The capacity of people to invent their own solutions for difficult problems plays an important part in development (Jannes 2000, 27).

Simon Velez Cathedral in Pereira (Koolbamboo, 2011) , Flavio Deslandes. Bambucicleta. Rio de Janeiro (onsitereview.ca,2010)

Portal towards Resilience

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Studio: Architectural Engineering aE7 MSc, TU Delft

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Contents

INTRODUCTION:

January 12, 2010 a 7.0 earthquake strikes the island of Haiti with its epicenter located near Leogane about 25 kilometers from Port-au-Prince. According to the Haitian government the earthquake caused 360,000 deaths, 300,000 injuries, and left 1 million homeless. These estimates have been contested however by international agencies, including the USAID (Schwartz,2011) who reached the following tolls: 46,000-96,000 dead, 220,000 injured, and between 1.5-1.8 million left homeless. Some of the major landmarks that collapsed due to the earthquake include the Presidential Palace, the National Assembly, and the Port-au-Prince Cathedral. In addition to the devastation seen near the epicenter in Leogane, as well as in the capital due to poor construction practices and uncontrolled urban density, Jacmel a city towards the south of the peninsula also suffered tremendous destruction with about 50-60% of the city being affected.

Fig.1 Devastation after the earthquake (Aljeandra201, 2011), (matternetwork.com,Thera N. Kalmijn 2011).

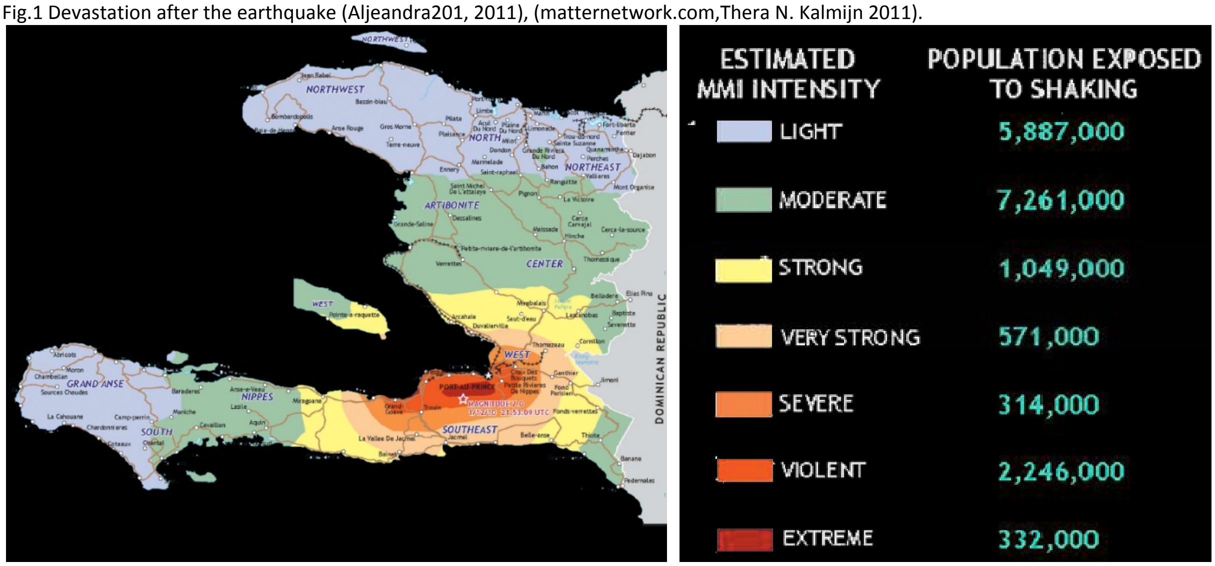


Fig.2 Earthquake map and epicenter (USGS/PAGER Alert Version 8, 2010).

POST-EARTHQUAKE [2010-present]:

Shortly after the earthquake Haiti found itself more or less invaded by international relief. This was hardly the first time international aid had come to the island (see appendix C for overview on Haiti's history), but in this instance the scale of aid and NGO's coming to Haiti was unprecedented. Unfortunately, due to a lack of governance, supporting infrastructure, and poor accessibility exacerbated by large amounts of rubble, the implementation of aid and rebuilding efforts have been extensively slowed down. It should be noted that relief and reconstruction efforts are usually structured under the following scheme: emergency relief, temporary camps and shelters for the internally displaced population, short term relief, eventual transitioning to long term reconstruction. What is critical here is supporting a balance between short term and long term schemes, rather than remaining focused on fast relief allocated through short term schemes.

OBJECTIVE “BUILD BACK BETTER”:

After the earthquake with such a vast number of agencies attempting to rescue Haiti from the devastation and years of neglect, the main slogan that emerged out of the rubble was the necessity to “Build Back Better”.

The main problem that arises with this zealous slogan and resulting approach is the lack of conscious and long term analytical decisions that take into account a holistic overview of a series of pressing problems that have existed within Haiti at a nationwide scale throughout its history.
Rather, the question that should be asked at this point is “What should be built back better?” Is it a building, a city, or a country? By reframing this pursuit, one can only begin to ask whether all the aid going into Haiti should be aimed only towards building back Port-au-Prince as it currently is. Essentially, the discussion that arises is whether this city is the best place to invest and rebuild as the nation’s capital in one regard, and also whether all the focus should solely be in ameliorating the welfare of the inhabitants of that city alone; and if by doing so will this really help Haiti in the long run.

To begin, one should assess the vulnerabilities existent in this geographic location. It should be noted that this is in fact the second time in Haiti’s history that Port-au-Prince has been destroyed due to an earthquake. The severity of the destruction in large part can be blamed to the lack of construction standards, uncontrolled growth, and building in a vulnerable area. The fact is that the Enriquillo-Plantain fault line runs right through Port-au-Prince. Due to extensive unplanned growth, the concentration of 2.5 million people has far exceeded Port-au-Prince’s limited capacity of supporting infrastructure, if any existed, for its inhabitants (Fig. 3).

Fig 3.

Thus, rather than rebuilding the capital, one should aim to build back a better Haiti. And a possible approach for this aim can be summarized as follows.

1- Target problems as opportunities
2- Evaluate where to invest within holistic parameters
3- Focus on long term sustainable development

IDENTIFYING PROBLEMS:

Essentially, there are three pressing problems that arise when taking a holistic overview of the development in Haiti: deforestation, high urban density, and the negative identity that has been associated with Haiti as the poorest nation in the western hemisphere.

Deforestation and the overall degradation of the island's ecosystem is quite alarming since it creates a series of compound problems. Due to the mountainous terrain and the consistent rainfall throughout the year, soil erosion becomes quite a precarious problem as the soil is no longer maintained at an inclined angle by means of plant life and root structures. This phenomenon also exacerbates flooding since the soil in the hills can no longer retain the seasonal rainwater and overflow runs down flooding the valleys and plains below, containing the most populated areas of the country. Additionally, desertification is also taking place since the top soil erodes taking a large portion of the nation's agricultural soil and depositing it right into the sea. The remaining soil is then rendered useless, having become desertic and losing its fertility (Reliefweb,2009).

As previously mentioned the **highly centralized urban density** found in Port-au-Prince gives rise to overcrowding and continuous unplanned growth without supporting infrastructure for its inhabitants. The "magnetic" force that causes a continuous migration to the capital is the centralized focus of the country's economy largely in this city alone. It becomes, therefore of vital importance that the nation take on a more holistic development plan and look into strengthening the diverse sectors of the nation and empower the richness that each region can offer for the good of the greater whole. One possibility which will be discussed at length later on in the report will look at the city of Jacmel, the capital of the Southern department of Haiti.

It is important to note that aside from the state of the nation's natural ecosystem and urban ecosystem, there also lays the identity of a nation, how it is perceived by others and how it perceives itself. Haiti currently suffers from a **negative public image and identity**, since it is the poorest nation in the western hemisphere. Historically many factors have contributed to this current status leading to a seemingly unending stunted economic growth, largely dependent on foreign imports, and hosting the highest ratio of aid workers per capita in the world. Essentially, Haiti has had little opportunity to thrive as a nation, causing a survival mentality to arise as a common way of existence passed down through the generations.

Fig 4. Deforestation (Reliefweb,2009), High urban density surrounding Port-au-Prince, Slum in Haiti (lachansondelacigale.blogspot.com, 2011).

RESEARCH FOCUS: Solving problems raised

The aforementioned problems should be treated as opportunities for development rather than inhibitors for growth. Since each of these issues is a symptom of a series of compounded problems, the approach to solving them has to be systematic and holistic. In other words, treating a symptom will not cure the root cause of a disease. Additionally, centralized attention to one issue, region, or in this case Port-au-Prince, actually forsakes the good of the greater whole. In fact, only a multidimensional and multi-regional approach to development will be able to actually sustain Haiti's future in the long term.

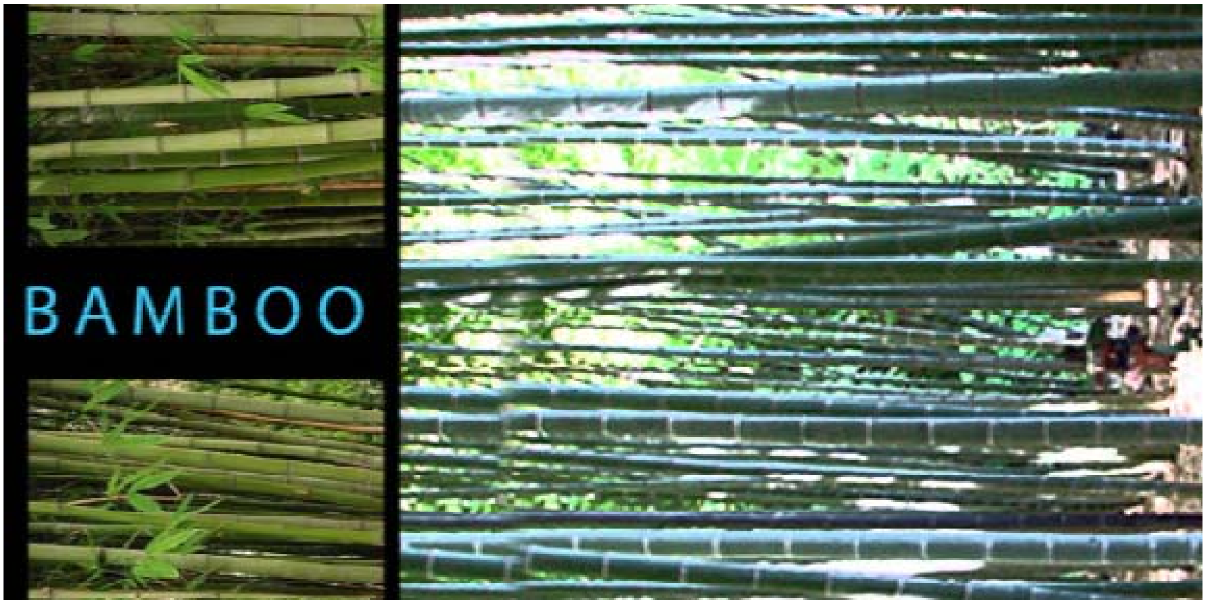
The main question then becomes within a long term sustainable development framework; how can decentralization be promoted, while restoring the ecosystems and support economic growth, in post-earthquake construction in Haiti?

In order to answer this question within the scope of this graduation project a necessary emphasis must be placed on the word *construction*. This in turn shifts the question to:

Within a long term sustainable development framework:
What resilient material can be utilized in post-earthquake construction in Haiti; to help promote decentralization, while restoring the ecosystem and supporting economic growth?

One possible strategy is exploiting the sustainable attributes found in bamboo while farming it as a plant, processing it for diverse purposes, and ultimately as a building material, which will be expounded upon in the following chapters. Additionally, the targeted decentralized site for the project will be Jacmel, a city also affected by the earthquake, presented as Haiti's cultural capital, and which coincidentally has already begun hosting bamboo farms and nurseries within its rural peripheries (see Part II).

PART I: SUSTAINABLE MATERIAL STRATEGY



Before introducing the material qualities in detail the following three sections will give an overview of the rational behind implementing bamboo within Haiti and how its use can actually aid in promoting decentralization, restoring the ecosystem, and support economic growth.

1.1 MATERIAL BENEFITS and SUSTAINABLE ATTRIBUTES: **FARMING BAMBOO**

To farm bamboo one can enumerate a series of requirements that need to be met, as well as the positive byproducts that farming bamboo will provide.

Farming Bamboo Requires:

To start off bamboo obviously requires land. The space necessary for generating 1000 bamboo houses per year designed for a social housing scheme in Costa Rica has been estimated to take up about 70 hectares. The amount of land this bamboo plantation takes is quite small compared to the 600 hectares of natural forest necessary to provide for the same amount of housing per year (Janssen,2000).
The secondary requirement is essentially cultivation expertise, which will need to be transferred within the Haitian context from other nations that have a longer history with bamboo use and application.

Farming Bamboo Provides:

Ecosystem restoration_
The benefits of bamboo plantations begin at a natural ecosystem level, performing a restorative role by rehabilitating the land. One of the main reasons for deforestation in Haiti is the need for charcoal and also wood as a building material. Bamboo can mitigate this trend by providing both a source for charcoal as well as a building material with a fast regenerative cycle. The problems currently facing the island pertaining to soil erosion and landslides, can also be alleviated since the rhizomes or the root system of bamboo actually binds the top soil. This is of course critical for agricultural productivity and the livelihood of the nation at large.
Bamboo has also been used successfully to prevent riverbank flooding, which could prove beneficial as Haiti suffered major deadly floods in 2008. Additionally, bamboo can sequester CO_2, improving the local air quality and improving the state of the environment in general. Finally, by providing soil cover and shaded groves there will be a

natural increase in biodiversity in addition to an overall restoration of the natural habitat of native species to the island.

Economic Growth_
At this level, bamboo can already begin to make an impact on the surrounding community, by providng employment in its cultivation. Some possible opportunities would be the management of a farm, cultivation activities, and harvesting activities.

Knowledge Transfer_
As previously mentioned, an opportunity arises for transfering the wealth of knowledge behind cultivation and harvesting expertise via local training. This action can further empower the local community in attaining a local means of economic freedom.

1.2 MATERIAL BENEFITS and SUSTAINABLE ATTRIBUTES: **PROCESSING BAMBOO**

Processing Bamboo requires:

After bamboo has been harvested, the curing of the bamboo culms is extremely important in order to utilize the highest strength and material properties of this natural material. Proper treatment for durability against mold and insects is essentially done through drying and curing.
The most important aspect of this practice is effectively removing moisture and starch content that could become a food source for insects. See appendix *H* for further information on typical curing and drying methods.

As far as the energy requirements necessary to create building materials of the same capacity, bamboo culms are quite competitive when compared to other material processing needs. For instance, it takes 1/8th the energy of processing concrete, 1/3rd the energy of processing wood, and 1/50th the energy of processing steel (Ghavami, 2007). Once again this is important to note as in the Haitian context, the limited supply of energy should be taken as one of the parameters for design. The decision making process in this respect becomes somewhat more complex when looking at generating bamboo composites or prefabricated bamboo building components. Essentially, here the proper knowledge for processing and manufacturing capabilities, along with energy use can increase depending on the level of processing needed. This aspect will be discussed in sections (I:3.1) in greater detail.

Processing Bamboo Provides:

Economic Growth:
Once again at this point in the material life cycle, bamboo can provide community employment opportunities. For instance, positions can be created in the pre-processing, preservation, and curing of culms. Furthermore, when preparing the material for building purposes a series of processing tasks need to take place solely for dried culms and even more so for processing of bamboo composites or building components.

Knowledge Transfer:
The knowledge exchange in this cycle would focus on durability and processing techniques.

Fig 5. Processing and drying Guadua culms (Marcelo Villegas, 2011).

1.3 MATERIAL BENEFITS and SUSTAINABLE ATTRIBUTES: **BUILDING WITH BAMBOO**

Building with Bamboo Requires:

In order for bamboo to thrive as a building material the following requirements must be met, which for the most part common building materials do not have to overcome or have already been established. First of all, bamboo can sometimes have an association with poverty and carry a negative social stigma as 'poor man's timber' (Adams,1998). It is therefore, paramount to establish the richness the material bears by removing the misconception that it is a low grade material with limited durability. These stumbling blocks will be overcome largely by proper knowledge transfer of processing techniques in curing and use, thus increasing its longevity, alongside demonstration projects that are accessible to the public at large.

Due to the large number of bamboo species and the varying properties that accompany them, it is essential to establish standards which can begin to control bamboo quality as a building material. It should be noted that the quality of construction is actually largely dependent on species type, the location where the culm was harvested, the age of the culm, and the size or diameter of the culm. Since all of these factors can vary greatly in a plantation, let alone several plantation, it is imperative that national building codes become established which assign culms diverse grades of structural safety and overall material quality.

A priority should also be placed on training and disseminating information which provides proper construction expertise. Some possible leads in this area have already been established by INBAR (International Network of Bamboo and Rattan) which connects several experts in the field at a global level. Making the knowledge and experience of countries within the same climatic zone as Haiti and with a longer and well established history of building with bamboo accessible would clearly benefit Haitian development.

Building with Bamboo Provides:

The instrinsinc positive aspects that bamboo provides and which should be exploited are numerous. These should be highlighted when designing with this material in order to overcome negative associations and doubts of the material's capability and performance.

Bamboo can be described as a resilient, regenerative and lightweight material. If bamboo plantations are located within a targeted region (closer to a building site), the material can be readily available for use while eliminating superfluous transportation costs. Since it can be locally grown bamboo has the added benefit of contributing to the local economy as a cheaper raw material for construction. When looking at the level of industrialization a nation possesses, a proposed building project along with the construction material should be appropriate within that context. Bamboo is quite fitting in this regard since it is quite easy to work with, has a fast construction time, and can accommodate a wide range of industrial processes. In other words, bamboo can be utilized with traditional technology with very low-tech tools, or can be treated to accommodate high-tech modern technology such as high pressured lamination or work in conjunction with high-tech connections (see sections I:4.1).

Due to this inherent flexibility the design possibilities and versatility of bamboo's expression can become quite numerous. Designers can utilize bamboo in a variety of forms, as natural cured poles, bamboo composites, or standardized components (see section I:3.1). This adaptability in fact allows the material to be used in low or high end markets, without forsaking its affordability and speedy construction time.

In fact it has been estimated that bamboo can provide affordable housing that is 20% cheaper than masonry houses (Paudel, 2003).

Economic Growth / Knowledge Transfer:

In this facet community employment opportunities and expertise would essentially be bounded around construction, manufacturing, distribution, transportation, and marketing. All of which are quite diverse in their scope and can establish quite a diversified economic base.

It is easy therefore to justify why bamboo is a good choice to use in post-earthquake reconstruction within Haiti. There are a wide variety of benefits that can be reaped at each stage of the life cycle of this material.

Since it was important to first establish why bamboo is in fact an appropriate choice within the Haitian context, the following three sections will further elaborate the qualities and properties of the material.

2.1 MATERIAL/PLANT QUALITIES: **REGENERATIVE + ADAPTIVE**

Bamboo is the name used to refer to all species within the Poacea *grass* family and can be described as "an evergreen plant with woody stemmed members" (Hidalgo-Lopez, 2003).

Bamboo is one of the fastest growing plants in the planet. The speed of regeneration is quite impressive as it has growth rates which range from 30-100cm per day. This causes the plant to attain its maximum size in 60-90 days after the shoots sprout. Within 3-6 years bamboo can be harvested for use, which is quite a contrast when compared with timber which has a 25 year rotation cycle to reach maturity.

GEOGRAPHIC DISTRIBUTION:

The resilience of bamboo is also exemplified, when one examines the geographic distribution of where this plant is able to grow and thrive naturally. In essence, bamboo is found throughout the world and can grow in a wide range of climates and regions, from sub-Saharan deserts of Africa to the cold mountain terrain of the Himalayas.
The following is a brief breakdown in percentages of where bamboo can be found:

- 64% native southeast Asia
- 33% grow in Latin America
- 3% Africa/Oceania

As far as the species found in America (North and South) the break down is described as follows:
Within North America there are 3 native species, within Latin America there are 440 species, and it should be noted that 7 of these are native to Haiti (UNEP-WCMC/INBAR, 2004).

Fig. 6 Left to right: Phyllostachys aurea, Tetragonoclamus angulatus, Phyllostachys nigra f. punctata, Phyllostachys violascens, Phyllostachys nigra f. 'Boryana', Phyllostachys viridis 'Sulphurea', Phyllostachys bambusoides (Image by Wetterwald M.F. bamboocentral.org).

CLASSIFICATION:

As can be seen in the image above the overall appearance and structural properties can vary widely from species to species. Currently, it is estimated that there are 1600 species of bamboo, and as with any natural material not all species are suitable for construction purposes. For instance, some of the smallest varieties grow to a height of 11 inches, while giant timber bamboo can reach heights of over 100 feet (Adams, 1998). The main distinction that exists however in all bamboos is the root type whether the rhizomes spread widely or clump (see appendix *G*). It has however, been estimated that about 65 species can be used safely for construction.

Currently in Haiti, there are as mentioned 7 species that have been identified as native to the island. The most prominent species are Bambusa Oldhamii, Guadua, Phyllostachys makinoi, Bambusa vulgaris, Bambusa Stenostachya, Dendrocalamus latiflorus (Le Nouveliste, 2007). *Complexe Bambou* a Taiwanese-Haitian cooperation based in Marmelade and Jacmel, is growing three species Guadua, Bambusa Oldhamii, and Bambusa vulgaris for construction purposes. Their focus up until recently has been restoring the ecosystem, but also as a material supply for furniture. After the earthquake the cooperation has shifted its focus into simple housing schemes. Additionally, bamboo nurseries are also being established through a Nicaraguan based company CO2 Bamboo, who is currently importing bamboo culms of the Guadua species (CO2 Bamboo, 2011).

Fig. 7 Bamboo plantation in Beaucher Marmelade Haiti (Le Nouveliste.com, 2010), Complex Bambou in Jacmel (Haitiwebs.com, 2011), Kenscoff bamboo garden (Up-lab.org, 2011).

