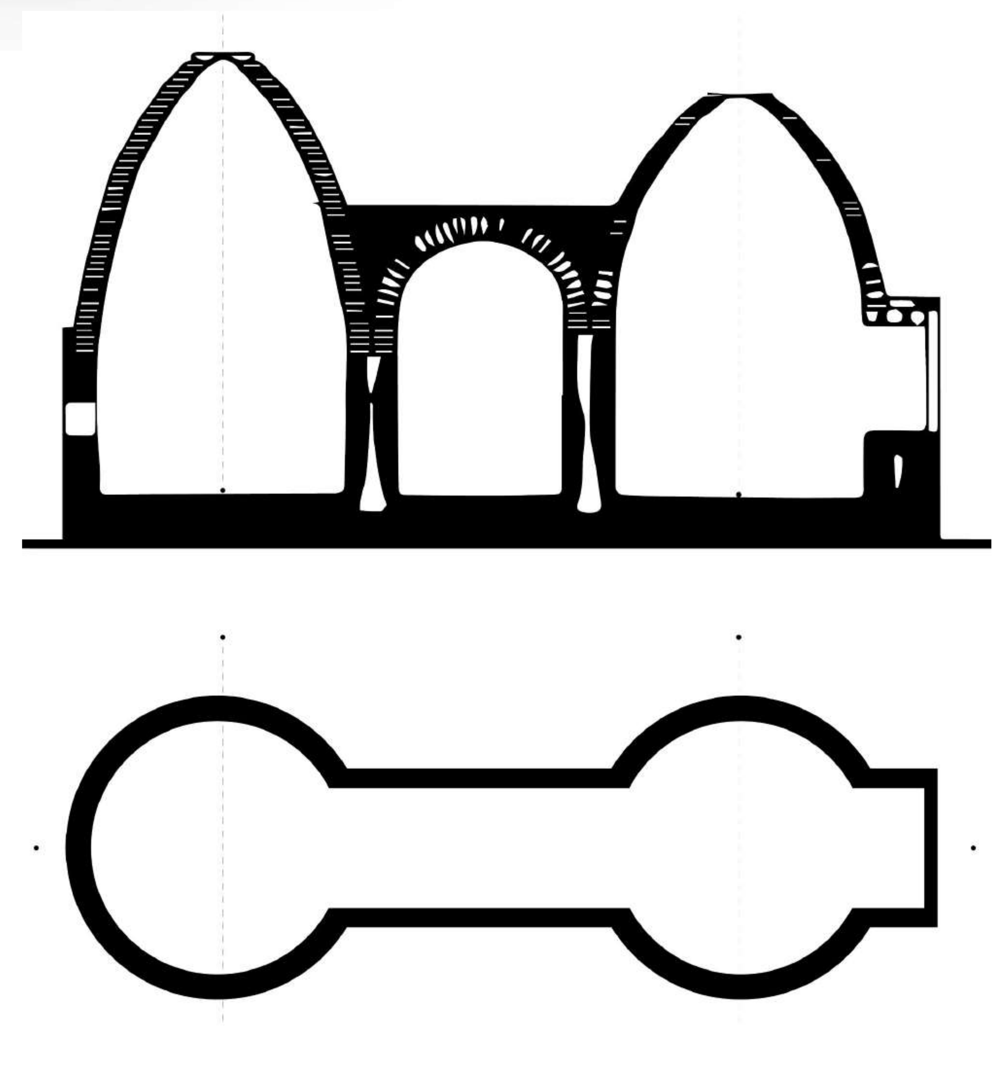
Climatic strategy: The beehive homes are an architectural tradition that are 250 years old. Made entirely from mud and clay bricks, and especially designed to fence off the heat and to retain cool air, the domes in fact not only give structural characteristics, but also allow for the hot air to rise and escape through the opening in the top, which is another way that sunlight is able to enter into space.

Social structure : due to its modularity as well as an easy construction, the layout and organization of these houses could expand quickly and strategically.

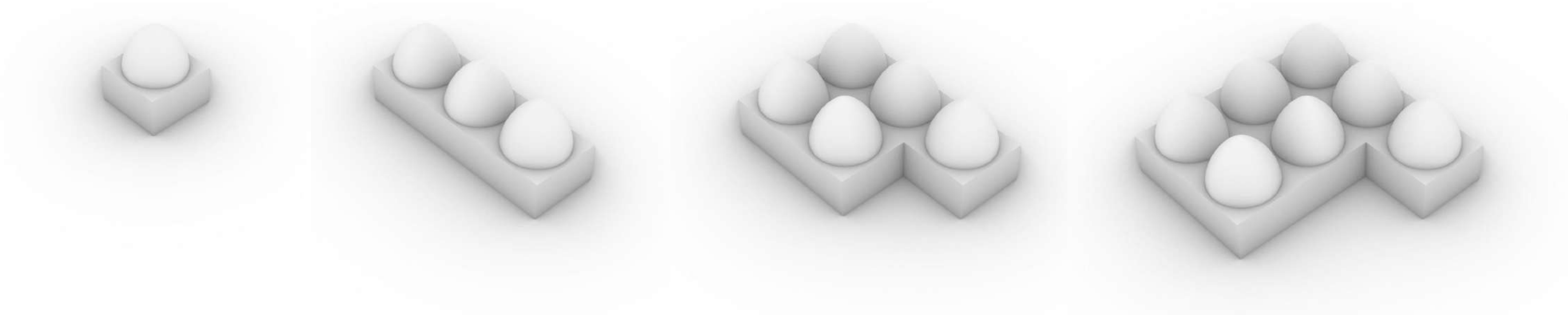




. design of the first dome



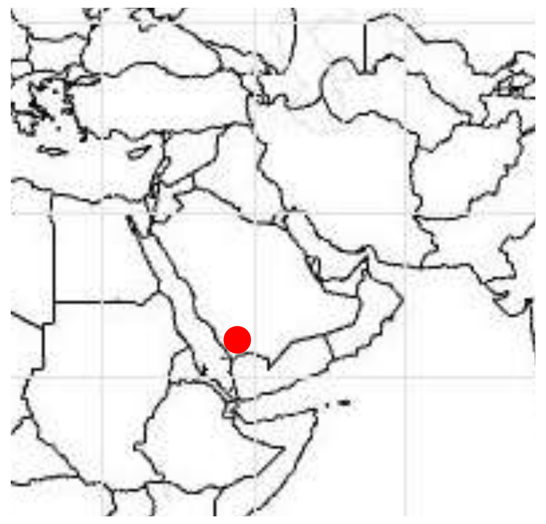
. design of the finalized dome which informed the overall layout of the homes



Research by: Aslinur Taskin
Drawings by: Aslinur Taskin

Iaac

Houses of Asir



Geography : *Asir region of southwestern Saudi Arabia.*

Climate : *subtropical*

Community : *Rijal Alma*

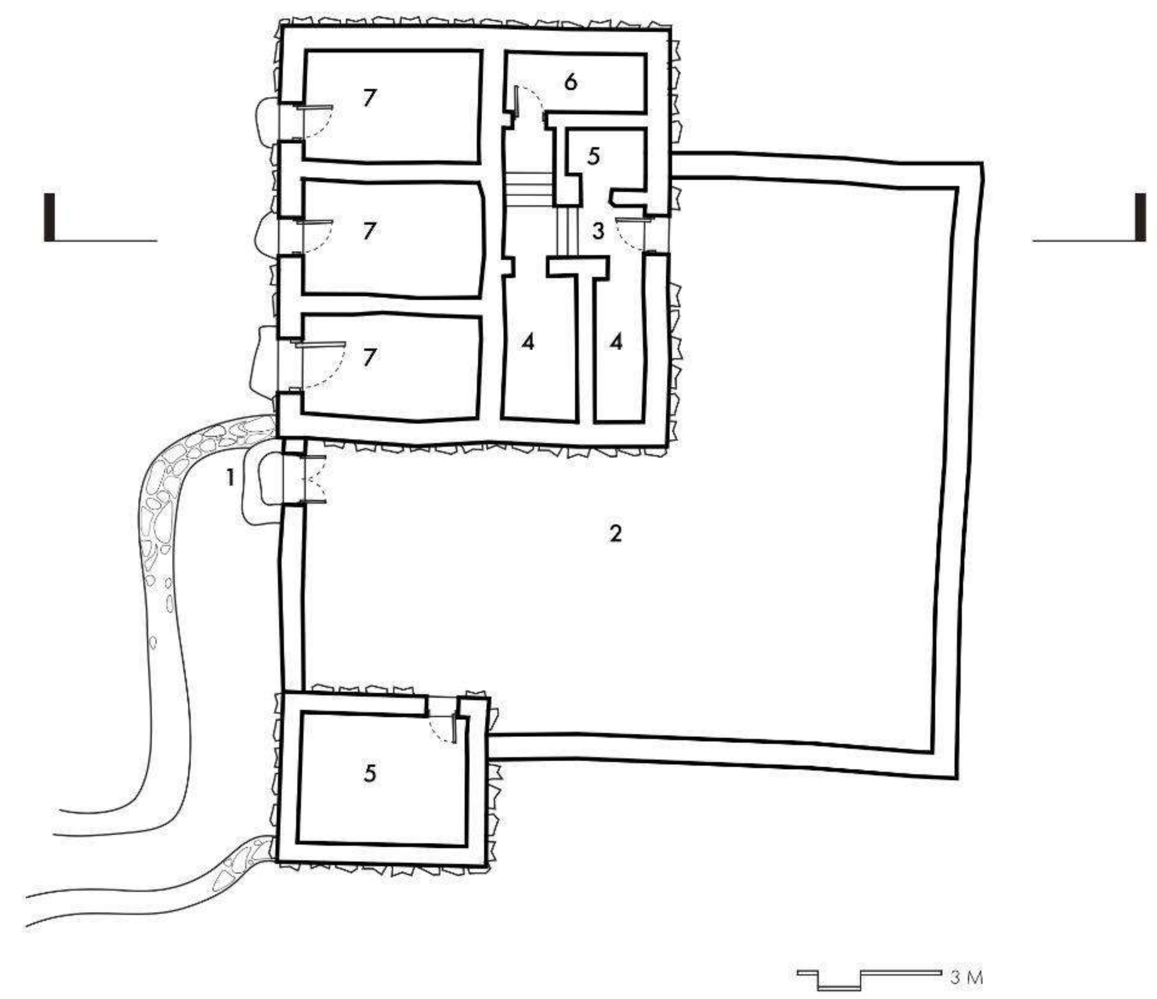
Construction technique*: Stone, adobe, Wood.*

Scale: *from two to five stories*

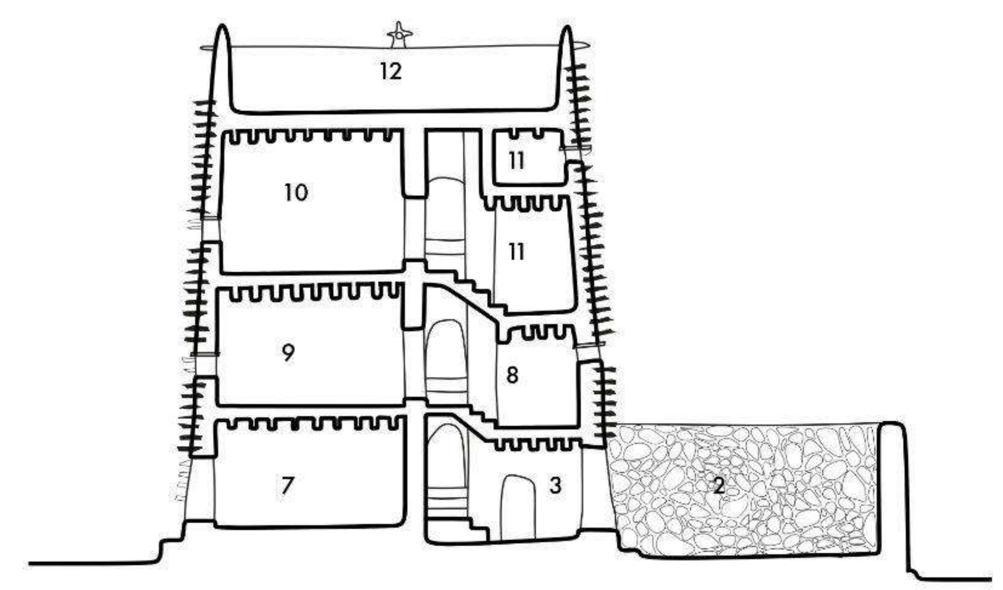
Period: *17th century*

Climatic strategy : The base layer, usually of stone masonry, is followed by a 50 cm high layer of mud, which is then capped with a coursing of thin stone, and allowed to dry before following it with the next coursing. The stone, protruding outwards, serves as a protective skin, redirecting rainwater to not touch the mud walls.

Construction technique: The Vernacular houses of 'Asir are characterized by the combination of mud and stone and the brightly colored stripes of its coursings. This architecture comes from the material's easy availability, the mud extracted in the valley and the stone gathered in the rocky hills.



IAAC 3dPA OTF | 2021-2022 | Mariam Arwa Al-Hachami



Vernacular Housing of 'Asir (K.S.A.)

KEY

1_Main Entry	7_Storefront
2_Courtyard	8_Storage
3_Entry Hall	9_Male Reception Room
4_Animal Stable	10_Female Reception Room
5_Animal Feed Store	11_Storage Room
6_Grain Store	12_Roof

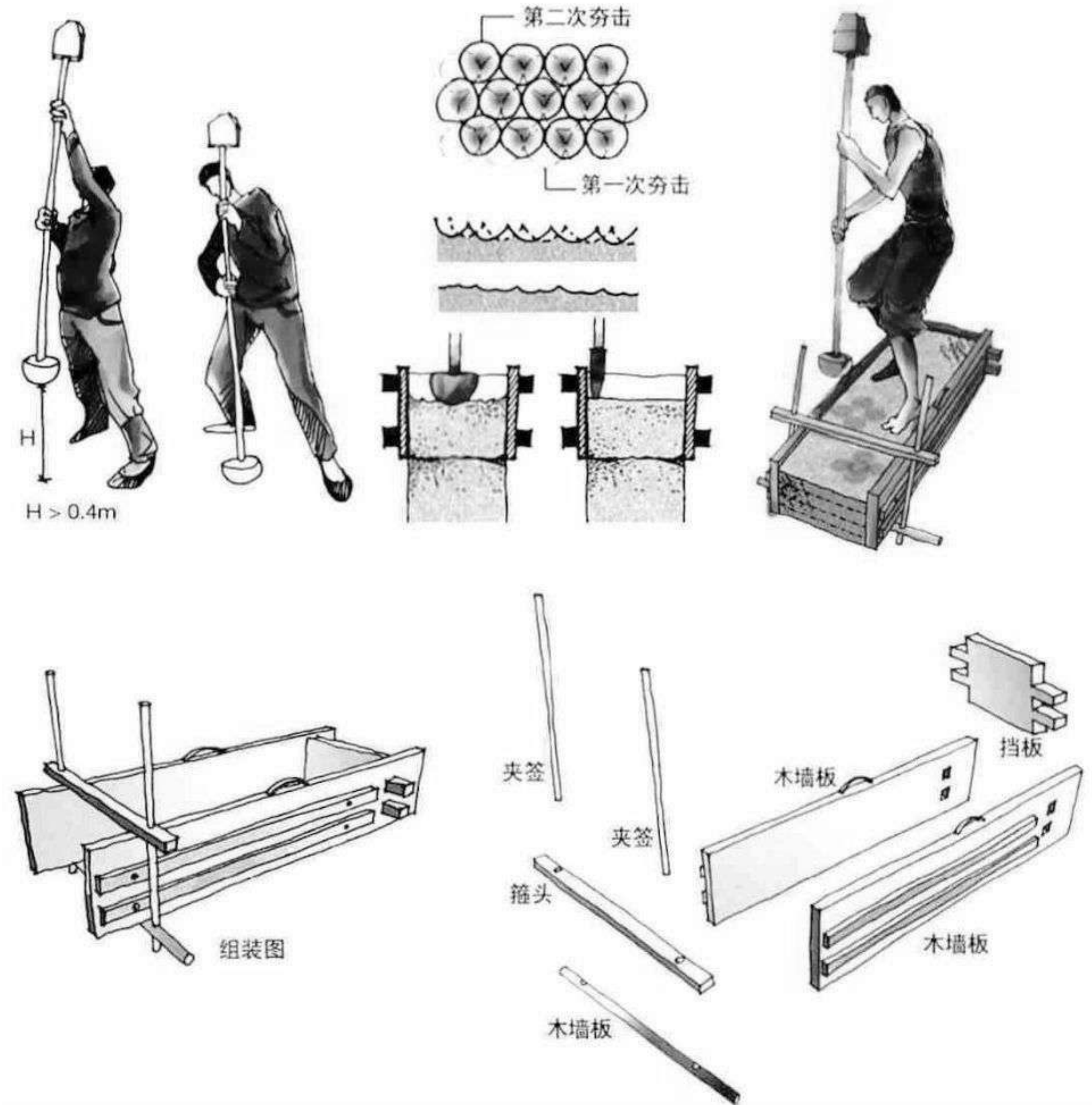
Research by: Aslinur Taskin

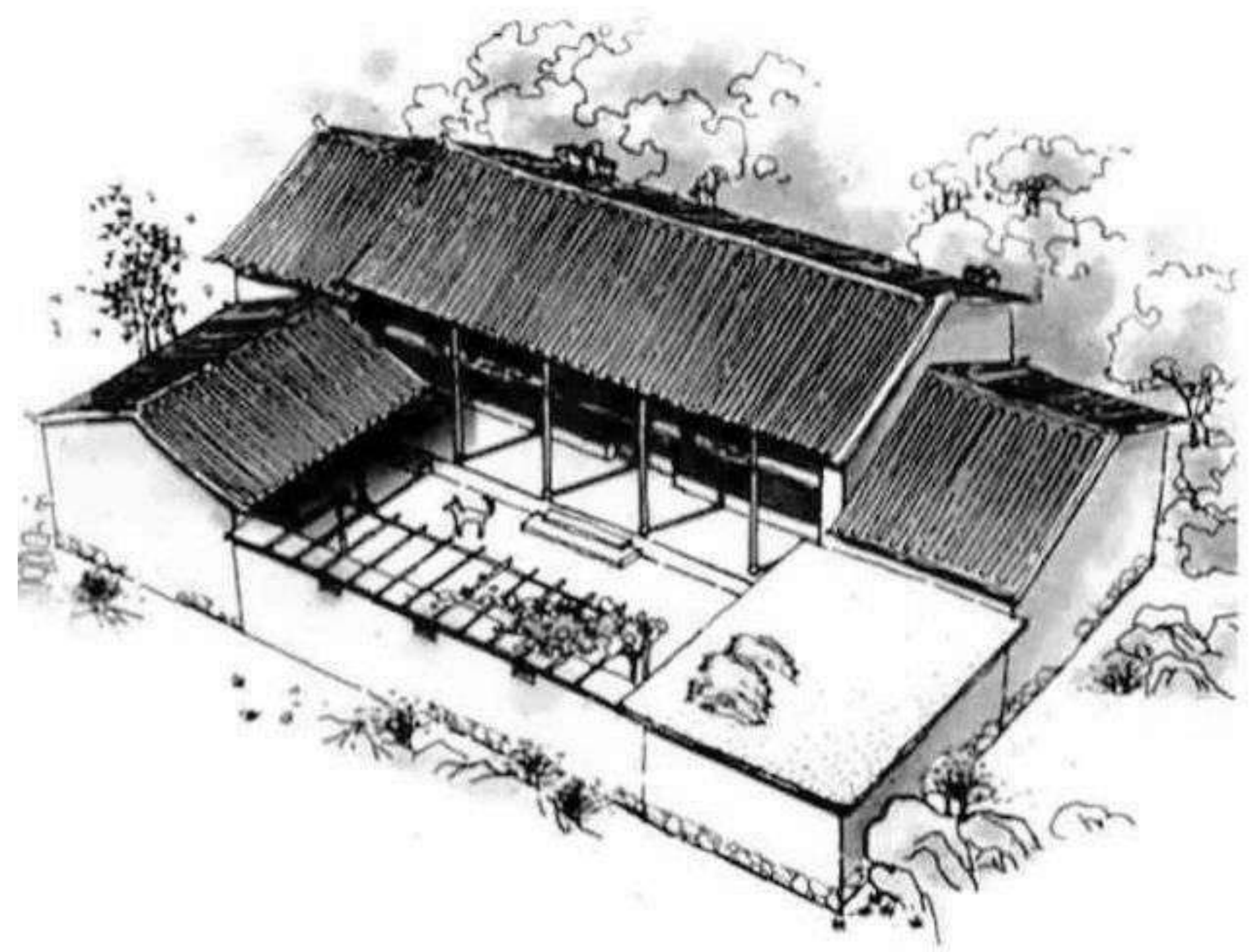
Drawings by: Aslinur Taskin

Ma'anqiao Village

Geography : *M'a'anqiao, China, Asia*
Climate : *subtropical*
Community : *Architects Mu Jun, Edward Ng, Zhou Tiegang, Wan Li, Ma Jie and Ma' anqiao inhabitants*
Construction technique: *Rammed earth*
Scale: *2 storey*
Period: *2008 -Reconstruction after earthquake*

Climatic strategy: the 2008 earthquake destroyed 263 out of 272 houses, as a response a group of architects launched a workshop in which the region's inhabitants and artisans are re-learning the ancient art of rammed-earth constructions.





Research by: Huanyu Li
Drawings by: ?

Bungha House

Geography *: Kutch Kachchh, Gujarat, Western India*

Climate : *Dry-Hot*

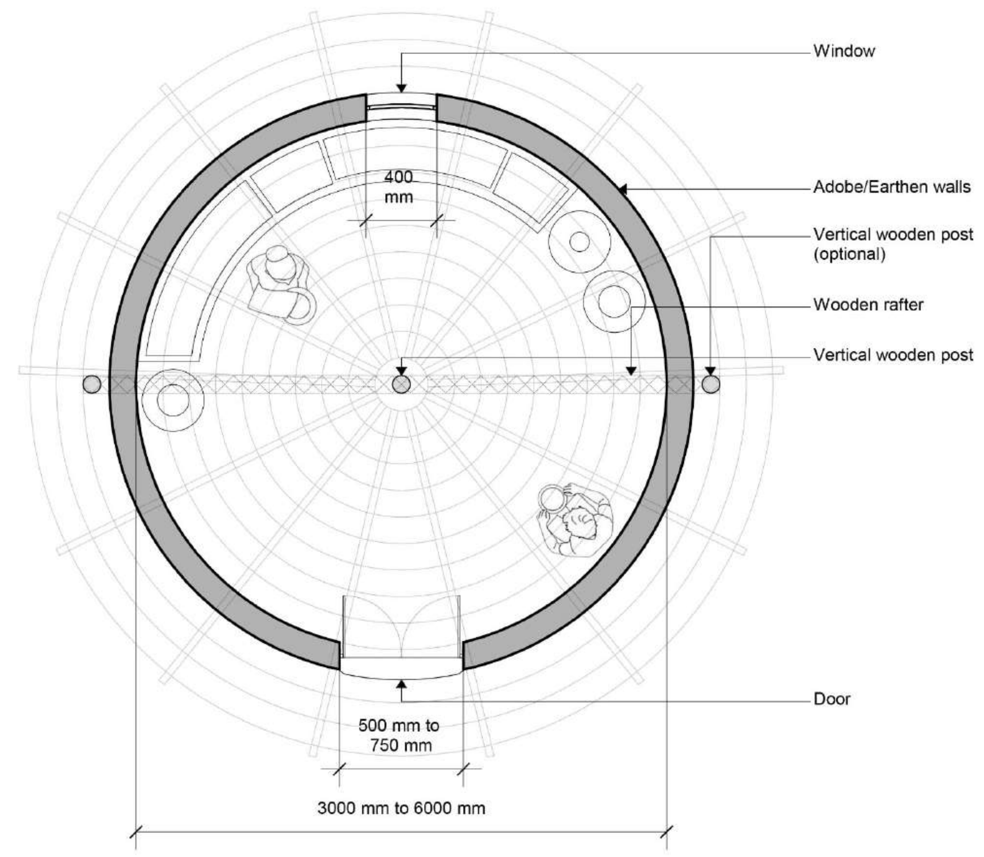
Community : *Bhunga village*

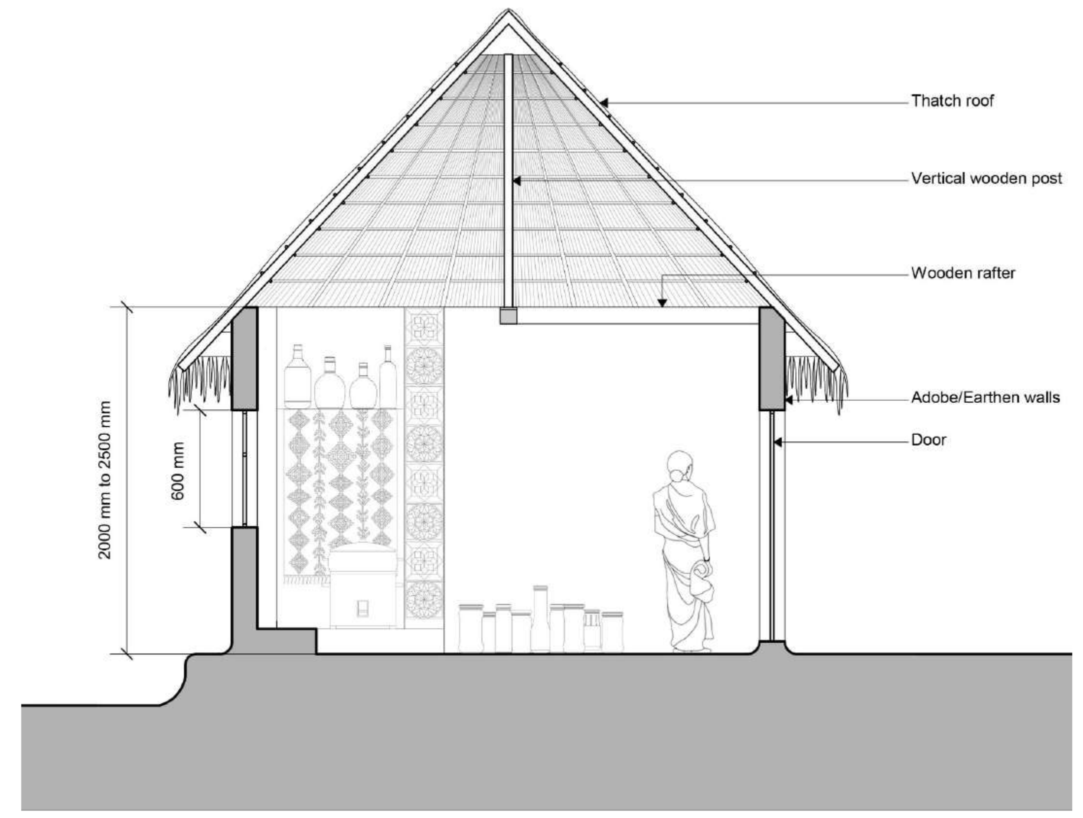
Construction technique: *Adobe walls, straw or lime, conical bamboo roof, thatch*

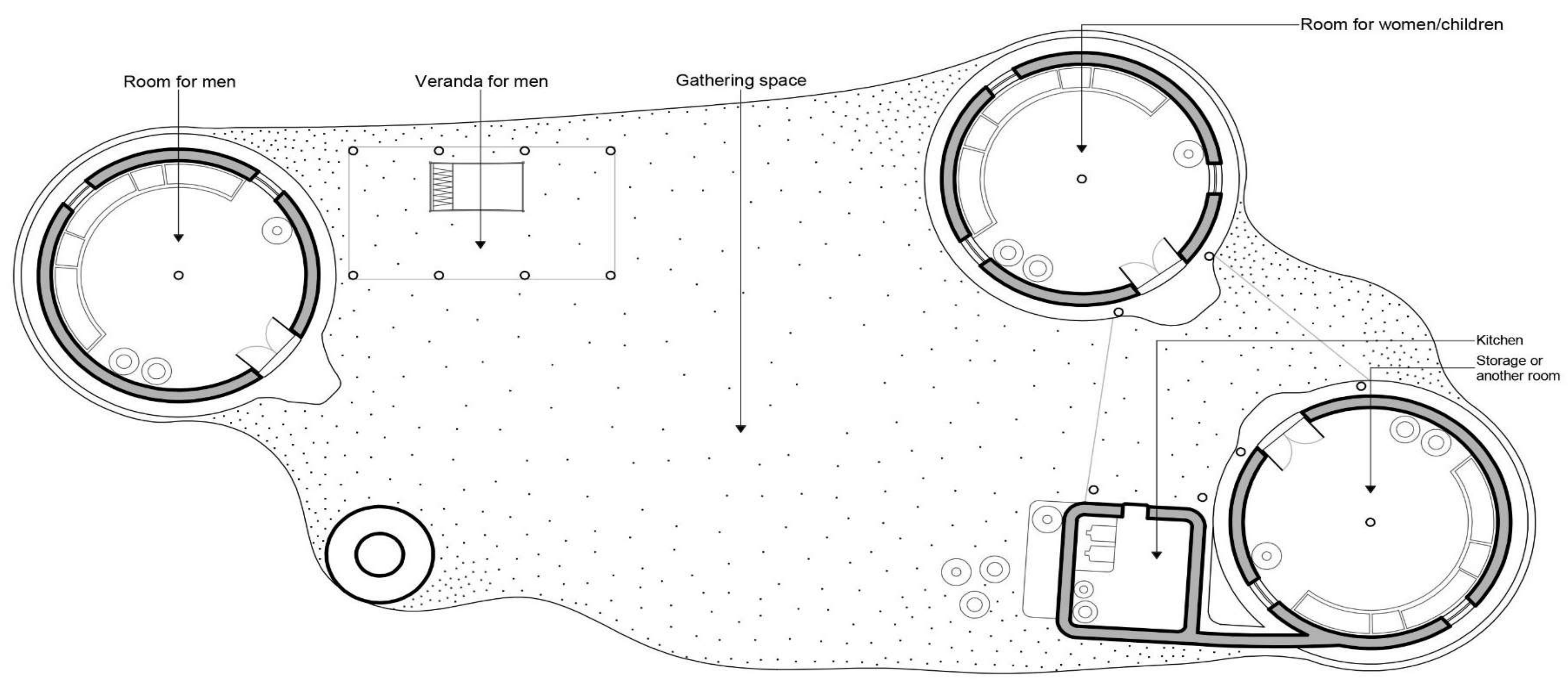
Scale: *H=3.5m, D=3-6m*

Period: *After the 1819 earthquake.*

Climatic strategy : After the 1819 earthquake, the Kutch inhabitants rebuilt structurally stable homes using circular adobe walls with a conical thatched roof protecting the wall from direct sunlight. Its wooden framed windows are set at a lower level for cross ventilation. In order to survive in the desert their circular shape protects against sandstorms and cyclonic winds. For maintenance, a regular application of lime plastering to the walls and floor is required, as well as the replacement of the dried grass on the roof.