Fig. 8 Complex Bambou workshop (Video snapshot 2011, http://vimeo.com/16544834)
and CO2 Bamboo nursery Guadua seedlings (Jacmel_news/cornell.edu, 2011).

Fig. 9 First bamboo house constructed in Petit Goave in April 2011 (CO2 Bamboo, 2011).

Fig. 10 First bamboo house constructed in Jacmel (C02 Bamboo, 2011).

2.2 MATERIAL PERFORMANCE: **PHYSICAL PROPERTIES**

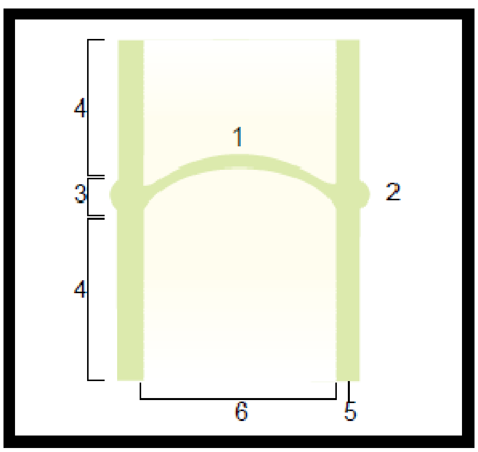
The properties of bamboo actually change according to the starch content and maturity or age of the culm, making bamboo useful for different purposes at different ages.

<30 days it is good for eating
6-9 months useful for woven baskets
2-3 years useful for bamboo boards or laminations
3-6 years useful for construction
>6 years bamboo gradually loses strength up to 12 years old
(Adams,1998).

In order to optimize the performance of bamboo it is necessary to understand the physical properties of the bamboo culm. Although different species have different wall thicknesses, and some species are entirely solid, the larger majority share the following characteristics.

Culm wall composition:
The exterior surface and softer interior portion of culm walls are protected by a natural waterproof film. The actual composition of the culm can be described as follows:
The wall is a natural composite containing a matrix: 50% (parenchyma), Fibers 40%, and Vessels 10%. The cellulose fibers and vessels actually act as reinforcement within the matrix creating a highly flexible and strong material after the stalk has been harvested.

Overall, bamboo culms are widest at ground level, but remain consistent in diameter throughout its length. For example, the culm of Guadua angustifolia species will have a diameter that varies between 10-24 cm reaching its full height in 3-4 months, but will remain fairly consistent along its length.



1. Diaphragm or septum: An inner disc that connects outer walls.
2. Ring
3. Node: Due to higher strength found near the node, connections should be located closer to nodal ring or septum. This disc basically connects the outside walls while strengthing the overall hollow tube, and creating distinct compartment of varying lengths.
4. Internode: Length varies from node to node, generally the length is larger at mid stalk.
5. Culm walls: Thickness depends on species, but decreases from bottom to top of culm.
6. Cavity: Overall width is largely dependant on species.

Microstructure:

The microstructure of the culm wall varies in density. Porosity decreases toward the exterior, reaching the highest density and highest silica content (5%) which effectively creates part of the waterproofing film. Its important to note that the irregular distribution pattern of the culm microstructure increases stiffness (the resistance against bending) of bamboo by 10%.
This has been described as “efficient performance comparable to a steel tube with high tensile steel on the outside and normal mild steel on the inside” (Jannes, 2000).
The reason this microstructure is formed in this manner, is basically due to the functional needs of the stalk to resist the constant wind forces it is subjected to throughout its lifetime. The higher stresses obviously take place at the exterior most surface of the stalk. Essentially, the natural environment will largely influence the formation of the microstructure, which will be optimized to resist the pressing forces (Stamm,2010).

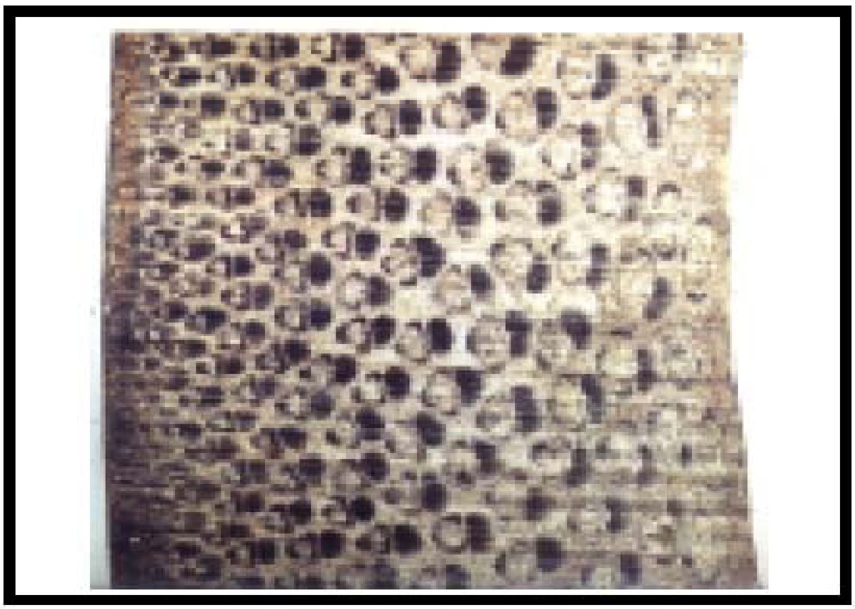


Fig. 11: Inner structure of culm wall Specimen 6x6mm (Jannes, 2000)

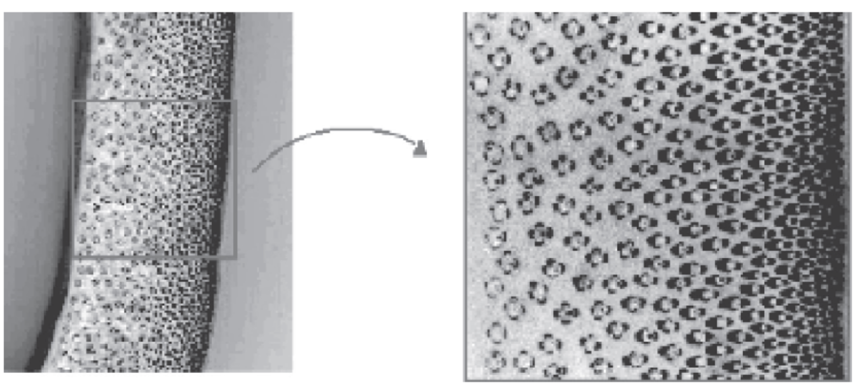


Fig. 12: Non-uniform fiber distribution of bamboo cross-section (Ghavami, 2004)

2.3 MATERIAL PERFORMANCE: **MECHANICAL PROPERTIES**

Bamboo has a high strength to weight ratio and high specific bearing capacity. As a cylindrical shell bamboo possesses high strength along its fibers and low strength transversal to its fibers. Nevertheless, bamboo effectively has excellent strength properties especially tensile strength. This is actually due to the dense accumulation of the rigid fibers in the edge zone which improve the values of elasticity, tension, shear, and bending strengths. Additionally, the tensile strength of exterior fibers is two to three times higher than interior zones.

Fig.13 (Tonges, 2001)

As far as tensile strength at the internode, it should be noted that the fibers curve towards the culm axis as a multiple-curved surface, the modulus of elasticity however is reduced at this point by 40%. This is due to the fibers running in a disordered pattern. Tensile strength also decreases with culms 5-6 years old (Tonges, 2010).

Properties:
Density = 500-800 kg/m3 (depends on quality of growing site/position of culm)
Young's Modulus: E=15000-20000 N/mm^2
Poisson's Ratio: v= 0.32-0.46
Tensile strength: o=160-370 N/mm^2
Compressive strength: o=60-100 N/mm^2
Bending Stress at Failure = 0.14* (Density) N/mm^2

Strength and material density:
It should be noted that there exists a unique correlation between the density of the material per volume and the strength that particular culm has. As seen in the images below, the culm with the thinner wall is of lesser strength than the thicker Guadua culm, therefore it is not used as a load bearing structural member. However, this is not always the case, as sometimes the thicker walls contain more porous microstructure decreasing its density (Tonges, 2010). A structural rule that has derived for this relationship is as follows: Bending stress at failure (N/mm^2) estimated as 0.14 times the mass per volume (in kg/m3) (Jannes, 2000 P. 22).

Fig 14. Culm wall thickness can vary widely in bamboo Guadua (CO2 Bamboo, 2010).

To further understand the strength of bamboo, a comparison with other building materials becomes a useful tool. As can be seen on figure 14 materials listed from greatest to least strength are as follows: Steel, Bamboo, Wood, Concrete. This clearly shows bamboo as an attractive substitute for steel.
With bamboo's highest tensile strength reaching 370 Mpa, this tensile resistance and specific weight of bamboo ends up being six times greater than that for steel (Ghavami,2007).

Compressive strength:
Strength in compression actually increases with age, culms 6 years old showed a 2.5 increase in strength over one year old culms. Also, the nodes play a big role in increasing the strength. When a compressive load is applied parallel to the culm axis, strength increases by 8% and 40% with a perpendicular compressive load. According to Tonges, the sea level and the age of poles are the two main factors which influence the silica content of the fibers or vessels in the plant, which cause the increase in strength (Tonges, 2010).

Stiffness: (E-modulus/material density)
As far as stiffness the same materials compare as follows, listed from greatest to least stiffness: Bamboo, Steel, Timber, Concrete. An explanation for this outcome would be the shape of the bamboo culms in addition with the diaphragms or internodes which increase the strength and stiffness of the culm's structural performance. In essence they prevent bucking of the culm wall from taking place.

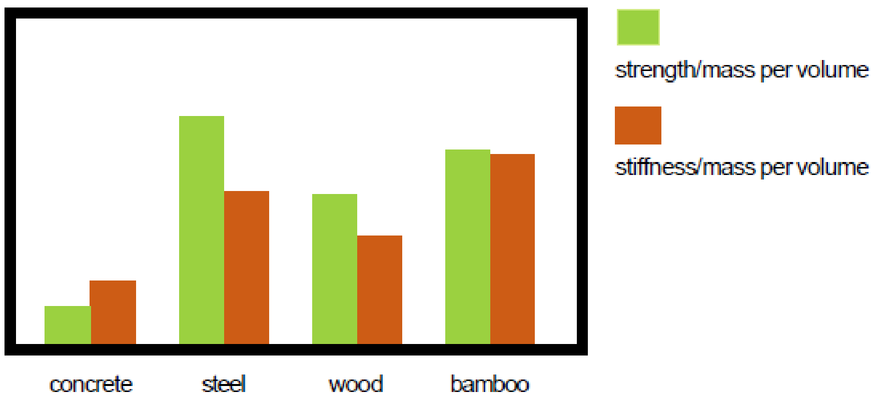


Fig.15 Strength and stiffness comparison (Jannes,2000).

Safety:
"Failure in bamboo is not failure" (Jannes, 2000, 22).
After bending test, when the bamboo specimen reached 'failure' all fibers along its length still exist without any damage, and for the most part the pole can return to its original straight form after the removal of the load. Only residual damage appears as broken bond between fiber, the circular cross-section does however lose strength (Jannes, 2000, 24). Bamboo essentially behaves well with compressive loads since the pole does not suddenly buckle or crack. However, shear fractures appear along the length of of the fibers, which can be present from overly dry cracks. The spread of these fractures is generally stopped at the internodes, effectively increasing the overall fracture toughness of the material. It is important to highlight that sections of the culm which will be designed to take on high levels of shear forces should be filled with mortar to increase their carrying capacity (Tonges, 2010).

Fig.16 Fracture of pole (Tonges,2010) Fig. 17 Shear failure and combustion behavior (Ecobamboo, 2010).

Bamboo in Fire:

Silicic acid concentration in dense fibers cause bamboo to be classified as a flammable but not combustible material. Components which are horizontal to the flames are less likely to ignite, in comparison to diagonal or vertical members. "On a horizontal bamboo cane, the flame spreads annularly to the next knot point (node). There the fire dies down because the flame cannot pass easily through the hardly combustible node (diaphragm) to the next segment (internode). If the internode bursts showing longitudinal and transversal cracks, the combustion is faster. Moreover, transversal cracks decrease the load-carrying capacity significantly (fatigue strength). A bamboo tube, that is filled with water, can stand up to 400°C at the bottom side, while the water cooks in the tube" (Tonges, 2010).

Creep:

An important attribute to bamboo is the fact that increasing deformation on the long term does not occur.

Shear:

Bamboo is stronger than wood in shear, since it does not exhibit rays like timber. This actually becomes an important attribute at joints, since "nails, bolts, pins and similar fasteners are used in such joints. In all these joints a hole is made in the bamboo, and the fastener is put through this hole. When in use, a tensile force from this fastener will be applied towards the end of the bamboo joint, resulting in shear"
(Jannes, 2000,24). Additionally, shear strength tends to be higher in bamboo canes that have thinner walls, due to the ratio of the rigid fibers to the sectional area. Also, the node is stated to have 50% higher shear strength than the internode fibers.

Shape:

Bamboo can actually be considered as nature's 'prefabricated' hollow tube. The high structural efficiency of the hollow tube can be compared to an I-beam. Also, when compared to a wooden beam, bamboo's hollowness increases its effectiveness as 1.9 times better than the former (Jannes, 2000, 17).

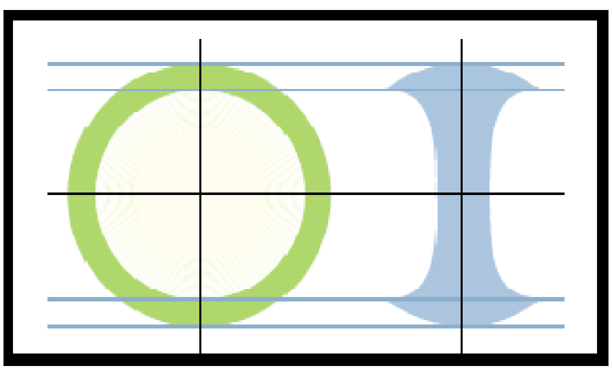


Fig. 18 Comparison of bamboo cross section versus I-profile

Structural efficiency of hollow tube:

Difference between moment of inertia (I) and the cross section (A):

The moment of inertia of bamboo is much less when comparing a rectangular cross section to bamboo's hollow tube which indicates that the structural efficiency of bamboo is very good (Jannes, 2000, 64).

Example by Jules Jannes:

If we take for d the value of 0.82 3 D, and we work out the formulas with this value, we get: I = 3.14 (1 – 0.824) D^4 4 64 = 3.14 3 0.55 3 D^4 4 64 = 0.03 D^4. In a similar way we get for A the value 0.26 D^2. We need a comparison between I and A, but I is related

I = p 3(D^4 - d^4) 4 64 and A = p 3 (D^2 – d^2) 4 4, in which:
p = 3.14
D = external diameter
d = internal diameter (for most bamboos d = 0.82 3 D)
t = wall thickness (evidently D = d + 2t)
to D^4 and A to D^2. So we take the square of A, A^2 = 0.07 D^4. This allows us to calculate the ratio between I and A: I = 0.40 A^2.

Timber mostly has a rectangular cross section: h = 2 3 b. From this ratio, and because I = b 3 h^3 412 and A = bh, it follows that: I = 0.16 3 A^2; a difference of 2.5 in favor of bamboo.

If numerical values, D = 100 mm and d = 82 mm, are substituted, then for bamboo:

I = 2.69 3 10^6 mm^2 and A = 2 570 mm^2.

If the same cross-section is considered for timber, then:

for a beam of 36 3 72 mm, I = 1.12 3 10^6 mm^2
for a column of 51 3 51 mm, I = 0.56 3 10^6 mm^2.

Test conducted by Saleme and Navarro to determine the efficiency of *elementary* structures:
Bamboo's structures was found to be highly efficient due to it's geometry and overall strong nature in relation to the ratio of the load supported and the weight of the structure.
For instance:
0.10m diameter and 0.30 m high tube of quebracho, weight 2.95kg breaks under 46 tons versus bamboo culm similar dimensions with 0.600kg breaks under 28 tons.
The resulting *Load /weight ratio*:
Quebracho breaks under load 15.590 times its weight, while Bamboo breaks under load 47.000 times its weight demonstrating its greater efficiency (Saleme and Navarro, 2002 p 66).

Allowable Stresses, *Resilience and Natural Hazards:*
Due to high tensile strength or elastic nature of its fibers, bamboo is extremely resistant to hurricane or earthquake forces. For instance, bamboo housing has resisted 200 kph wind forces with appropriate detailed connections (BambooLiving,2011). This high resistance can be explained by the plant's microstructure designed to withstand wind moment forces during its natural growth cycle. Bamboo is also highly resistant to earthquake forces, which again make a strong case for utilizing it in the aftermath of the Haitian earthquake. An example of the material's exemplary resistance was recorded in Costa Rica, where a 7.6 earthquake hit the country in 1992. At the epicenter there were 30 bamboo houses which remained standing without any damage, while the surrounding masonry structures had crumbled all around (INBAR,2010).

Performance:
In order to understand the how the performance of bamboo compares in case of dynamic overloading, hurricanes or earthquakes, Jannes describes the mean stress at failure of timber, concrete, and bamboo.
"To make stresses between concrete/steel/bamboo comparable: the value of the stress in the material when the building is in normal use is taken as the unit", this becomes the so called "allowable stress" (140 N/mm^2 for steel and 10 N/mm^2 for timber) (Jannes, 2000, 18).

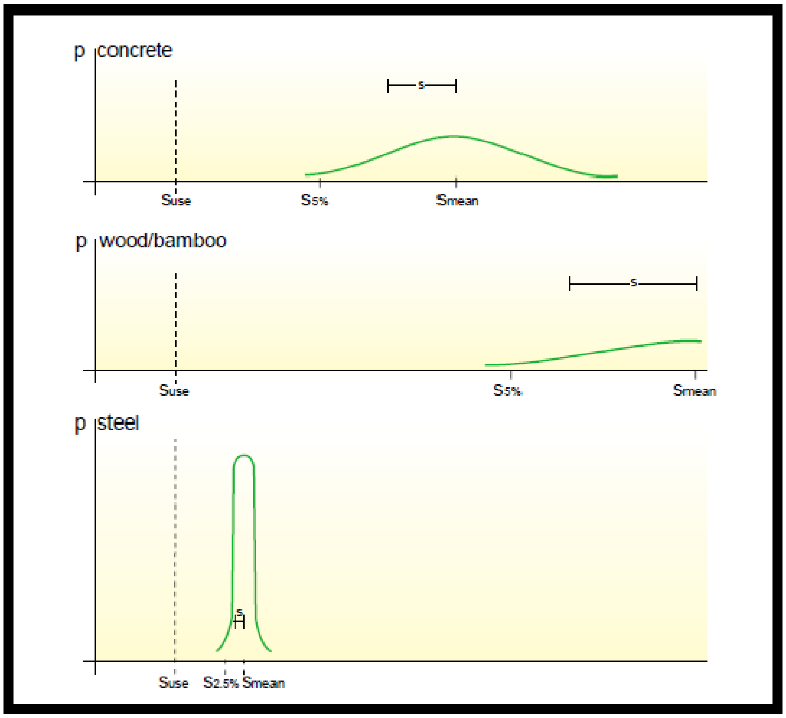


Fig. 19 Comparison safety between materials (Jannes, 2000).

When a disaster occurs stresses will get multiplied, possibly becoming double the allowable stress.
"In such cases, stresses in steel will come into the area of failure, but not in timber and bamboo. This means that steel structures will suffer much damage, while most structures of timber or bamboo will remain in good condition" (Jannes, 2000, 21). This is further explained by Tonges, "Statistically steel fails before concrete does and if steel failed long ago and 80 percent of the concrete constructions collapsed, then only 10 percent of the constructions of bamboo and wood would fail, as seen on the diagram.
Another advantage of bamboo, which is not taken into account in the statistical consideration before, is the absorption of energy in the joints. At excessive load, about 85 percent of the energy is used for the deformation of the joints, and only 15 percent cause elastic bending of the material" (Tonges, 2010).

The conclusion is simple: "A bamboo house is a good place to stay during a hurricane or an earthquake (provided the house has been built with proper care)…If a bamboo house has suffered from a heavy earthquake, some bamboo elements in it might show some damage. But the house will still be standing and habitable! Some temporary repair measures – such as winding a rope around the damaged bamboo – are all that would be required till the damaged posts or beams can eventually be replaced" (Jannes 2000, 24).

Additionally, due to the lightweight of bamboo, "seismic loads lose their relative importance; their great performance allows them to rapidly absorb any type of loading, depending uniquely on an adequate structural design and a proper constructive resolution, and finally, their flexibility makes them able to dissipate seismic energy" (Saleme and Navarro, 2002). Bamboo houses weigh about 40% less than traditional ones, thus reducing seismic loads in the same proportion. "An adequate architectural design, a well-balanced distribution of rigidity and mass, and an efficient technical management combine together to obtain this true seismic-resistant architecture" (Saleme and Navarro, 2002, 67).

2.4 GUADUA BAMBUSA ANGUSTIFOLIA

Since Guadua is one of the species currently growing in Haiti, and it is also a species that holds many desirable characteristics for building construction, this particular species will be chosen as the focus for the materialization of the building design.

Guadua Angustififolia can be described as a thorny clumping bamboo, one of the largest neo tropical bamboo. Can grown in altitude below 1,500m, but is also found in altitudes 2,500m (Plantationhouse.com, 2010).

PHYSICAL PROPERTIES:

- Relatively high resistance to both rot and wood-eating insects.
  "It has been observed repeatedly that ordinary hardwoods used in conjunction with this bamboo have had to be replaced because of insect damage while the bamboo still remains serviceable. The original untreated siding, of boards…in a forty-year-old plantation house at Pichilingue in department Los Ríos, Ecuador, was still in a serviceable condition in 1945, long after the hardwood floors had had to be replaced" (Arizaga,2002).
- 21cm daily growth (Guaduabamboo.com,2010).
- Typical height 25m
- Typical diameter 10-15cm, maximum 24cm (Hidalgo,2003).
- Diameter fairly consistent for first 15 meters, then tapers at top (Plantationhouse.com, 2010).
- Insulation decrease heat transfer by 2 degrees (CO2bamboo.com,2010).