Research by: Sakshi Pawar

Drawings by: Sakshi Pawar

Social structure
Geometry can emerge from a community's social culture, such as the courtyard serving as a space for gatherings and social interaction even in continental climates, the same way urban aggregation of houses comes from the need for togetherness.

Ksar Taourirt

***Geography :** Atlas Mountains, Ouarzazate, Morocco.*
***Climate :**   Dry-Hot*
***Community :** Amazigh*
***Technique:** Rammed earth-adobe*
***Scale:**4,5 hectares, 6m height*
***Period:** 19th century*

Social structure: Ksar Taourirt was constructed in the 19th century. It served as a residence for the Glaoui tribe. The inhabitants relied on agriculture for sustenance, cultivating crops, trading, and crafting such as pottery-making, weaving, and metalworking. These skills were passed down through generations and played an important role in the local economy. With its interconnected houses and narrow alleys, the Ksar protected from extreme desert temperature, inside the houses, rooms were often arranged around a central courtyard, served as a focal point for family life and provided a cool retreat from the heat of the day.

Research by: Mehdi Harrak
Drawings by: Mehdi Harrak

New Gourna village

Geography : *Theban necropolis, Luxor, Egypt*

Climate : *Dry-Hot*

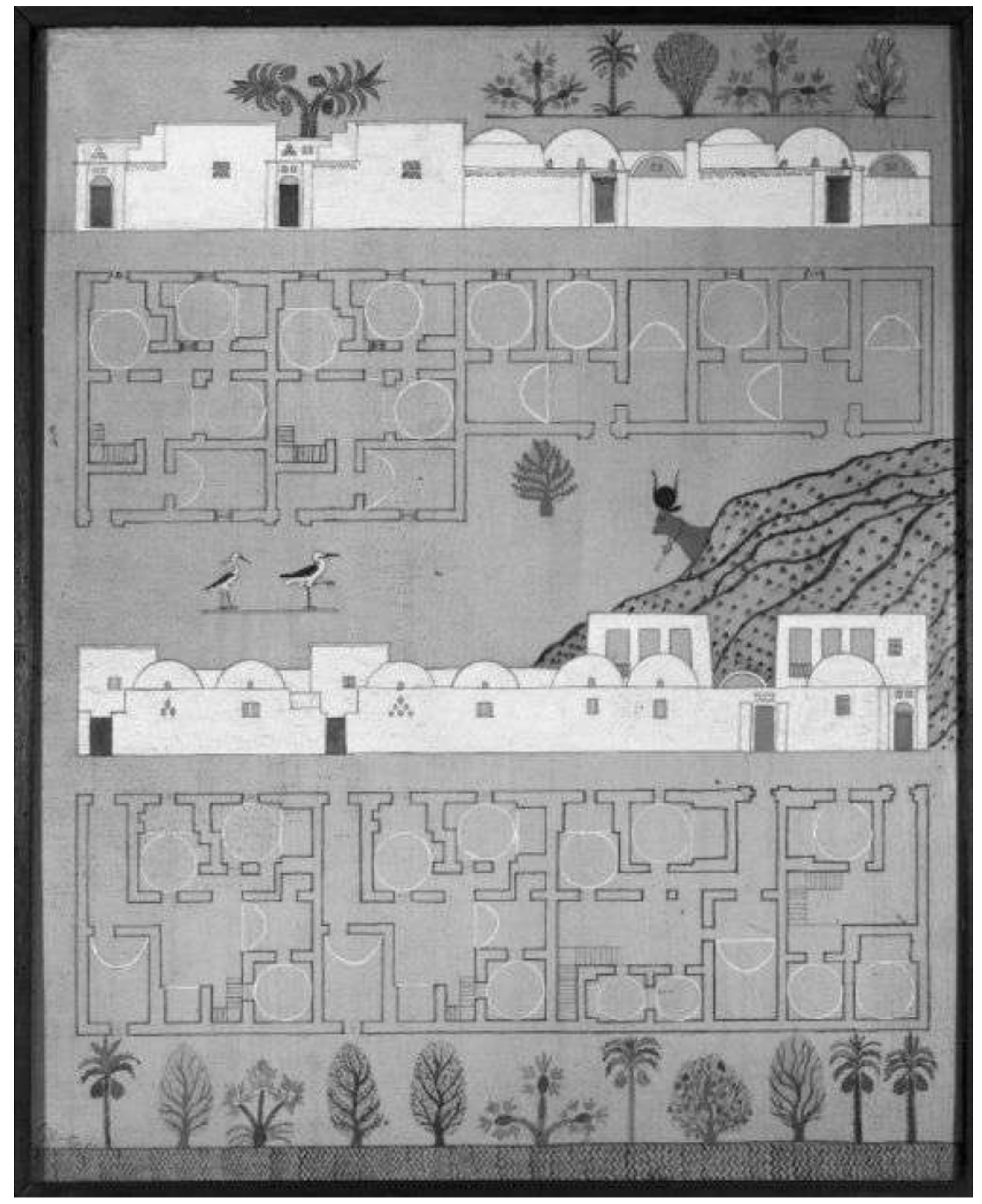
Community : *Gourna*

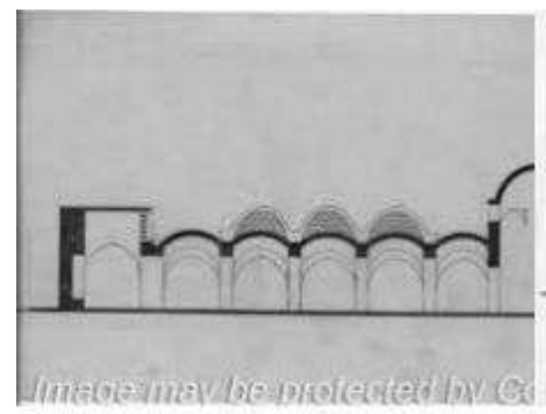
Construction technique: *adobe (mudbrick)*

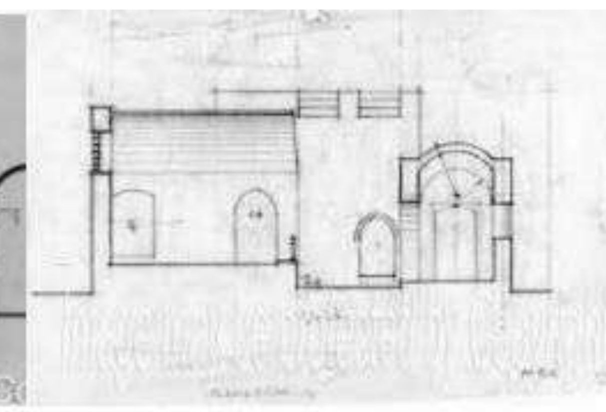
Scale: *two storeys*

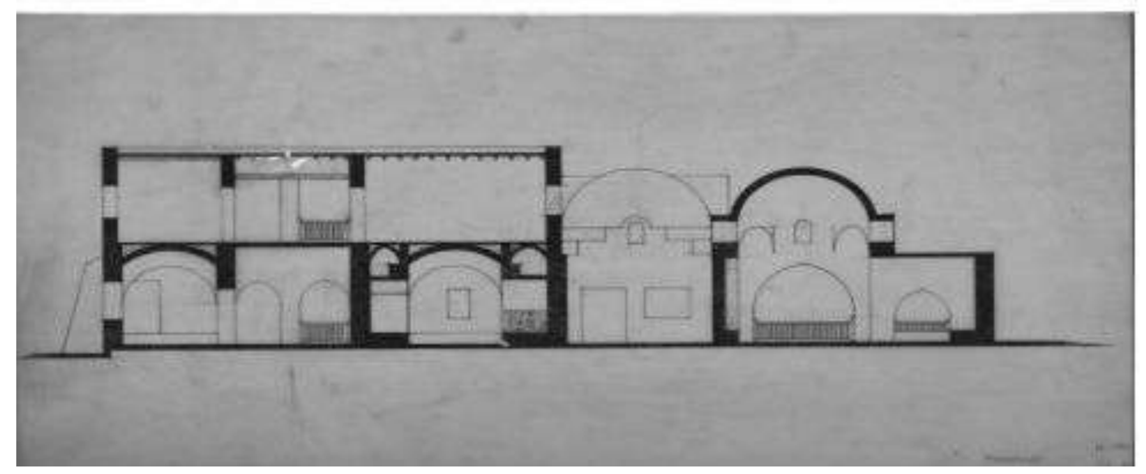
Period: *1945 and 1948*

Social structure : *In the 19th century, Gourna began as a farming settlement near Luxor, positioned at the base of the Theban necropolis. By 1945, it had transformed into a village with around 7,000 inhabitants, relying on the pillaging of ancient Egyptian tombs. A decision by the Egyptian Department of Antiquities was then made to relocate the village to a new location closer to Luxor, commissioning the architect Hassan Fathy. Working with the community, he integrated traditional earthen materials and building techniques.*









Research by: Sammar Z. Allam, Abanub Nagy

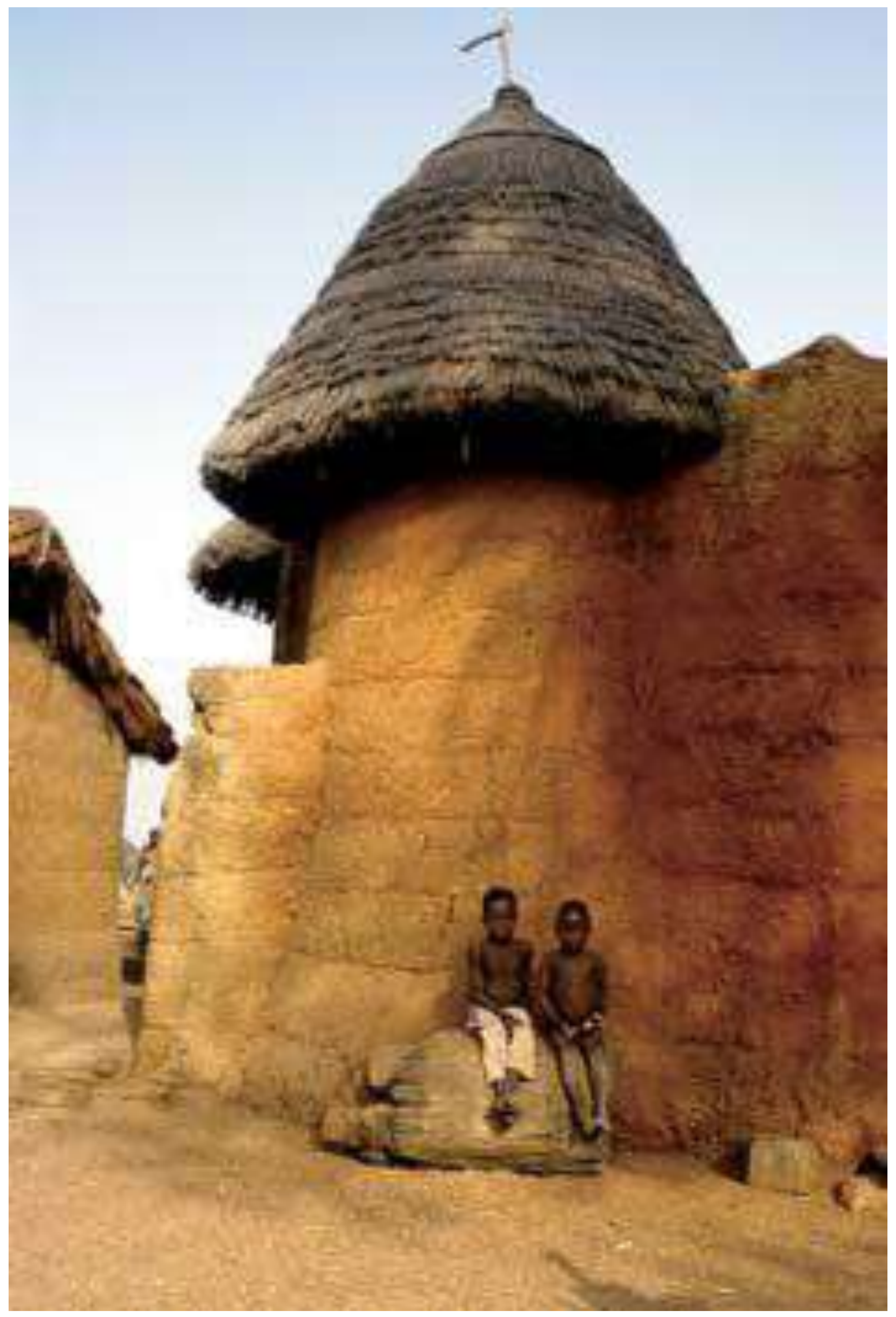
Drawings: External

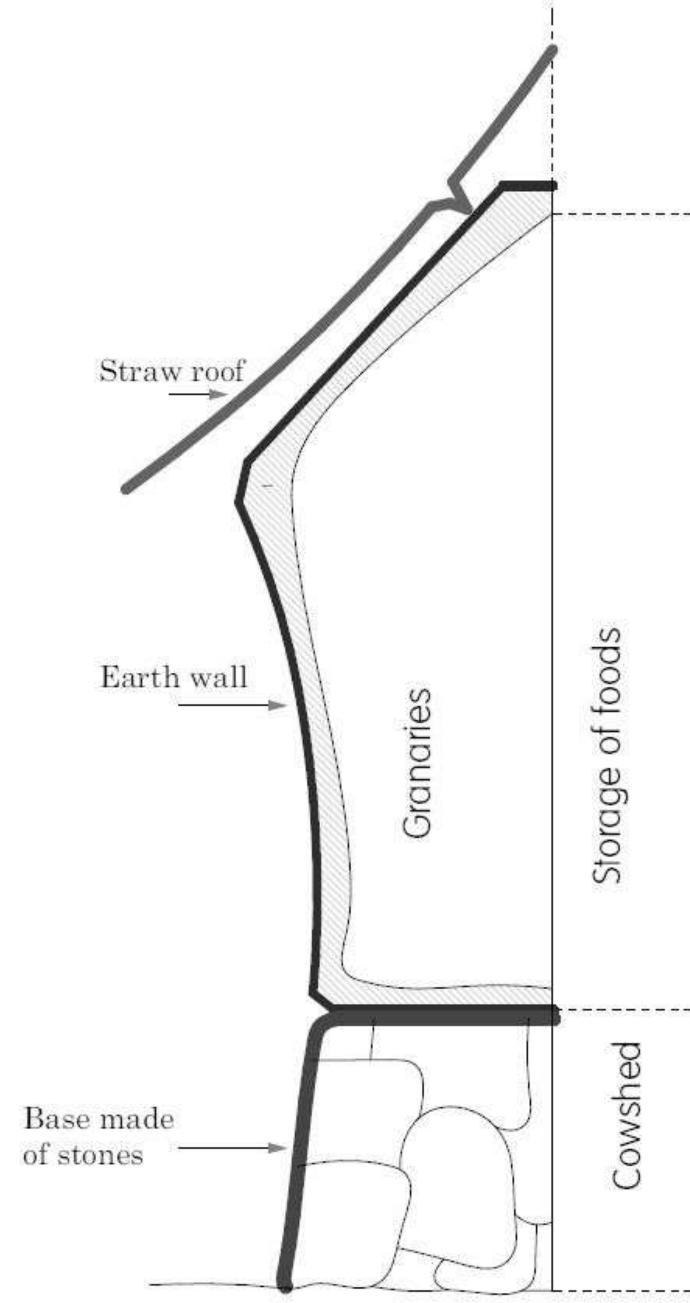
Tata

Geography : *Mount Kenya, central Kenya*
Climate : *subtropical*
Community :*Gikuyu*
Construction technique: *wattle and daub, thatch*
Scale: *5m diameter, 4m height*
Period: *-*

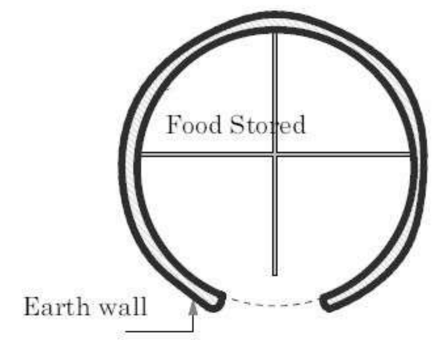
Social structure: These circular and ovoid earth constructions serve both as a house, as granaries and also as stables, they are built directly on the ground, with a stone base and without foundations anchored in the ground. In the case of the granaries, the animals occupy this basement while the upper level is used to store the food of the family.

Construction technique : The walls are handmade with earth mix, in successive layers of about 30 cm in height. A drying time of one to several days is necessary between the application of each coat. The highest parts of the construction have about 12 layers. They are therefore around 3m60 high.
The waterproofing is sometimes done with a mortar of earth mixed with cow dung.The roofs are typically thatched with straw or palm leaves

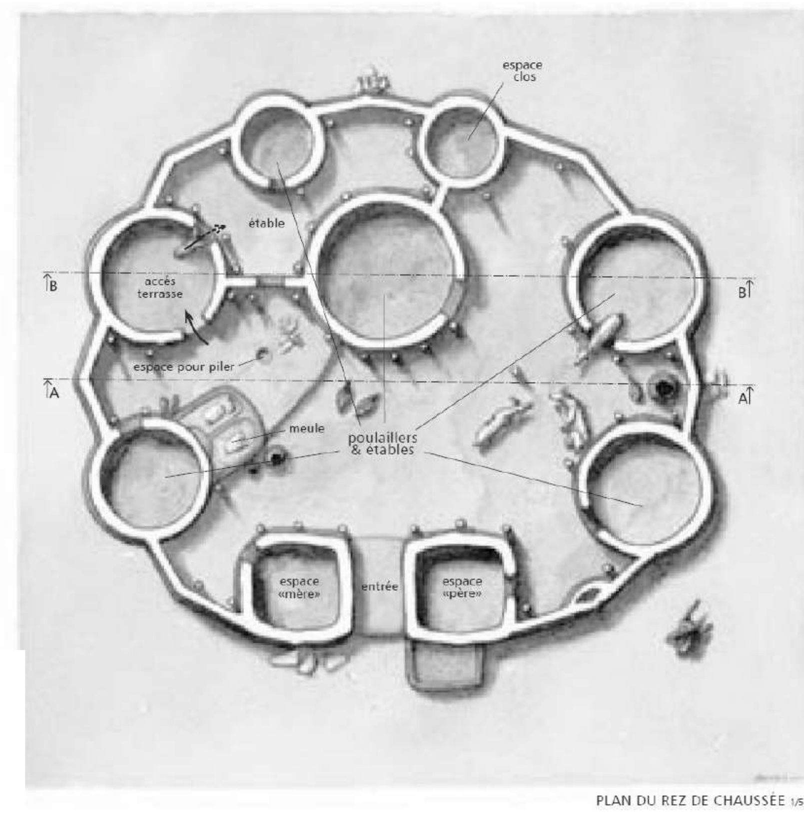




SECTION



GroundFloor Plan



Earth lodge - Bordei houses

Geography :*Oltenia region, Romania*

Climate : *Mediterranean*

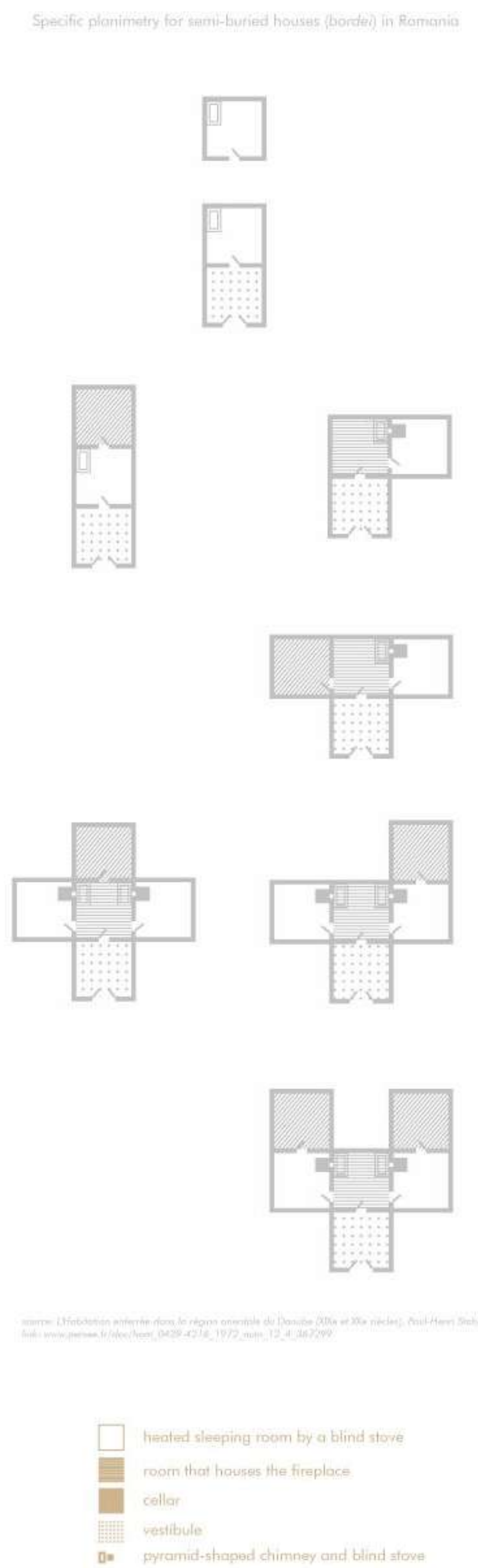
Community : ***Architect ?***

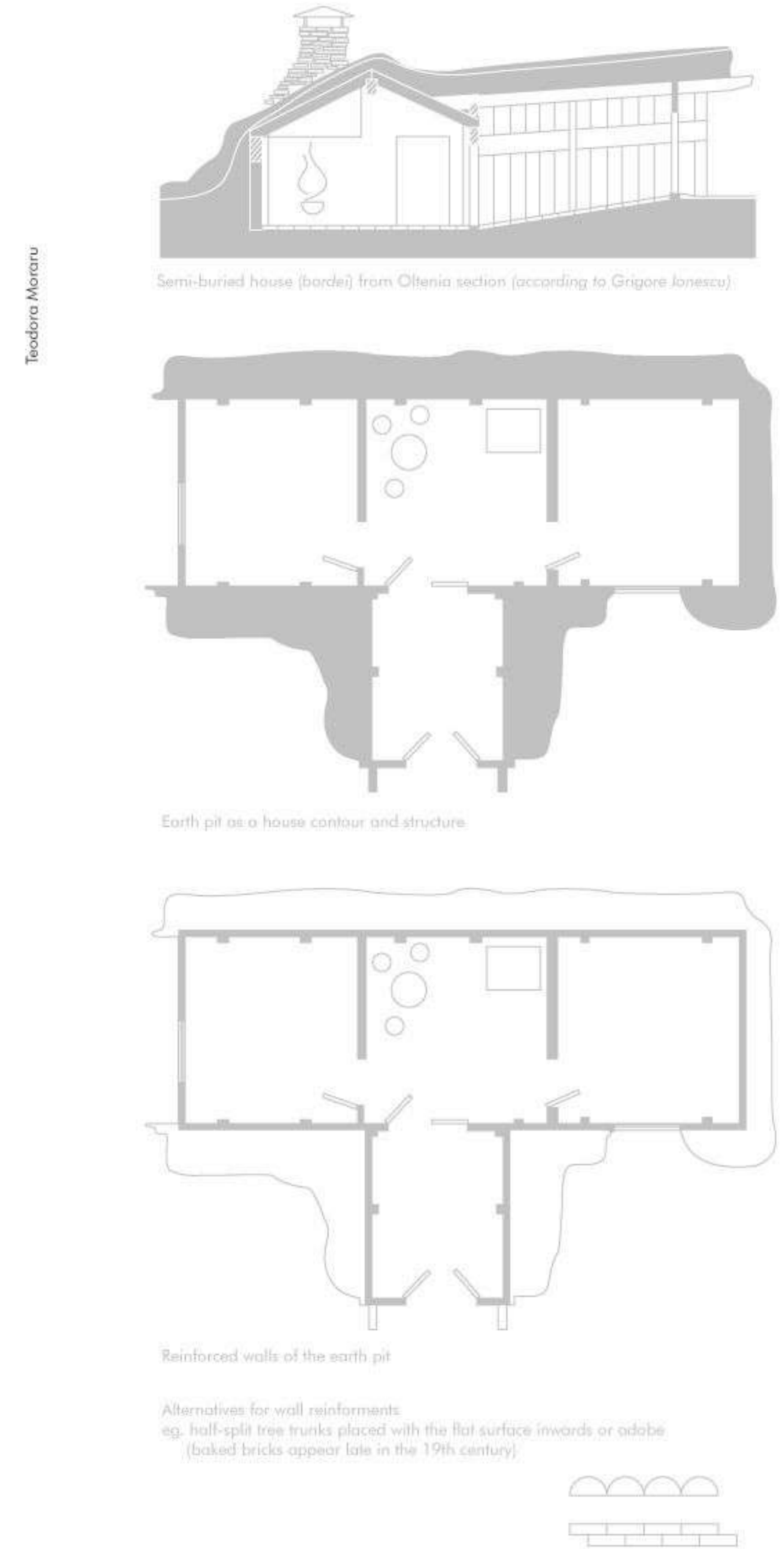
Construction technique: Earth, wood

Scale: *partially underground house-1 story*

Period: *Neolithic period*

Social structure : Besides houses, semi-subterranean buildings sometimes had other destinations such as churches, grain storage, animal shelters or textile workshops. Earth lodges were constructed partially below and partially above ground level. The building was covered with a thick layer of earth. The interior floor level was generally at 0,6-1,2 m below ground.





Research by: Teodora Moraru
Drawings by: Teodora Moraru

Tu Lou Dwelling

Geography : Southern Fujian, China

Climate : Subtropical

Community : Hakka, Hoklo, Minnan

Construction technique: Stones, Rammed-earth, branches, Wood structure roof, clay tiles

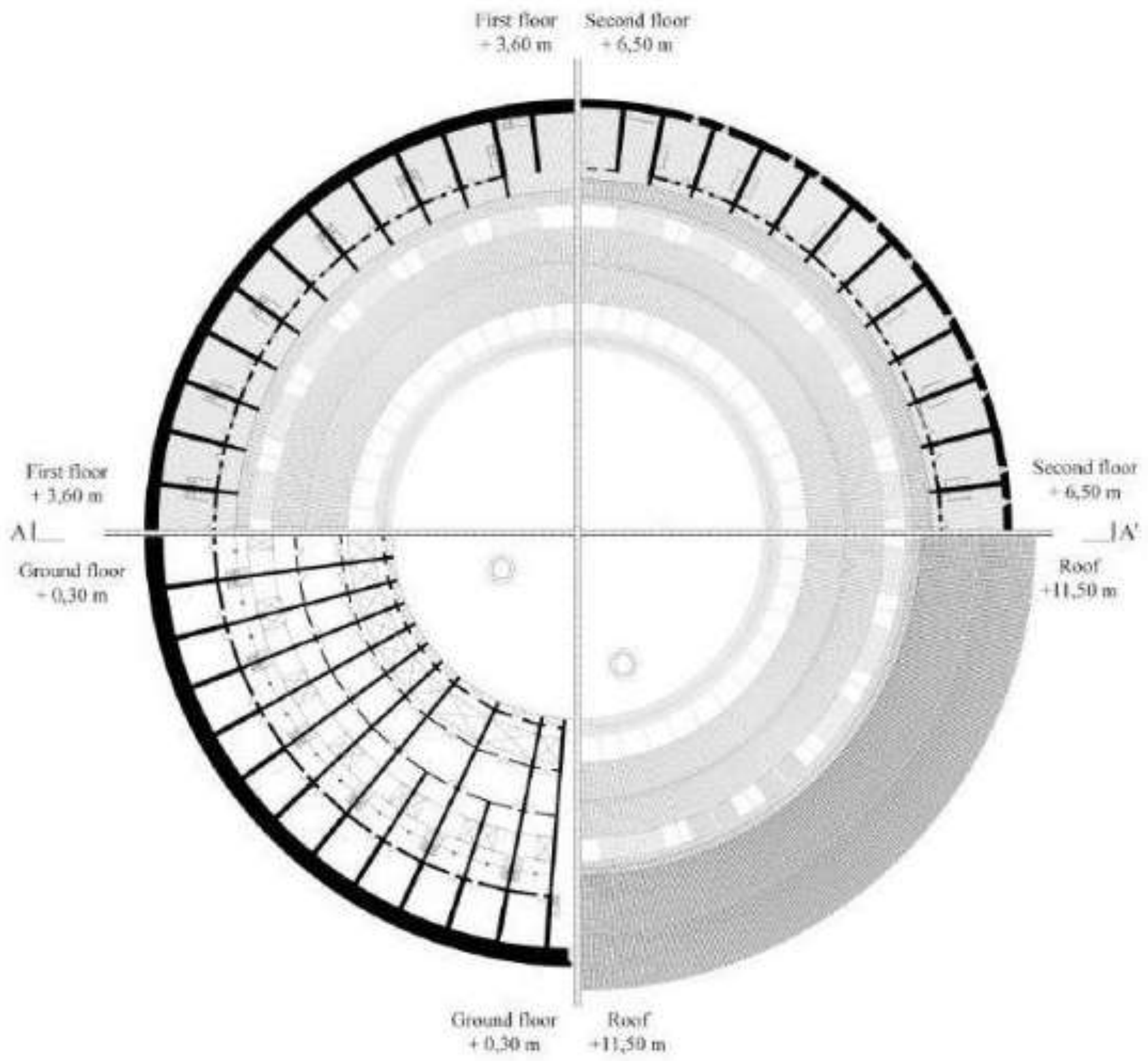
Scale: 3 to 5 floors high; up to 80m of diameter.

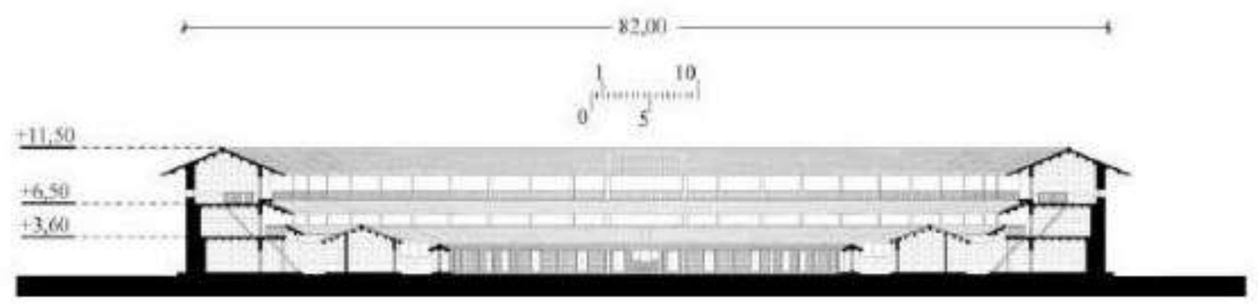
Period: XIV - XX century

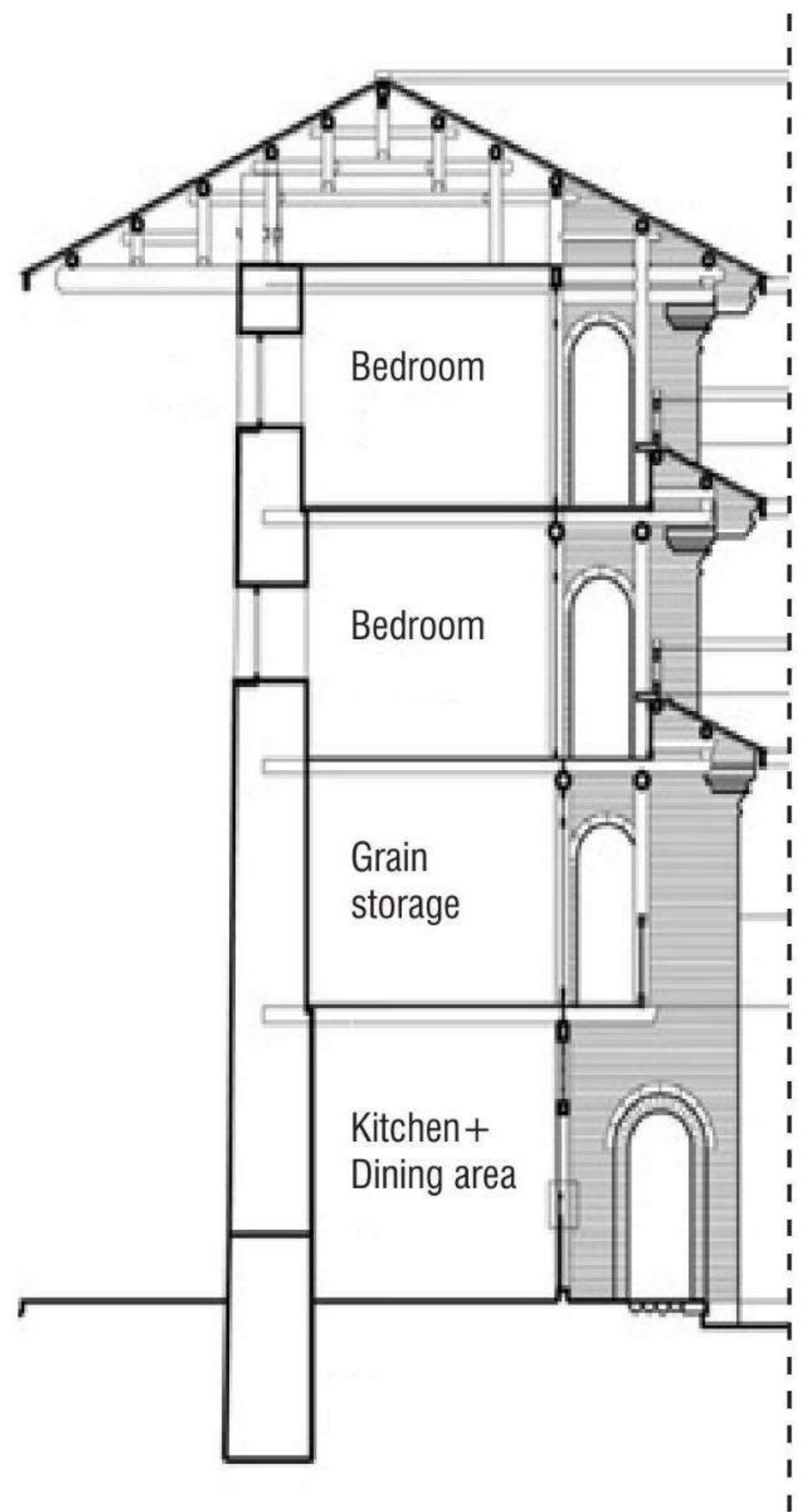
Social structure : The houses are disposed radially around the center, which was left free as common space with, sometimes, communal areas such as schools, granaries, guest rooms. Every family in the Tulou community enjoys perfect equality because every room in a Tulou is the same size and has exactly the same design.

climatic strategy : (Tu) earth (Lou) buildings, is a massive circular fortress built by the Hakka people to protect themselves from invasions of the Mongols.

Construction technique: It is an enclosed structure that is usually circular or rectangular in shape and is used to house multiple families, in 2 to 5 storeys high. The outer wall is constructed using the rammed earth technique : a building process involving the compression and compaction of the earth inside wooden movable formworks. The wall is made of modular blocks, called ban, inside each ban, longitudinal bars made of bamboo reeds and branches are inserted. In order to protect the structure from rainwater, the raw earth wall is placed on a large foundation made of dry-stone masonry with pebbles.







Research by: Leonardo Bin, Yang Xiao

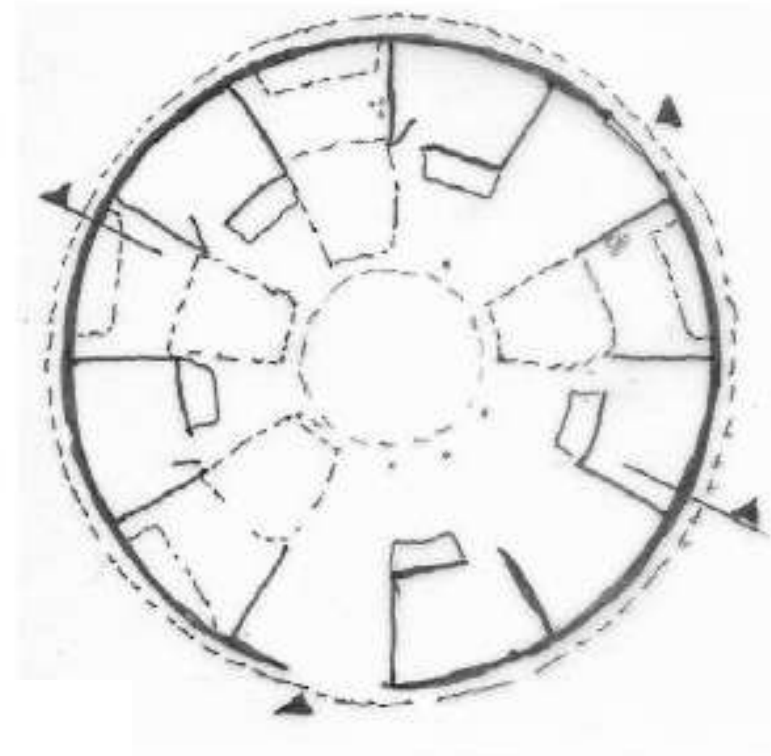
Drawings by: Leonardo Bin

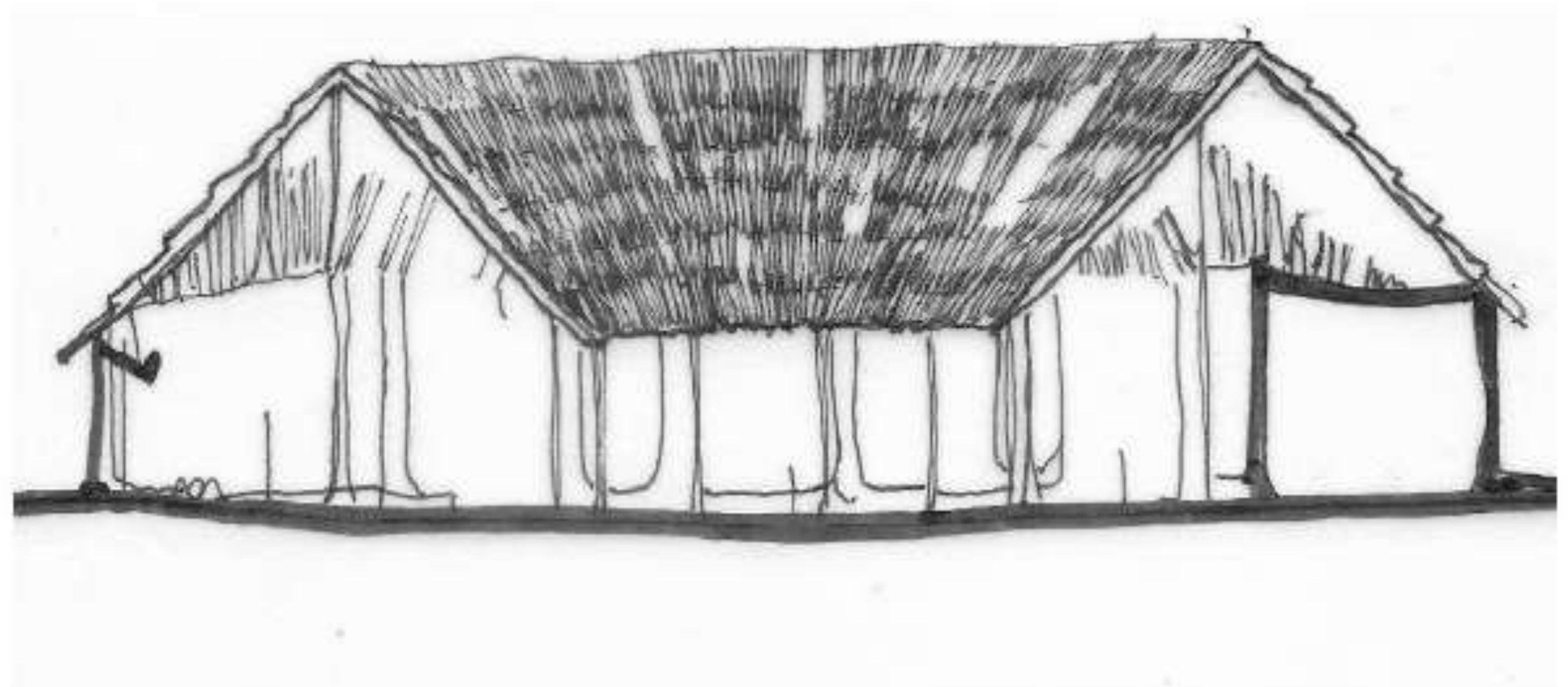
The Dida's Annular hut

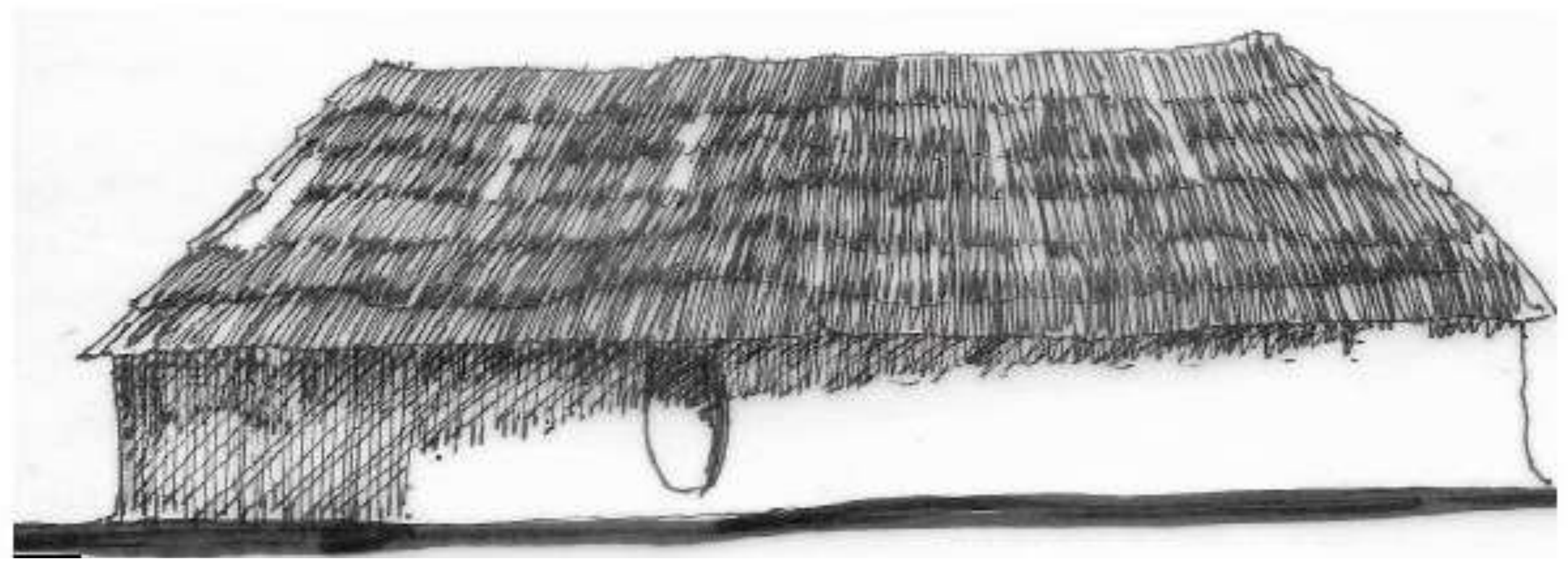
Geography : Sassandra River, Ivory coast
Climate : Tropical
Community : Krou ethnic group
Construction technique: *wattle and daub*
Scale:from 5m to 15m diameter? 3,80m height
Period: -

Social structure: Its scale varies, hosting extended families, or a single household. In large huts, the central opening serves as a courtyard an extension of the house, and distributing to different rooms of the family, in smaller huts, the opening is only an impluvium concentrating water to the “canaris” (a spherical pottery) on the ground

Construction technique : The impluvium house consists of a two sloped thatched roof surrounding a circular inner courtyard.





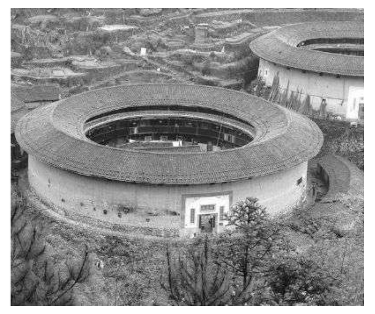


Research by: Noel Akroma
Drawings by: Noel Akroma

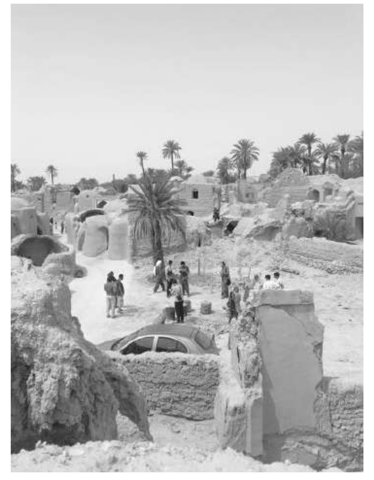
Geography

Asia





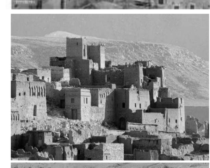
Middle east

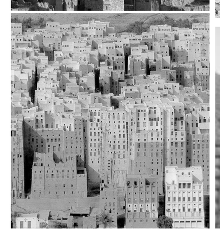
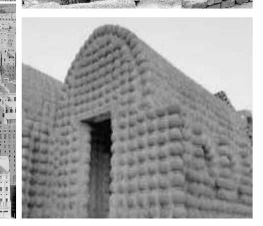
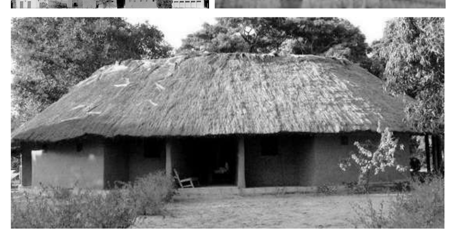