CONSIDERATIONS:

- Guadua needs to be immunized against 'xilofagos' insects.
- Guadua should not come into direct contact with water or sunlight. Ultraviolet rays can cause culm to overly dry out causing fissures and discoloration. Changing levels of moisture can cause rotting of the cane (AIS,2001).
- Employ Velez's directive "hat and boots", covering the canes and raising foundations from the direct contact with ground.
- If Guadua is covered with shingles made of clay, these should be kept from coming into direct contact, as the can transmit humidity via capillary action.

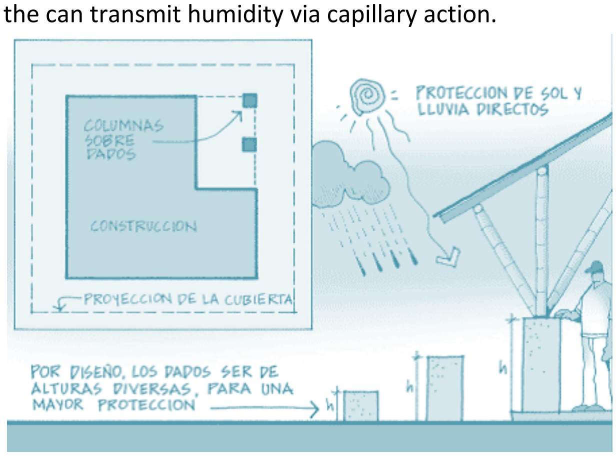


Fig 20. (AIS,2001)

MECHANICAL PROPERTIES:

- 4m maximum span for beams (Colombian Association of Antiseismic Engineers_Guadua manual).
- Where minimum deflection is not desired, the green bamboo culms can be bent to the opposite curvature before installation (creating a super elevation) (Rottke, 2003).
- Deflection test: Tube diameter 70-100 mm, wall thickness 6-12 mm, used for a span of 3,60 m. The elastic deflection was min=1/25,9; max=1/16,1; on average 1:20,1 of the span.


Fig. 21 Bamboo testing at Aachen University (Rottke, 2003).

Characteristic material values in kN/cm²		Guadua	Timber softwood S10 (DIN 4074 T 1)
MOE		1800 -2000	1.000
Tension | | fiber		15,0	0,7
Average elastic modulus of bending		1900	
Compression | | fiber	Effective length = 3,22 m 2,09 m 0,37 m	2,7 3,9 5,6	0,85
Bending strength (without shrinkage cracks)		10,0	1,0
Average elastic modulus of tension		1900	
Shear strength		0,9	0,09
d = 12 cm ; d_i = 9 cm		A = 50 cm^2 W = 100 cm^3 I = 700 cm^4	

* Lower values should be utilized to stay on safe level.

Fig. 22 Testing results of Guadua Angustifolia from Aachen University, (Tonges, 2001).

STRUCTURAL SYSTEMS utilizing Guadua:

- Cane used as single post and beams
- Lineal frameworks of single and double bending
- Flat and spatial trusses
- Arches
- Rigid Frames
- Hyperbolic paraboloids, Conoids
- Simple and complex geodesic domes

Additionally, structural concepts in bamboo have also been divided into three simple systems (Evolucion de Estructuras en Bamboo conference (Puebla, Mexico 2008):

1. Traditional Structures: "Reduces the traditional structures into woven stystems or simple post and beam concepts, using fish mouth joinery or natural fibers like vines and rawhide. Basic tool is the heap knife.
2. Modern Structures: "Based on traditional concepts but have a more sophisticated level in joinery techniques…The elements are straight and relatively short sections of the culm are used. The joints are bolted and grouted cement. Although the tools like electric drills and chisels are quite simple, a very high skilled labor is required. The raw material needs to be straight and uniform.
3. Contemporary structures: "pay respect to principles like protection by design, but its geometry is three dimensional and "free of form". It plays with curves, "shell" shapes, "hypars"; joinery is either very simple or highly engineered. The size of these buildings can be very big, due to the use of the natural fibre lengths of entire bamboo culms. The raw material can be curved, conical and crooked, short or large, depending on the object (Stamm,2010).

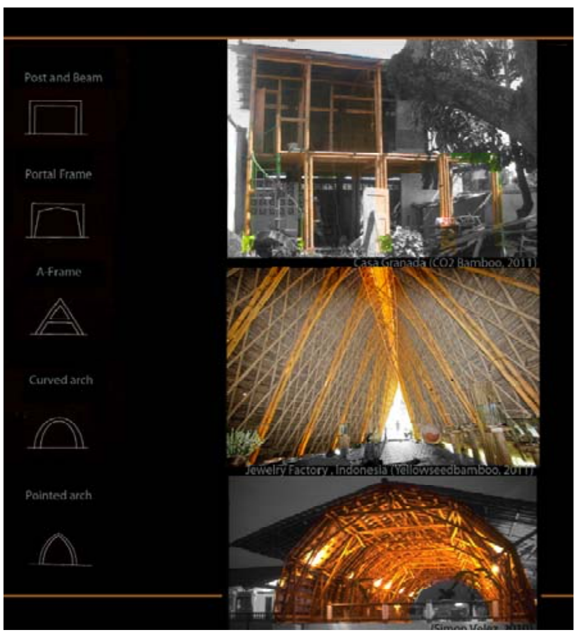


Fig. 23 Traditional and Modern structures: CO2 Bamboo House in Granada 2011, Jewlery Factory Indonesia 2011, Simon Velez Pavillion, 2010.
Fig. 24 Contemporaty structures: Simon Velez Pavillion 2011, and Green School Indonesia Pavillion (Yellowseedbamboo, 2011).

Fig.25 Bamboo bridge at technical University in Pereira (Jorg Stamm, 2010).

3.1 PROCESSING CONTINUUM

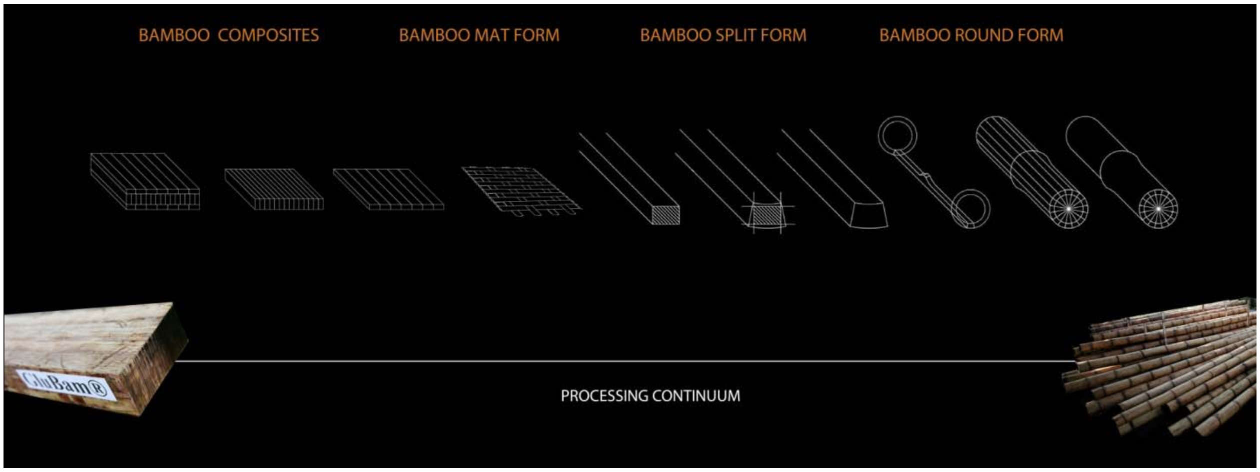


Fig. 26 Processing continuum from highest to the least amount of processing. (Laminated bamboo, bamboo mat products, bamboo strip based products, cured bamboo culms).

In order to utilize this material to its full capacity it is important to understand the wide spectrum of application and its high degree of versatility. Building with bamboo can begin with the round culms that have been harvested, dried, and cured. The process that follows is creating strips from the culm wall by splitting the culm further. The strips created can then be used without any further processing, or highly processed. In the case for the least amount of processing the splits can be used to construct trusses, as reinforcement within concrete or plaster, or for free form spatial webs. On the other hand, the highest level of processing utilizes bamboo strips to create laminated elements for structural purposes.

Additionally, strips can also be woven to create mats which in turn generate pre-fabricated panels. These mats can then form part of a composite material either with concrete or resin. The following sections will elucidate the aforementioned building systems and products and how they can be grouped for further clarity.

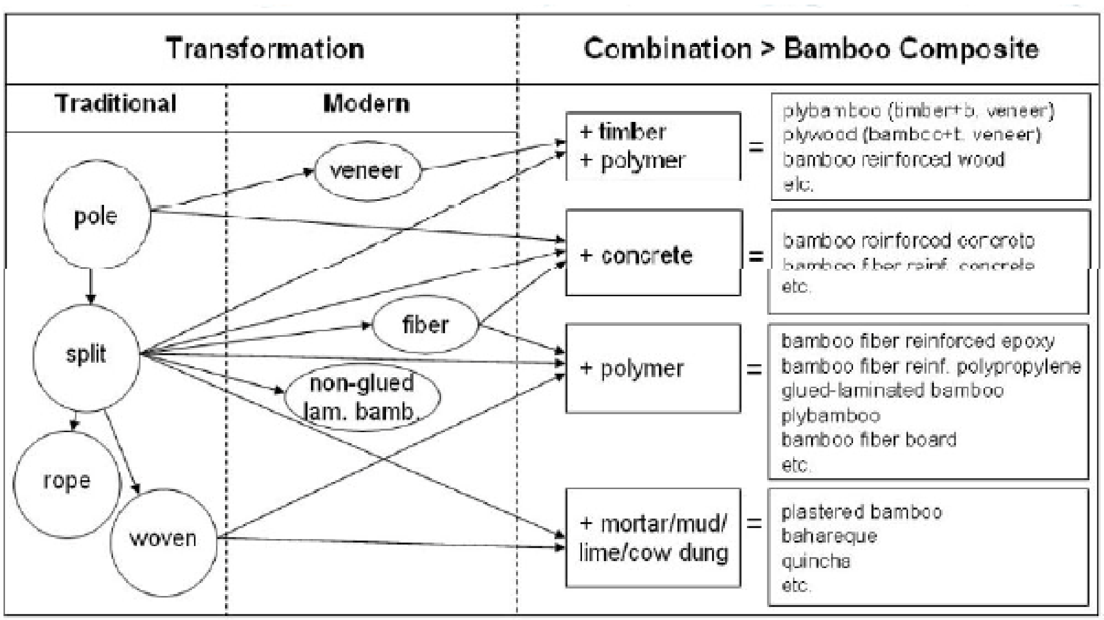


Fig. 27 Bamboo based materials (Andry Widyowijatnoko and Martin Trautz, 2010).

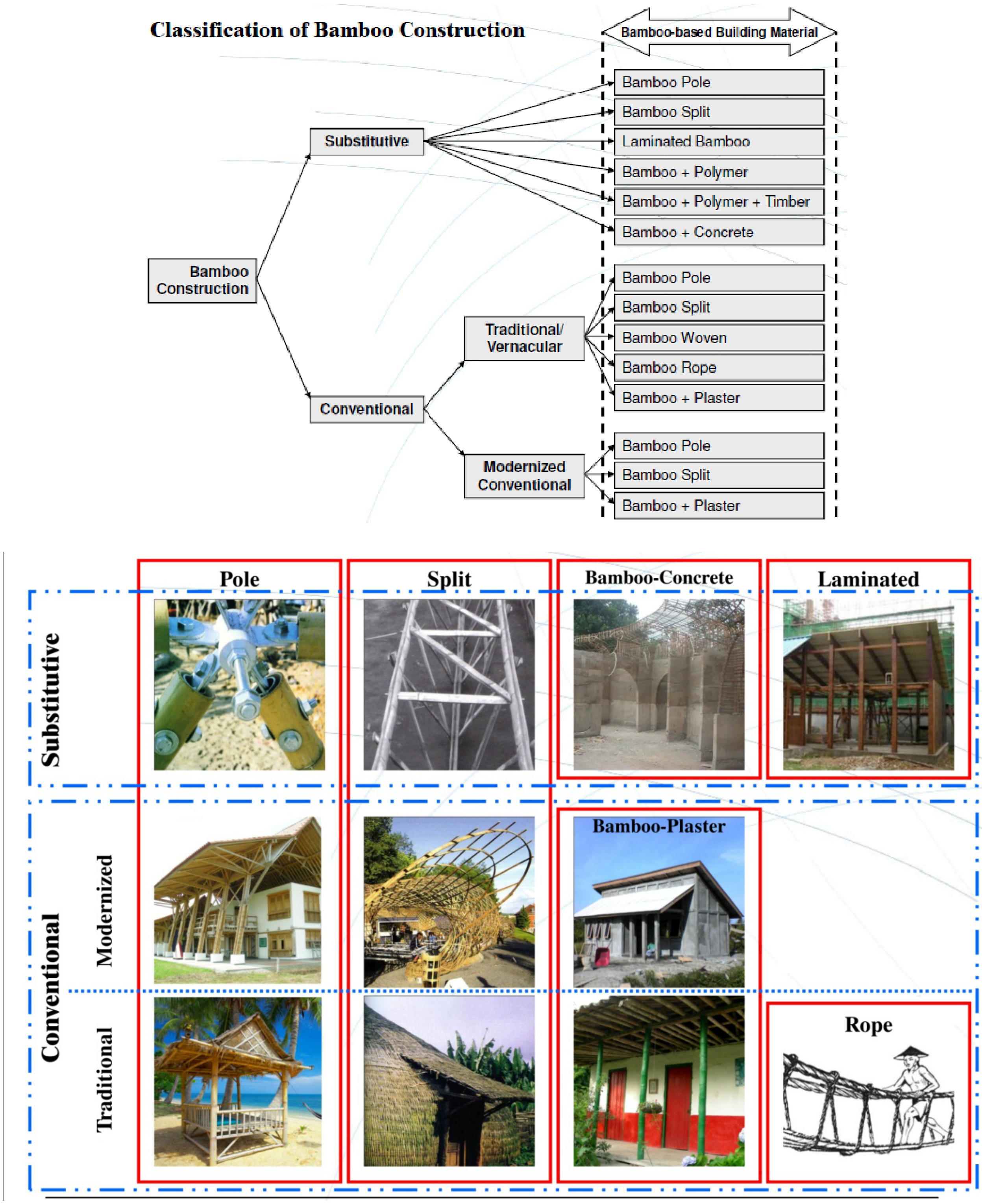


Fig. 28 Classification charts (Andry Widyowijatnoko and Martin Trautz, 2010).

3.1.1 BAMBOO ROUND FORM

Fig. 29 Cured culms before erection of Markus Heinsdorff's German-Chinesse House for Expo in Shanghai 2010, (Heinsdorff, 2010).

From the processing continuum, the most straightforward use of bamboo culms is the use of non-processesed but cured rods. In this case the rods chosen for construction must be dried to have the ideal moisture content not higher than 20% lower than 10%, and sufficient strength for structural use, with additional protection against rot and insects (AIS,2001). Additionally, the canes should be selected based on maturity, specific density, straightness, and coloration (Ecobamboo.com, 2011). These culms can then be readily used for posts, beams, or truss elements.

Posts and beams:

In traditional and vernacular architecture bamboo culms are most often utilized as post, beams, and bracing elements. For the most part, the construction can be likened to timber framing. However, due to the specific characteristics of the bamboo poles, this similarity cannot be carried too far.

Fig. 30 CO2 bamboo renovation of house in Granada (C02 Bamboo gallery, 2011).

The following standard guidelines have been developed over time in Colombia where construction with this material has a longer history, but is recently being compiled in a more accesible information base. (AIS-Prieto, Mogollon and Farbiarz, 2001).

Columns:

- Design to take vertical and oblique loads.
- Columns should be well jointed to base, top of wall, roof overhang.
- Columns should be well braced between each other and tied to structural walls
- Depending on the span, load, and proportion of the building, columns can adapt to the designed needs by increasing the number of poles utilized as part of the column.

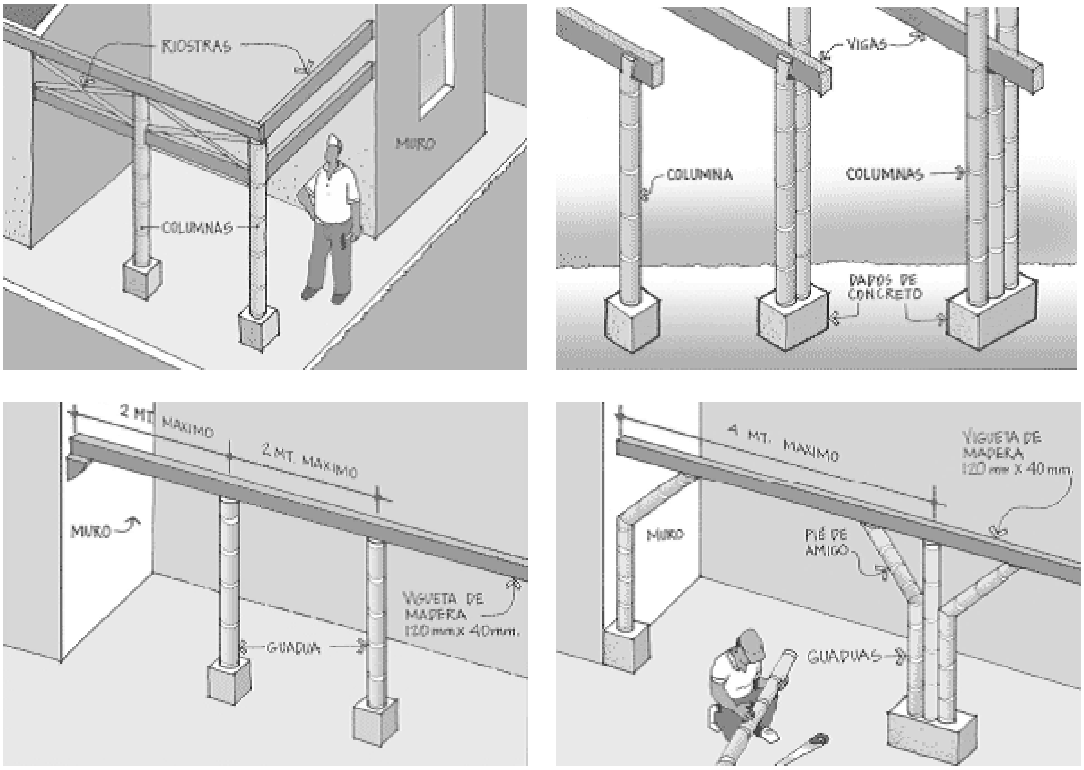


Fig. 31 Bracing between columns, adaptability of column size dependent on load, span, proportions (AIS,2001).

Beams:

- Load carrying beams must be designed to carry horizontal and vertical loads, and must transfer the load to structural walls. They need to be tied in with roof overhead that can act as a diaphragm for the walls.
- Where the Guadua transfers the load with the wall beneath, the internodes must be filled with concrete and then bolted with the structure.

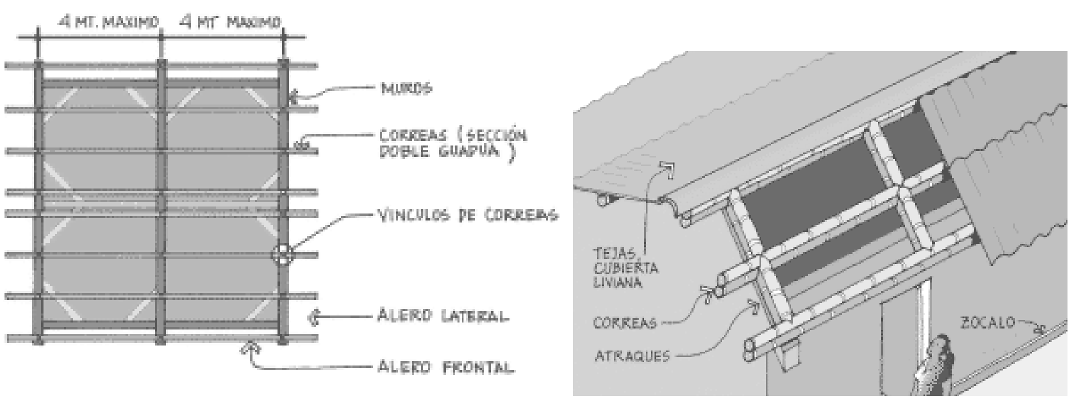


Fig. 32a Recommeded beam spans and connections in typical Guadua roof construction (AIS,2001).

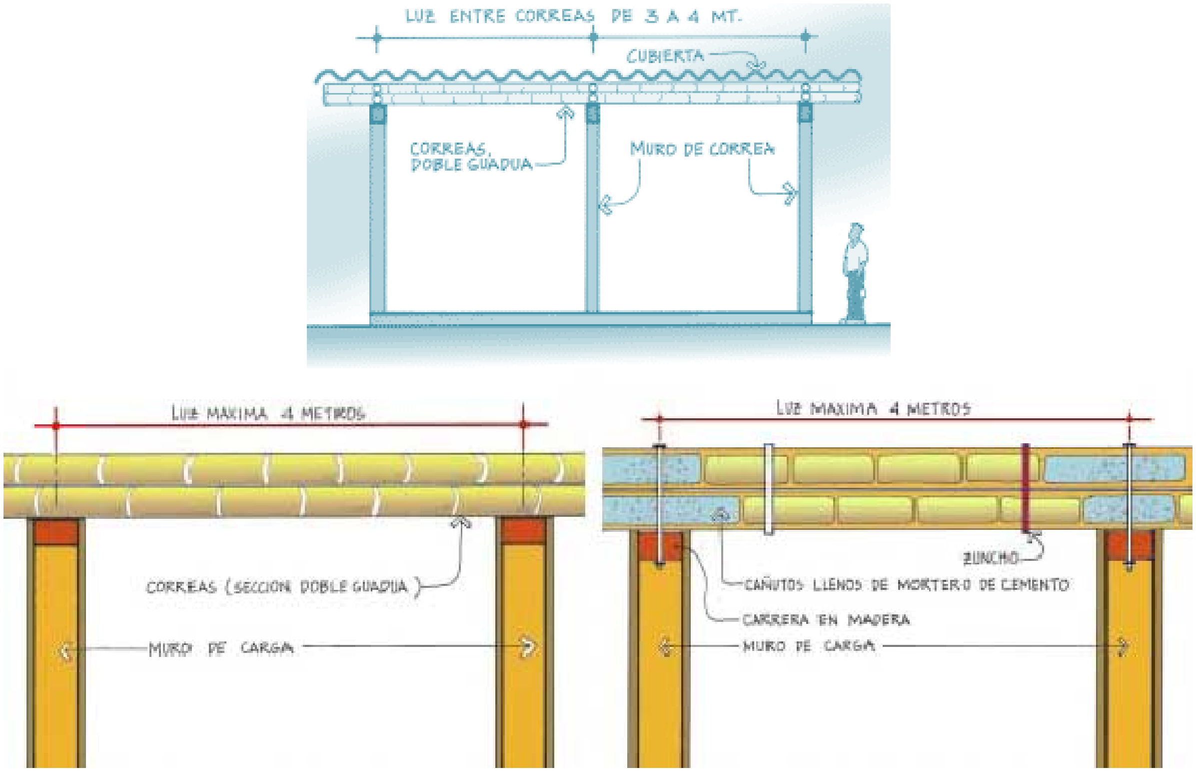


Fig. 32b Recommeded beam spans and connections in typical Guadua roof construction (AIS,2001).

Bamboo trusses:

The use of trusses as a structural system can be scaled to create the framework for the whole building or to support floors or roofs.

Fig. 33 German-Chinesse House for Expo in Shanghai 2010 by Marcus Heindroff (Heindroff, 2010).

Trusses built in bamboo are still progressing in their design and load bearing capacity as the improvement in the joints specifically mortar grouting, is presently increasing the overall structural performance.
The use of mortar grouting “allows transferring the loads from one bamboo to another by using not only steel bolts but also through the cement cylinder inside the hollow bamboo culm, that distributes the pressure on the thin wall towards the strong diaphragm at the nodes” (Stamm, 2010).

Fig. 34 Bamboo truss pilot project India (Vengala, 2002) and Koolbamboo House in Peru (Koolbamboo gallery, 2010).

Arches + Deformation of Culms:

An additional benefit to the high elasticity present in bamboo, is the ability of the poles to be curved. In fact all culms have a curvature to them which the designer must consider. For the most part giant species grow quite erect and yet remain flexible in the top part of the culm. Guadua aculeta species, which is found in Mexico, is however an exception which actually naturally grows forming huge arches. Traditionally in Indian the natural curvature of bamboo culms has been exploited to some degree during the Vedic Age. Temples and houses were built to reflect the natural curvature of the plant. The forms later known as "lotus domes" and "lotus arches" evolved by placing the top part of the culm at the bottom part of the structure which is better in compression, further allowing the construction of more organic-like shapes (Lopez-Hidalgo,2003).

In addtion to the natural curvature of the plant, culms can also be deformed in a natural or artificial manner. While the culms are still living, the following deformation naturally take place if the culm reaches a barrier that hiders its vertical growth: the culm grows with some inclination, the culm forms a "siphon-like" curvature then continues vertical growth, and finally if the curvature does not have sufficient space and takes place to close to the grown the shoot will die (Lopez-Hidalgo,2003). Hidalgo has also described some experiments where formwork is applied to the shoot as it is growing and the plant can take on the specified shape within 2-3 months, by this time the shoot will have reached 10 meters in length and the formwork can be reused.

It should be noted that square sections of bamboo can also be grown if a square formwork is fitted at the shoot base. In fact square bamboo sections have been carefully manufactured in Japan for downspouts for houses.

Fig. 35 Deformation trials- Wooden formwork and shoot growing, bamboo square cross-section (Hidalgo, 2003).

After harvesting, it is still possible to deform the culms to some degree, or simply to exaggerate the already existing curvature. For culms with wider diameters and thicker interior walls, they must be 'pre-curved' during drying. Warm bending is also possible for strips as seen in the image below on the right by Tonges. Warm bending of whole culms is generally practiced on smaller sized culms which will be utilized for furniture and care should be taken in the process.

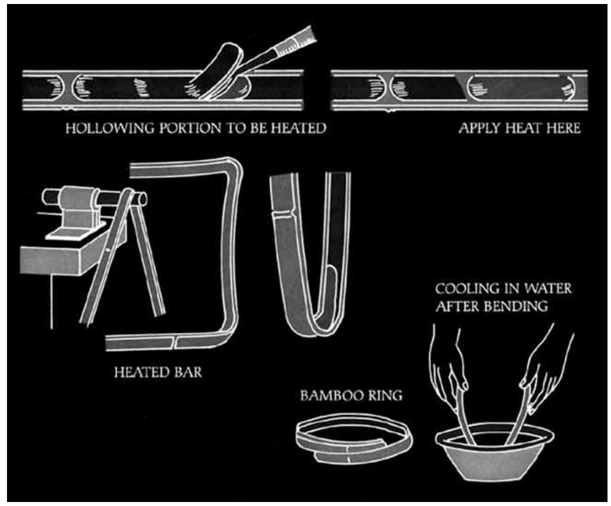
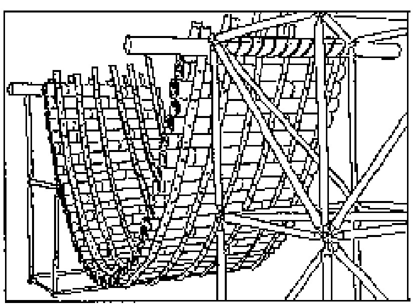
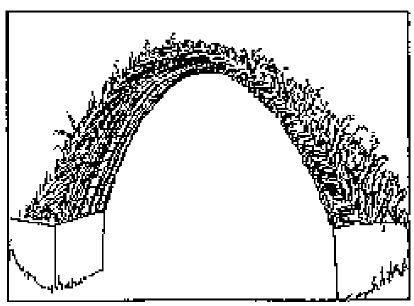


Fig. 36 Cold bent bamboo poles and warm bending process (Tonges, 2005).

Large span roofs:

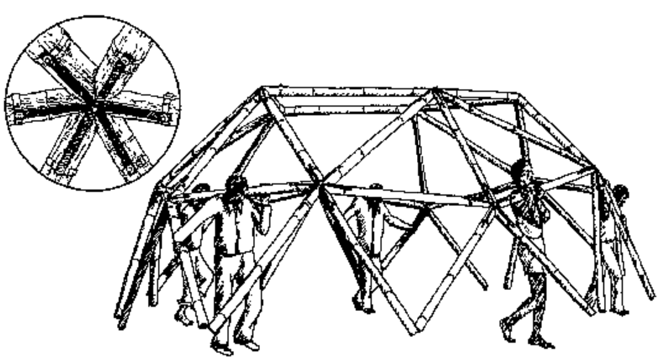
The research laboratory for Experimental construction at Kassel College of Technology, tested the following concepts:





The barrel vault contains its stability by compressive forces perpendicular to bamboo's axis. In this case the culms were inverted to obtain the ideal catenary shape. The arch is the connected to a ring beam on the supporting wall.

Fig. 37a Barrel vault construction (Minke, 2005)



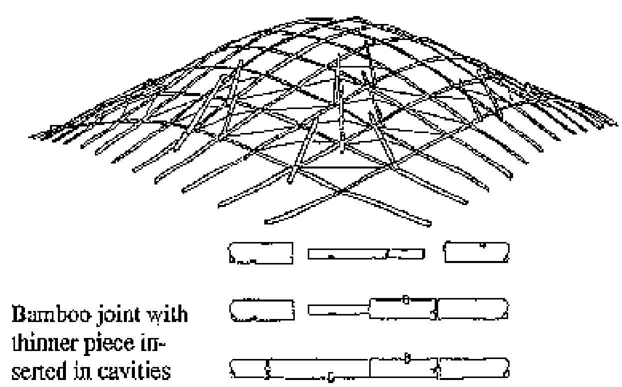


Fig. 37b Large span dome designs by Kassel College of Technology (Tonges, 2005).

The designed dome spans 5 meters, utilizing 1.5m long sections, connected to create a series of rigid triangles. The grid shell with a square base was developed as a part of a development project for less industrialized nations, which chould use local materials and tools. The grid was constructed with section of 4m and 30mm diameter. The canes were joined through a smaller segment inserted into the cavity of the bamboo cane. The overall dimensions of the constructed roof were 6x6meters, which were then connected to a ring beam on the structural walls beneath. The waterproof membrane used was first a thach cover with a proposal for ferrocement.

The following are other large span roof designs by engineer Christoph Tonges.

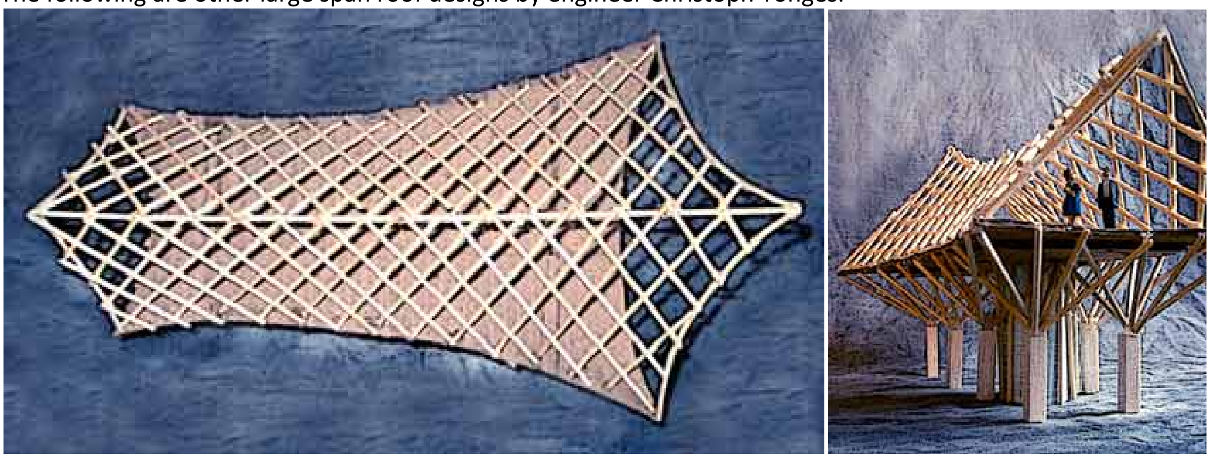


Fig. 38 Model of design for Corporacion Autonoma Regional del Quindio (Tonges, 2005).

Fig. 39 Model of design for 27m span roof for playing field University of Pereira in Colombia (Tonges, 2005).

3.1.2 BAMBOO SPLIT FORM: Low and high processing

Fig. 40 Implementation of bamboo splits with low processing

Fig. 41 Implentation of bamboo splits with higher levels of processing


Fig. 42 Bamboo splitting tool (Tonges, 2005).

Bamboo splits are the product of cutting the round culm into a series of segments. In this form the splits can be used to create a series of strip based products. The least amount of processing makes use of the splits for reinforcement of masonry, or concrete slab reinforcement. When these strips are layed flat they can create 'esterilla' wall boards or woven wall panels where a plaster finish can be applied, which will be discussed later in detail.

The more recent use of bamboo splits is their use in a laminated manner. The splits are glued together forming a high strength material. Xiao Yiang an engineering leading in the development of this bamboo based product has tested bamboo laminated beams able to support a 10 ton truck (Zhou,2007). Although, this method appears to be out of the reach of less industrialized nations, Jorg Stamm an expert in the field has presented a possible method for non structural laminated panels for small scale factories in Colombia (Stamm, 2002).

Bamboo wall systems:

Bahareque System: This is a traditional system utilized in Latin America, predominantly in Colombia and Ecuador, where this anti-seismic construction has outlasted many tremors (Farbiarz,2001). This system has two variations, solid and hollow.

Solid type: Horizontal bamboo laths fixed on both sides of culms or timber space filled with mud.

Hollow type: Flattened bamboo fixed on both sides of culm, then plastered with mud or cement mortar.

Quincha System: This is a variation of the bahareque system was developed in Peru. "Since the 1746 earthquake, the most destructive one in Lima, Quincha has been extensively adopted because, apart from satisfying the needs of its seismic resistance, it turned out to be more inexpensive, quicker and more versatile to fulfill the symbolic conditions that every monumental architecture demands" (Saleme and Navarro, 2002). The main structure is wooden or bamboo frame, then covered with bamboo esterilla, green side facing inwards.

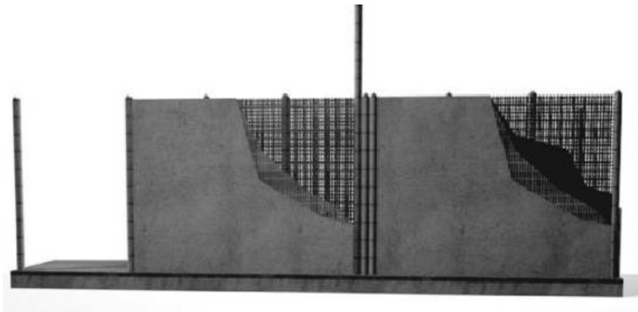


Fig. 43 Hollow and Solid Bahareque walls rendering by Arch Daniel Romero (Paudel, 2007).

Fig. 44 Construction of esterilla panels and bamboo housing in Nicaragua (CO2 Bamboo,2010).

Grid wall system:
Another version of these prefabricated wall panels system can be termed 'grid systems'. Diverse versions of this structural system can be found in Indian and Asia. IPIRTI (Indian Plywood Industries Research and Training Institute), for instance has buit some projects utilizing a modular system where bamboo columns are located 1.2m on center acting as load bearing elements. The main connection at the roof takes place via wooden plates and at the bottom through an embedded concrete foundation. Spanning between the columns are laths of bamboo with chicken mesh, which are then plastered with cement (much like the Bahareque and Quincha system). The bamboo lath along with steel dowels brace the structure between columns (Paudel,2007). A similar modular system is seen in some pilot projects in Indonesia, where the main loadbearing structure is not the usual whole bamboo pole, but rather only a semicircular half that is used to construct and connect the panels together (Widyowijatnoko,2010).

Fig. 45 Grid wall system rendering by Arch Daniel Romero (Paudel, 2007) , Fig. 46 Prototype bamboo housing in Bali, Indonesia (Widyowijatnoko,2010).

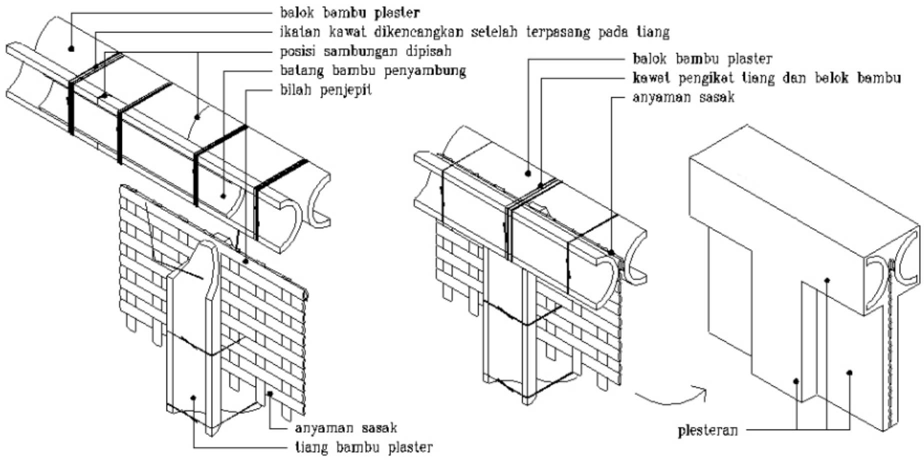


Fig. 47 Detail of bamboo half-rounds connection bamboo housing in Bali, Indonesia (Widyowijatnoko,2010).

STRUCTURAL BEHAVIOUR:

According to the data gathered by Colombian engineer Josef Farbiarz, regarding bahareque walls and assemblies the following conclusions were reached:

- Bamboo and bamboo-wood bahareque behaves as a homogeneous material that exhibits ductility under lateral loading.
- Wood frames with dove tail connections are stiffer than bamboo frames with bolted connections
- It is possible to predict the behavior of bamboo strut walls based on the behavior of panels made of similar materials.
- It is possible to predict the behavior of tridimensional assemblies based on the behavior of of a single panel.
- The weak link within the load transmission chain in bahareque construction is the connection mechanism. (Farbiarz, 2001).

	Unit Shear Force V (KN/M)	**Compression stress Fg (MPA)**	**Total Traction Force T (KN)**
Verification section	Horizontal of the Wall. Lower border (See foot Note 1)	Net section of the stud in the end of the wall.	Anchorage of the end of the wall.
COMPOSITION OF THE WALL Guadua and wood framework. With two diagonals, minimum one for each meter of wall length. Minimum 40% of studs in sawed wood. End studs in sawed wood. Top and bottom girders in sawed wood. Plastering with esterilla and mesh in both faces.	12.00	4.00	25.00
Guadua only framework. With two diagonals, minimum one for each meter of wall length. Top and bottom girders in guadua. Plastering with esterilla and mesh in both faces.	8.00	8.00	10.00

Note 1: Shear allowable V values must be multiplied by a factor of 0.50 if wall is recovered with cement mortar, mesh and esterilla only on one face. Note 2: Expressed values are intended for walls anchored to the foundation, and one to each other, in accordance with that settled down in the Chapter 7 of the present title. (Prieto, Mogollan, and Farbiarz, 2001). Bahareque walls don't depend on resistance of unions between the guaduas, rather their rigidity. Joints within framed elements are secondary to whole framed modular wall to foundation, floors, or roof.

CONSTRUCTION GUIDELINES FOR BAHAREQUE WALLS 1-2 STORY:

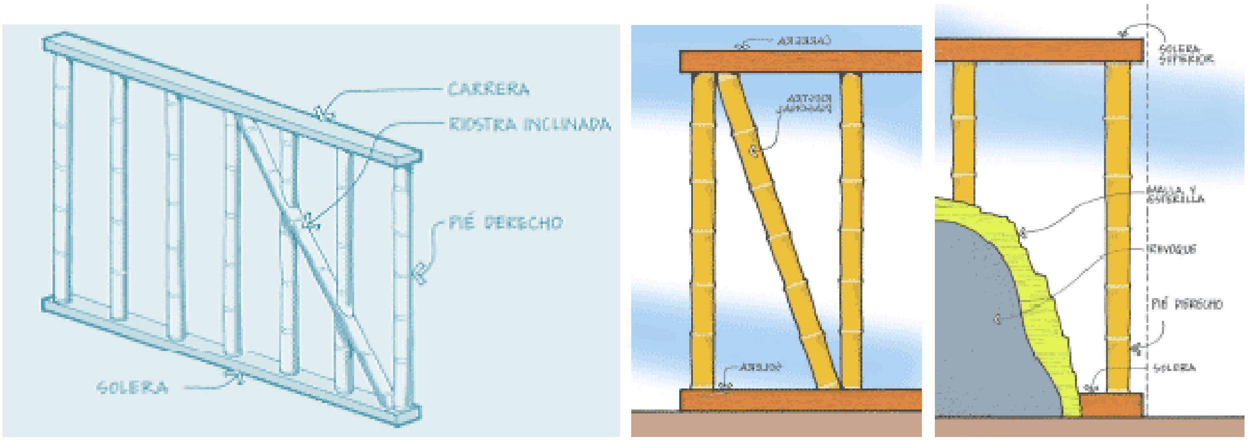


Fig. 48 Composite wall system with bamboo as internal structure (AIS,2001).

- Structural wall with diagonal and vertical bracing, resist vertical and horizontal loads from wind or seismic tremors.
- Structural walls with no diagonal bracing should only be used for vertical loading.
- Structural walls need to be continuous from foundation.
- Concrete Bahareque can then be plastered onto framing using esterilla boards with or without metal lath.

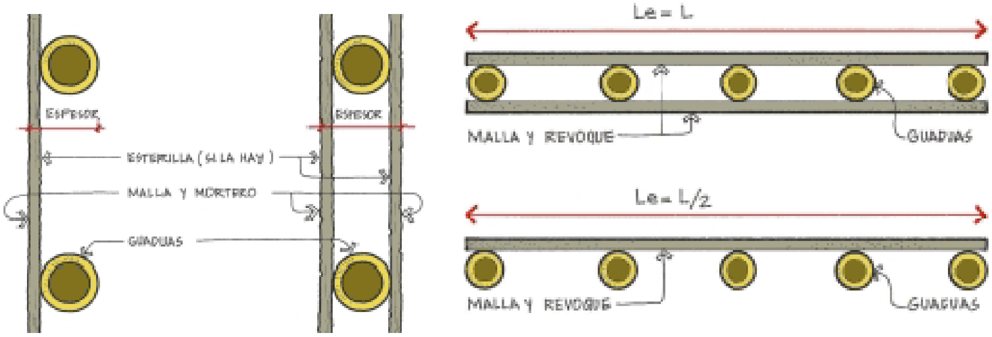


Fig. 49 Composite wall system with bamboo as internal structure recommended spacing (AIS,2001).

- Wall width for structural walls covered on both sides, based on average diameter of guaduas in addition to the width of wall assembly (esterilla, cement, metal lath, finish).
- It's preferable that wall frames are covered on both sides, effective wall length divided in half with only one layer.
- Bearing beams must have minimum width comparable to the diameter of guadua culms.