Africa








South america

North America

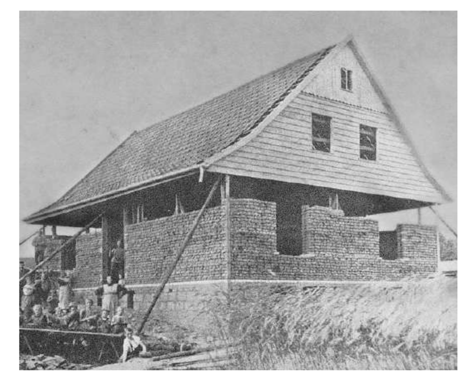


Europe





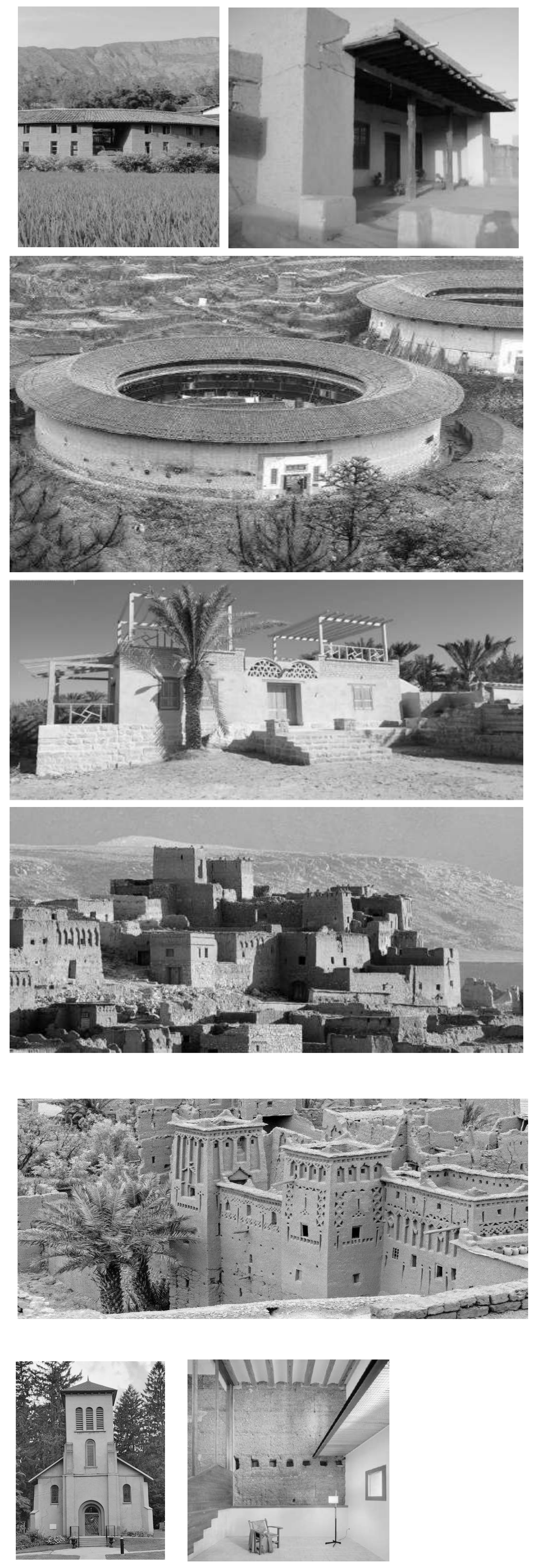




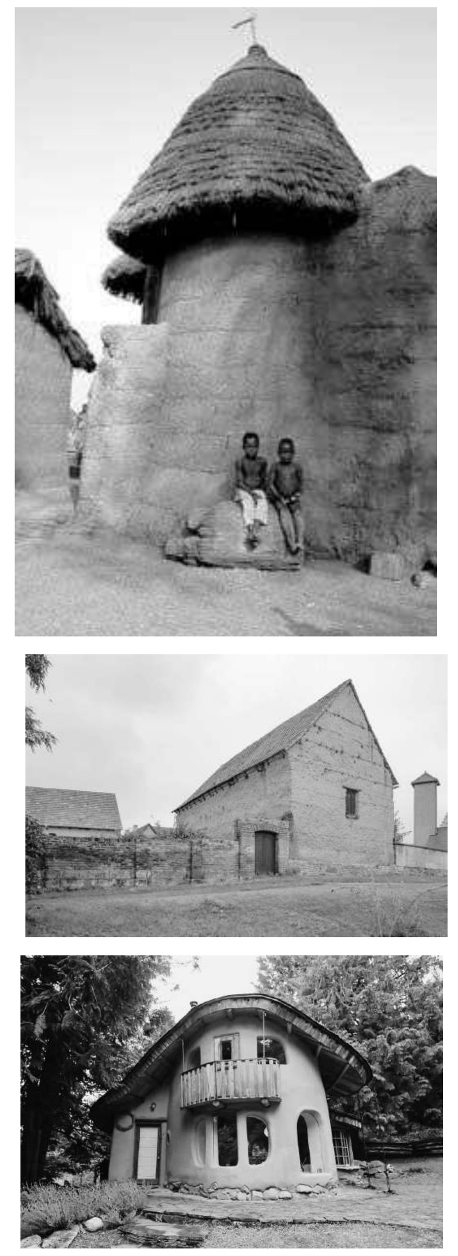
Construction technique

Adobe

Rammed earth

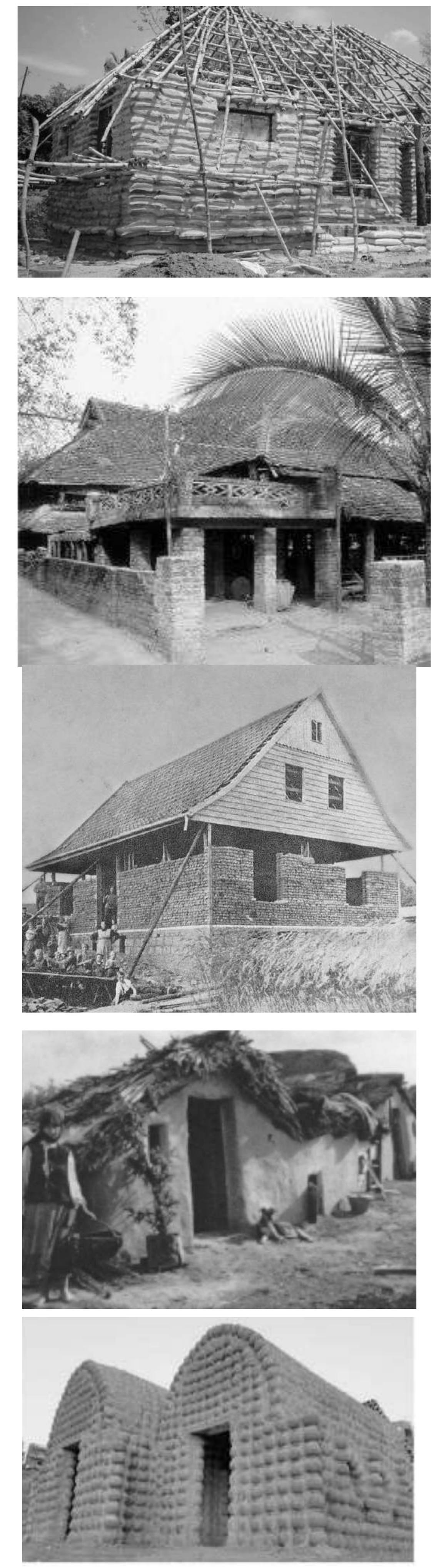


Cob



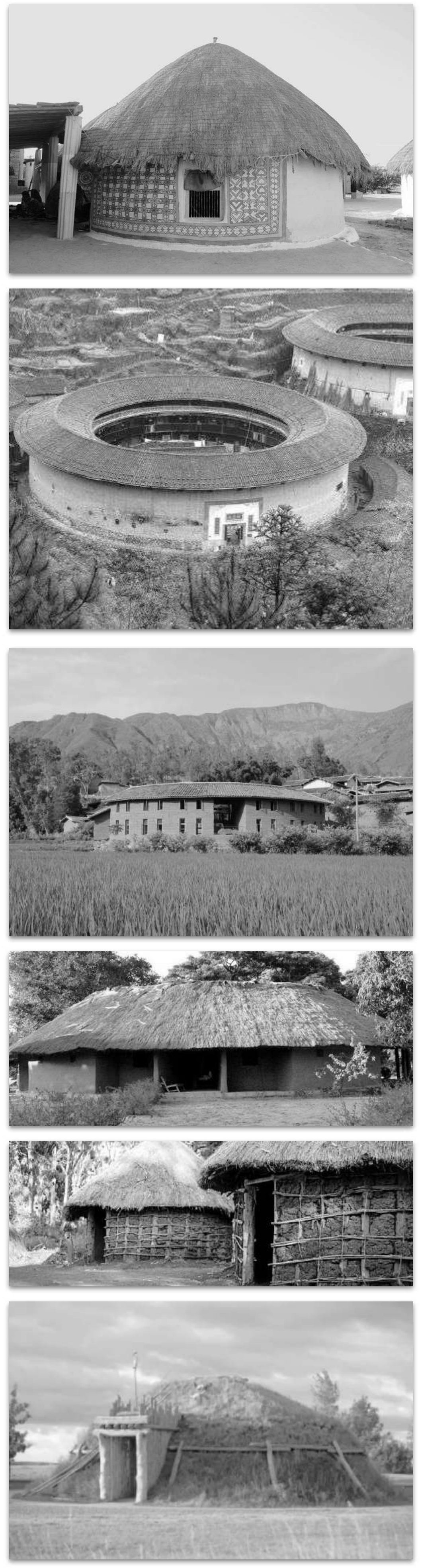
Wattle daub

Other

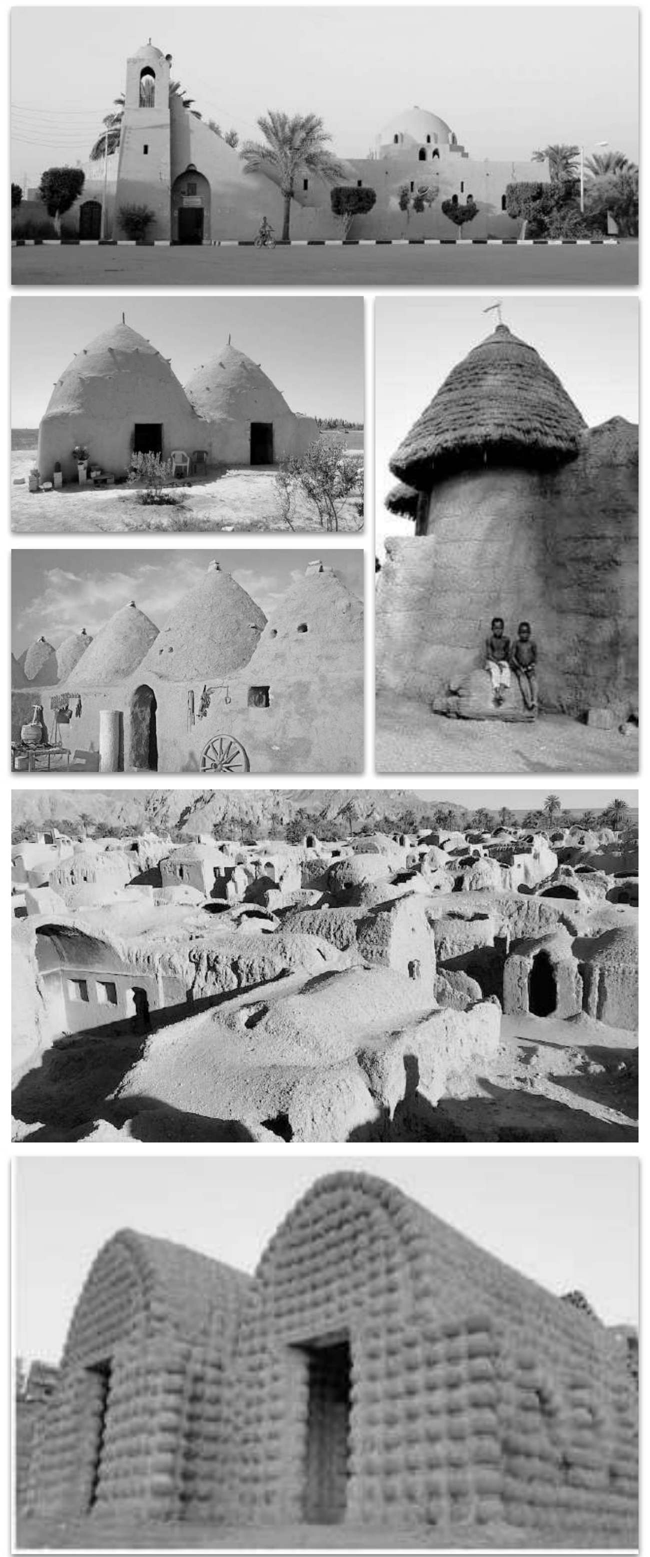


Geometry

Circular

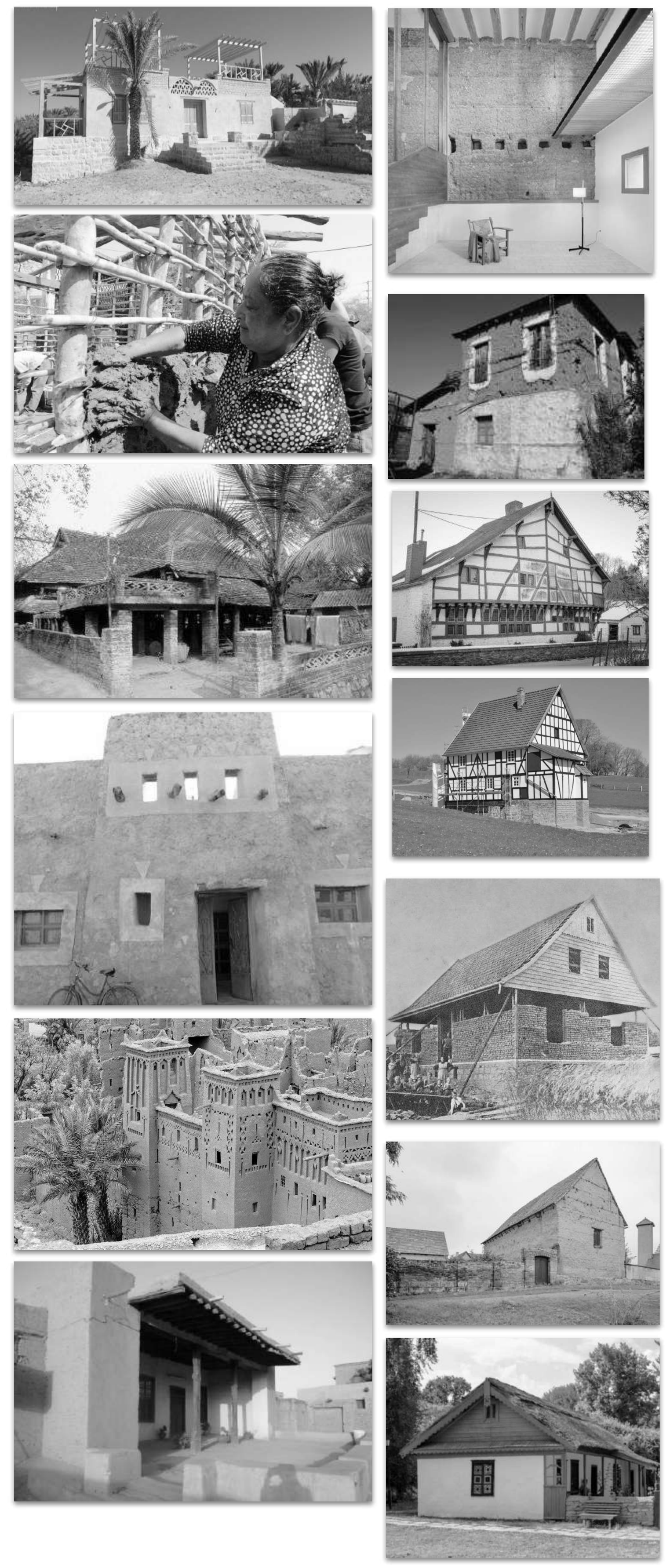


Spherical

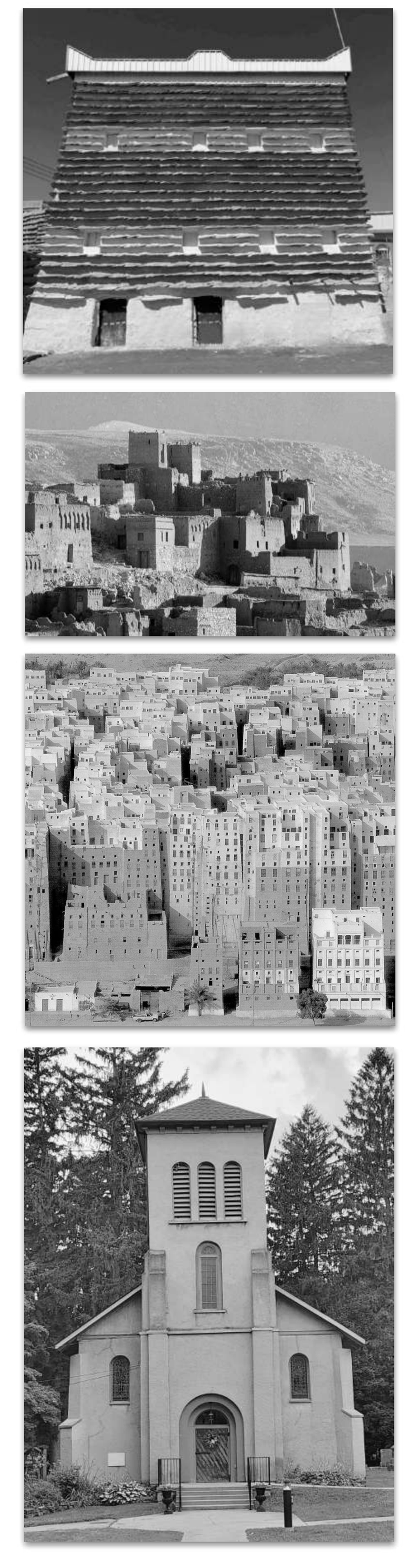


Organic

Orthogonal



High



Geometry

Construction technique

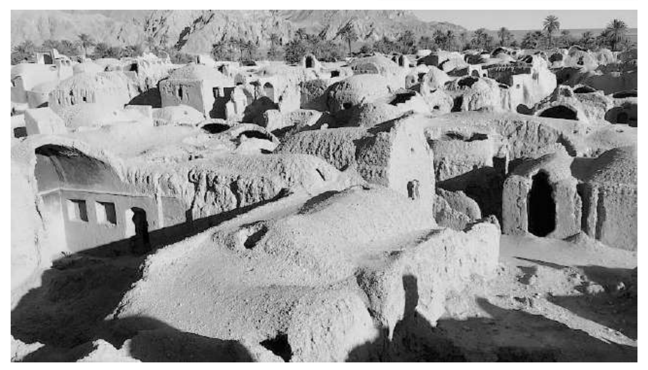






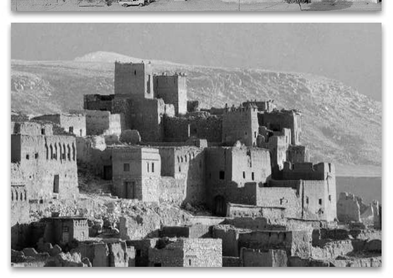
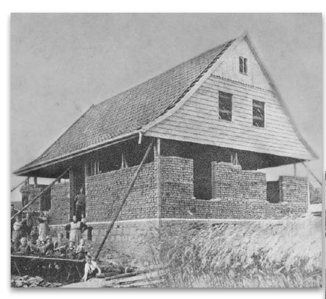








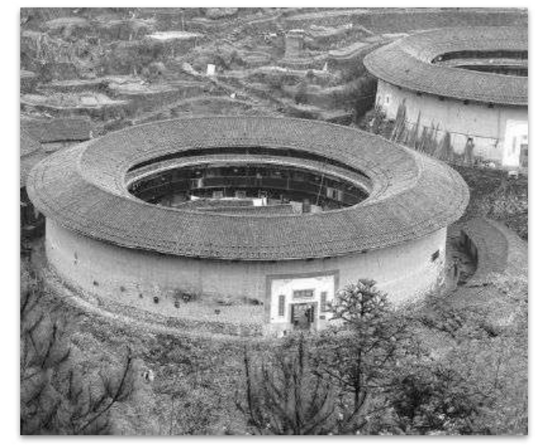


Climatic strategy




Social structure




II. digital analogy

digital analogy explores the integration of the insights of the above into 3D printed construction detail, wall designs and architectural strategies, addressing the three challenges with a different point of view.

1. Construction technique
For 3D printing, earth is sourced on-site and used for construction. Despite the integration of fibers that offer some tensile strength, earth predominantly works in compression, and benefits from traditional knowledge in wall openings, domes, arches and vaults.

Sourced earth

Worksite, Ourika, Morocco

Vernacular architecture embraces the use of locally available earth. Builders gather earth from nearby sources. With water as a binding agent, this mixture is transformed into cob, adobe, or rammed earth, depending on the region and technique employed. It can then be shaped into bricks or applied directly to construct walls.

3D printing techniques that use locally sourced earth materials involve sourcing locally available earth, sifting it, and then mixing it with fiber additives for stability and flow. The mix is extruded layer by layer to shape walls and structures.

1. Worksite, Teixit, collective prototype, 3DPA 2024

Mixed fiber

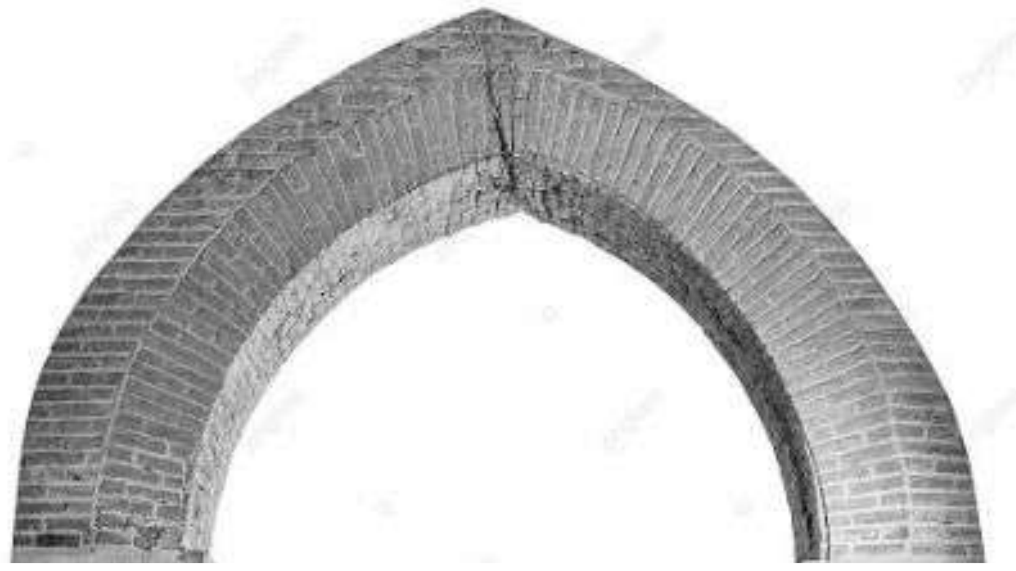
Daub mix, Mexico

In traditional earth techniques, natural elements are incorporated, such as straw or dung, to enhance its properties. Earth is mixed with fibers such as straw, osier, etc., to improve performance and binding in the wet state.

In 3D printed architecture, earth is mixed with fibers (such as sisal, enzymes) for extrudability in the wet state and binding tension in the dry state.

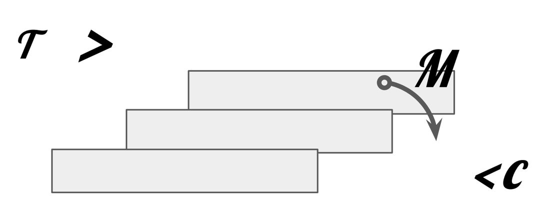
1. Mix, Teixit, collective prototype, 3DPA 2024

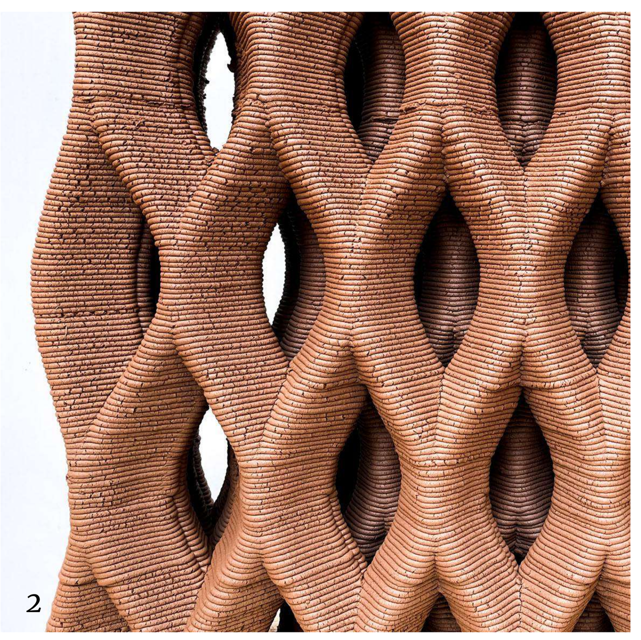
Pointed arch



The pointed arch is common in Gothic, Byzantine, and Islamic architecture. It begins by laying the first row of bricks, known as the voussoirs, followed by the bottom row of the arch, known as the soffit or intrados. At the top of the arch, the width gradually decreases to form the pointed apex.

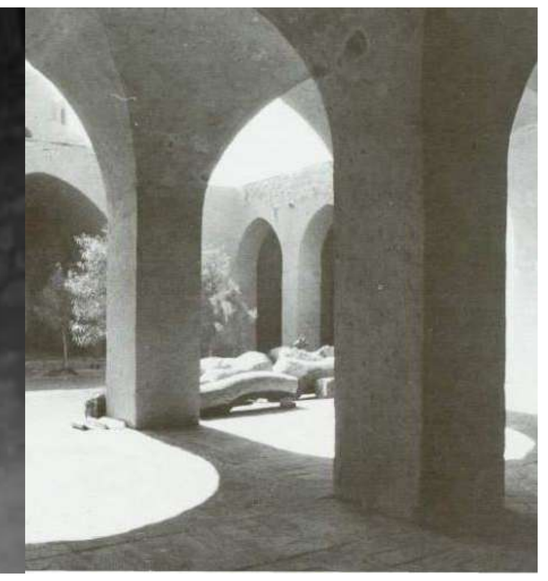
In 3D printing, the layers overlap at a maximum overhang of 25°, forming a pointed shape that reproduces the apex.





1. Opening in 3D printing, by Jing-Wen Chiou & Christopher Bierach, 3dPA 2019/20
2. 3d printed windows and wall porosity, by Luis Jayme Buerba, Lynette Masai and Tapiwa Mirirai Manase, 3dPA 2020/21
3. Teixit, collective prototype, 3dPA 2023/24

Vaults



Geography : *Theban necropolis, Luxor, Egypt*

Climate : *Dry-Hot*

Community : *Gourna*

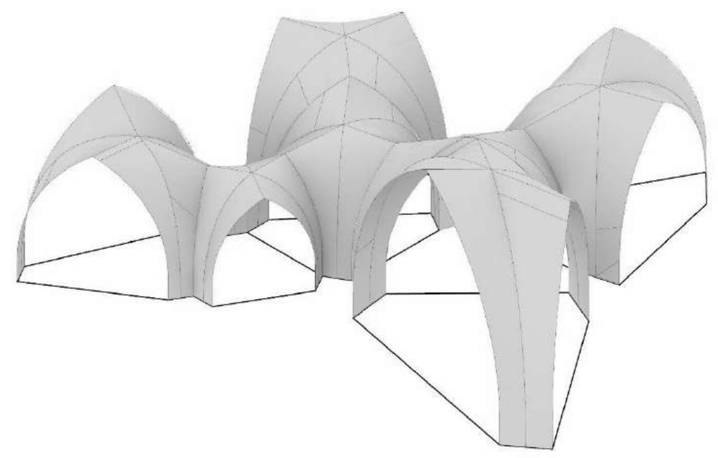
Construction technique: *adobe (mudbrick)*

Scale: *two storeys*

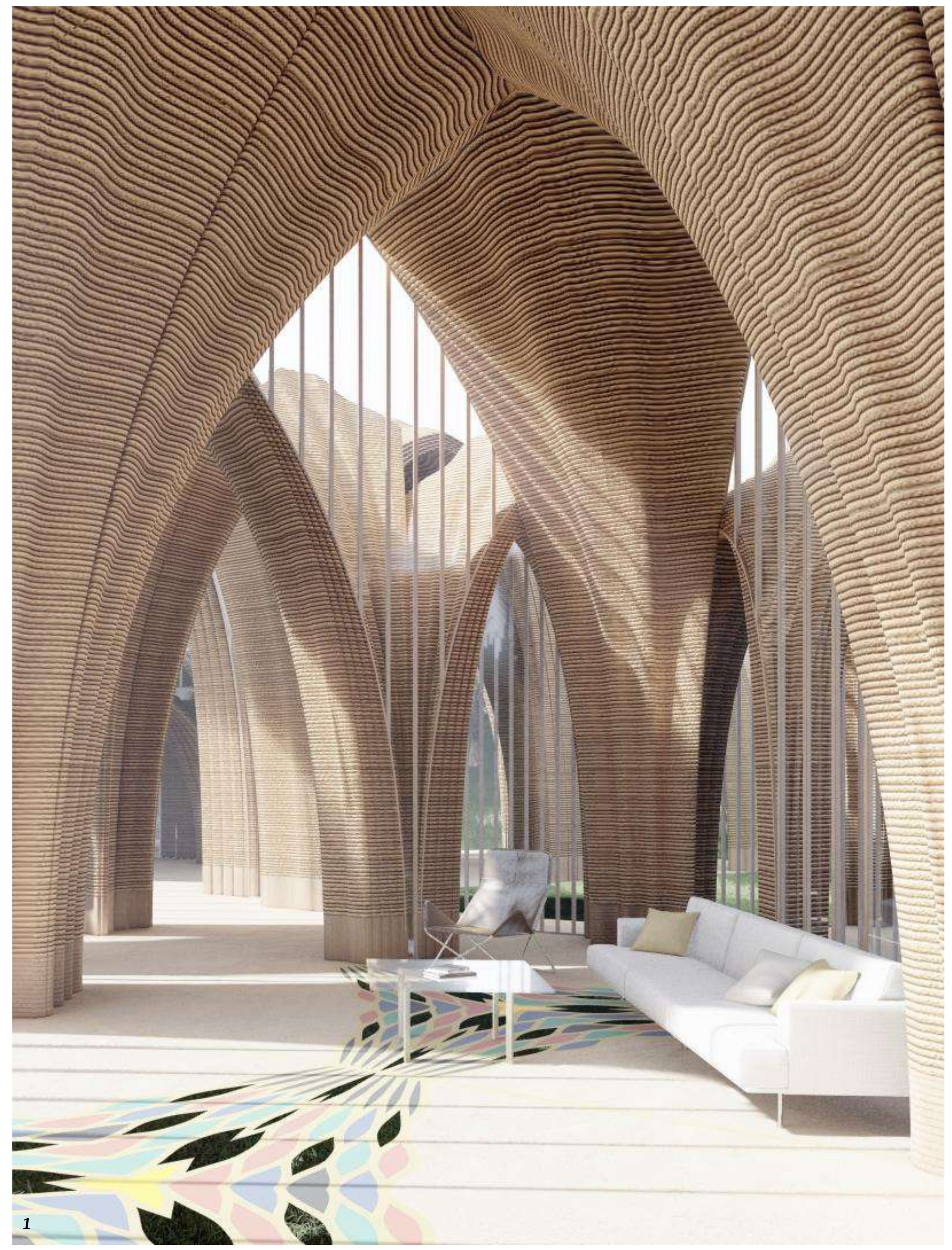
Period: *1945 and 1948*

A groin vault is formed by intersecting two barrel vaults at right angles, distributing weight efficiently to supporting walls or columns. Ribs at the intersection provide both structural support and decorative elements.

In 3D printed design, vaults are reproduced by layering the material according to the geometry of the vaults. The geometry gradually enlarges to create an overhang until it joins at the intersection point. Once the printing process is complete, the resulting structure is a three-dimensional representation of the groin vault.