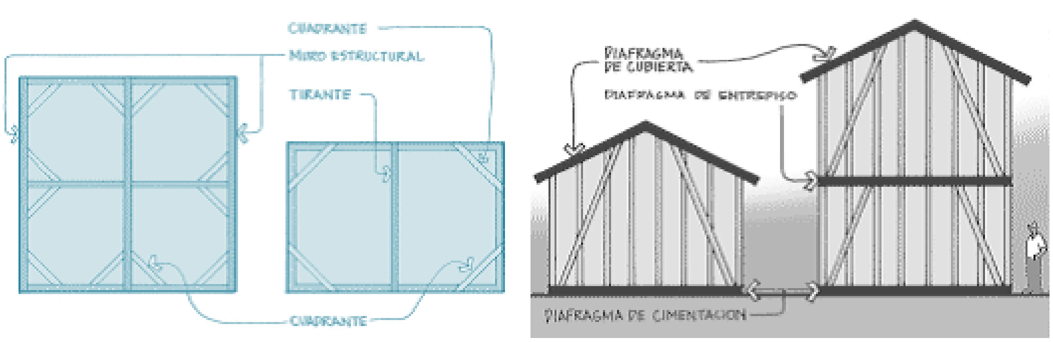


Fig. 50 Typical bracing recommended on one and two story structures (AIS,2001).

- Special care needs to be taken between beams, walls, and diaphragm joints.
- Diagonal bracing in plan is necessary to keep the integrity of structure
- Length of structural walls in either direction of structure: $L_i \geq 0.17 A_P$
  Minimum length where Li is the total length of walls without apertures in direction i.
  Ap is the covered area between floors.

Bamboo woven panels:

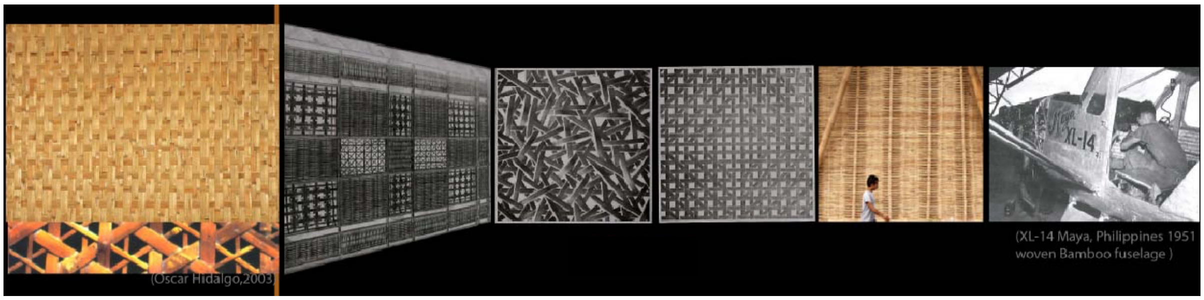


Fig. 51 Woven bamboo panels achieve high degree of diversity through woven techniques or pattern applied.

Thickness: 0.6-1.2mm
Width: 12-18mm
Specific weight: 0.6-0.8g/cm^3
Moisture content: 12-15%
Panel weight-
Plain woven panel: 1.2-1.3kg/m^2
Treated with filler and finishing:1.55-1.75kg/m^2
Tensile strength of strips-
Maximum (plain): 1,830kg/cm^2
Average with nodes: 1,330kg/cm^2
Minimum with nodes: 635kg/cm^2

Shear strength of mat panel-
Strips set at 90°: 110kg/cm^2
Strips set at 45°: 245kg/cm^2
Bending strength of strips-
Maximum: 1,500kg/cm^2
Average with nodes: 850kg/cm^2
Compressive strength of strips-
Average: 365kg/cm2,
Minimum: 250 kg/cm^2
Modulus of elasticity: 2x10^5 to 3x10^{5}kg/cm^2

Weaving bamboo splits into panels actually has a long and enduring history, specially in Japan and China with five to six thousand years of tradition. More than 150 methods exists for producing diverse woven products, with some of the main methods being cross-stich work, threading, and inserting ribs (Fig. 51). The manufacturing of woven products is quite simple as bamboo strips and threads are produced from
2-4 year old culms by splitting the culm wall vertically. The strips are then dried to allow for a moisture content between 12-15% (Hidalgo, 2003). The strips should be the same thickness and dimension in order to cut them into 'threads' according to the required and desired design of the final panel or woven product. Weaving bamboo splits could be considered quite an elaborate and labor intensive process, but yielding potentially exquisite panels and finished products. Apart from non structural scrims, woven panels can also be utilized structurally as seen in the last image in figure 51. There the XL-14 Maya plane utilized the lightness and strength of bamboo to design the fuselage purely of woven bamboo panels which where shaped with resin. The process of creating composite panels will be discussed in section I:3.1.2.

Bamboo cable:

Fig. 52 Bamboo cable
Diameter: 2-30cm
Tensile strength: 1,863kg/cm^2
Carrying capacity
(effective length 0.79m): 6 tons

Bamboo cable is a significant way to exploit the high tensile strength of bamboo fiber, which is comparable to steel's carrying capacity and it can easily surpass it as previously mentioned in section 2.3. Historically, the most common use of bamboo cable is found in China. Here bamboo cable is used for the construction of suspension bridges, some spanning up to 100 meters, as well as, the construction of gabbions, and tracking sailing vessels.

Manufacturing bamboo cable is similar to the process found when creating the strips for woven panels, however, in this case the strips are twisted or plaited around an inner core made from the interior of the culm wall. Since the strips used for the cable are taken from the exterior part of the culm, they contain a higher silica content which increases its durability and strength. Bamboo cable has the potential tensile strength of 1,863kg/cm^2 ranging up to 3,018kg/cm^2. In addition to the high tensile strength values listed, one should note that bamboo cable actually possesses a great asset in highly humid or rainy conditions. In essence, plaited bamboo cable's strength can actually increases 20% when it is fully saturated with water. For instance, a 0.79m bamboo cable that was tested showed that its carrying capacity actually increased from 5 tons to 6 tons simply after the fibers had become fully saturated with water. This is quite the contrast when compared to another natural fiber, such as hemp, which looses 25% of its strength when it becomes wet (Hidalgo, 2003).

3.1.3 BAMBOO COMPOSITES

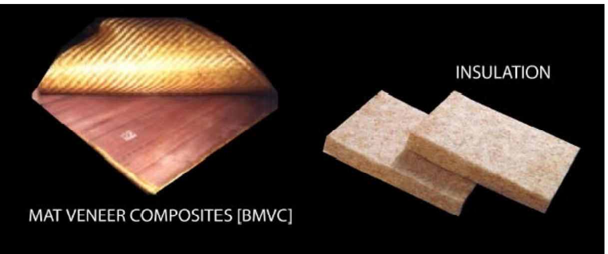


Fig. 53 The versatility of bamboo is seen through the variety of materials avaliable: mat boards, roof sheathing, mat veneer composites with plywood sandwiched in between, insulation, roof sheathing panels, and even corrugated roof sheet panels.

The vast potential of bamboo as a building product can clearly be seen as the possible combinations and explorations of 'new' materials continues to increase as bamboo becomes more accessible to the building industry. Another dimension of bamboo based products are those coming forth from a combination of different materials, thus creating a series of composites. For the most part bamboo composites stem from woven splits which are then formed into integral panels once processed with resin, wood, or even concrete. Composite materials seem to be quite attractive as the combination of strengths between materials often outweighs the weakness of one sole material.

Bamboo mat boards:

Typical mechanical properties:
Thickness: 3.7mm per layer
Max Load: 1907 N
Load bearing capacity: 4.77 N/mm
Weight of sheet: 7.2 kg (1.05m x1.8m)
Modulus of Rupture: 40.45 N/mm^2
Internal Bonding Strength: 1.3-1.4 N/mm^2

The manufacturing process for bamboo mat boards and roofing sheets is actually the same, what varies is whether resin is applied or not. Bamboo culms are split into thin slivers 0.6mm-1.5cm wide, these are dried to 15% moisture content, and are then woven into mats. When woven they usually cross at 45° or 90°. The mats are then soaked in adhesive resin allowed to drain and dry. It should be noted that the amount of resin applied to each mat, the length of time allowed for dripping and the manner of application, all influence the overall quality and economy of the process. Metal plates are then used to press mats together under high pressure to form flat boards or corrugated panels, which are then trimmed to desired shape. The resin impregnation becomes critical if the used desired is for roof sheathing panels since this application alone makes the panels suitable roofing material. Additionally, UV coating is also added and recommended for greater longevity (IPIRIT, 2001).

Bamboo floor panels:

Typical mechanical properties:
Density: <0.9g/cm^3
Moisture content: 12% Fg[MPA]
Bonding strength: 2.5N/mm^2
Static bending strength (longitudinal):
>98N/ mm^2 (thickness <15mm)
>90N/ mm^2 (thickness >15mm)
>90N/ mm^2 (thickness >25mm)

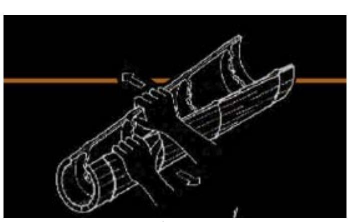
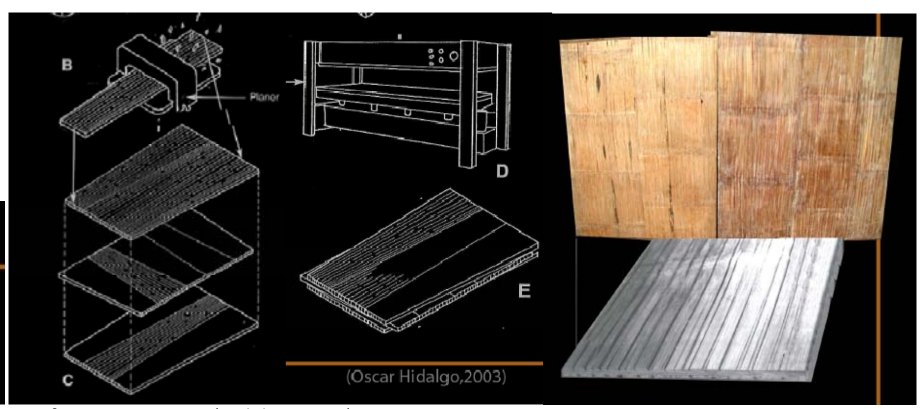



Fig. 54 Bamboo floor panels typical manufacturing process (Hidalgo, 2003).

The manufacturing of floor panels most common in Colombia and China, utilize the exterior surface of the bamboo culm which contains the strongest fibers. The flattened culm is typically made into 4 meter long sections, where the diaphragms are removed to form 3,5, or 7 ply panels with a typical ply thickness of 3mm and core thickness of 3-5mm. The plies are oven or air dried reaching 12% humidity content and are then treated by immersion with preservatives and adhesives. Traditionally urea formaldehyde resin or phenol formaldehyde resin is utilized, however to make the process more sustainable bio-resins should be incorporated. At this point panels can be covered with a wood veneer or plastered for additional protection. It is recommended that a waterproof coating be applied to all sides of the plybamboo in order to maintain the dimensional stability of the board, avoiding swelling in length or width.

Bamboo as reinforcement:

Bamboo and concrete would seem to be a great combination since one could potentially exploit the high tensile strength of bamboo along with the high compressive strength of concrete.

However, this remarkable has proven to be challenging and needs further exploration, testing, and development since thus far bamboo reinforced concrete elements have shown a series of inadequacies. The main shortcoming seems to be the negative effect produced as bamboo elements absorb water during the curing process, highly reducing the overall structural strength. One additional factor that has been a problem in the past, is the lack of bonding between the two materials. However, some studies by Khosrow Ghavami have started to produce some favorable results by developing effective chemical treatments on bamboo surfaces. Thus producing effective impermeability, increasing the adhesion properties whereby the surface of the bamboo becomes rougher and increases a uniform bonding to the concrete throughout the structure by 400% (Ghavami, 2007).

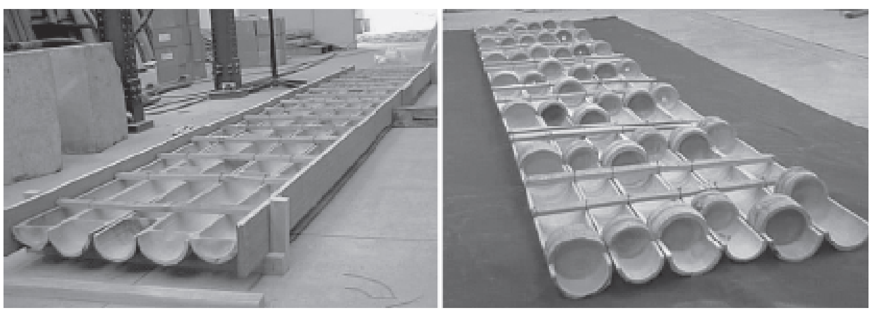


Fig. 55 (a) Semi-circular bamboo culms utilized as tensile reinforcement
(b) Semi-circular bamboo culms with full diaphragm as shear connector with shearing resistance strength 10.89 MPa.

Fig. 56 Bamboo reinforced slab before testing (Ghavami, 2007).

In fact, some great strides have been achieved with some pre-treated bamboo sections. As seen in figure 57, close observation was taken on a 15 and 10 year old sample of bamboo and steel reinforcement respectively. The bamboo reinforced beam was tested and prepared at the PUC-Rio University where it was treated against insects

and adhesion to concrete was improved by adding IGOL-T a bonding agent. After its removal from the concrete a decade and a half later, the overall appearance of the bamboo sample was quite satisfactory and after testing its mechanical properties, only a slight deterioration in its tensile strength was perceived. In comparison, a steel reinforced column in one of Rio's metro tunnels was found with extensive corrosion and needing replacement after ten years of service.
These type of positive results continue to make bamboo quite an appealing substitute for steel. And make the advancement and integration of bamboo into more conventional building systems and materials a desirable goal.

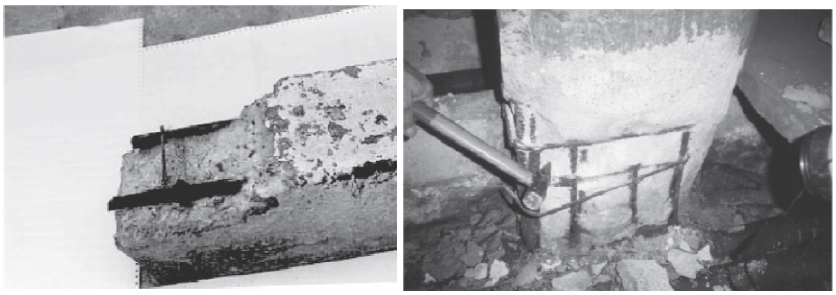


Fig. 57 (a) Bamboo reinforcement after 15 years in open air.
(b) Steel reinforcement after 10 years in closed area (Ghavami, 2007).

4.1 BAMBOO JOINTS

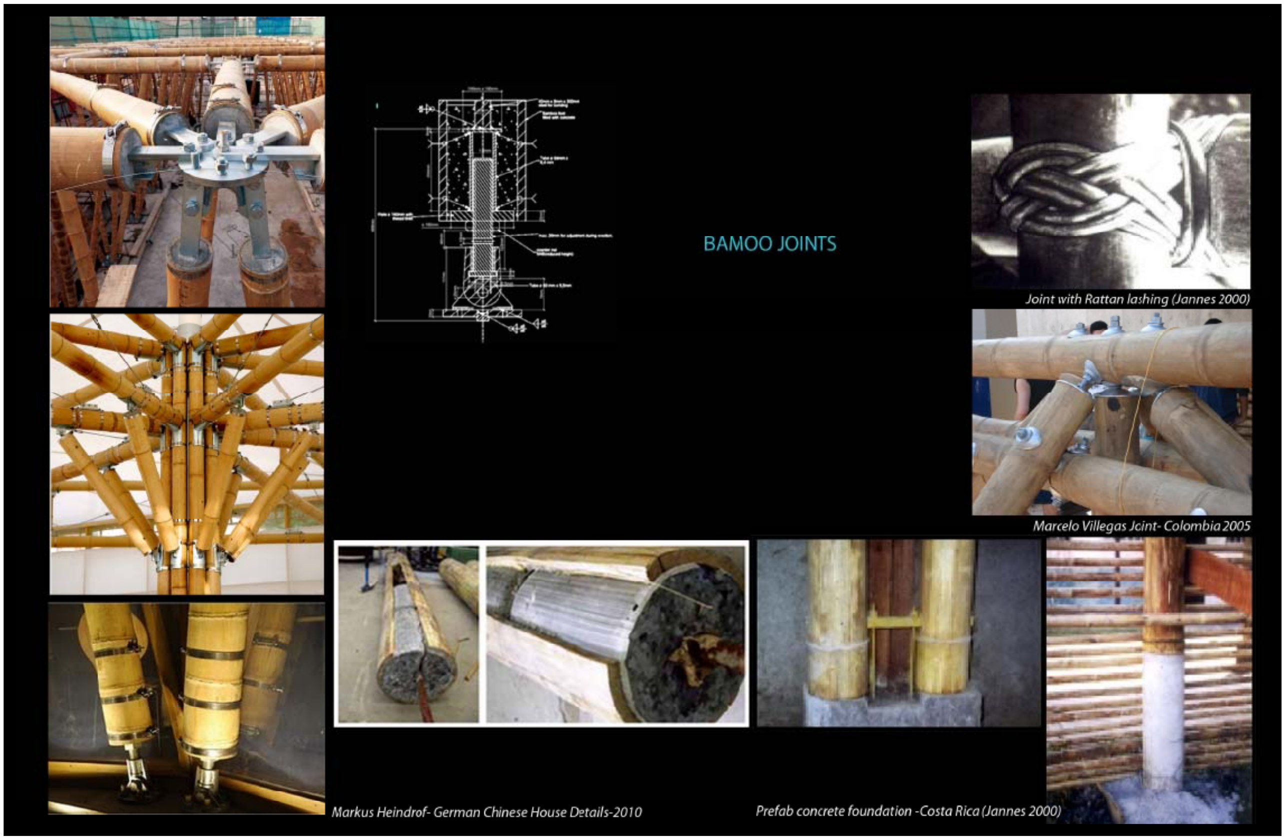


Fig. 58

Bamboo joints have quite an extensive variety, which can also be fitted within a processing spectrum, with high level of processing at one end, such as milled connections to 'low-tech' joints on the other end of the spectrum, such as rattan lashings.

Joints are quite critical as only through a well designed joint can a building achieve structural continuity between elements, and "forces can be transmitted according to a safe and prescribed manner...keeping deformations under control" (Jannes, 2000). Also it is through the joint that the full qualities of bamboo can be exploited, specially its tensile strength.

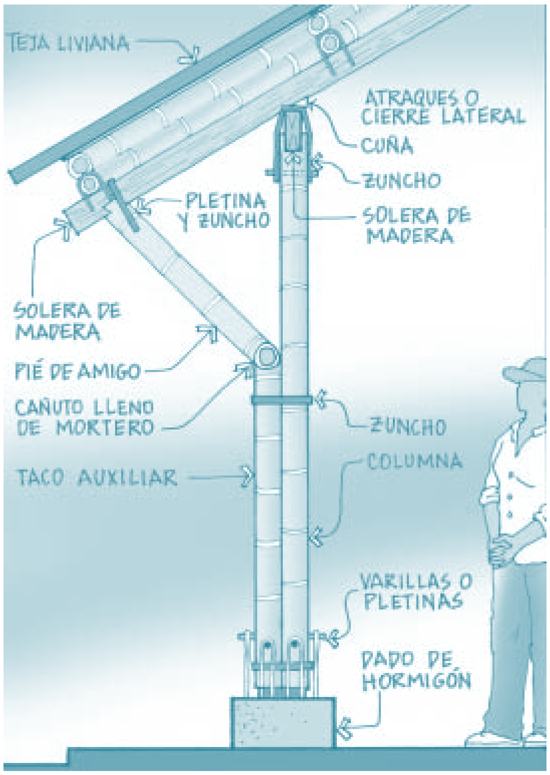
In order to understand how bamboo culms should be connected together, its important to note the constraints found within the material.

- Anisotropic material: Longitudinal cellulose fibers are strong and stiff compared to transversal ligning fibers that are soft and brittle.
- Unidirectionally reinforced composite has little tangential capacity.
- Culm dimensions vary widely in size, thickness, shape
- Internodes and open ends are vulnerable to crushing
- Joints should be placed near the nodes, whose location also varies widely

In the case of Haiti, sophisticated industrialized methods might not be readily available, therefore joining methods that fit the context should be considered. It should be noted that many joints which are termed as 'sophisticated' are utilized and were developed in Latin American countries such as Costa Rica or Colombia (Fig. 58, Marcelo

Villegas). There is of course a good level of simplicity that should be employed when designing any joint, for ease of duplication and construction.

The following are guidelines and details for traditional Guadua construction recommended by the Colombian Association of Antiseismic engineering.



- Nailed connections: Guadua culms should not be nailed together, as this can cause fissures in the wall fibers.
- Bolted connections: Perforation must be made with high speed tools to avoid splitting of fibers on impact.
- Perforated internodes should be filled with mortar to increase strength.
- Steel tabs and plates used in bolted connections need to resist high tensile forces.
- Footings: The guadua culm should not be in direct contact with the ground or concrete to avoid moisture via capillary effect. Guadua should rest on a steel sleeve or other waterproof material. The sleeve should be continually connected to the concrete footing to transfer compressive loads. Internodes at base need to be filled with cement mortar.
- Connection between walls: bolted connection should be placed 1/3 the length of the wall.
- Knee braces for roofs should not have an inclination less than 60 degrees.