1



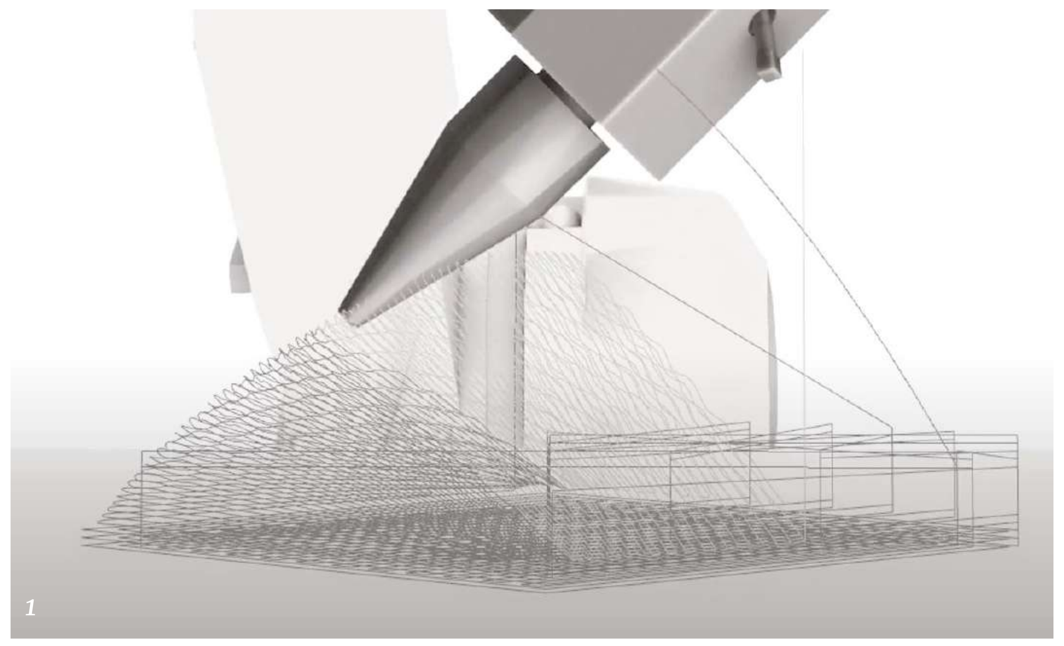
1. Trinitat Mosalas, by Abanoub Nagy , Dnyaneshwari Mete, Kevin Mwangi and Paco Pioline, 3dPa 2022/23
2. Rib Inclinations for Vaults, by Paco Pioline, Kevin Mwangi Njoroge, and Dnyaneshwari Mete, 3dpa 2022/23
. Rib Geometries for Free-form Enclosures, 3dpa 2022/23

Nubian vault

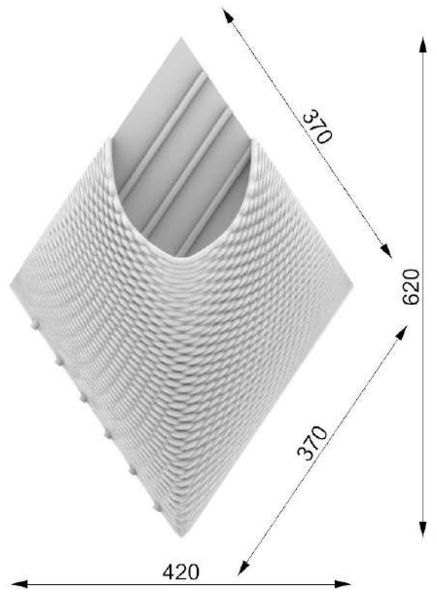
Geography : *Theban necropolis, Luxor, Egypt*
Climate : *Dry-Hot*
Community : *Gourna*
Construction technique: *adobe (mudbrick)*
Period: *1945 and 1948*

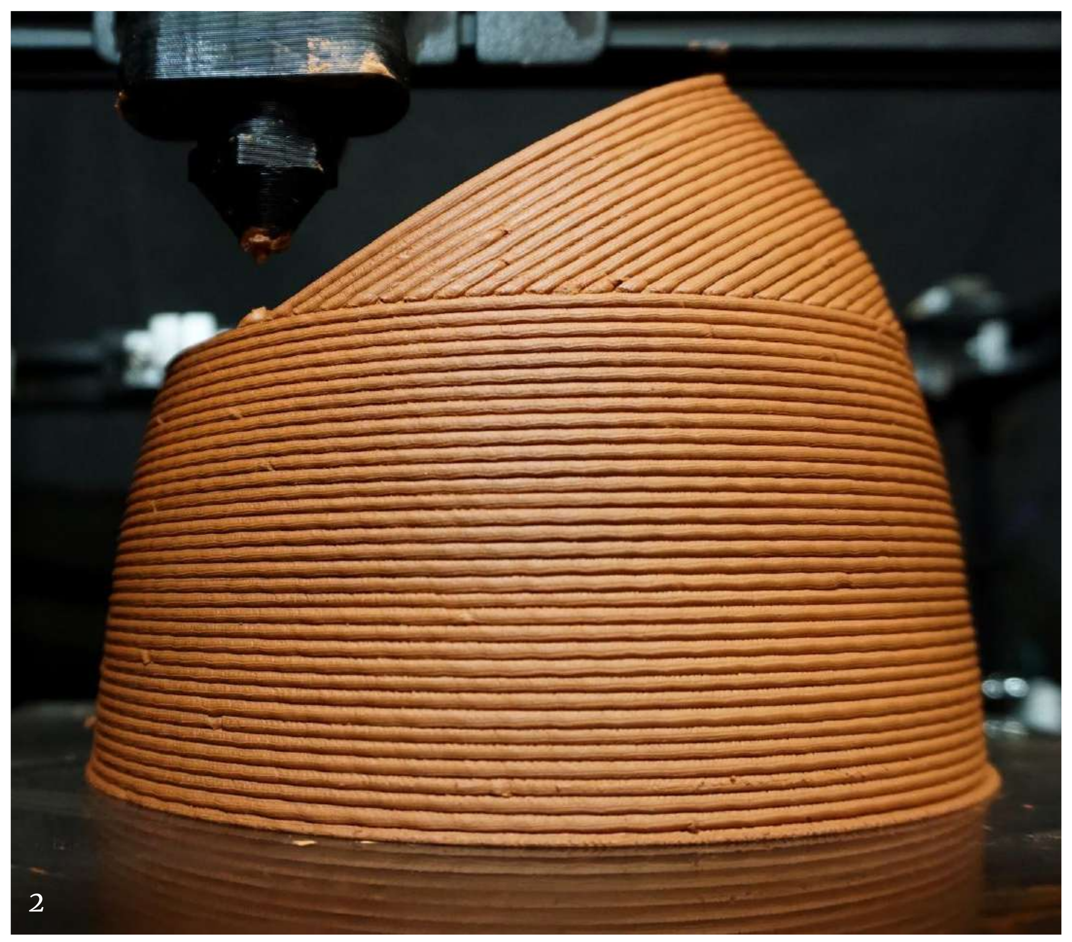
In vernacular architecture, a solution to build vaulted roofs without any timber framework is a technique called the Nubian Vault. Standard mud bricks are laid one after another off of a vertical wall, creating an angled arch that is self-supporting from the beginning of construction.

3Dprinting has reinterpreted this technique by following a nonplanar, angled slicing toolpath.

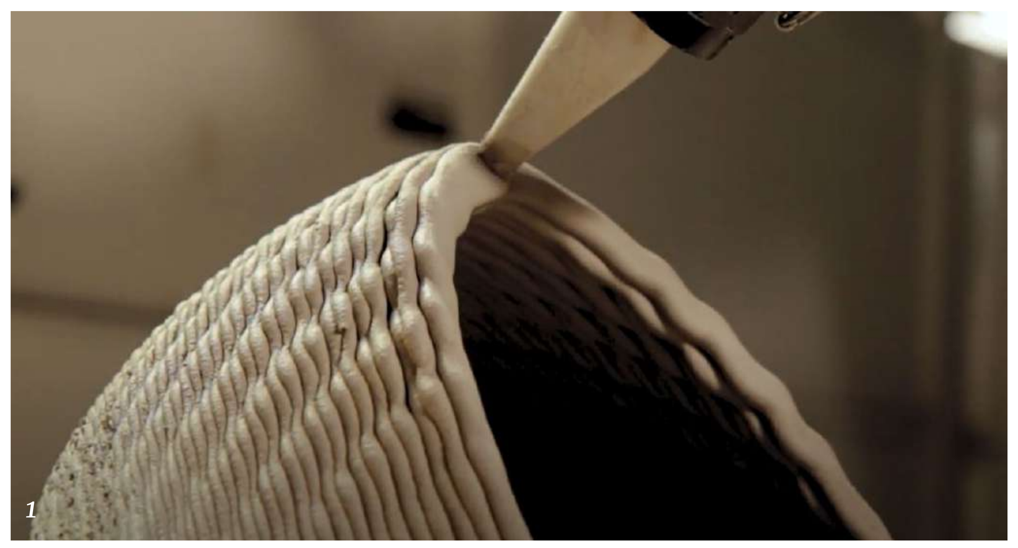


1

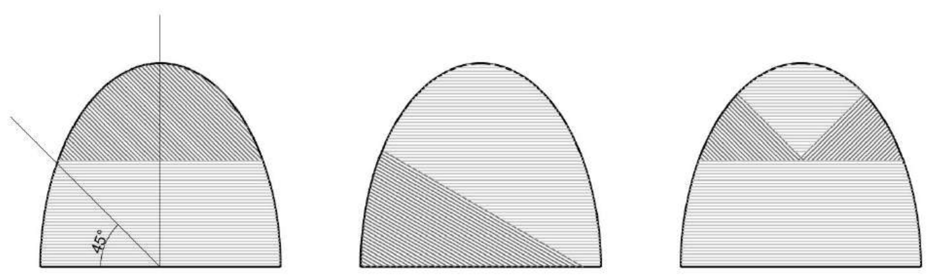




2



1



2

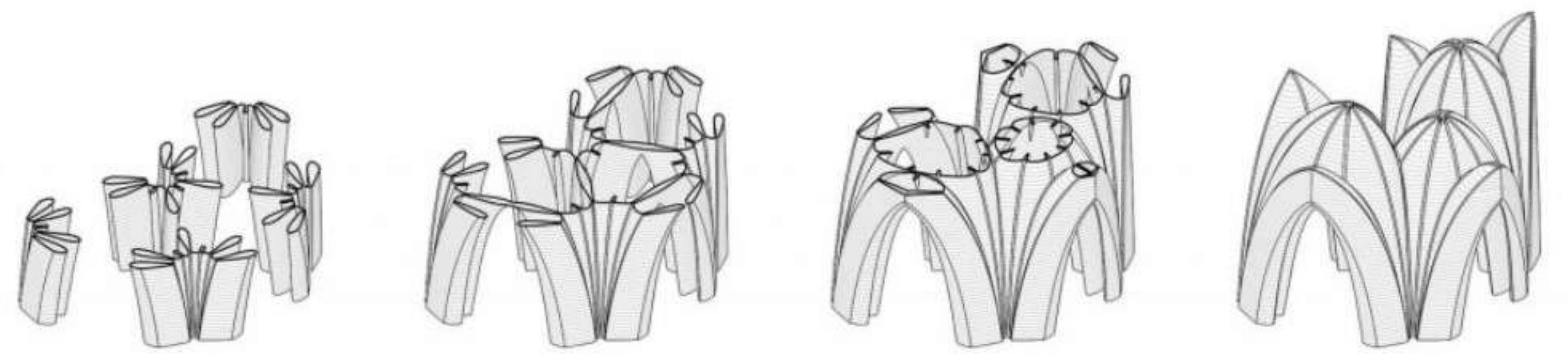
1.CO-MI-DA, collective prototype, IAAC 2021/22
2. 3D printing vaults and domes, by Brenda Freitas and Nitha Shivapuram, 3dPa 2020/21

Ribbed vault- Pointed dome

Romanesque rib vaulting, Peterborough Cathedral (begun 1118) south aisl

In Gothic architecture, ribbed vaults are used to cover wide spaces. They are composed of a framework of crossed or diagonal arched ribs, which reduce the weight and thus the outward thrust of the vault.

The 3D printing technique reinterpreted the concept of Gothic ribbed vaults to connect the geometry at the top and print on top of it completely. This technique is used for building a pointed dome.

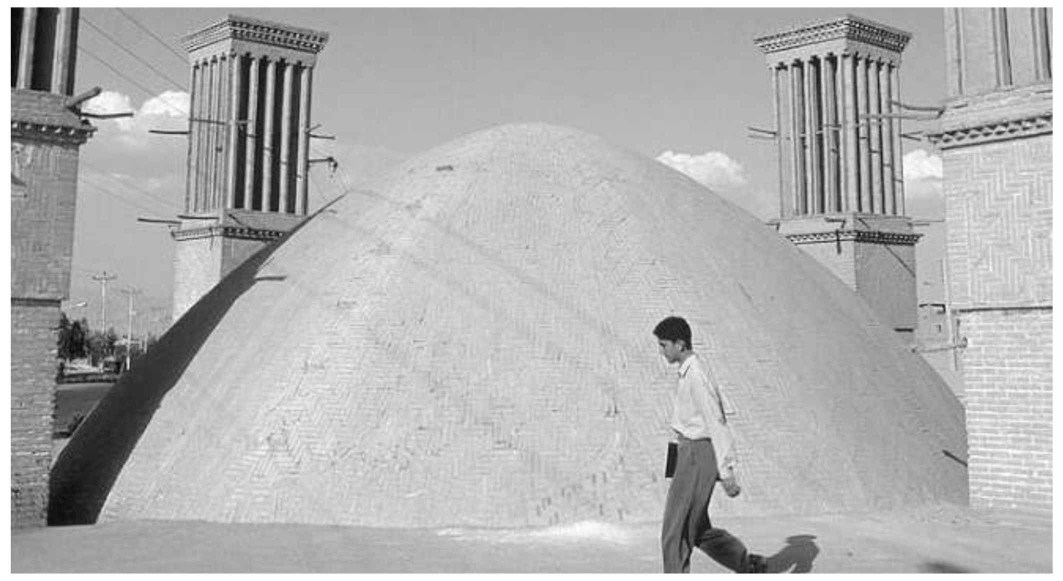


1

2

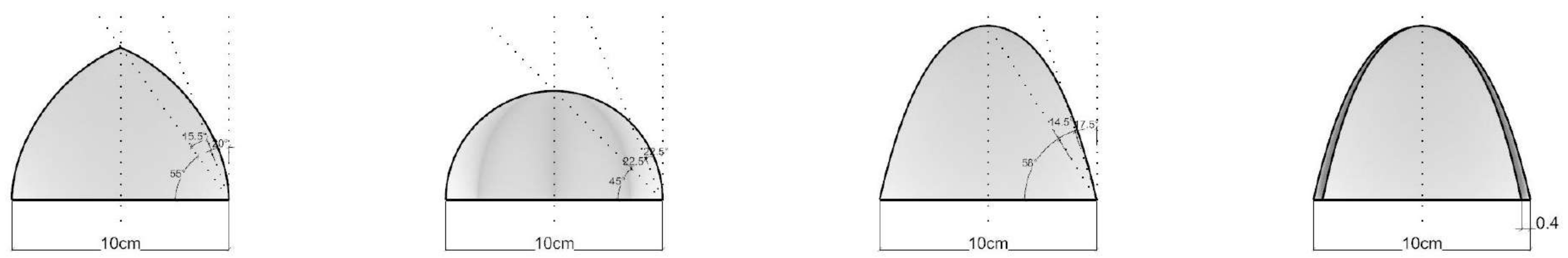
1. 3D printing vaults and domes, by Brenda Freitas and Nitha Shivapuram, 3dPa 2020/21

Catenary dome



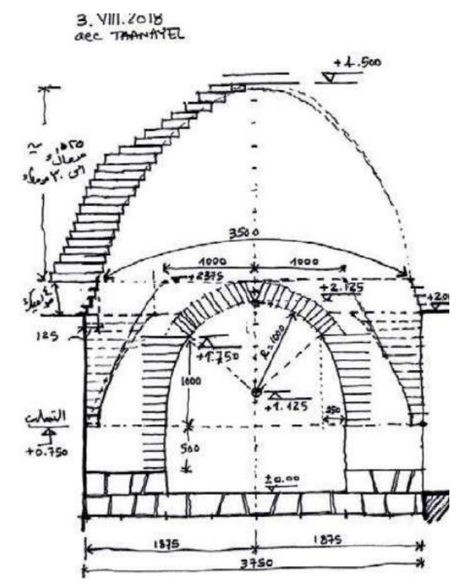
Catenary dome in vernacular architecture is the ideal mathematical form to bear a maximum weight with minimal material. This profile also reduces the pressure effect of the impact of water drops on the walls. It requires Installing a flexible material such as cables, ropes, or chains along the predetermined path of the catenary curve between the fixed supports.

In 3D printing, an enhanced fiber placement strategy was developed to minimize the risk of dome displacement and buckling.



1. 3D printing vaults and domes, by Brenda Freitas and Nitha Shivapuram, 3dPa 2020/21

Corbelled dome



Geography : *Beqaa Valley*

Climate : *Mediterranean*

Community : *in Taanayel*

Construction technique: *Sun dried mud bricks + earth coating*

Scale: *Up to 6 meters high*

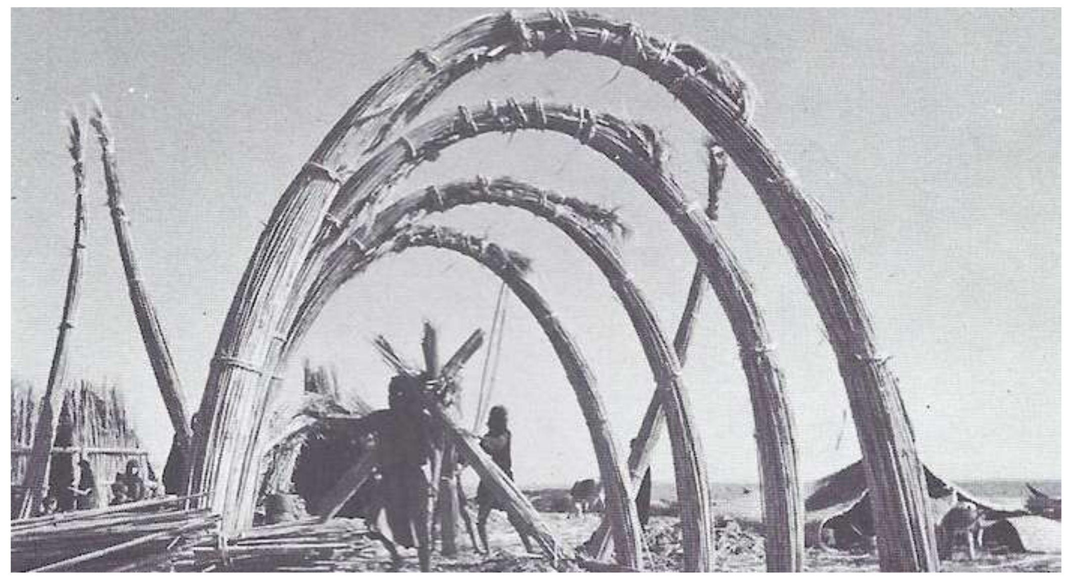
Period: *5000 millennium bc*

Corbelled domes constructed using corbelling techniques, with each layer of material protruding slightly inward until they meet at the top.

The emphasis on using this technique for building domes in 3D printing is due to the extensive costs associated with traditional formwork in terms of time and material. The process involves the printer depositing layers of extruded earth with an inward overhang until they meet in the center, forming a corbelled dome shape.

1. 3D printing vaults and domes, by Brenda Freitas and Nitha Shivapuram, 3dPa 2020/21

Adjustable support systems



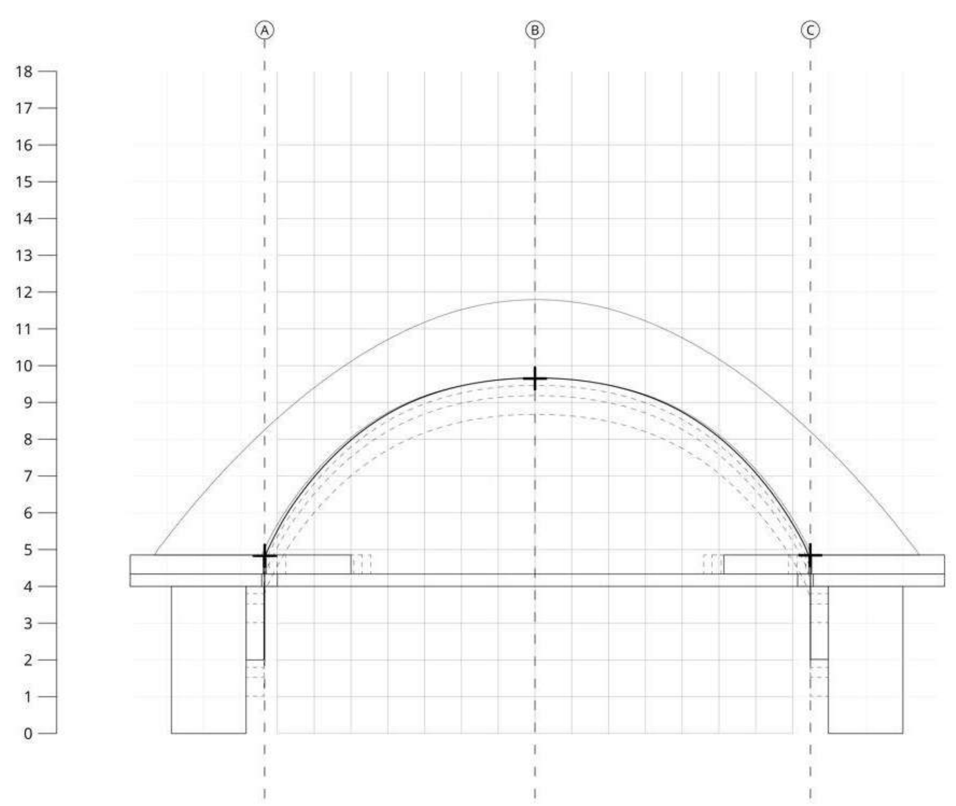
Traditional pitched brick construction in North Africa in the 1940's (Fathy 1976). Reference: Auguste Choisy, "L'Art de bâtir chez les Byzantins"

Adjustable frameworks in vernacular architecture are often constructed using flexible materials such as bamboo or grass structures.

In 3D printing, the design of the scaffolding is adjustable and consists of three distinct elements: strip, which is a thin plywood supporting the clay arch in a state of active bending; columns and bracing, which hold the strip in place and allow for its movement; and connection, which connects the strip and column, allowing for the regulation of the height of the wooden support arch.

1

2



2

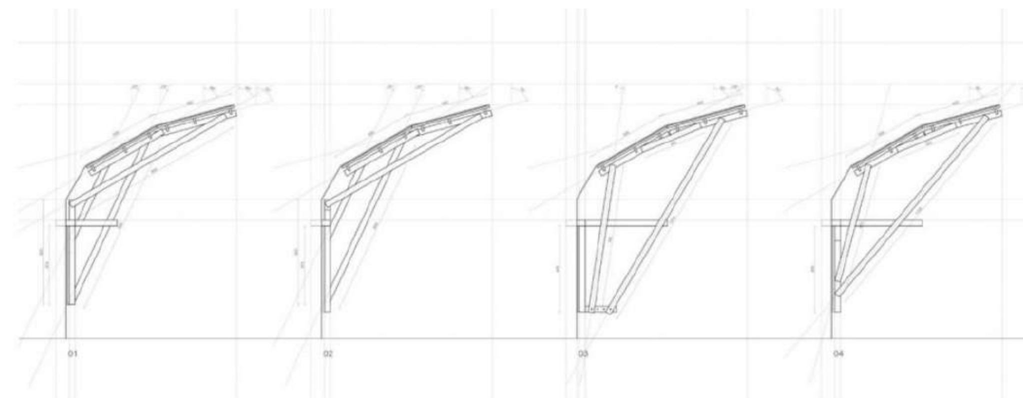
1.Volta, collective prototype, 3dpa 2022/23
2.Adaptive Support Systems: Retraction Control in Arched Vaults, by Nader Akoum, Mara Luisa Muller de-Ahna, and Kingsley Claudin Jacob, 3dpa 2022/23

Discontinuous temporary support systems

Geography : *Mexico*
Climate : *Subtropical*
Community : *-*
Construction technique: *Pumice blocks*
Period: *21st*

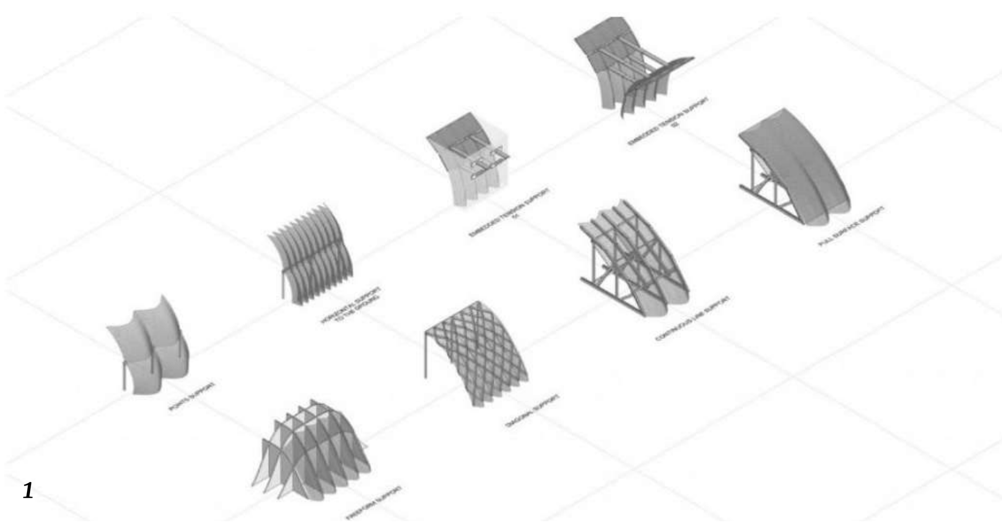
The scaffolding system for arches and vaults is often used to temporarily support the structure and test extreme overhangs, such as catenary vaults. These are built with pumice blocks laid against movable formwork, using minimal scaffold and no rebar. The building is self-supporting without vertical concrete columns, and the form is moved to construct the second half of the vault.

In 3D printing, a variety of supports and formworks have been explored in the realm of 3D printing architecture. As a response to inadequate results due to printing without support systems, temporary embedded supports for cantilevers were designed.



1

1



1

2

2

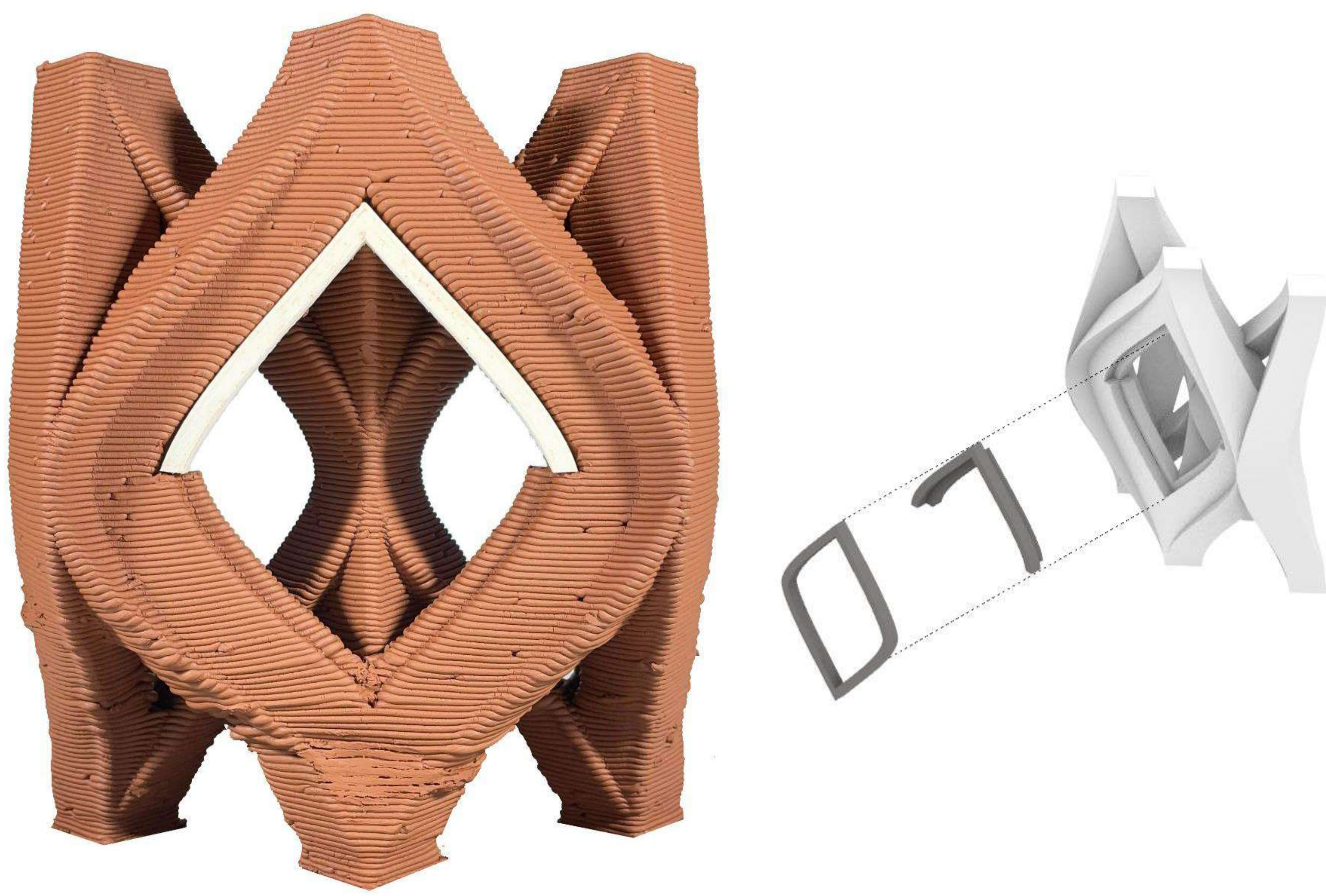
1.3d printed with earth on support structure, by Nzar Faiq Naqeshband & Mohamad Fouad Nader Hanifa, 3dpa 2018/19
2.Temporary support system for cantilevers, Bruno Ganem Coutinho, Francesco Polvi and Zackary Bryson,3dPA 2019/20

Lintel for overhang opening

Geography : *the Beqaa Valley, Northern Syria*
Climate : *Mediterranean*
Community : *Taanayel*
Construction technique: *Sun dried mud bricks*
Scale: *Up to 6 meters high*
Period:*5000 millennium bc*

In vernacular architecture, overhang openings are created using slanted mud bricks leaning on each other to form a lintel, ensuring even distribution of the load. Masons typically round these openings during the coating application process.