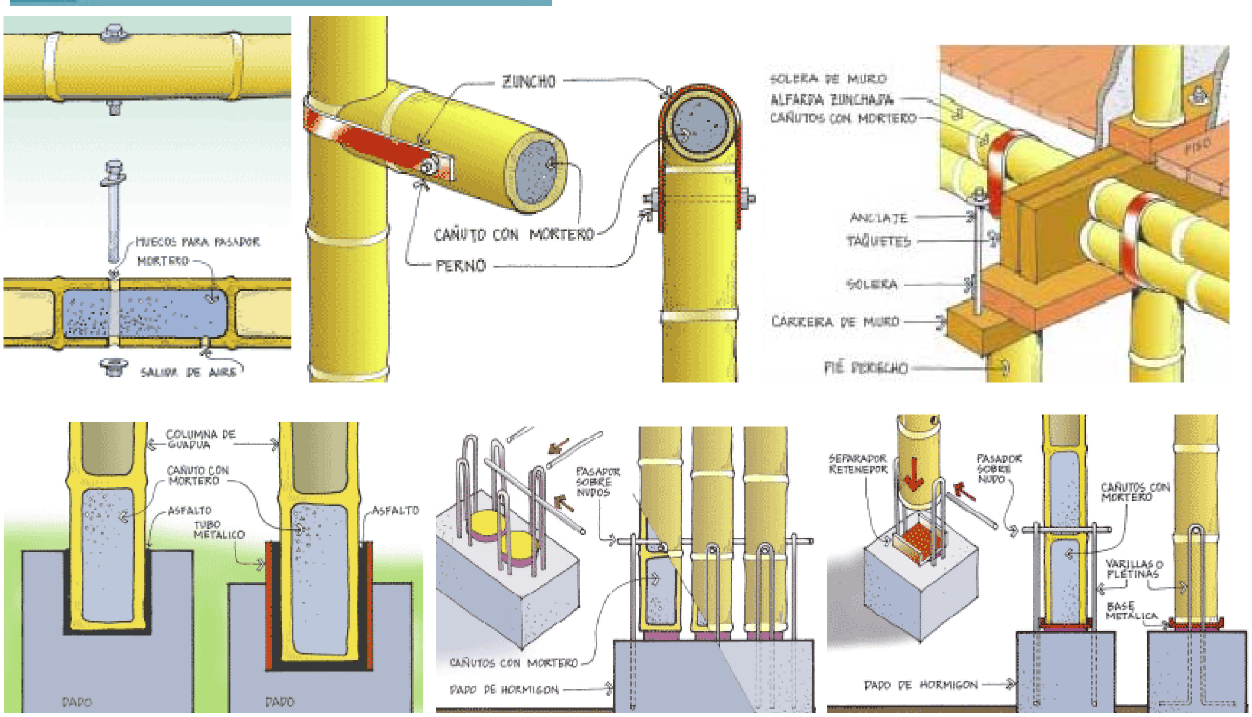


Fig. 59 Recommended typical details and connections (AIS,2001).

CATALOG OF JOINTS:

Fig. 60
Bolted connections:
Highly common connection due to simplicity, stability, high durability, and ability to transfer compression and tensile forces (where steel plates or tabs used). This type of connection depending on specific detailing can merges the strength of steel, mortar, and bamboo. The internodes are drilled, steel rods inserted and nuts on either side secure the connection, mortar injections are usually recommended for added strength and increasing loading or spanning capability of bamboo culms. Here eccentricity is found in load transfer since connections do not meet at one point (Tonges, 2005; Jannes,2000).


(Tonges, 2005)


(C02bamboo, 2011), (Jannes, 2000)

Fig. 61
Fish-mouth connections:
This is a typical and original connection that is unique to bamboo construction. The culm is uniquely shaped as a fish mouth with a special drill in order to fit the round shape of the bamboo culm. Numerous variations of this joint are often used to transfer compressive loads.

(Tonges, 2005)

Fig.62
Cross bar:
Additional supporting bars with bolted connections, must be prevented from twisting, therefore they should be placed between other structural members.
Cam connections:
Beams are supported via struts in order to prevent twisting, as well as transferring the load to main supporting column.


(Tonges, 2005)

Fig.63
Multi-culm column connection:
A standard practice is to add several culms to strengthen the structural capability of one single culm, thus allowing greater loads to be transferred safely throughout the structure.

(Co2bamboo, 2010)

Fig.64
Offset connections:
Due to the nature of bamboo construction, offset connections are the norm in conventional designs. This of course incurs eccentricity as the loads at each juncture are being transferred at several points.

(Co2bamboo, 2010)

(Tonges, 2005)

(Jannes, 2000)

Fig.65

Clamped support with 1-4 culms:

According to Tonges, the metal pipe seen in the image below establishes a rigid connection for a single bamboo column, which is then injected with cement mortar. This type of foundation connection is in lieu of the more common connection of rebar acting as the anchoring agent for the column insert as seen in Fig. 66.

The the four member column establishes a flexurally rigid connection by creating bolted connections among all four members which are then cast together with concrete.

(Tonges, 2005)

Fig.66

Simply supported connections:

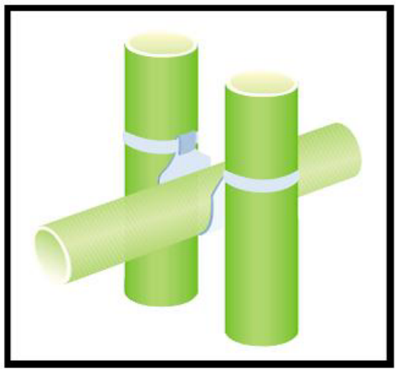
The most common connections for the base of bamboo structures, are steel rods inserted into the internode at the base of the culm which is then injected with cement mortar for rigidity and stability. Elevating the culm from direct contact with moisture and water is very important for the longevity of the structure. Its important also to keep the metal rod protected from the elements, keeping it safe from corrosion. Simon Velez, has developed a conical steel fitting specifically for this purpose.

(Tonges, 2005)

(Jannes, 2000), (Simon Velez, 2008)

Fig.67
Tied connections:
The use of natural fibers (rattan, coco-palm, bast, or bamboo) are commonly found in traditional or vernacular structures. These connections are made with high or low level of craftmanship by tying the fibres between members. As the fibres dry around the tied bamboo the strength of the fibres actually increases.
-Bamboo rope tensile strength: 720kp/cm^3
-Rope 5cm thick: able to bear up to 14 tons.
(Rwth Aachen,

(Jannes, 2000)



Design from Costa Rica of bamboo joint reusing plastic bottle packaging (Jannes,2000).

Fig.68
Wood insert connections: These joints create seamless details as they are hidden inside the hollow core of the culm, and have the benefit of utilizing standard hardware and detailing typical for timber construction.

Joint designed with plywood connectors (Jannes, 2000).

Fig.69a
Recent connections:

Detail designed by Renzo Piano (http://bambus.rwth-aachen.de, 2002). renzo piano) and a similar detail to Simon Velez's detail is seen here developed by Koolbamboo (koolbamboo.com, 2008).

The variety of joints and possible connections in bamboo appear to be quite numerous. However, the prevailing division between most details, as mentioned, is the degree of processing or industrialized technology employed in manufacturing them. Traditional joints although readily available even in rural zones have little resistance to forces. In contrast current trends have made unique strides through a combination of mortar, steel rings, metal tube inserts, conical steel or fiberglass fittings able to withstand greater loads and transference of tensile forces. Joints with mortar filled culm cavities have vertical or parallel bolts that connect culms together. The recommended loading is up to 7KN tensile force for mortar filled nodes with parallel bolts or 10KN for vertical bolts according to Jenny Garcon a columbian researcher (Hidalgo, 2003). A similar version of this detail by David Trujillo, which utilizes 12 small bolts radially placed along a steel ring, could reach a maximum resistance of 70KN for tensile strength and in order to avoid more than 0.5cm deformation in the structure, the recommended usable load was set at 20KN. Ultimately, researchers are aiming to design a connection detail that could effectively take advantage of the immense potential found in bamboo's tensile strength ±100KN, in addition to reducing the added weight and labor intensive site work of mortar filled joints.




(Koolbamboo.com, 2008).


Fig.69b Marcelo villegas and Koolbamboo collaboration, (koolbamboo.com,2008).

Fig.69c German Chinese House Joint details (Heinsdorff, 2010).

The following classification of joints was developed by Jules Jannes, where he divides the possible connections seen above into the following groups:

- Group 1 – full cross-section
- Group 2 – from inside to an element parallel
- (Group 3 – from inside to an element perpendicular)- only theoretical significance
- Group 4 – from cross-section to element parallel
- Group 5 – from cross-section to element perpendicular
- Group 6 – from outside to element parallel
- (Group 7 – from outside to element perpendicular)- only theoretical significance
- Group 8 – for split bamboo

Group 1:

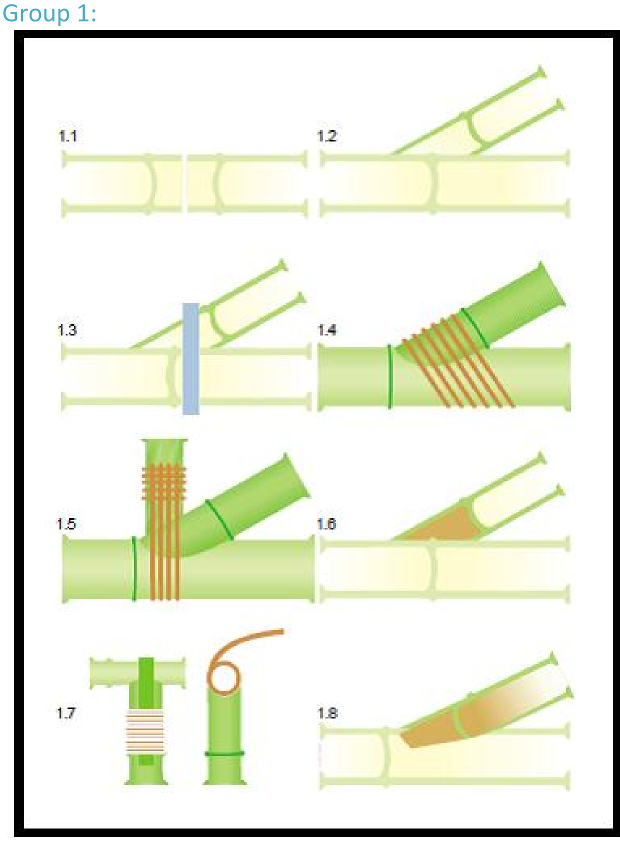


Fig.70 Joints with full contact between cross-sections (Janssen, 1981).

Group 2:

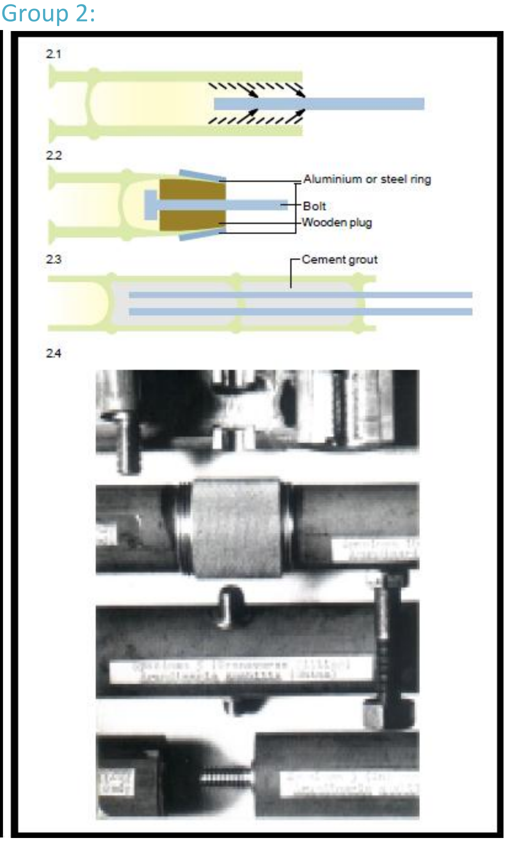


Fig.71 Joints from inside to an element parallel (Janssen, 1981).

Group 4:

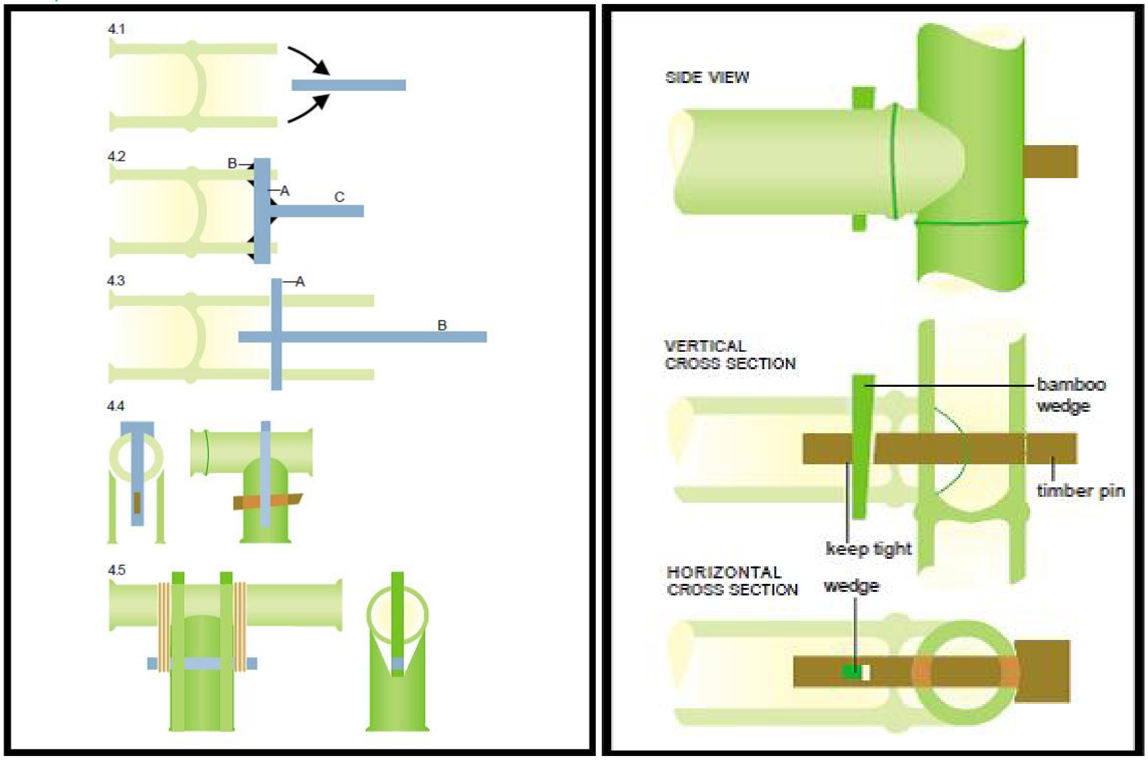
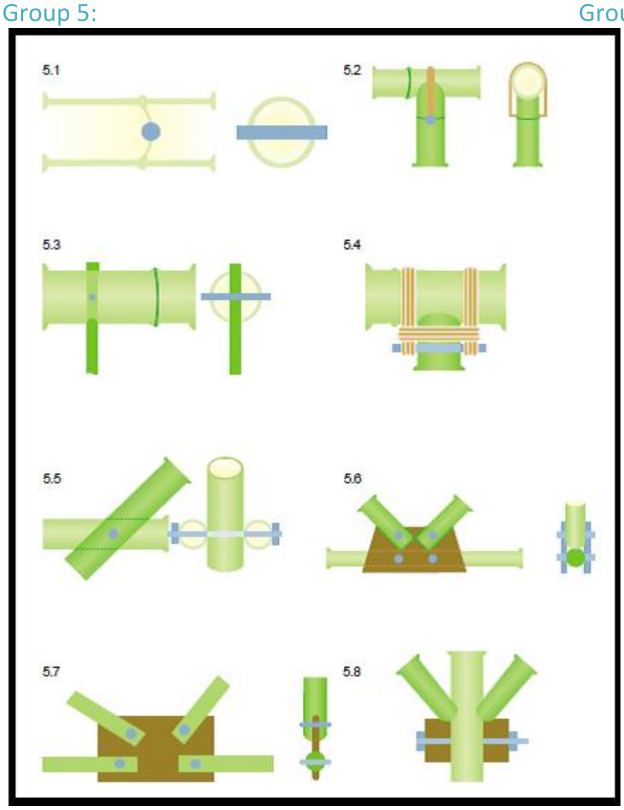


Fig.72 Joints from cross-sections to an element parallel (Janssen, 1981).

Group 5:



Group 6:

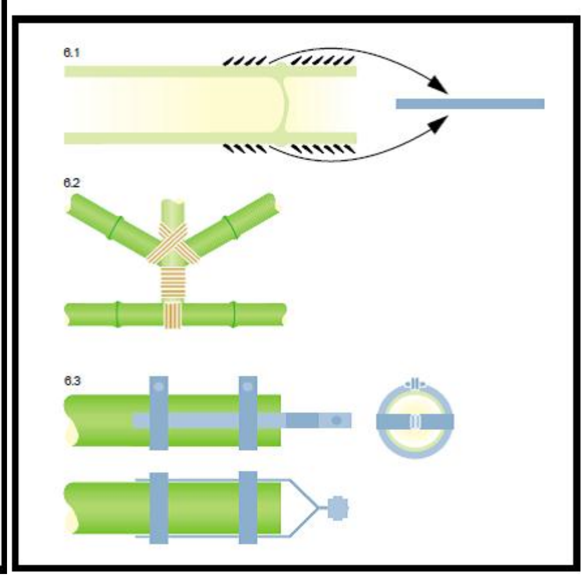


Fig. 73 Joints from cross-section to an element perperdicular to the culm
Fig. 74 Joints from outside to element parallel (Janssen, 1981).

5.1 BUILT PROJECTS

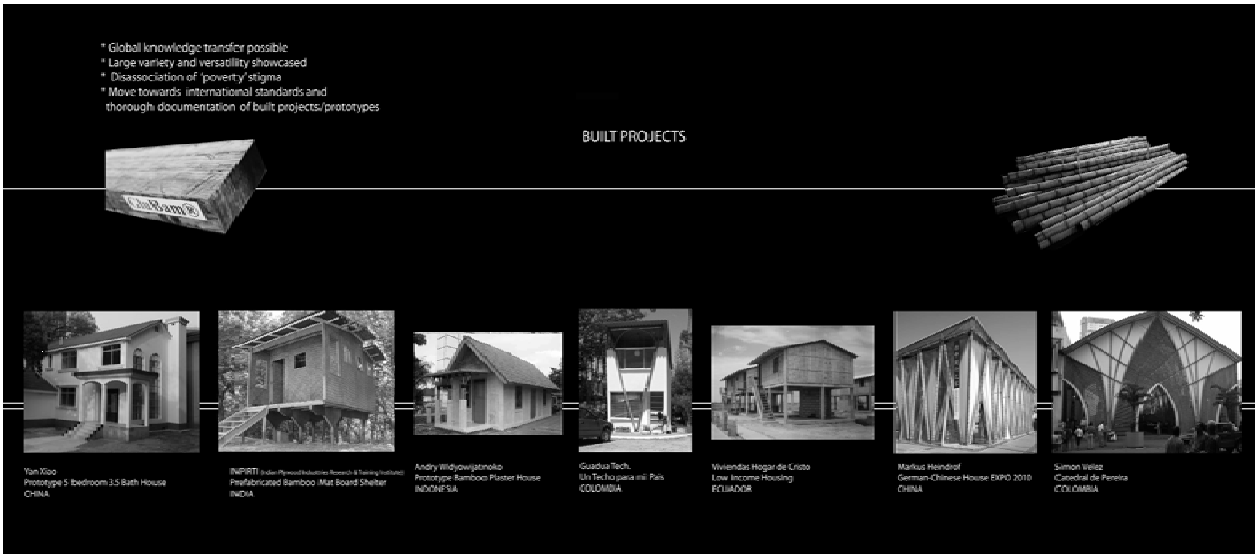


Fig. 75 Built bamboo projects demonstrating and alignment with degree of material processing.

There is quite a growing number of projects that have been built in the last decade that have brought bamboo once again to the forefront as a noble and sustainable material that has vast versatility and possible uses. By taking a snapshot of a handful of projects in quite diverse location worldwide, its clearly visible that the application of bamboo seems accessible to a large range of global markets with the potential to impact local economies positively. Additionally, the use of technology to process the natural bamboo culm can be highly advanced or fairly simple, falling anywhere along the processing continuum previously mentioned. This flexibility is one of the attributes that actually makes bamboo highly versatile and readily available for highly industrialized nations or less industrialized nations.

Fig.76 Source:
(USC Viteri School of Engineering, 2009)

At one extreme are projects from China by Yan Xiao, whose prototype house contains 5 bedrooms and 3.5 bathrooms. At first glance this house appears fairly conventional, possibly built with present day traditional products. In fact, this house is innovative in implementing laminated bamboo products –GluBam- at the whole of its construction. All wall framing, floor joists, and roof trusses are made of what he has coined as plyboo.

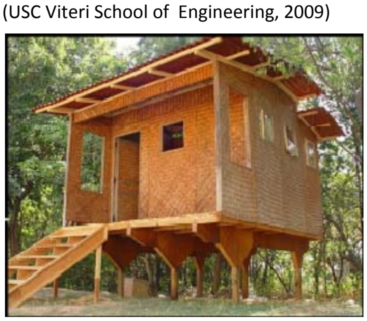


Fig.77 Source: INPIRIT

The Indian Plywood Industries Research and Training Institute (INPIRIT) researches, promotes, and builds many pilot projects as well as test a series of bamboo based products with diverse levels of processing throughout India. The project seen here is made from prefabricated bamboo mat board panels, which make the assembly quite fast once delivered on site.

This prototype Bamboo Plaster House was designed by Andy Midyowijatnoka in Indonesia. This house also begins to look quite conventional once the bamboo panels are plastered over with cement.
The technology utilized in this house focused on a woven grid wall system, which is more elaborate and takes more time to erect on site when compared to the prefabricated panels.

Fig.78 Source: Widyowijatnoko, 2007.

Guadua Tech a bamboo design company based in Colombia designed the following for a national competition, Un Techo para mi Pais (A roof for my country). This project can be categorized in the middle of the processing sprectrum, as a hybrid project. Guadua Tech utilizes natural bamboo culms, in addition with prefabricated bamboo panels. The bamboo culms which are designed as a large scale truss system are left exposed while the bamboo panels create the infill.

Fig.79 Source: Guaduatech.com, 2010.

Viviendas Hogar de Cristo an organization in Ecuador which focuses on providing low income Housing. These projects are built in one to two days and processing on the bamboo infill panels in minimal. The culms are flattened and then fitted within the concrete frame system.

Fig.80 Source: Hogardecristo.org.ec,2010.

The German-Chinese House EXPO 2010 in China by Markus Heindrof is one of the most recent bamboo projects that exemplifies the use of bamboo in modern structures. Although, the project utilizes the culms with the least amount of processing, the joints utilized are highly sophisticated and are at the other end of the processing spectrum. Therefore this project exemplifies the combination of two extremes of technology and processing in the structure and detailing.

Fig.81 Source: Heindrof,2010.

The final project on the continuum in Fig. 75 is by Simon Velez who has elevated the use of bamboo and has played a major role in removing the negative social stigma connected to this material not only in Latin America but globally. He is credited with having introduced cement mortar into bamboo internodes and joints, thus increasing the strength and spans of bamboo structures. Velez's works truly exemplify the aesthetic nature of the material and its affordable potential. For instance, the Catherdal de Pereira (Fig. 82) has an area of 700m^2, only took 5 weeks to construct and cost US$ 30,000.

Fig. 82 Catedral de Pereira in Colombia, 2001

Fig. 83 Templo Sin Religion in Cartagena, Colombia 2008

Fig. 84 Stable in Colombia

Fig. 85 Casa de Campo in Brazil

Fig. 86 Museo Nomada-5000m2 at Plaza del Zocalo in Mexico, 2008 (commons.wikimedia.org,2010).
Fig. 87 Pavillion in Colombia

PART II: DECENTRALIZED LOCATION_ JACMEL, HAITI

Since the cultivation of bamboo needs space for growth, this inherently requires a decentralized location away from Port-au-Prince. The ultimate location of the project was chosen in part due to its proximity to the actual sourcing of the bamboo material itself. Coincidently, some bamboo farms have already been established in Haiti within the peripheries of Marmelade and Jacmel. The targeted decentralized city for the AE_Msc graduation project will be Jacmel, located in the Southeast department of Haiti.

Fig. 88 Jacmel urban fabric impression, city location

1.1 JACMEL'S LOCATION

Jacmel is located 25 km away from Port-au-Prince, it takes on average 3 hours to arrive to Jacmel via Route National 2. Jacmel also has a small airport that can receive small planes, and a sea port located at the Jacmel Bay. Additionally, route 208 will eventually permit the arrival into the Dominican Republic due east (Fig 88).

Jacmel is uniquely woven into the plain between mountainous terrain and the Jacmel River. This gives the city a somewhat protected location from trade winds, since the valley basin and bay area is located on the leeward side of the mountain chains.

Jacmel was also affected by the 2010 earthquake, suffering a high level of loss, with an estimated 50-60% of the city being affected. Since the city's population is 137,966 (2003 census), compared to the 2.5 million of Port-au-Prince, it had to go without immediate assistance after the disaster as aid focused on the more populous capital. The following map (Fig. 89) shows the amount of devastation that took place throughout the city's infrastructure.

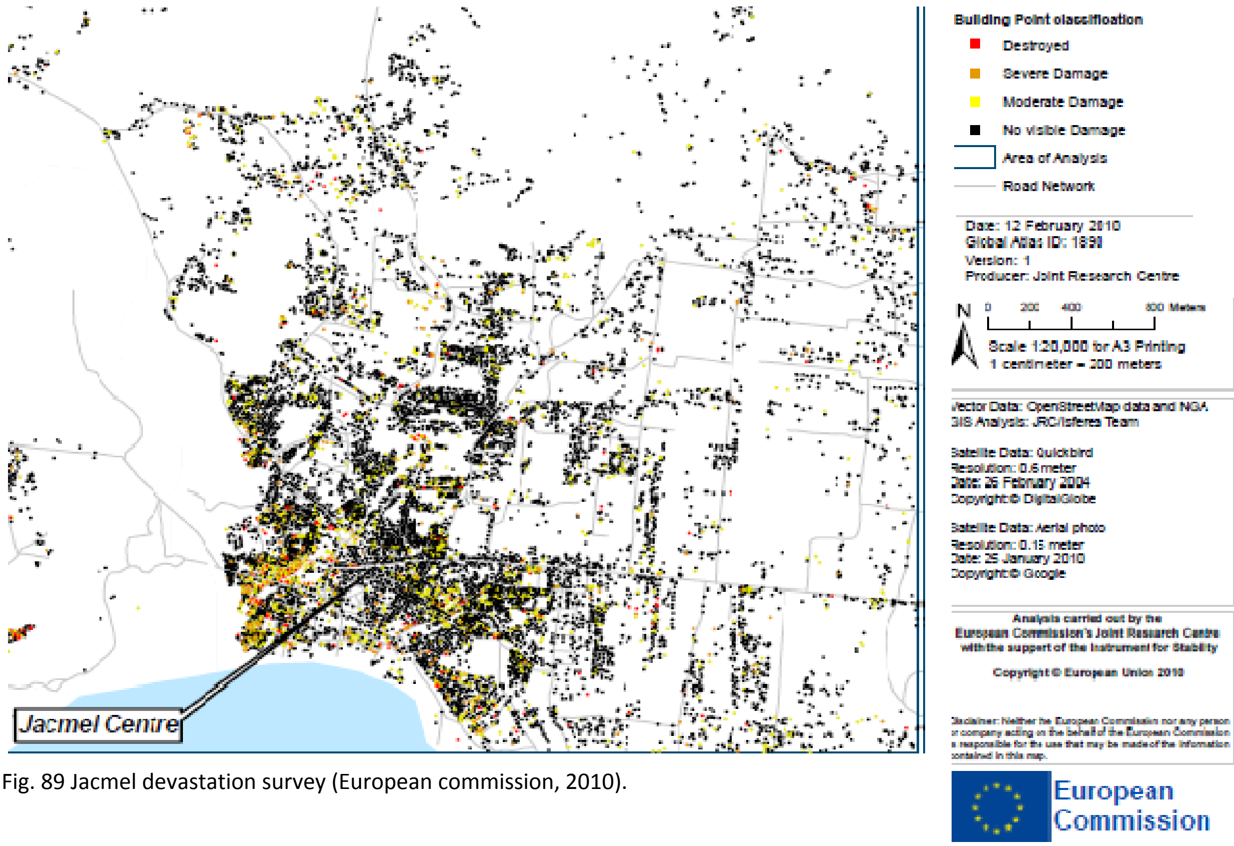


Fig. 89 Jacmel devastation survey (European commission, 2010).

There are two initiatives of growing bamboo in Jacmel one from the Nicaraguan based CO2 Bamboo, which is establishing Guadua nurseries in La Valle de Jacmel, located to the west of the Jacmel's river. The other organization is the Taiwanese-Haitian cooperation that established its bamboo farm and warehouse 1 km outside of Cayes-Jamel. Their cooperation in Haiti has sought to restore the ecosystem, but has also established strong ties with the agricultural production of the area.

Application for Project:

After a thorough analysis, the main access routes from Port-au-prince, the Dominican Republic, the sea port and airport in the city were indentified, as well as the location and proximity to bamboo farms, possible building sites were pinpointed.

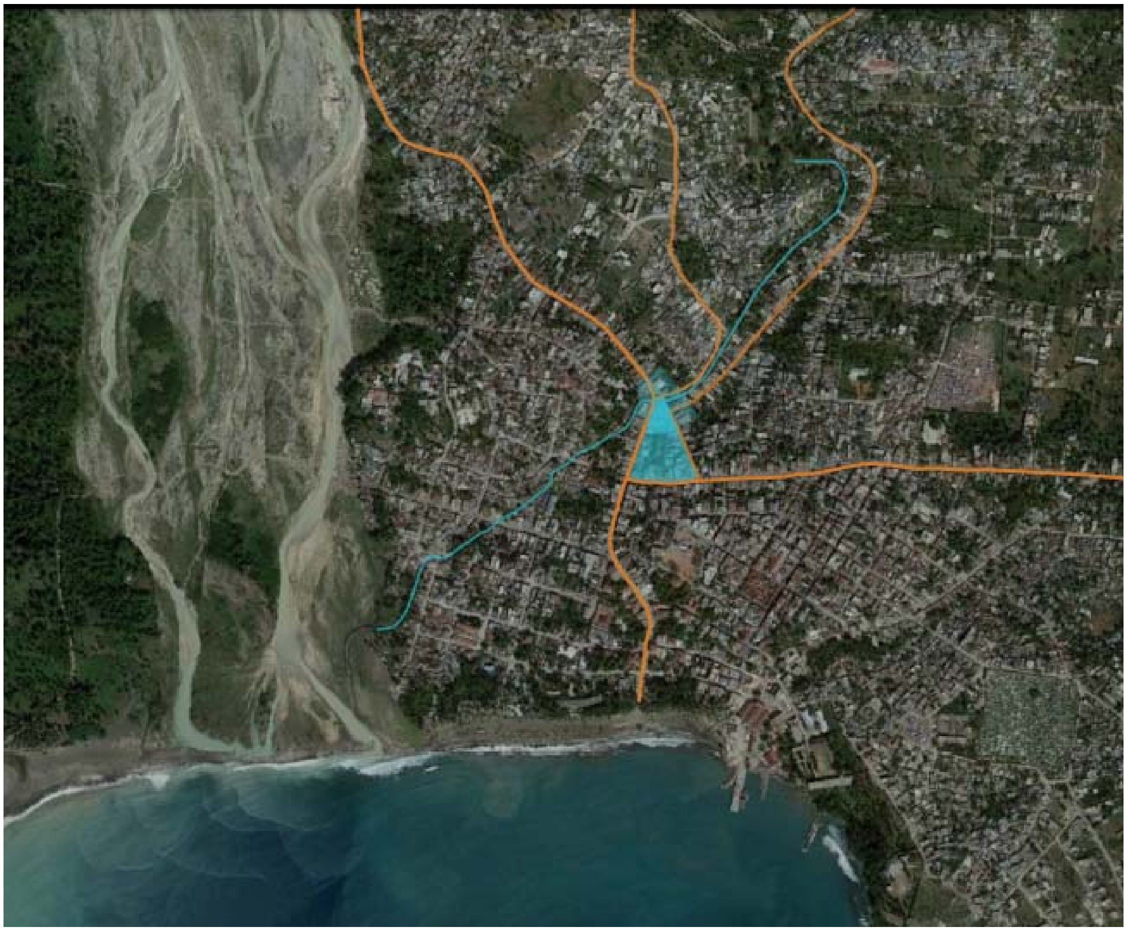
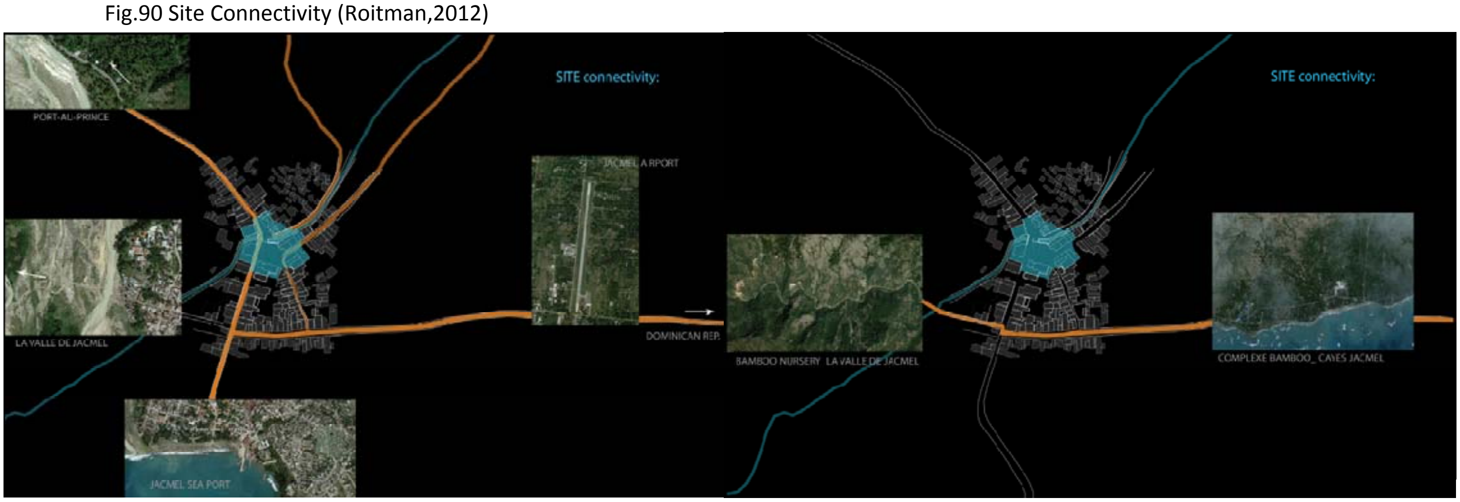


Fig.90 Site Connectivity (Roitman,2012)



2.1 JACMEL'S IDENTITY

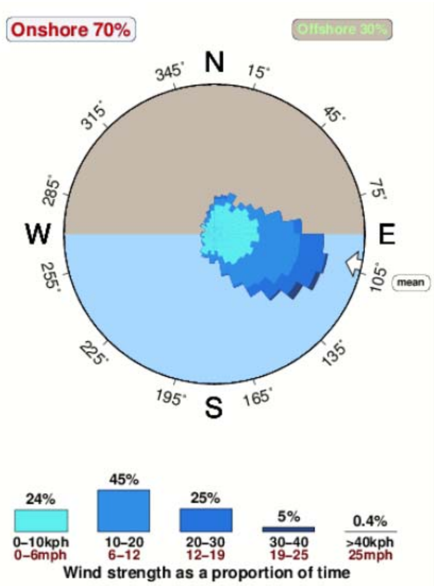
The city was actually the first in the Caribbean to have electricity, and it seems its resourcefulness and creative pursuit towards progress has not died out. Jacmel is quite a good candidate for investment given its unique identity as Haiti's cultural and artistic capital. Each year Jacmel becomes a destination for Carnival, where artisan's papier-mache artwork is put on display. Also, Jacmel's music and film festivals are also becoming major events gathering thousands. This is partly due to Haiti's only film school, the Cine Institute. The urban fabric of Jacmel boasts of its French colonial heritage left by wealthy *commersants* of the coffee trade in the colonial period. In fact the city was in the process of becoming a UNESCO world heritage site. Jacmel is also a prime location for ecotourism, with its exquisite beaches, hikes, and other natural attractions. The city is already a destination for Haitian nationals and is currently attempting to rebuild its international touristic appeal while rebuilding the affected infrastructure post disaster.

Fig. 91 Jacmel's identity

Application for project:

By identifying the priorities and local identity of Jacmel's locally desired development, suitable programmatic function for the building were established.

3.1 JACMEL'S CLIMATE

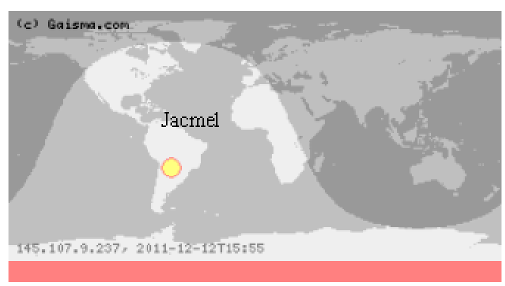


Wind:
The prevailing wind direction are due north and north-east between September and November, and from the east and south-east between April and October. For the most part the South-east department is exposed to the winds coming from the Caribbean sea, and has been affected by a series of cyclones (Hazel (1954), Ella (1958), Flora (1963), Cleo (1963)) (CNUEH-Habitat, 1997). Although, the prevailing wind directions can help with the orientation of the building and design, it should be noted that the microclimate in the specific site should be analyzed. And due to the high humidity it is recommended to use passive cooling methods integrated into the design.

Solar radiation:
In order to avoid excessive heating, buildings should orient the shortest side of the building facing east-west.

Fig.92 Jacmel wind statistics;
Spring averages since 2007 (Surf-forecast.com, 2011).

Latitude: +18.24 (18°14'24'N)
Longitude: -74.54 (72°32'24'W)
Time Zone: UTC-5 hours
Caribbean Sub-region
Altitude: ~20m



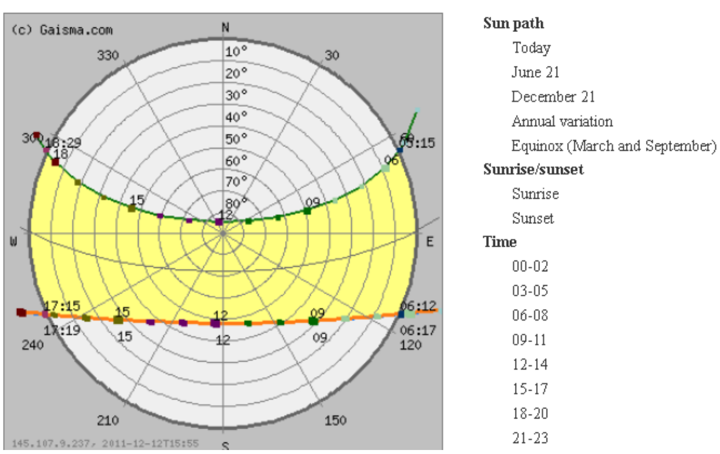


Fig.93 a: Jacmel Sunrise, sunset, dawn and dusk times graph,
b: Sun path diagram (Gaisma.com, 2011).

Precipitation and temperature:

The rainy periods are from April to May and from August to October, while dry periods are from November to February and from June to July. The driest weather occuring during January and December, while the wettest month is May receiving an average of 238mm of rail, sleet or hail.

The year comprises of two seasons: Very hot from March through November with the highest temperatures in July. The hot season is from December through February.

Hours of sunshine in December average about 7.9 per day and 9.1 in August. Overall, Haiti receives 3115 sunshine hours annually and aproximately 8.5 sunlight hours per day.

Diurnal cycle: The maximum difference in temperature during the day and night is 10-12 degrees Celcius.

Yearcly cycle: The maximum difference in temperature during the year is 6-8 degrees Celcius.

The average temperature for the plains of lower slopes of Jacmel are 30 degrees Celcius (CNUEH-Habitat, 1997).

Variable	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Insolation, kWh/m²/day	4.43	4.88	5.32	5.72	5.78	6.17	6.20	5.95	5.27	4.67	4.22	4.11
Clearness, 0 - 1	0.58	0.56	0.55	0.54	0.54	0.57	0.58	0.56	0.53	0.52	0.53	0.56
Temperature, °C	24.63	25.10	25.72	26.20	26.33	26.30	26.03	26.09	25.89	25.67	25.25	24.79
Wind speed, m/s	6.80	6.71	6.34	5.58	5.70	6.14	6.81	6.26	5.42	5.19	6.33	6.82
Precipitation, mm	43	56	96	174	238	131	106	166	176	195	93	44
Wet days, d	9.8	7.7	7.8	8.1	10.9	10.6	12.8	12.8	13.8	15.4	11.7	10.6

These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center; New et al. 2002

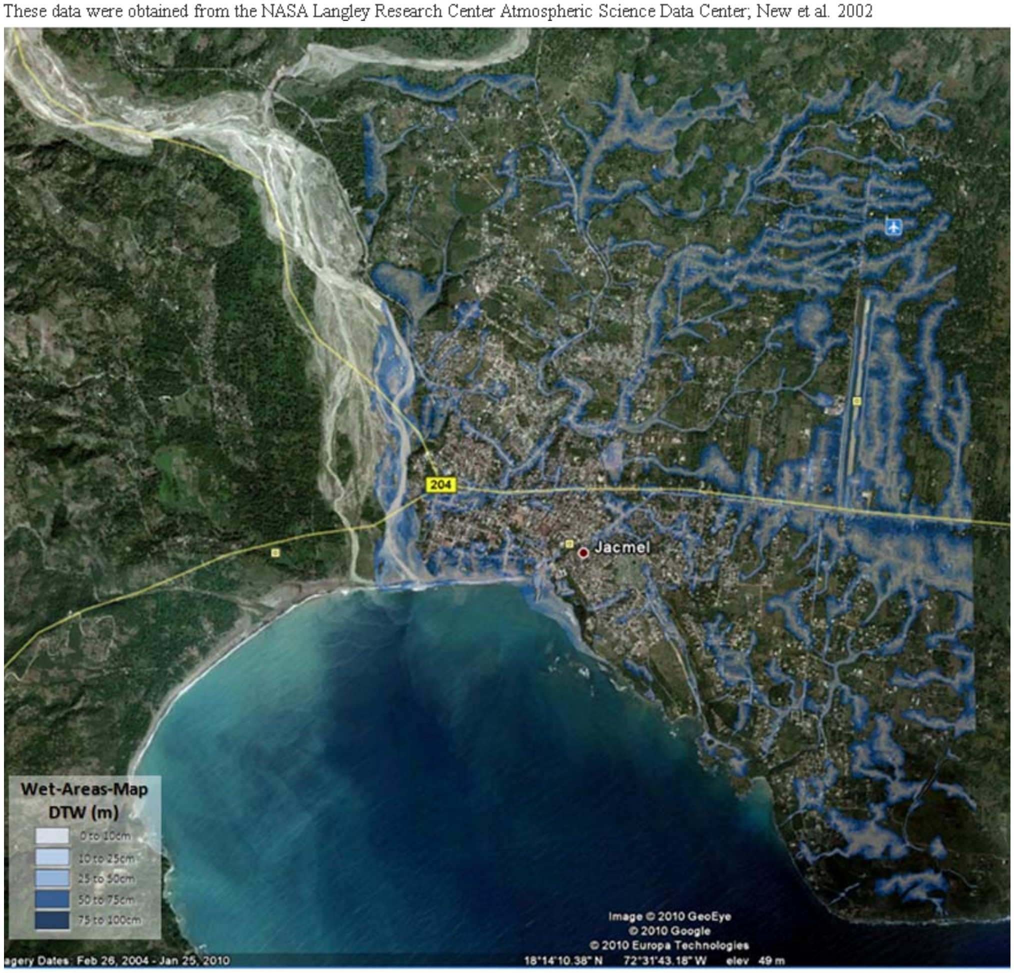


Fig.94 a: Solar Energy and Surface Meteorology (Gaisma, 2007), b: Watershed areas surrounding Jacmel

Average temperature: 26°C
Range of average monthly temperatures: 24-26°C
Warmest average max/high temperature: 26.33°C
Coolest average min/low temperature: 24.63°C
Mean relative humidty for average year: 49.2%,
Mean relative humidity monthly basis ranges from 43% in July to 56% in October.