The integration of lintels into 3D-printed openings was investigated to create larger openings with bigger overhangs. A frame is integrated after printing in the wet state of the material.



1

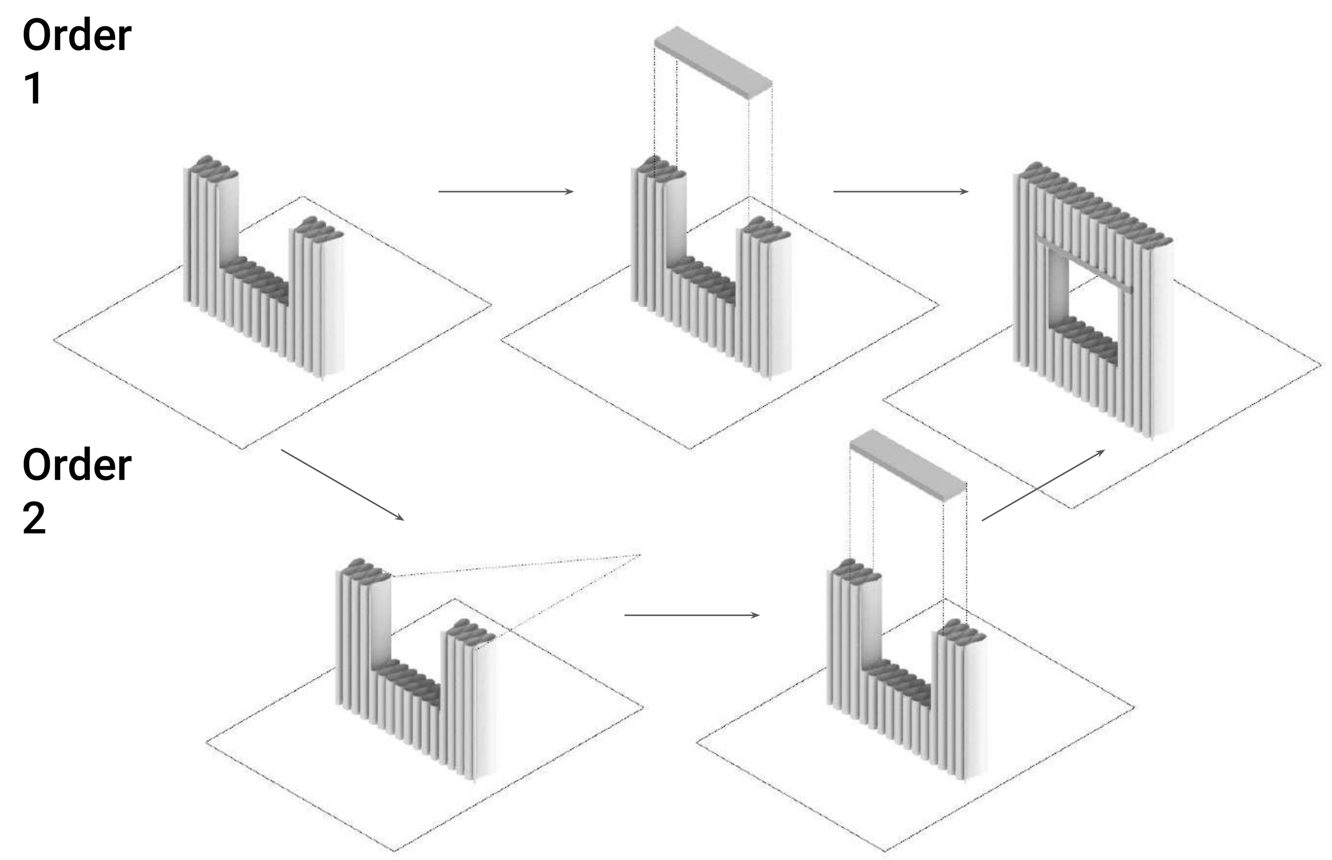
1.Integration of prefabricated frames within 3D printed Earthen wall openings, Sara Ayoub, Marietta Kaltsa, Sakshi Pawar, 3dpa 2023/24

Lintel for horizontal opening

Geography : *the Beqaa Valley, Northern Syria*
Climate : *Mediterranean*
Community : *Taanayel*
Construction technique: *Sun dried mud bricks*
Scale: *Up to 6 meters high*
Period:*5000 millennium bc*

Lintels support the weight of multiple bricklayers and are typically made of solid wood. They should be at least 20 cm wider than the opening to rest on the jambs on both sides. The thickness of the wooden lintel planks varies based on the number of bricklayers they support.

In 3D printing, a protocol outlines the digital and manual steps required for lintel installation. The infill located in the lintel and jambs is designed with greater complexity to support the load.



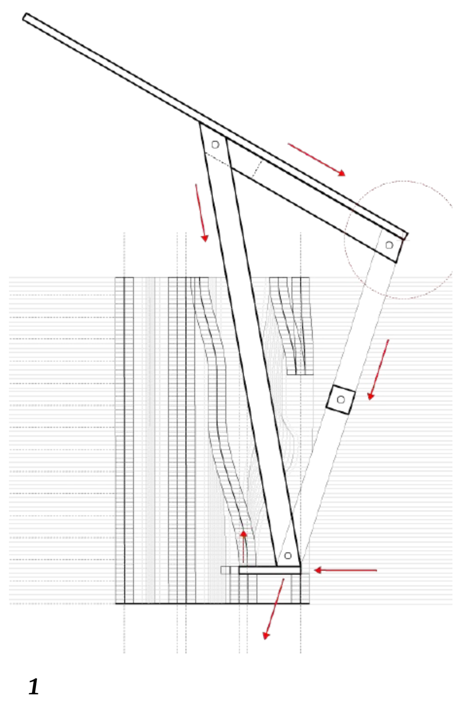
1.Integration of prefabricated frames within 3D printed Earthen wall openings, Sara Ayoub, Marietta Kaltsa, Sakshi Pawar, 3dpa 2023/24

Wood connection

***Geography** :Grupont, Belgium*
***Climate** : maritime climate*
***Community** :*
***Construction technique:** Wattle and Daub technique*
***Scale:** 4 stories*
***Period:**16th century*

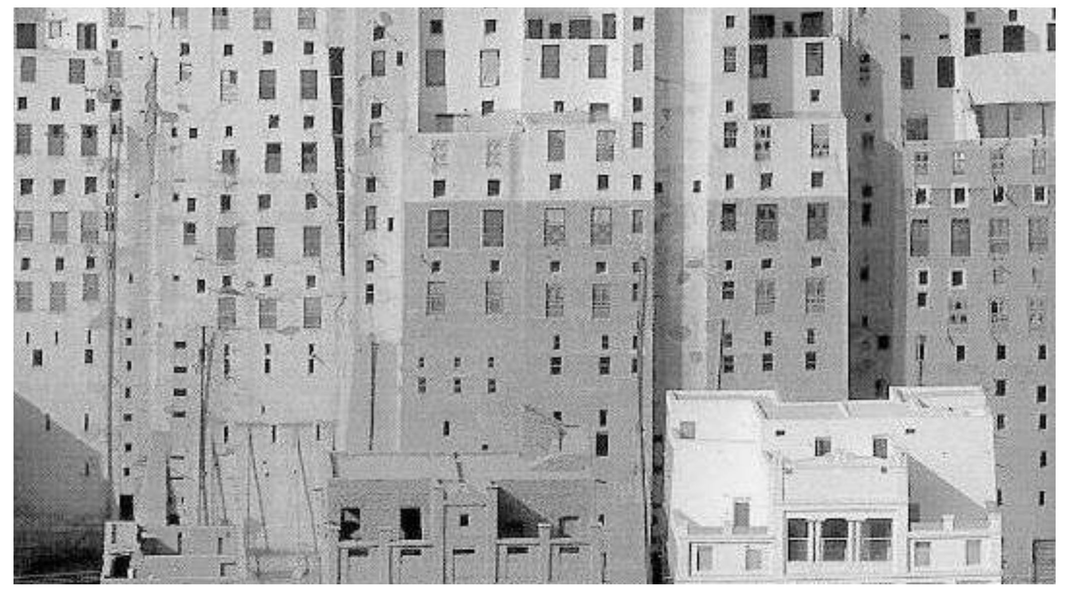
Wood in traditional architecture is used to provide structural support and stability. It forms the framework for walls, roofs, and openings, distributing loads and reinforcing vulnerable areas. Wooden beams, posts, and braces bear the weight of the structure and resist lateral forces such as wind and seismic activity. Joinery techniques ensure secure connections between structural elements, enhancing overall stability.

In 3D printing for earthen construction, wood can still serve as a structural support, albeit in a different form. Through the printing process, wood-infused filaments or composite materials can be utilized to create load-bearing elements such as beams, posts, and bracing. These elements provide essential support and stability within the printed structure.



1.Tova, collective prototype, 3dpa 2020/21
2.Heat conductivity, 2020
3.Staircase, collective prototype, IAAC, Wasp 2019
.Digital adobe, collective prototype, 3dpa 2018/19

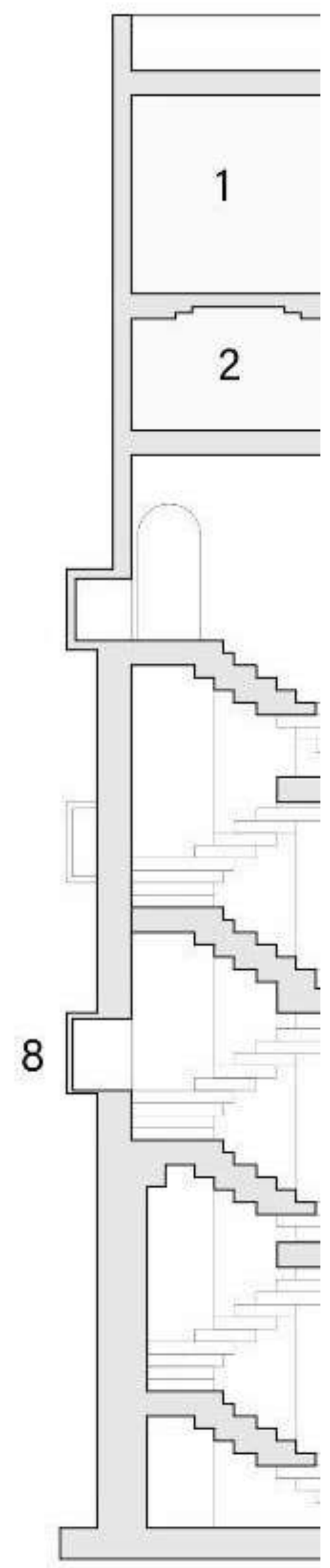
Vertical mass distribution

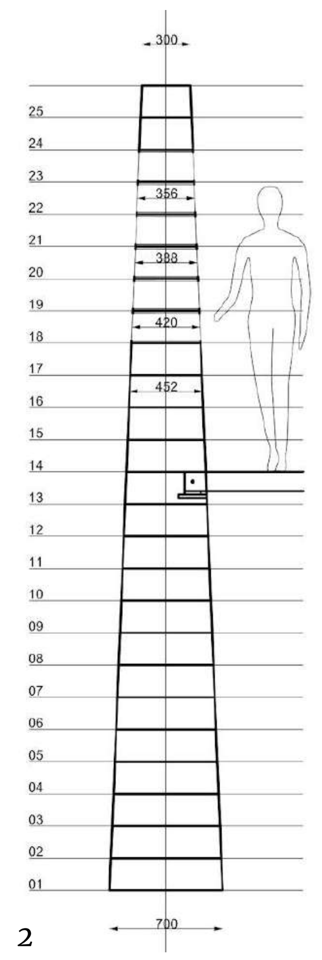


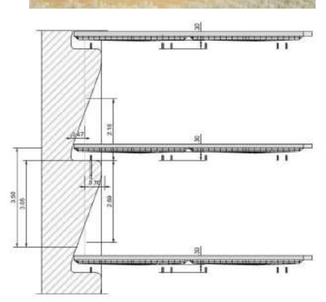
***Geography** : Shibam, Hadramawt valley, Yemen*
***Climate** :   Dry-Hot*
***Community** : Hadramawt*
***Technique:** Adobe (Mud-bricks)*
***Scale:** 6 storeys*
***Period:** 16th century*

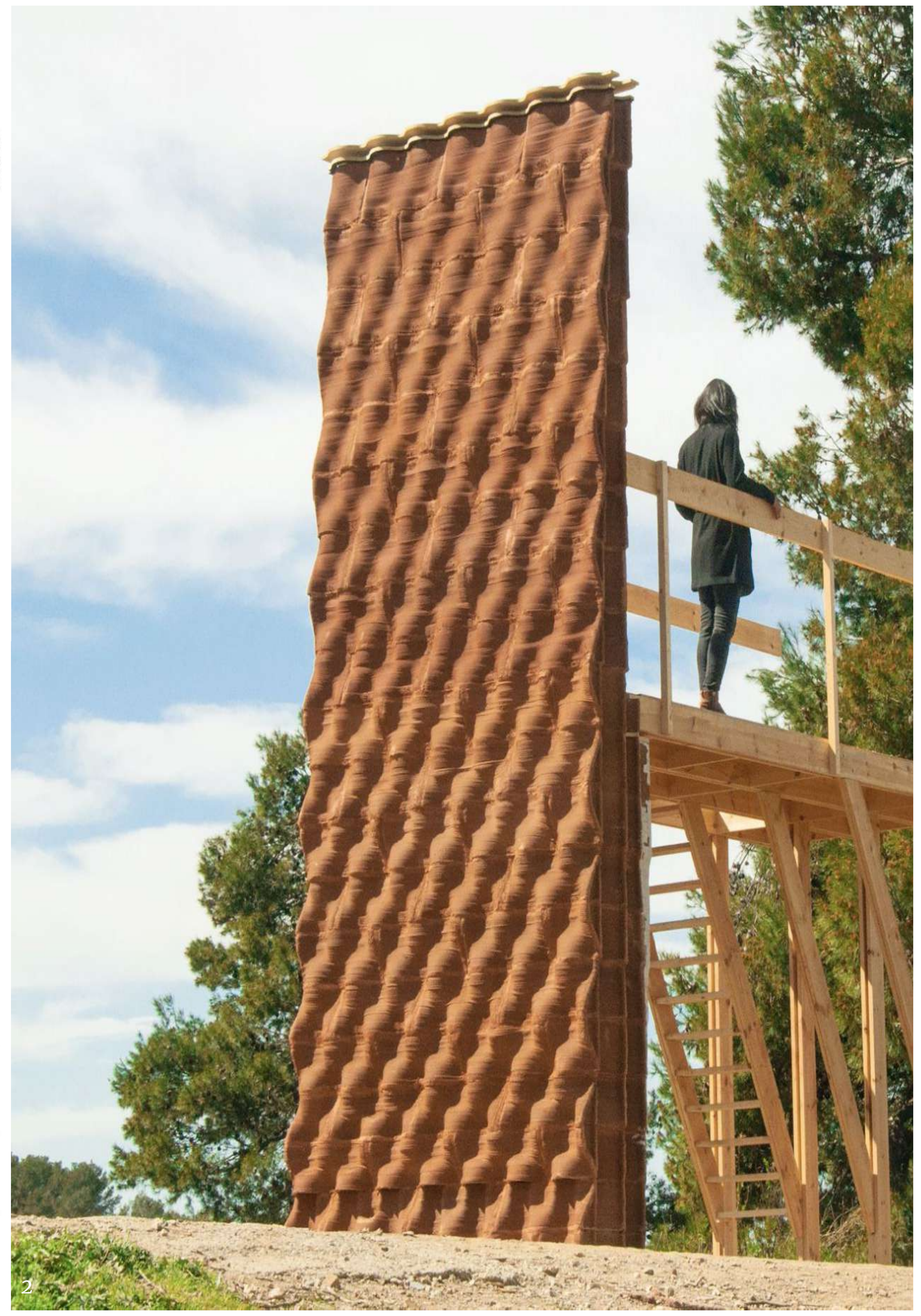
Mass distribution in vernacular architecture is a response to building taller structures. It involves using massive walls on the lower levels and thinner walls on the upper floors, allowing for buildings to reach up to 6 storeys.

Digital design enables the distribution of 3D printed material to balance the load, allowing for a change in thickness of the printed wall to support higher self-bearing structures.









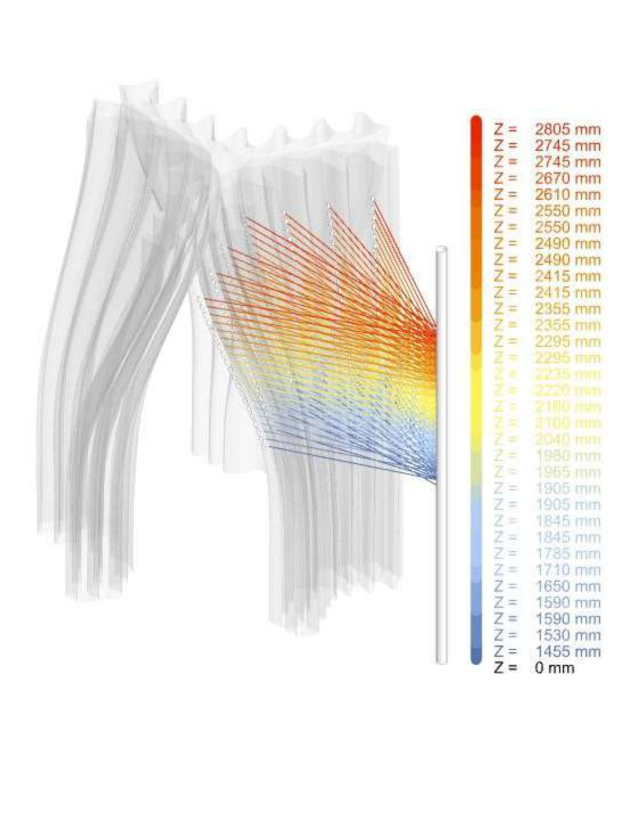
1. Section, Shibam tower.
2.Digital adobe, collective prototype, 3dPa 2018/19
3.Walls & Slabs [IAAC x ITKE], 3dpa 2022/23

Structural fiber

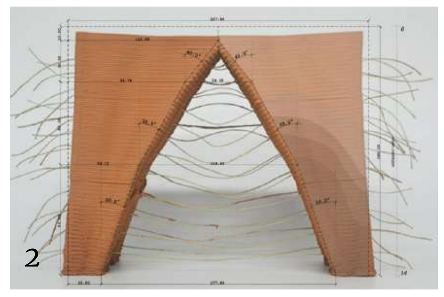
Geography : *Shibam, Hadramawt valley, Yemen*
Climate : *Dry-Hot*
Community : *Hadramawt*
Technique: *Adobe (Mud-bricks)*
Scale: *7 storeys*
Period: *16th century*

Structural stability in the walls was enhanced by integrating branches between courses of mud brick construction. Branches and thimbles enable the clamping of the walls, minimizing risk by reinforcing the cantilever using fibers.

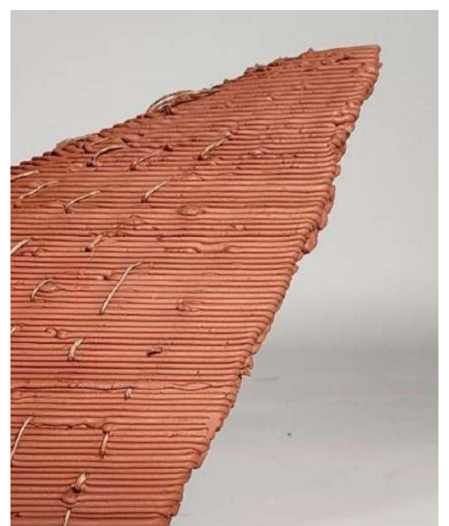
In 3D printing, tensioning fibers are explored between layers of printed earth, serving as a reinforcement system in the wet state. This approach offers more design freedom and the possibility to print with fewer materials, allowing for increased overhang.



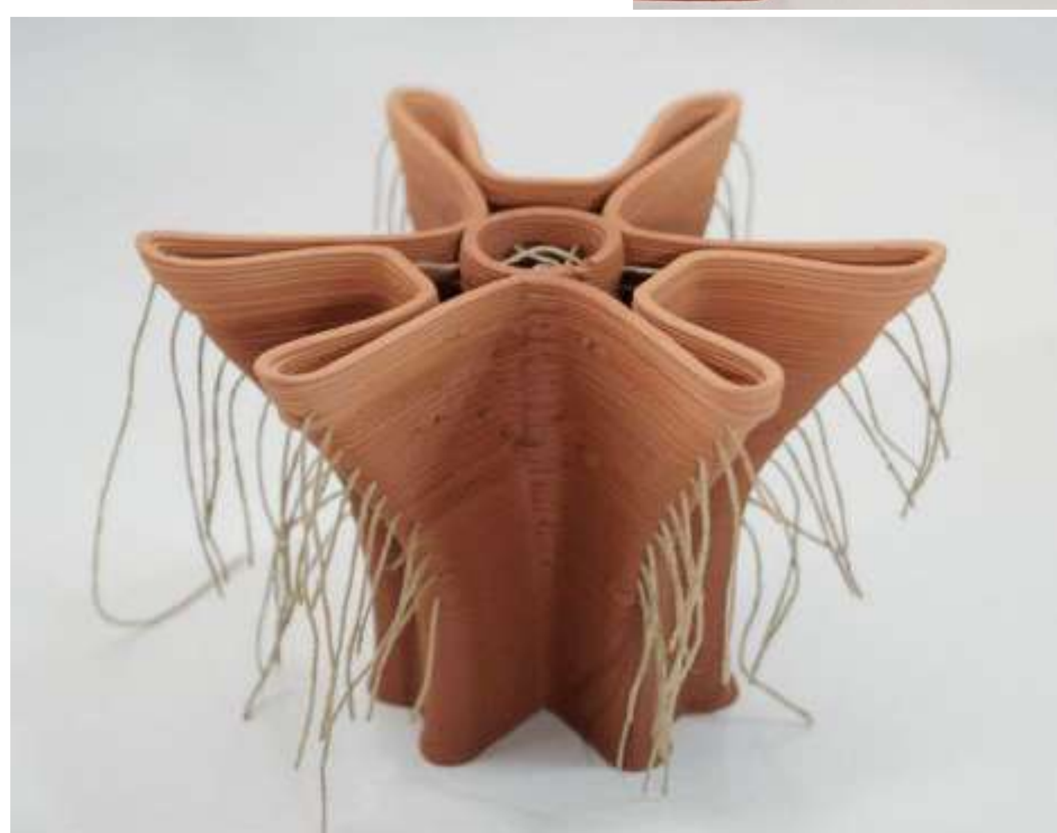
1



2



3



4

5

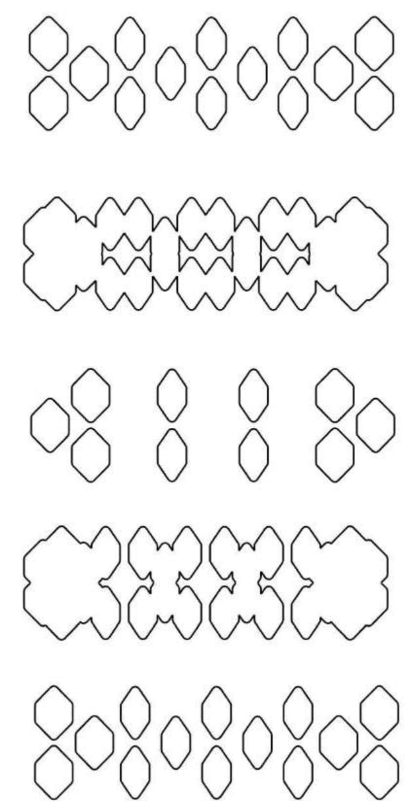
1.Fiber Reinforcement Cantilever, Adrian Patrascu, Nestor Beguin, Teodora Moraru, 3dPA 2022/23
2.Planar Fiber Reinforcement for Cantilever, Jett D., Marta N., Shazwan M., and Ionut Adrian P, 3dPA 2022/23
3.Multidirectional Fiber Reinforcement for Cantilevers, by Abanoub Nagy , Dnyaneshwari Mete, Huanyu Li, 3dPA 2022/23
4.Continuous fiber, Aslinur Taskin, Hendrik Benz, Michelle Bezik, 3dPA 2019/20
5.Fiber reinforcement in 3D clay printing, Jae Shin & Angelika Bocian-Jaworska, 3dPA 2019/20

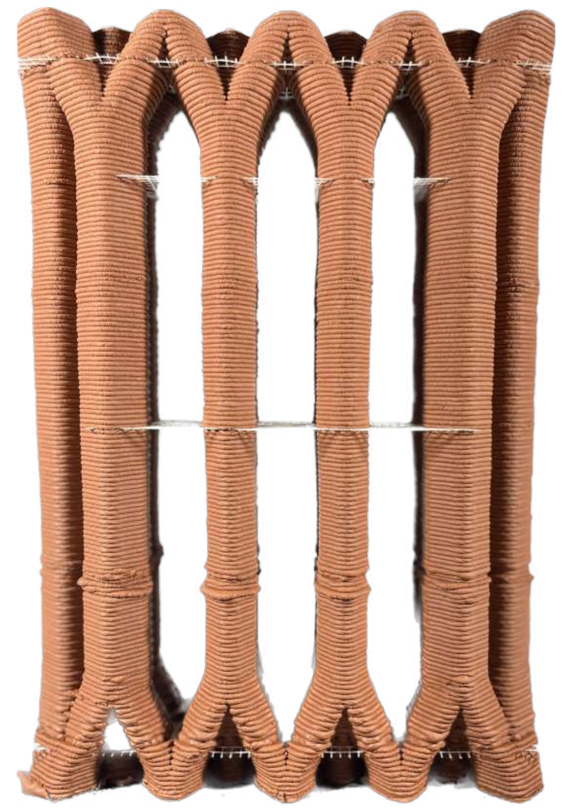
Mesh

Geography : *Shibam, Hadramawt valley, Yemen*
Climate : *Dry-Hot*
Community : *Hadramawt*
Technique: *Adobe (Mud-bricks)*
Scale: *7 storeys*
Period: *16th century*

Structural stability in the walls was also addressed by integrating branches between courses of mud brick construction. Branches and thimbles facilitate the clamping of the walls, minimizing risk by reinforcing the cantilever using fibers.

In 3D printing, the use of mesh has been explored for its ease of use, grid structure, and performance in both wet and dry states.





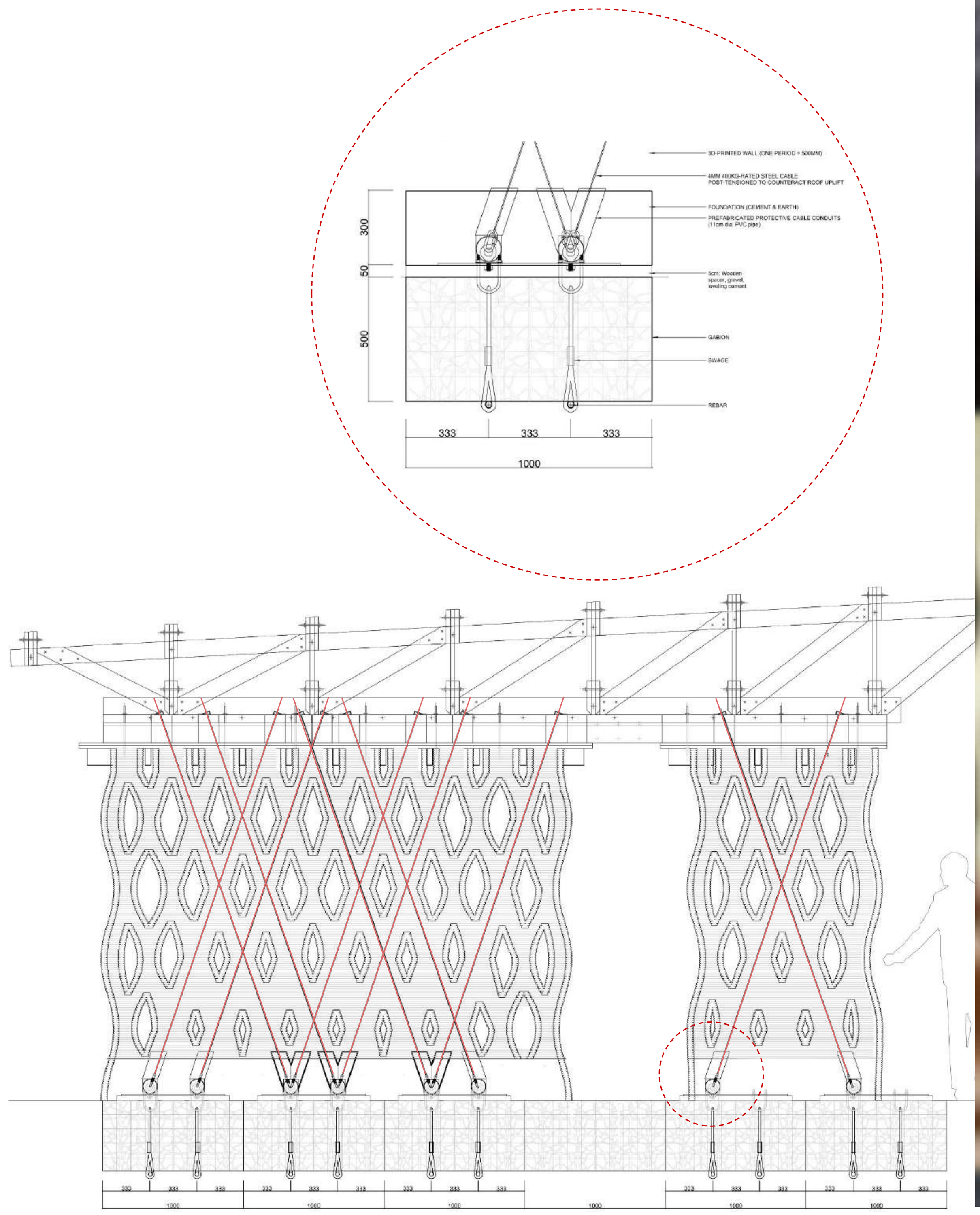
1.Teixit, collective prototype, 3dPA 2024
2.Vertical openings applied to the diamond space frame, Joseph Naguib, Vassela Tabakova, Justin Hanlon, 3dPA 2024

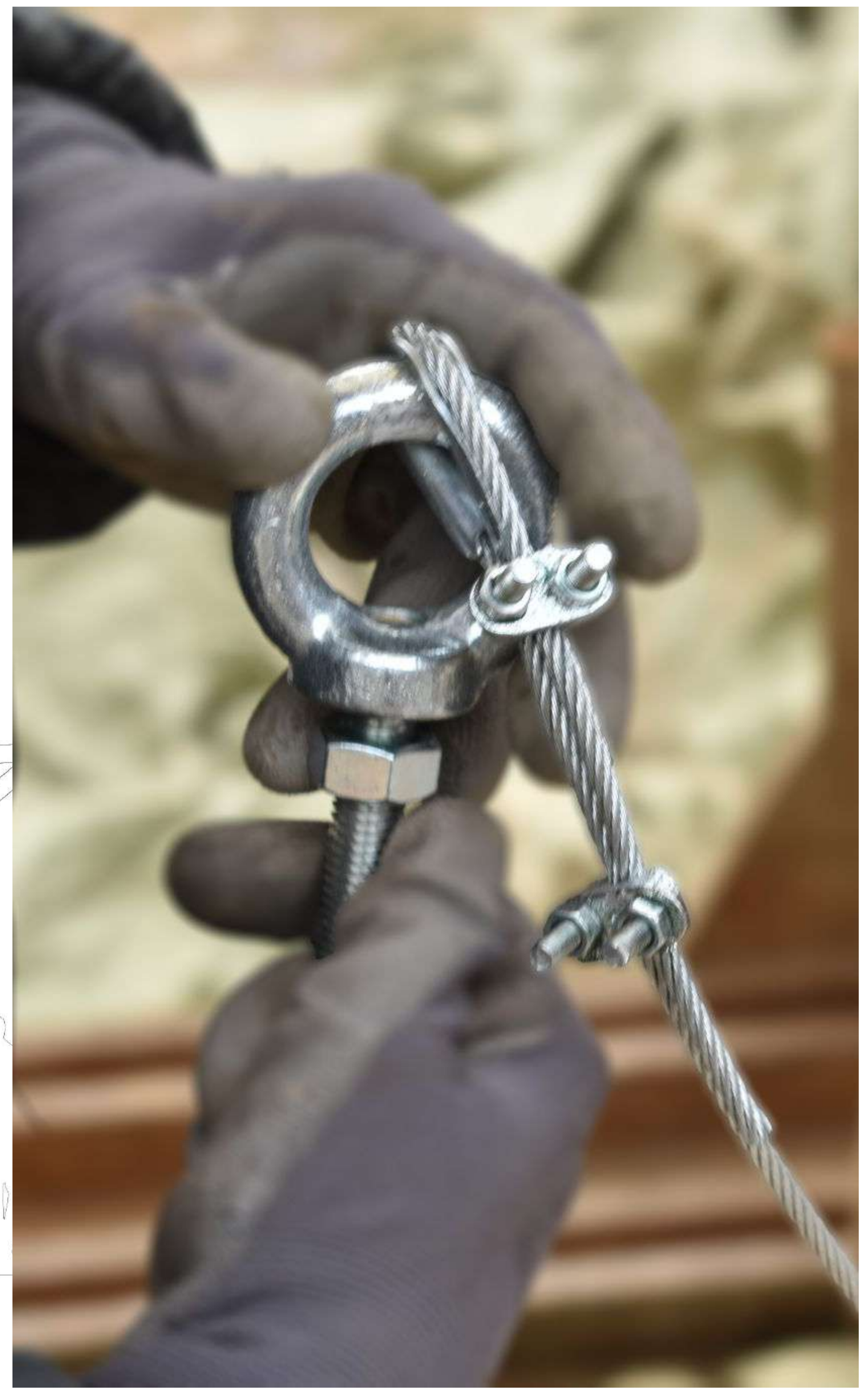
Post-tensioning

Boltshauser-**Kiln Tower for the Brickworks Museum / Boltshauser Architekten**

Post-tensioning is a post industrial technique used in construction and structural engineering to reinforce concrete structures such as beams, slabs, and bridges. The process involves placing high-strength steel tendons or cables inside ducts or sleeves within the wall and then tensioning them. The material used is traditionally concrete, in this exemple, Boltshauser used this technique with rammed earth blocks.

3d printing allows designing cavities, protected by the PVC tube assemblies, with horizontal access holes at the bottom of the plinths. These assemblies are designed to counteract the wind lift on the roof with up to 500kg per cable.





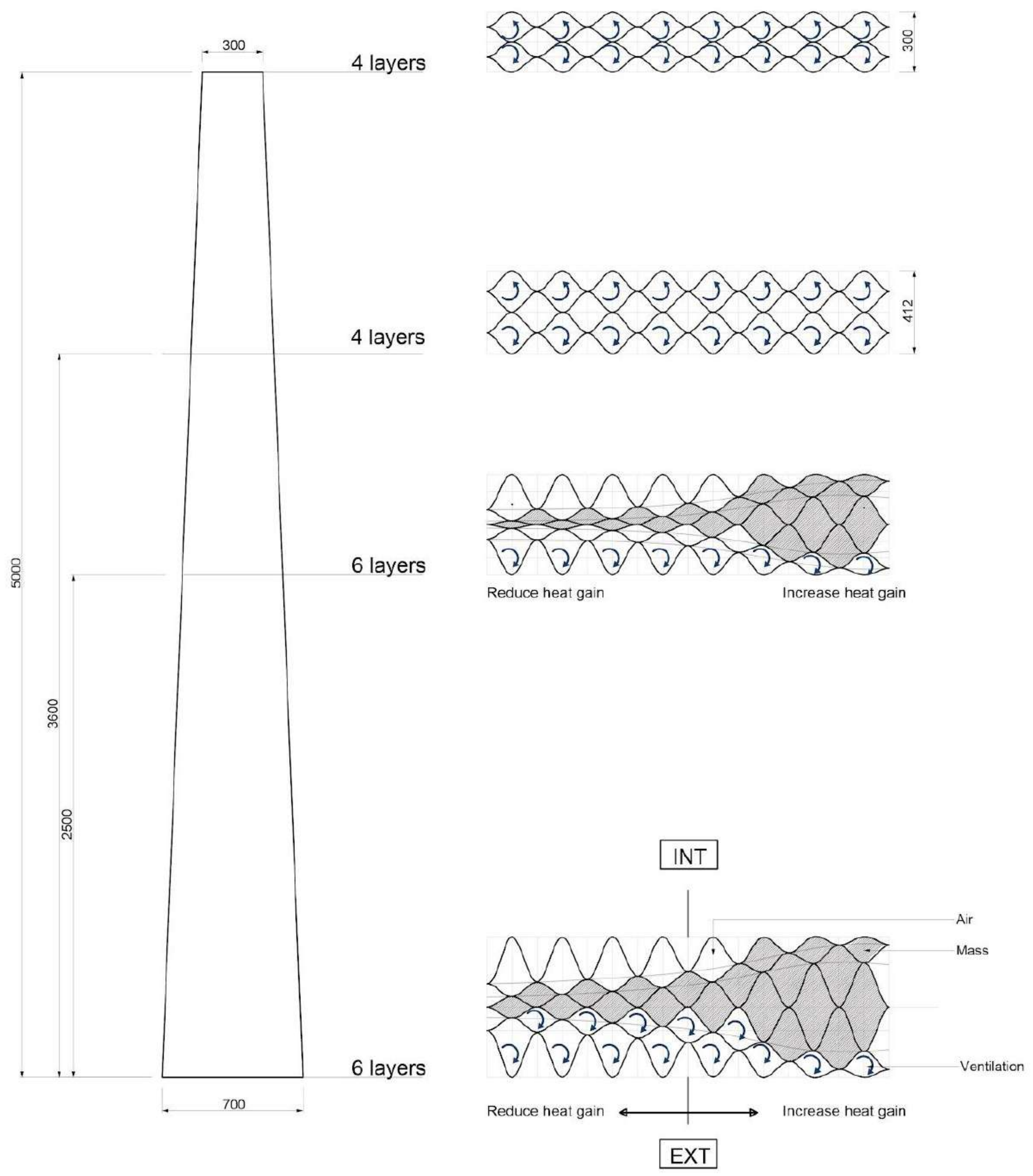
1. climatic strategy
diverse housing typologies, construction techniques and details have evolved over time to offer conditioning and protection from weather variations, such as temperature, wind, rain, and light.

Wall cavity

Geography : Al-Nazlah, Fayoum, Egypt
Climate : Dry-Hot
Community : Architect: Hamdy Elstouhy
Technique: Repetitive clay pot, Vault/arch.
Scale: 5m height, 800m²
Period: 2019

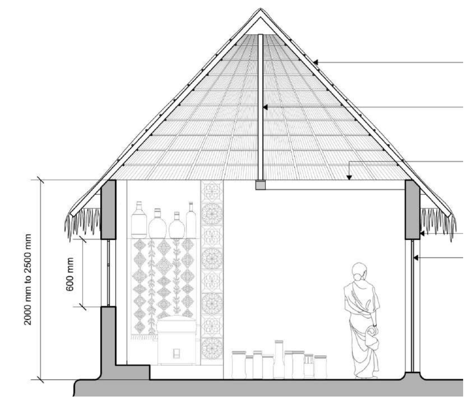
In vernacular architecture, pots are hammered into a spherical form to create insulation. The walls consist of two layers of pots, forming a double-cavity insulation to shield from external heat.

In the Digital Adobe prototype, some cavities are filled with locally available earth for insulation and thermal inertia. Ventilation and air cavities are designed to regulate heat exchange and thermal transmission. Vertical shafts in the wall section facilitate airflow from bottom to top, transferring excess heat caused by radiation into the air.



1.Digital Adobe, Cavity network within 3d printed earth wall, collective prototype, 3dPA 2017/18

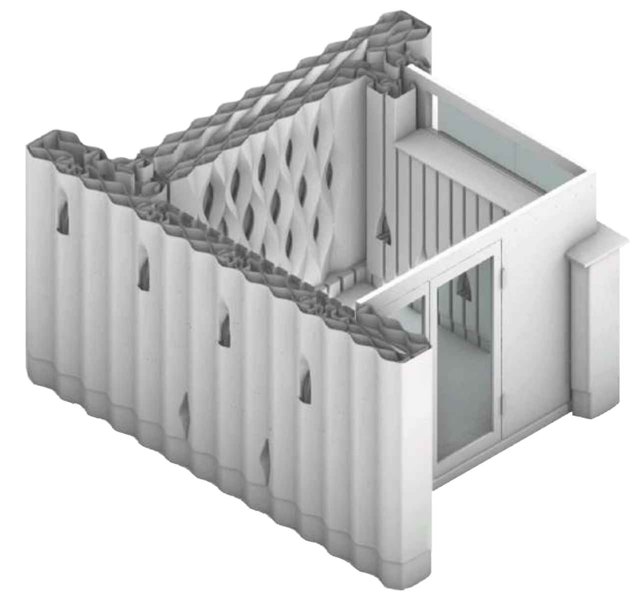
Cross ventilation

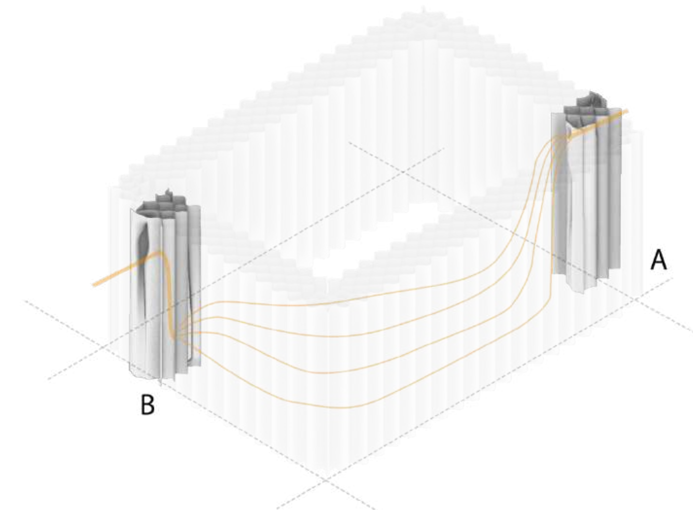


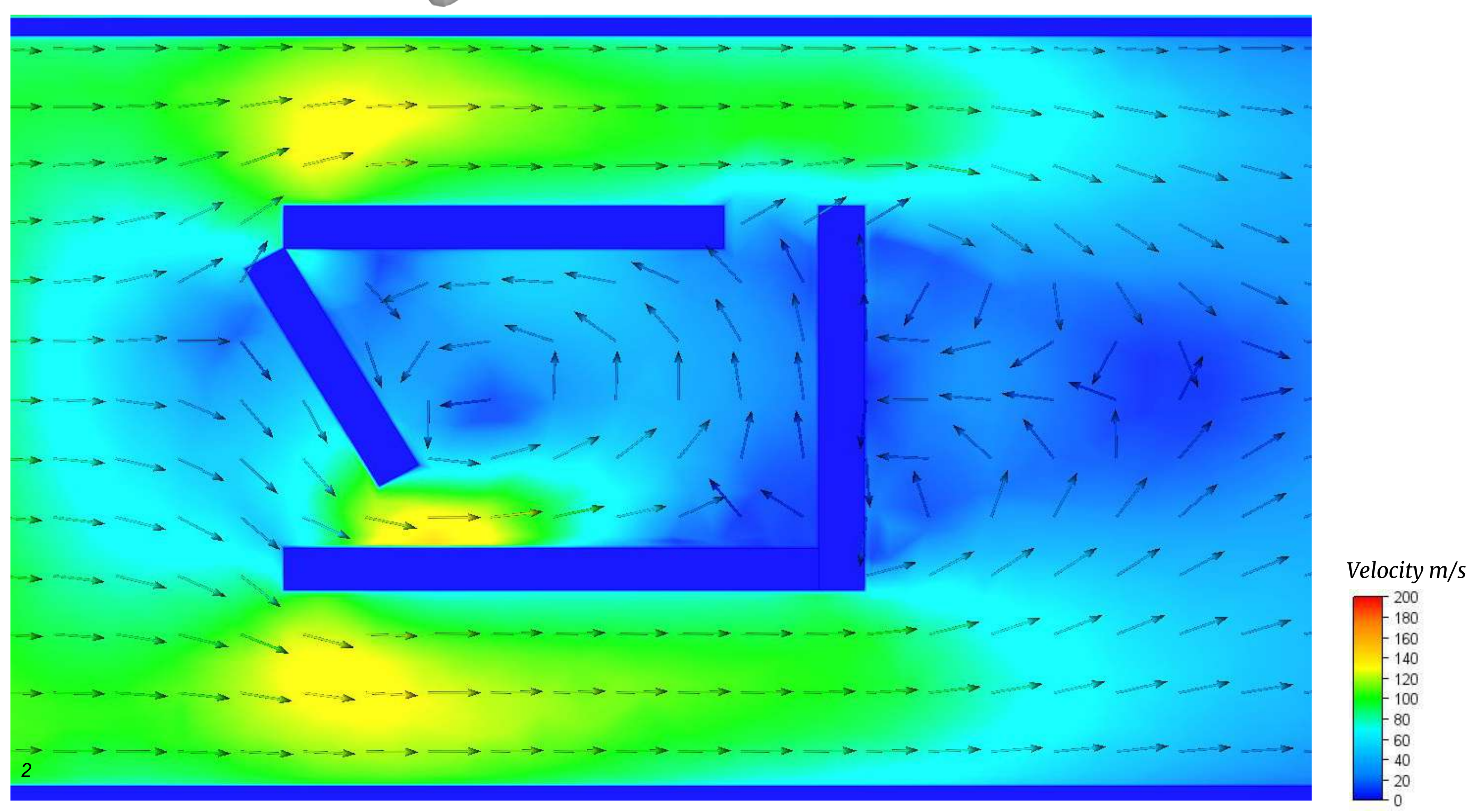
Geography : *Kutch Kachchh, Gujarat, Western India*
Climate : *Dry-Hot*
Community : *Bhunga village*
Construction technique: *Adobe walls*
Scale: *H=3.5m, D=3-6m*
Period: *After the 1819 earthquake.*

Openings in vernacular architecture are positioned opposite sides of the building for airflow. The wind blows against one side of the building, creating a positive pressure zone, on the opposite side, a negative pressure zone is formed, driving air to flow through the building, from the side with higher pressure to the side with lower pressure.

Incorporating 3D printing and digital tools can enhance the analysis and optimization of cross ventilation in 3D printed buildings. These tools help specify the precise locations, length, width, and depth of openings, as well as their angle and size within opposite walls, facilitating accurate airflow.

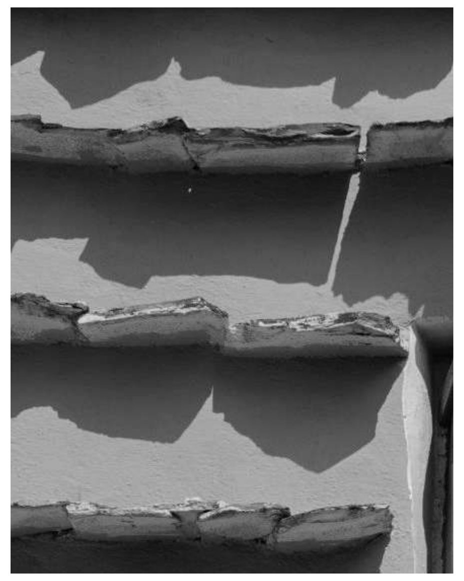






1.Tova, collective prototype, 3dPA 2021/22
2.Airflow and natural ventilation, by Adel Alatassi, Deena El-Mahdy, Marwa Abdelrahim, 3dPA 2021/22

Self shading

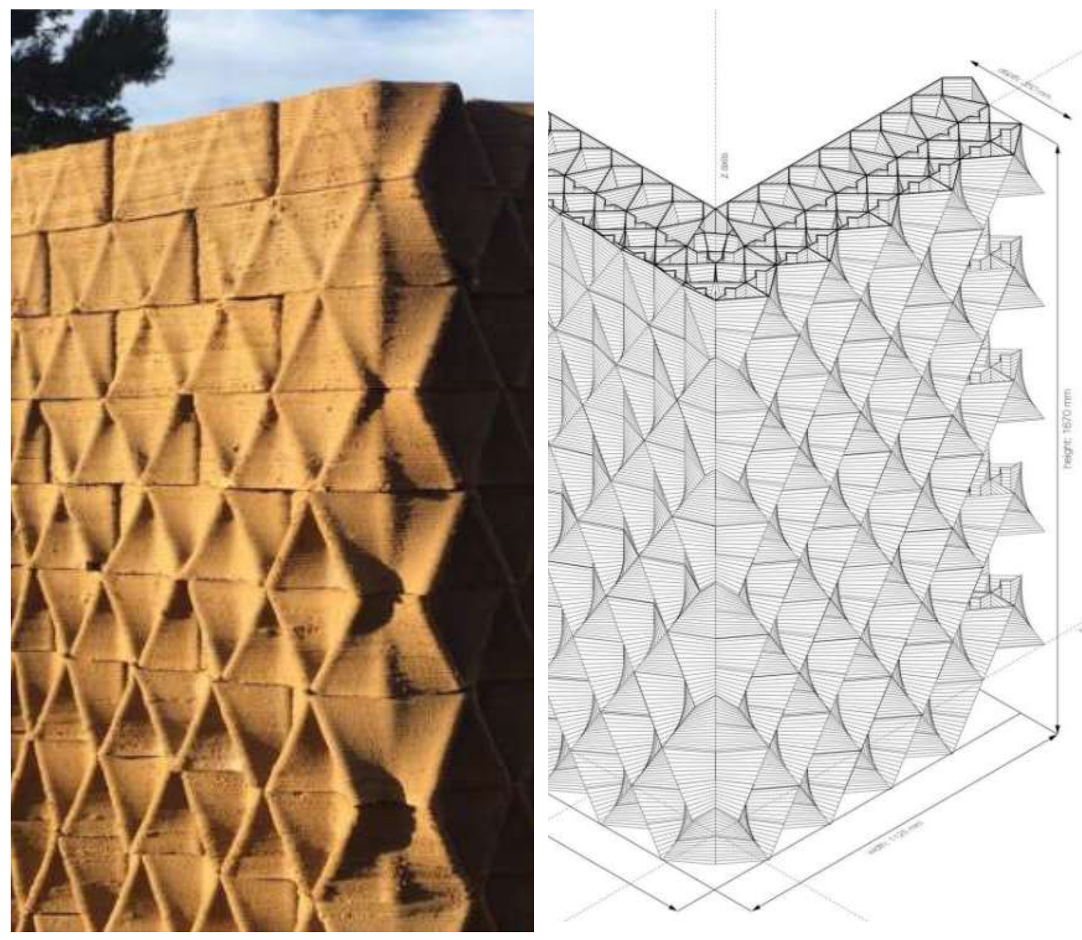


Geography : *Asir region of southwestern Saudi Arabia.*
Climate : *subtropical*
Community : *Rijal Alma*
Construction technique: *Stone, adobe, Wood.*
Scale: *from two to five stories*
Period: *17th century*

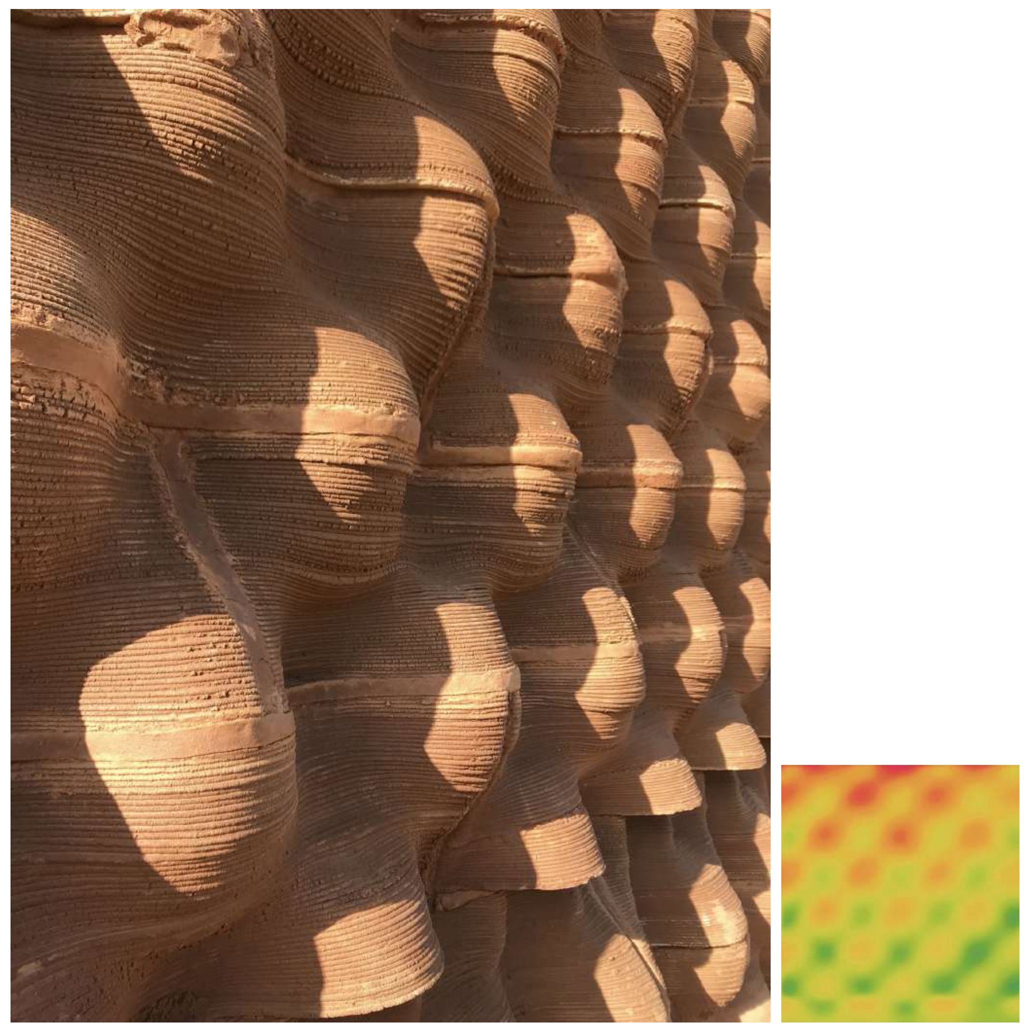
In vernacular architecture, self-shading is a strategy to naturally regulate indoor temperatures, it is implemented through building orientation, roof overhangs, thick earthen walls, and also external elements such as brick or stones.

With digital analysis tools, different angles of inclination of surface detail are tested in order to find the maximum self-shaded area possible. It is tested for summer and winter vectors, and an average optimum of inclination was chosen.

This study shapes a textured geometry creating a play of light and shadow.



1



2

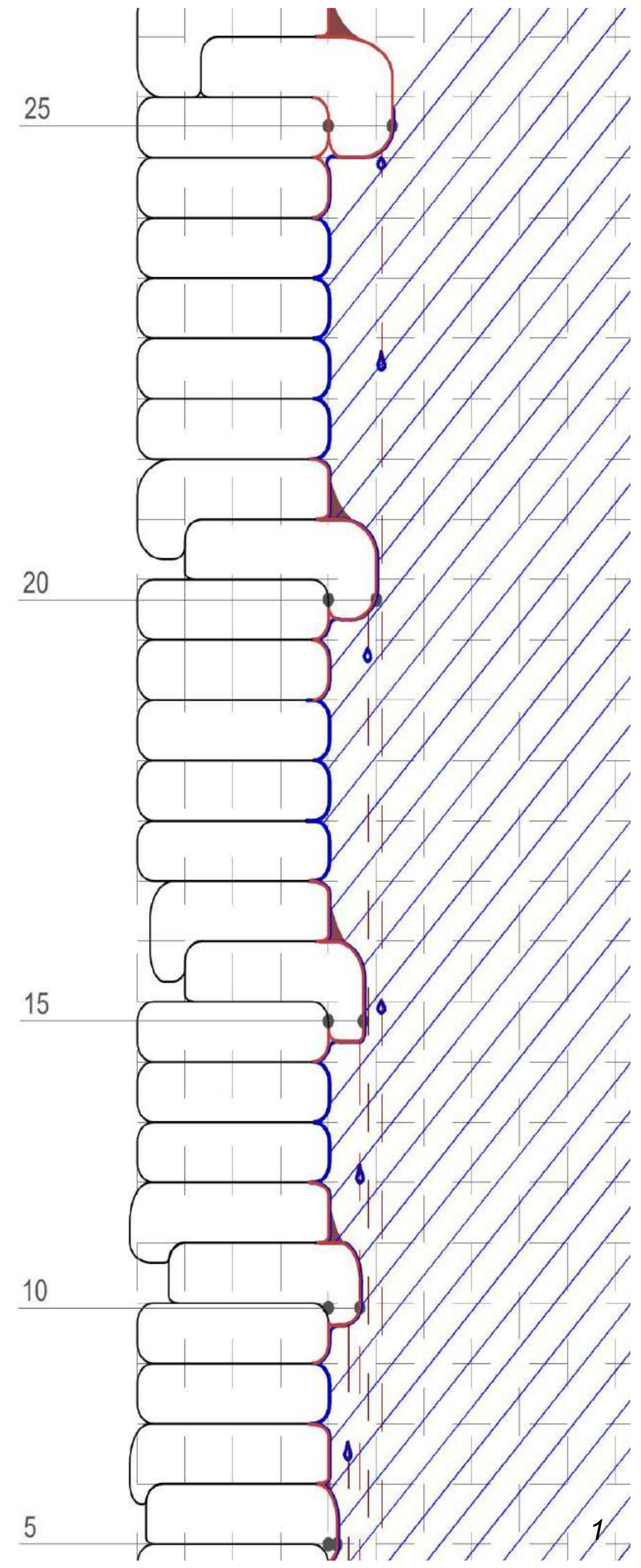
1.TerraPerforma, collective prototype, 3dPA 2017/18
2.Digital Adobe, Cavity network within 3d printed earth wall, collective prototype, 3dPA 2017/18

Rain protection

Geography : *Asir region of southwestern Saudi Arabia.*
Climate : *subtropical*
Community : *Rijal Alma*
Construction technique: *Stone, adobe, Wood.*
Scale: *from two to five stories*
Period: *17th century*

In vernacular architecture, layers of stone or brick are used for rain protection, they are followed by layer of earth, topped with a coursing of thin stone. This configuration allows rainwater to be redirected away from the earthen walls, as the protruding mineral element acts as a protective barrier.

A 3D printing solution for water erosion involves redesigning earthen structures, a designed infill is used to increase runoff time, along with a protective coating.



1

2

1. Earth wall texturing as protection mechanism for erosion, by Harrak Mehdi, Khaloian Nareh and Laalou Mouad, 3dPA 2021/22 -
2.Tova, collective prototype, 3dPA 2021/22

Evaporative cooling

Geography : *North africa*

Climate : Arid

Community : *-*

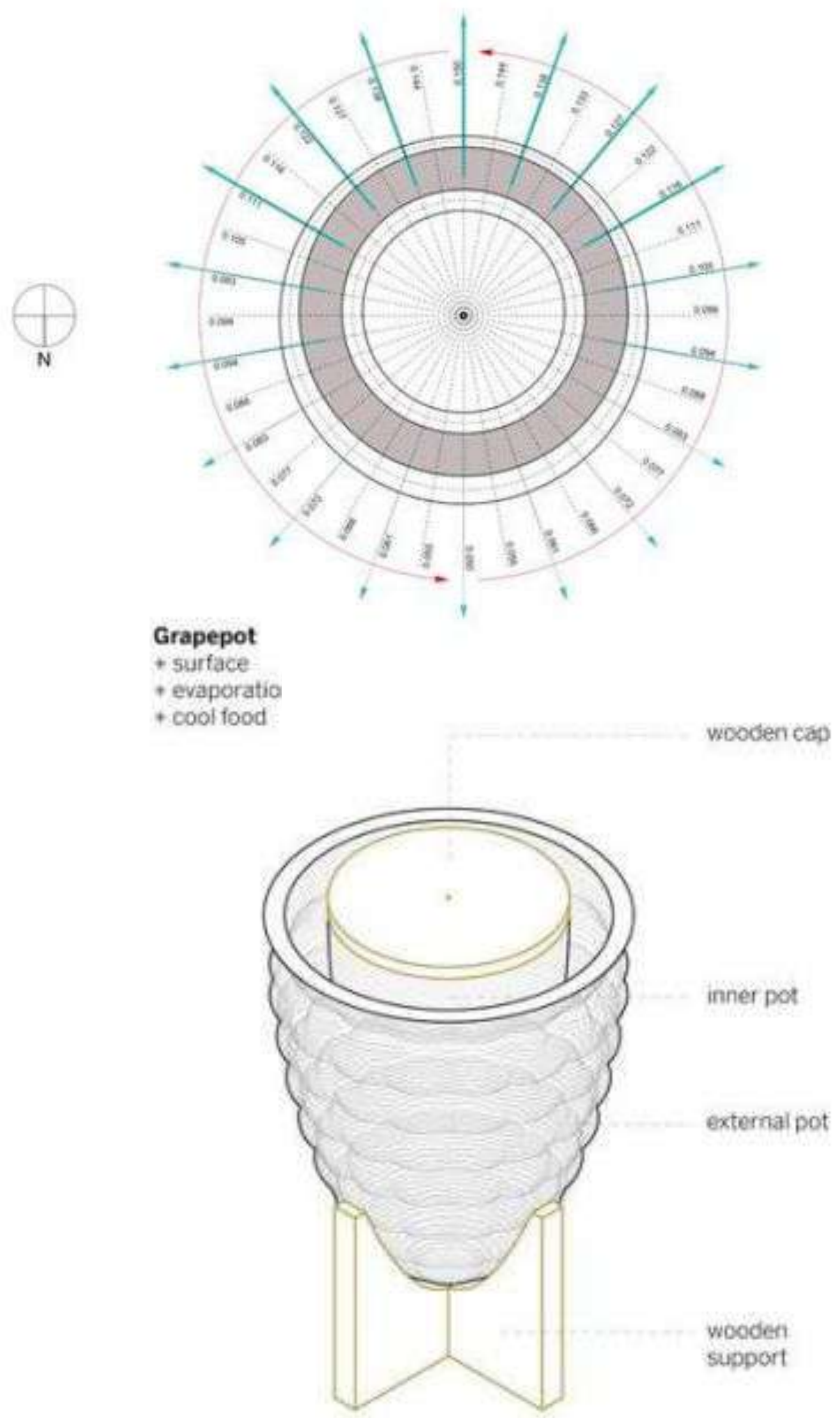
Construction technique:*Clay, local earth*

Scale: *500mm diameter*

Period: *2500 BC*

The zeer pot is an electricity-free refrigeration device utilizing evaporative cooling. It consists of a porous outer earthenware pot lined with wet sand and containing an inner glazed pot for food placement. Evaporation of the outer liquid draws heat from the inner pot, cooling its contents. The device is versatile, requiring only dry air flow and water. lowering ambient temperature.

3D printing tests were conducted to design and fabricate a zeer pot, optimizing its geometry and texture for climatic performance and measuring the evaporative cooling phenomenon. Evaporative cooling occurs naturally, where heat energy is absorbed during water evaporation,



Zeer Pot, maximising evaporative cooling performance, 3dPA 2017/18

3.Social Structure

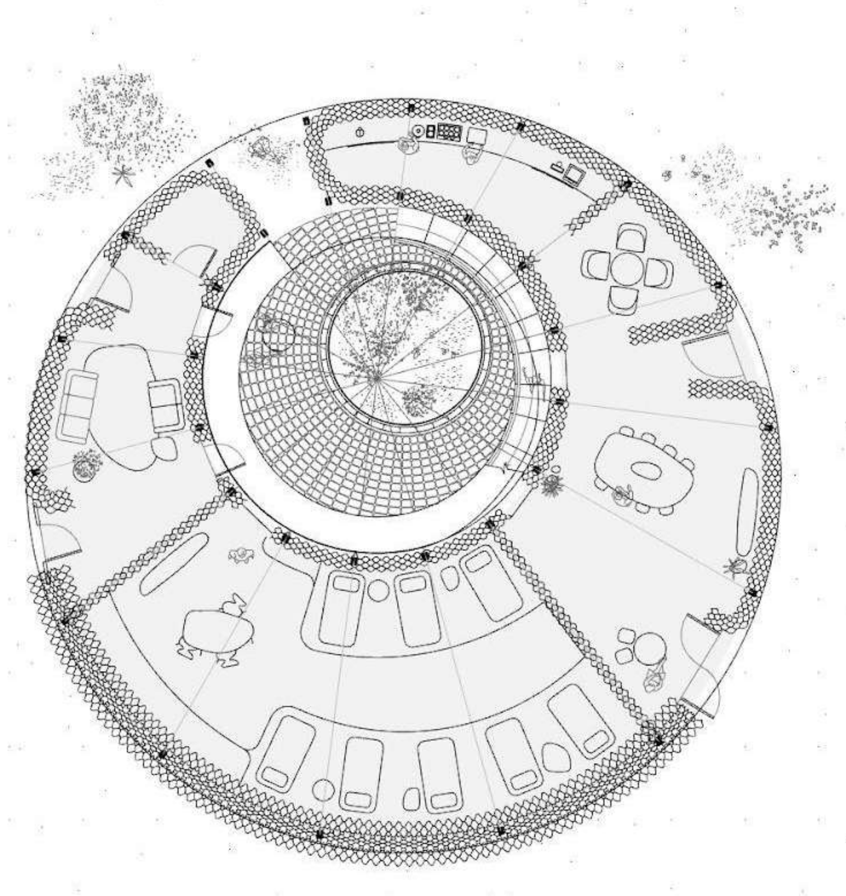
In various design projects, agglomerations inspired by the spatial organization of communities are explored in accordance to the specificities of 3d printing with earth, exemplified by the arrangement of houses around a central courtyard or public space.

Courtyard

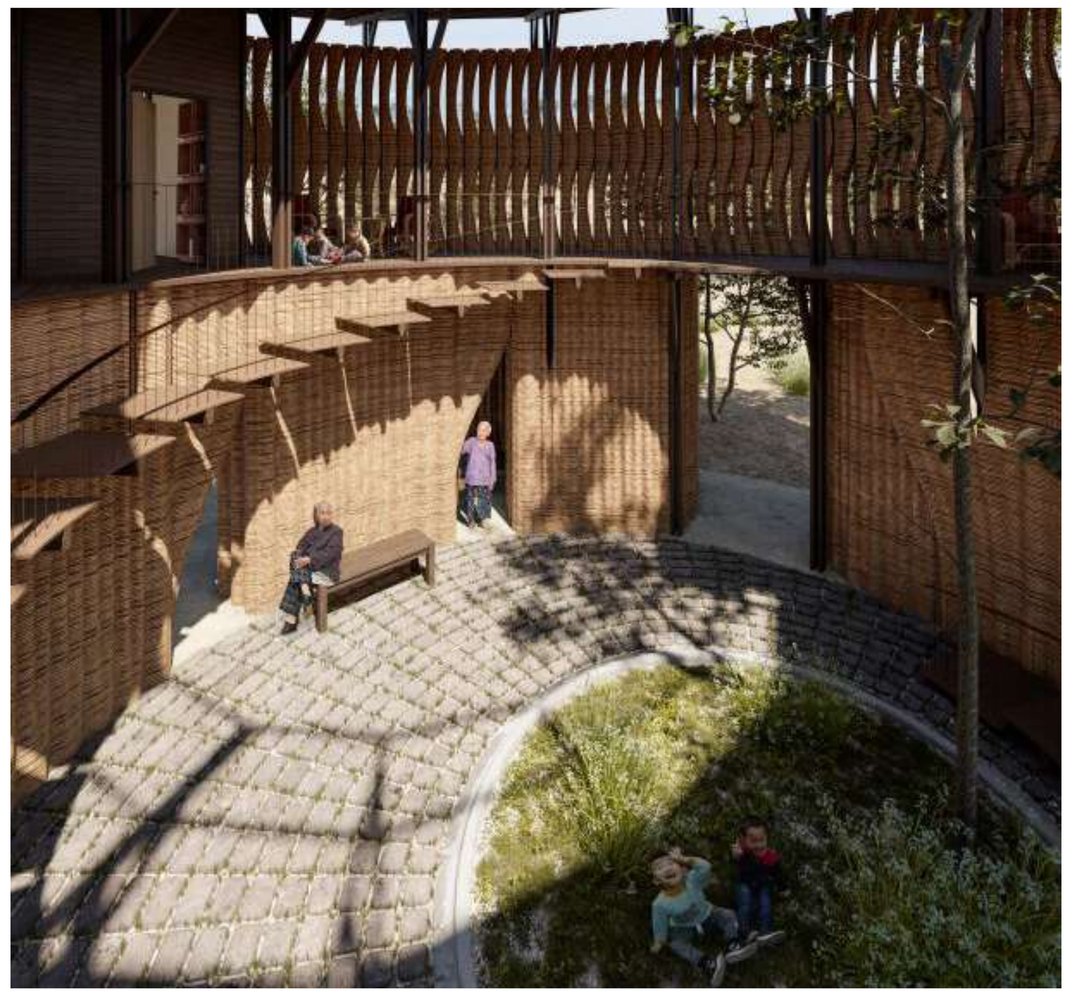
Geography : *Southern Fujian, China*
Climate : *Subtropical*
Community : *Hakka, Hoklo, Minnan*
Construction technique: *Stones, Rammed-earth, branches, Wood structure roof, clay tiles*
Scale: *3 to 5 floors high; up to 80m of diameter.*
Period: *XIV - XX century*

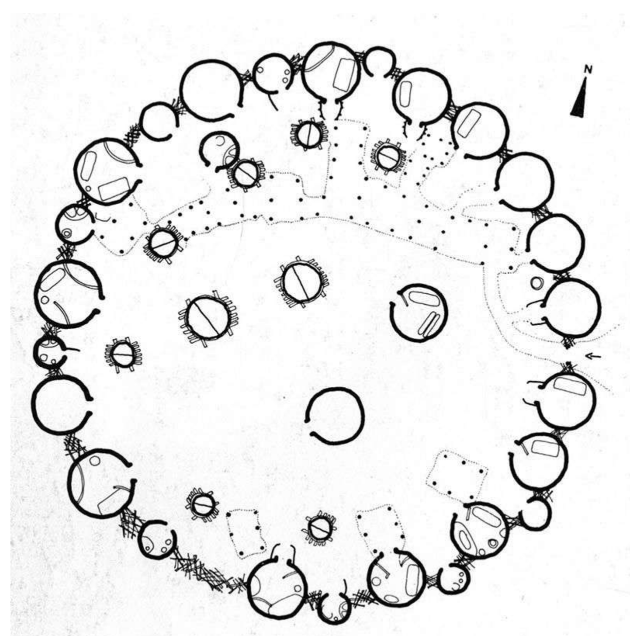
In circular courtyard configurations, the houses are disposed radially around the center, which was left free as common space with communal areas such as schools, granaries, guest rooms. Every family in the Tulou community enjoys perfect equality because every room in a Tulou is the same size and has exactly the same design.

Projects in the studio follow a radial development around a central courtyard that represents the core of the building. All around the courtyard different common spaces take place such as a common kitchen, communal living areas and, on the southern side, the bedroom for the kids.



1





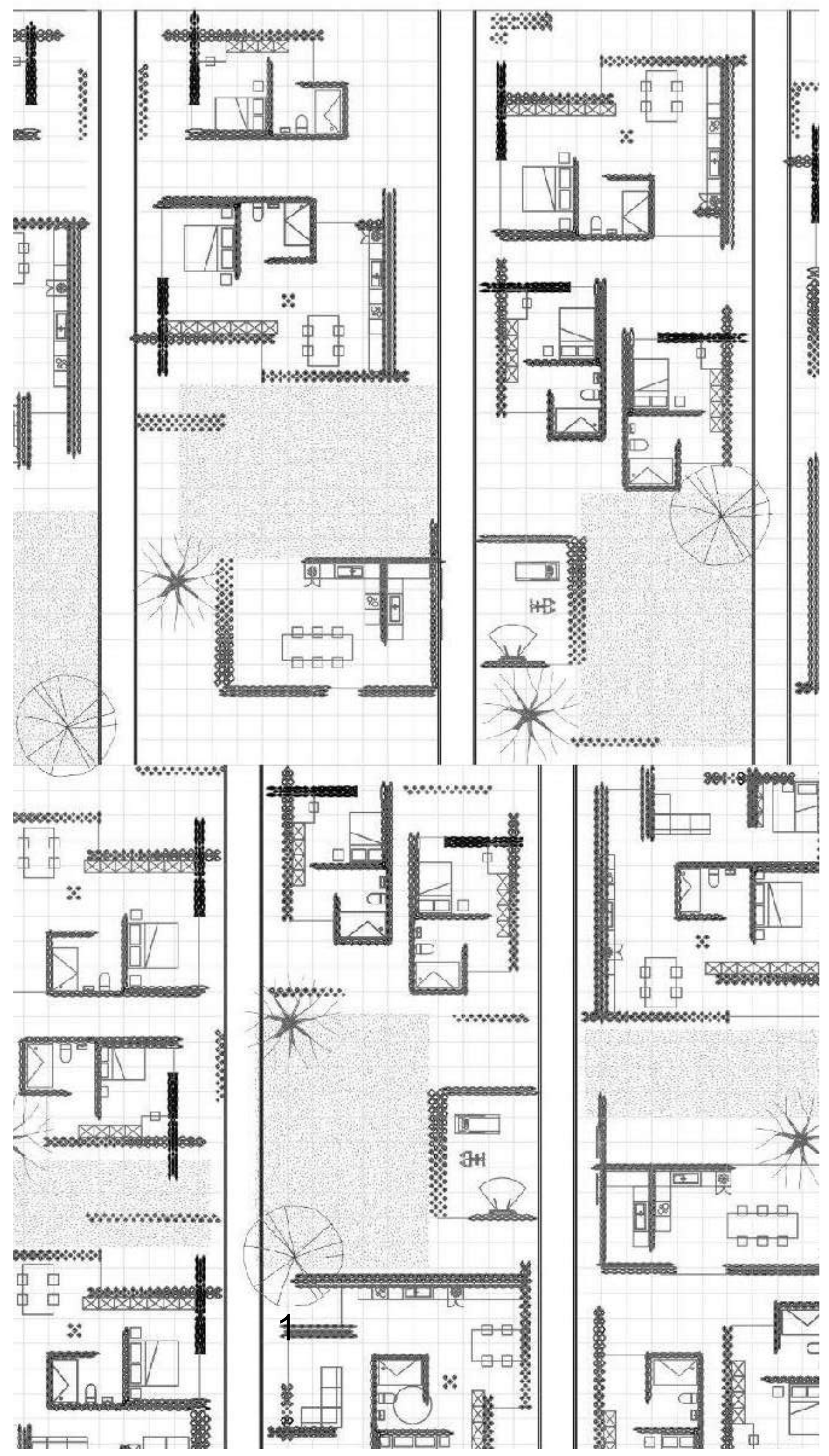
2

1.Residence in Fujiang, China Leonardo Bin, Mariam Arwa Al-Hachami, Nawaal Saksouk
2.Musgum mud hut plan, Cameroun.

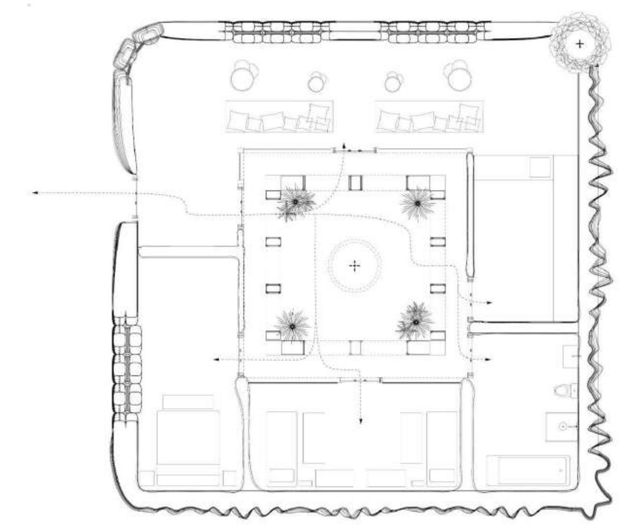
Geography : *Atlas Mountains, Ouarzazate, Morocco.*
Climate : *Dry-Hot*
Community : *Amazigh*
Technique: *Rammed earth-adobe*
Scale:*3 ha, 6m height*
Period: *17th century*

Courtyards in Mediterranean architecture create central gathering spaces surrounded by shaded arcades and sometimes water elements for cooling. This spatial dispositive serves not only as a climate regulator, but also as a space multiple social uses, providing a gathering space for families, as well as the privacy they need.

In 3d printing studio projects, both architectural and urban proposals were developed featuring spaces recreating the mediterranean patio.



1

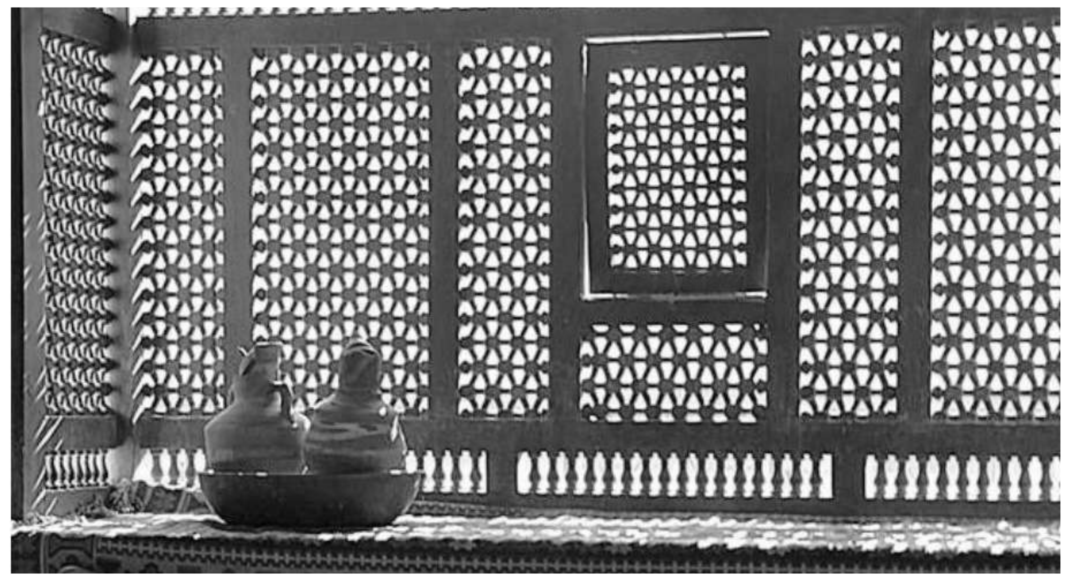


2

3

1.Luz project, Sara Ayoub, Marietta Kaltsa, Sakshi Pawar, 3DPA 2023
2.Studio Morocco, Medhi Harra, Mouaad Laalou, Nareh Khaloian, 3DPA 2021
3.Casa Fami, Joseph Naguib, Justin Hanlon, Vessela , 3DPA 2023

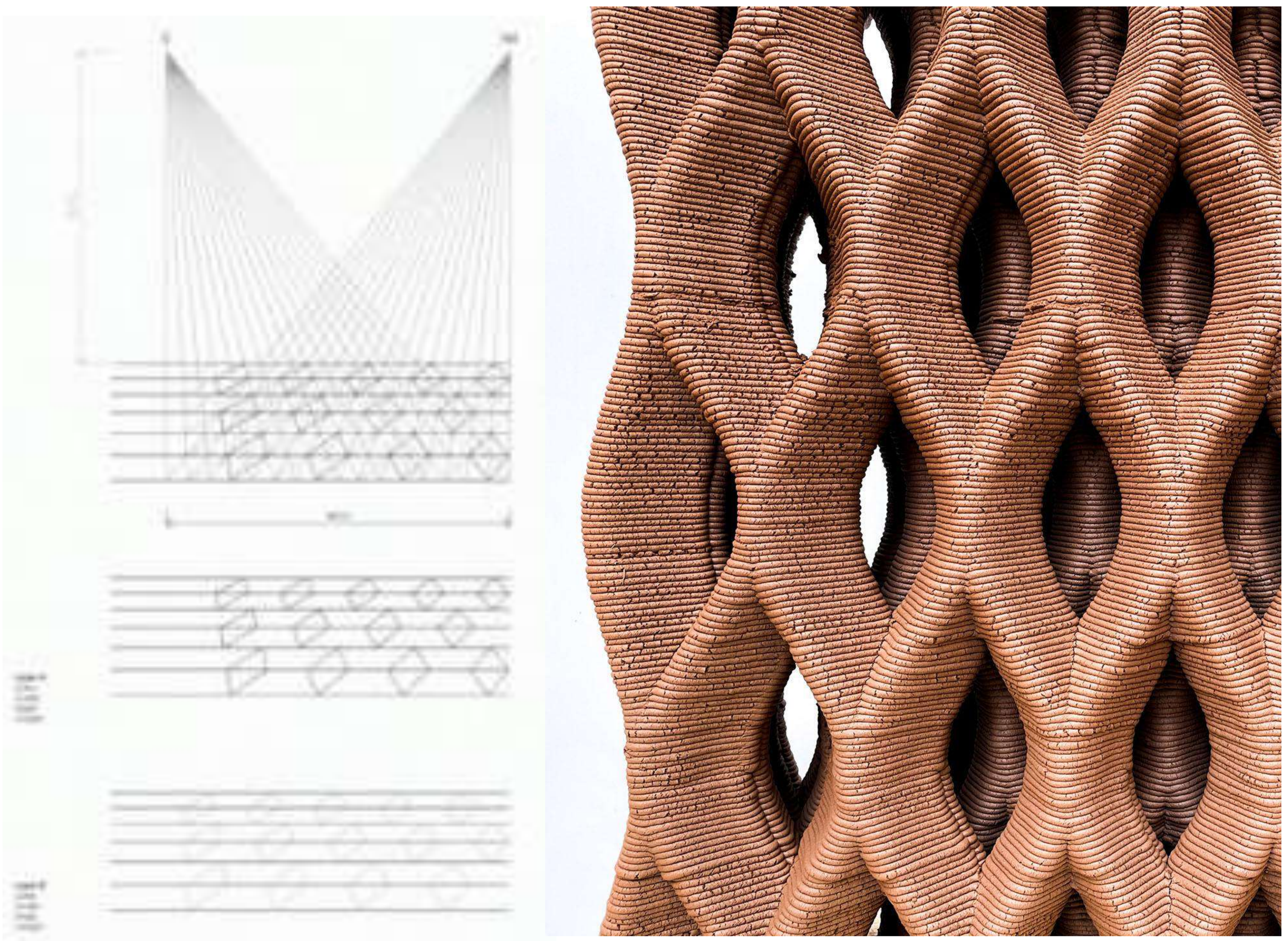
Privacy



Geography : *Imam al busiri mosque, Bayt Al Seheimy, Alexandria, Egypt.*
Climate : *Arid*
Community : *-*
Construction technique: *Wooden balcony*
Scale: *-*
Period: *-*

The *Moucharabieh* windows feature grills or lattices, replacing glass and shutters. These grills are composed of small, turned wooden bobbins arranged in intricate geometric patterns. Moucharabieh allows light and air to enter the interior while shading it from the sun's heat.

A digital version of moucharabieh is formed out of a replicated pattern of varying sizes. The basic period shape ensures that no surfaces exceed roughly 25 degrees from the vertical, adhering to printability limitations regarding overhangs.



Research into 3d printed windows and wall porosity, by Luis Jayme Buerba, Lynette Masai and Tapiwa Mirirai Manase, 3dPA 2020/21