Watershed areas:

The main river in Jacmel is clearly the Great River of Jacmel with the following smaller bodies that feed into the river and end at the Jacmel's bay: Orangers, Source Bretoux, Source Pasket, Source Titi, Source Fleury, tributaries Gauche Gosseline. Care should be taken when choosing rebuilding sites although the terain in Jacmel is quite mountainous it is located at a costal plain and certain low lying areas are more likely to flood than others.

4.1 BUILDING SITE CONTEXT

The design will be focused around the aims and priorities of the city by addressing them directly or indirectly. Since one of main priorities within the city at this point in time is rebuilding and construction after the earthquake, the resilient and seismic resistant qualities of bamboo should be showcased in order for this material to be implemented in the rebuilding of the city at various scales, from private housing to public buildings; thereby rebuilding a more enduring urban fabric and future.
However, in order for bamboo to become a widely utilized building material it needs a higher degree of exposure to increase local interest and understanding of all the benefits its application can bring.

The project site for this thesis project will therefore be located at a key point in the city; the main entry and arrival from the National highway coming from Port-au-Prince. As a primary stopping point from other cities the site already has a high traffic profile. This will allow the proposed public building to become highly accessible, allowing Jacmelians or those visiting from other Haitian cites to come into contact with the use and application of the material. In so doing, the local initiative of using bamboo as a building material, after the crop is well established, will increase while helping continued efforts to highlight the existing strengths of the city and its appealing touristic features.

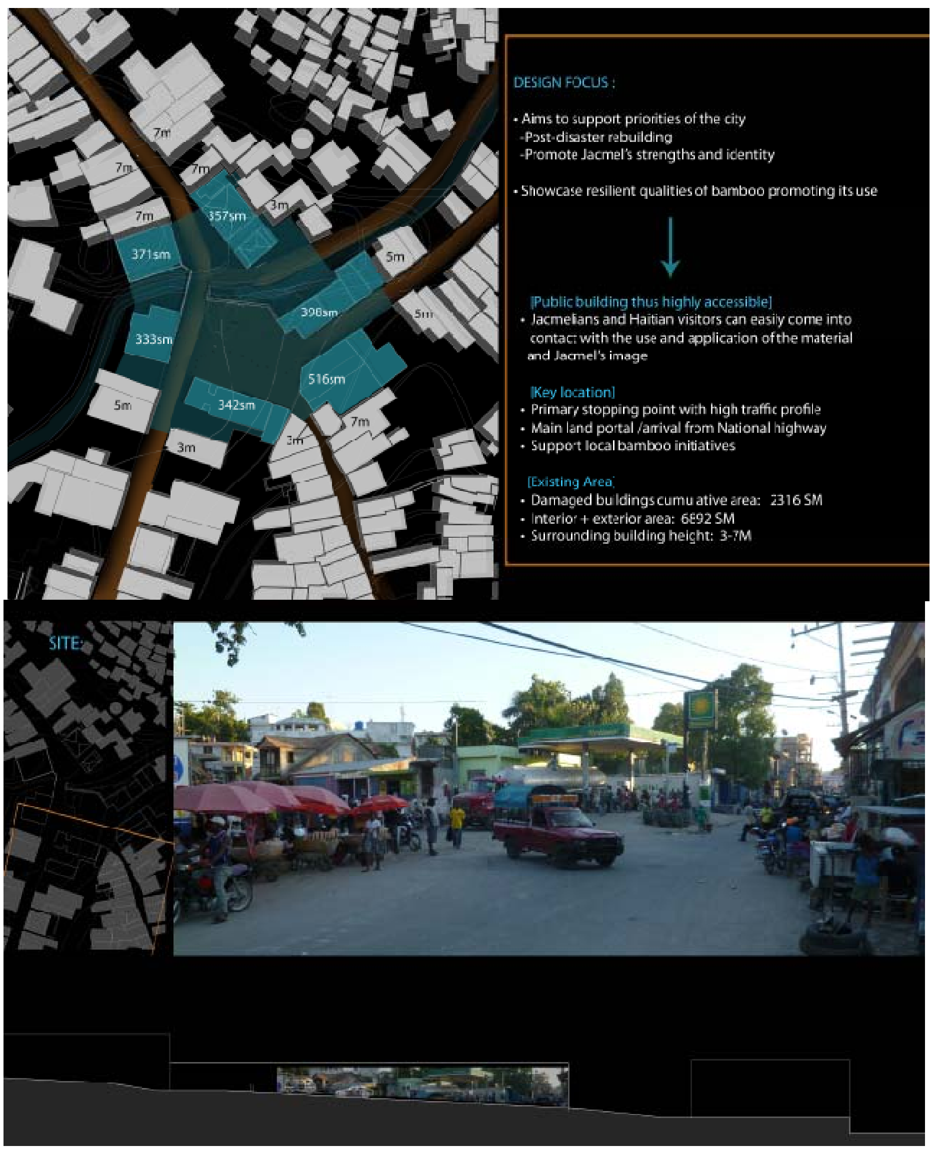


Fig. 95a **Site Analysis**
Jacmel city image courtesy of Arie van Amerongen and Wouter Pocornie (Roitman, 2012).

Currently, the site hosts a series of activities providing the primary stopping point from other cities. Here, a series of vehicles park getting refreshements, gasoline, and some vehicles are being serviced or fixed up. There is a high degree of merchants present who are drawn by the opportunity for economic exchange. Many are waiting in the shade of surrounding buildings and trees, possibly for some transportation to take them to Port-au-Prince or other surrounding cities. The buildings surrounding the plaza were actually all damaged in the earthquake, which is another factor in deciding the building site location. The context and use of the buildings surrounding the building site is quite varied, from a fueling station, bars, as well as dwellings.

Fig. 95b Site Analysis
Jacmel city images courtesy of Arie van Amerongen and Wouter Pocornie (Roitman, 2012).

4.2 BUILDING SITE MICROCLIMATE

The building site lies in the what appears as a basin like location, however the elevation change is quite diverse through the square and surrounding built up area. It is hard to determine whether the site receives a high level of winds or if these are blocked by the descending terrain due east. The lowest point on the site follows the descending landscape towards the wash westward leading to the Grand Riviere de Jacmel. The surrounding buildings are a variety of one to three story buildings, and depending on the ultimate massing of the proposed design they could provide additional shade to the final built proposal or surrounding site. The dried up wash on the north side of the site along with two large trees located in the middle of the site could be a potential source for lowering temperatures and increasing thermal comfort.

Fig. 95c **Site Analysis**
Jacmel city image courtesy of Arie van Amerongen and Wouter Pocornie (Roitman, 2012).

PART III: HYBRID PUBLIC BUILDING

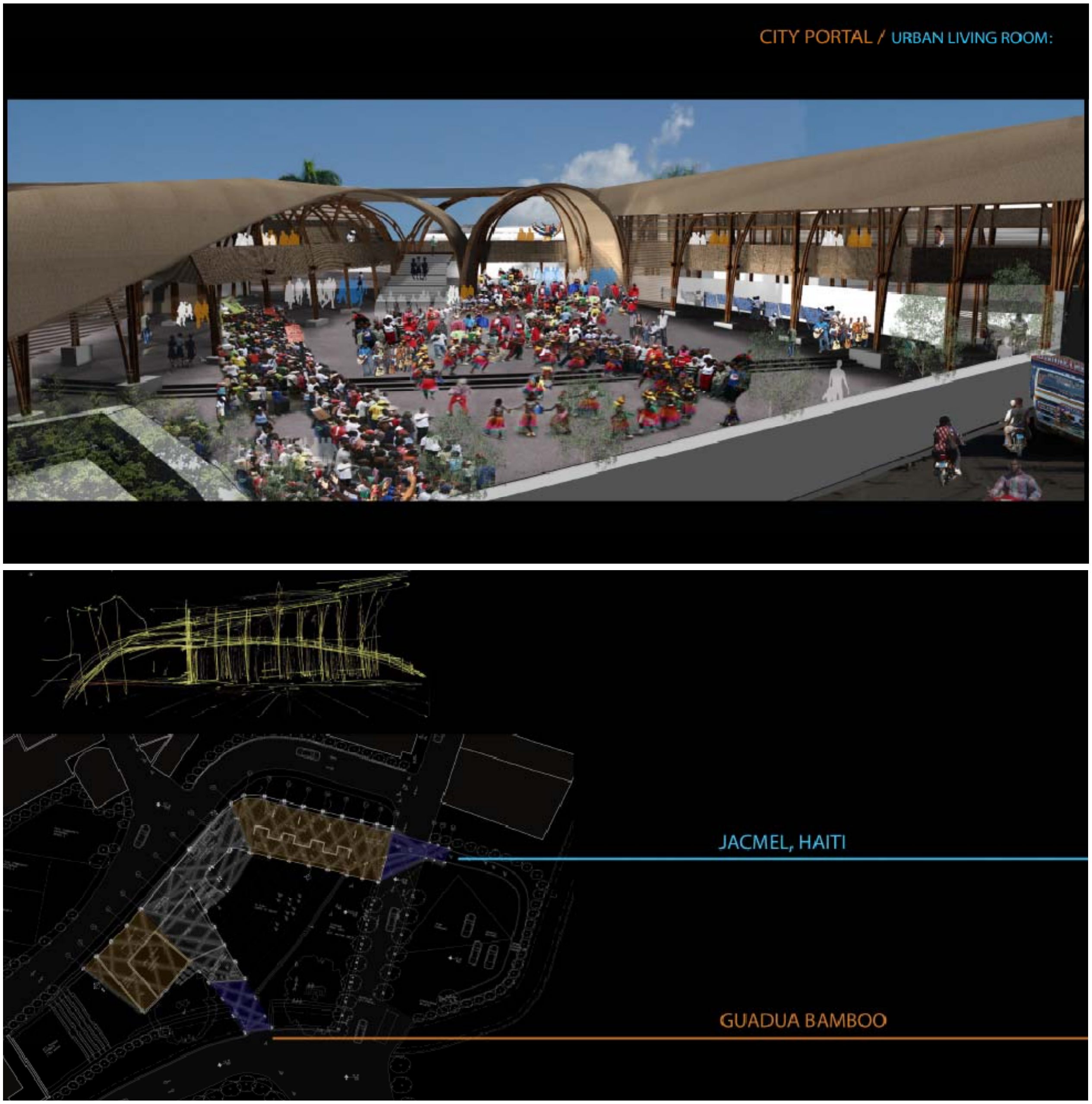


Fig. 96 Design Proposal: Jacmel City Portal/Urban Living Room (© Roitman, 2012).

1.1 BUILDING DESIGN_PROGRAM

The building will host the arrivals and departures partly through a transport station. Along with these transport related activities, the building will take advantage of the level of visitors giving place to economic exchange for merchants, while highlighting both the richness within Jacmel and the use of bamboo as a building system. In order to allow a free flow of exchange in knowledge and the city's identity, the following functions will be strategically interwoven in the massing of the building: flexible community spaces for gatherings, flexible space for workshops including bamboo technology, flexible space to showcase artisans work and student's work from film, art, and music schools; permanent exhibition space for city's architectural and historic heritage; 'point of contact' service desks for tourist information.

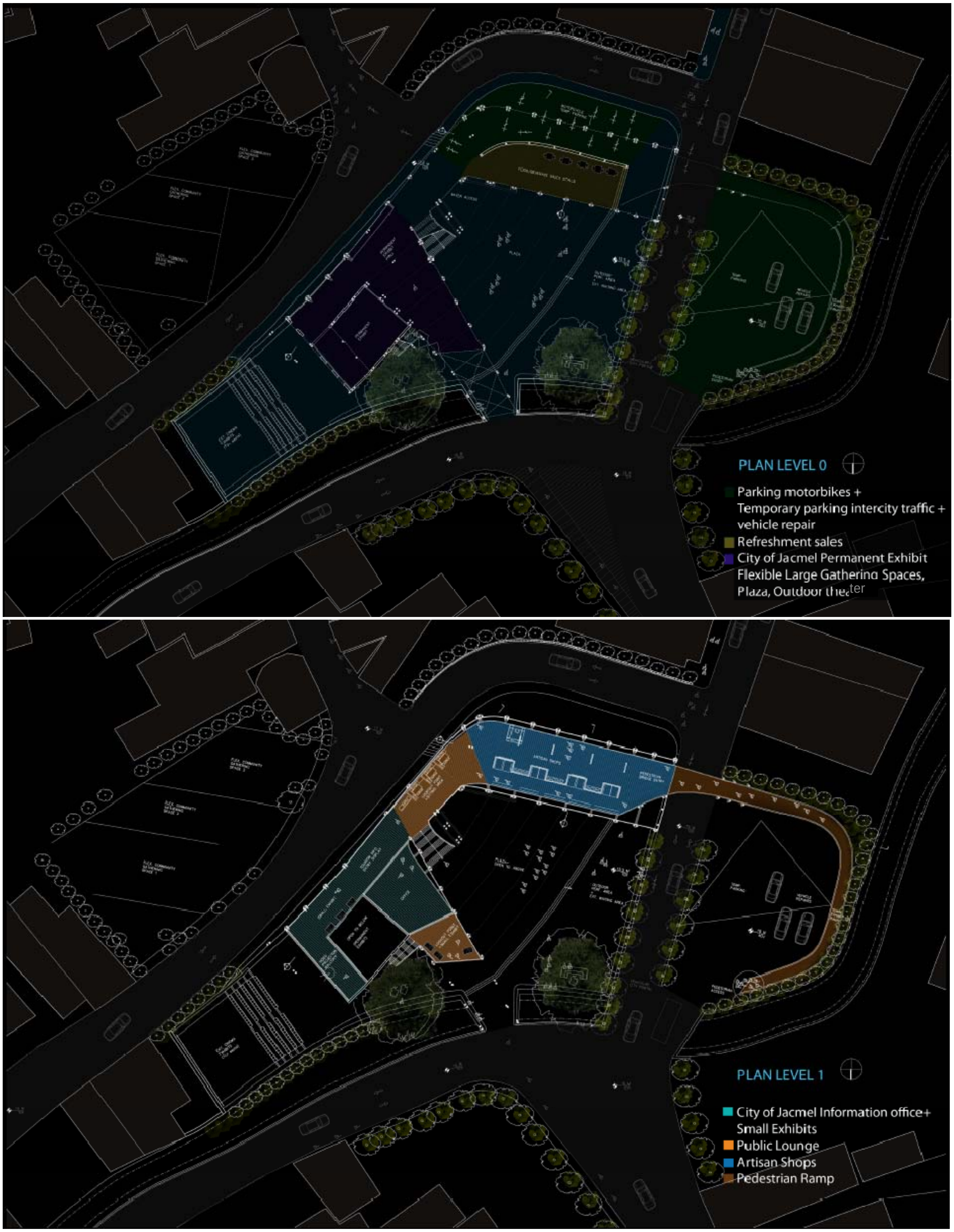


Fig. 97 Design Proposal Plan: Jacmel City Portal/Urban Living Room (© Roitman, 2012).

2.1 BUILDING DESIGN_CLIMATIC STRATEGY

Since in the Haitian context, interior spaces have a secondary role, the proposed design redefines conventional built typologies with a porous hybrid program and built structure which supports cultural flows providing flexible spaces for Jacmel's identity and strengths to be displayed (art, films, music, festivals). The Haitian lifestyle -"Life taking place on the streets"- can freely flow through informal and improvised encounters between Jacmelians, Haitian, or foreign visitors helping to strengthen the local economy. By elevating interior/exterior spaces to function like traditional interior spaces, occupants can truly enjoy the cooler ventilated and shaded public spaces.

Fig.98 Design Proposal Renderings: Jacmel City Portal/Urban Living Room (© Roitman, 2012).

The proposed Urban Living Room is designed to unfold while maintaining a constant relationship with the exterior, inviting in natural ventilation yet protecting against the harsh weather conditions found in Haiti, intense heat, humidity, and rain (Fig.99a). Therefore, the main branches of the building and plaza portals are directly facing the prevailing wind direction decreasing wind shadows and effectively cooling all covered spaces, as well as reducing the temperature of the exterior spaces (Fig.99b). The public plaza also benefits from the venturi effect as the wind velocity is also increased as it passes through the portals transitioning from the street into the Urban Living Room (see elevation Fig.100a).

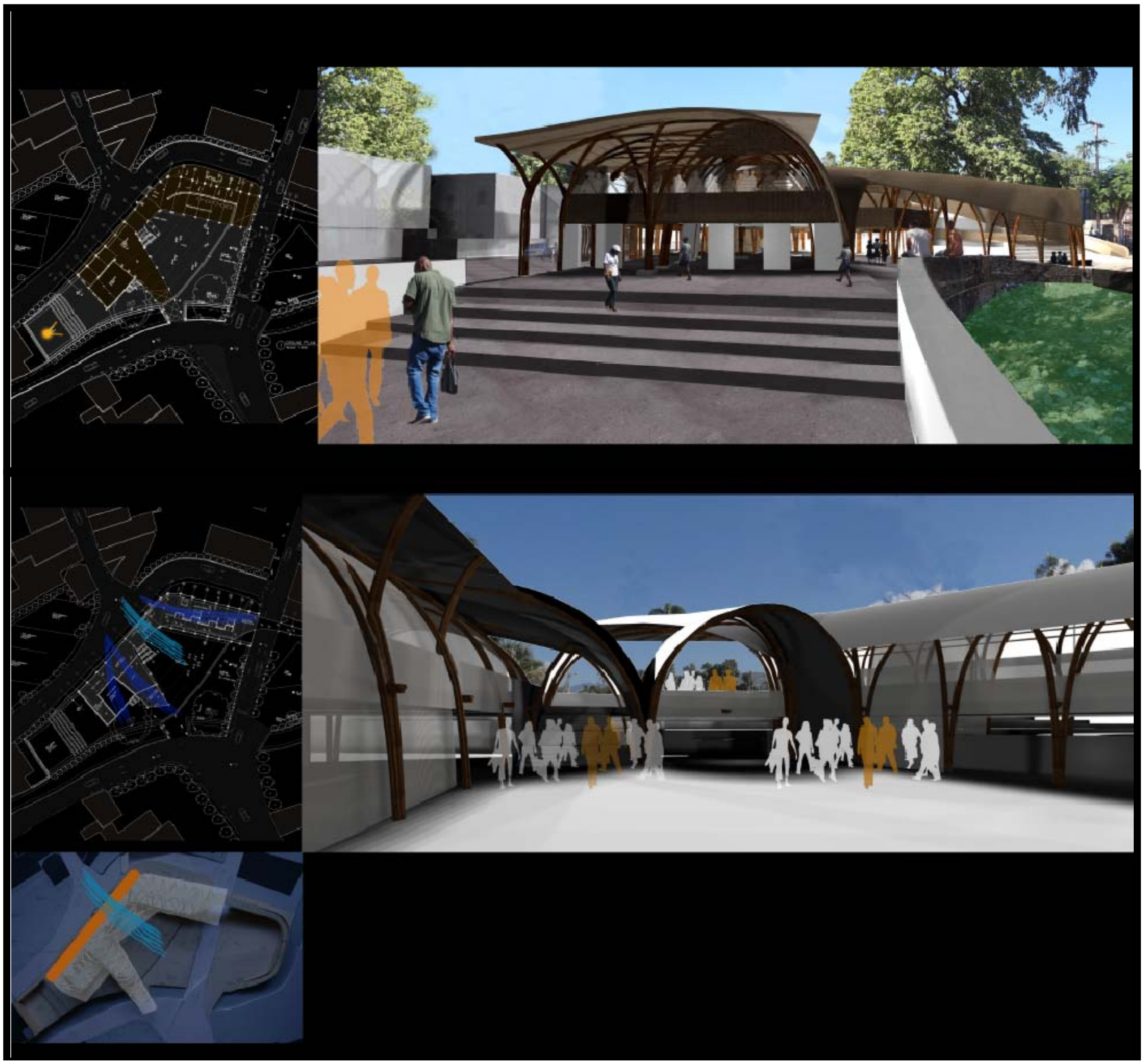


Fig.99 Design Proposal Renderings Jacmel City Portal/Urban Living Room (© Roitman, 2012).
a:Cinema court, b:Natural ventilation scheme

The changing height of the 'branches' was strategically designed to take advantage of the change in ground elevation while playing a big role in promoting natural ventilation. By utilizing the venturi effect, increasing the wind velocity from the eastern facade toward the increasingly taller spaces at the west cooler habitable shaded spaces were created. Natural cooling was further emphasized by the stack effect taking place within the taller spaces (see section Fig.101a). Additionally, care was taken to orient the shorter sides of the built up spaces east-west in order to reduce excessive heating. Due to the intensity of the sun as well as rain throughout the year, the roof and facade elements are of integral importance in providing appropriate protection. The roof's undulating curvature is strictly linked with the incidence angles of the sun at this location thus cutting off direct solar gain throughout the year, while providing sufficient shading all along the perimeter of each branch. The facade system employs the idea of layering by utilizing diverse degrees of density through screening elements. The design effectively creates a exterior layer that acts as a rainscreen and provides shading via fixed shading elements (Fig. 100b seen in blue). Along with this exterior layer which already cools the immediate air surrounding the covered space, the users can further accommodate their thermal comfort through the movable shading scrims (Fig. 100b seen in orange).

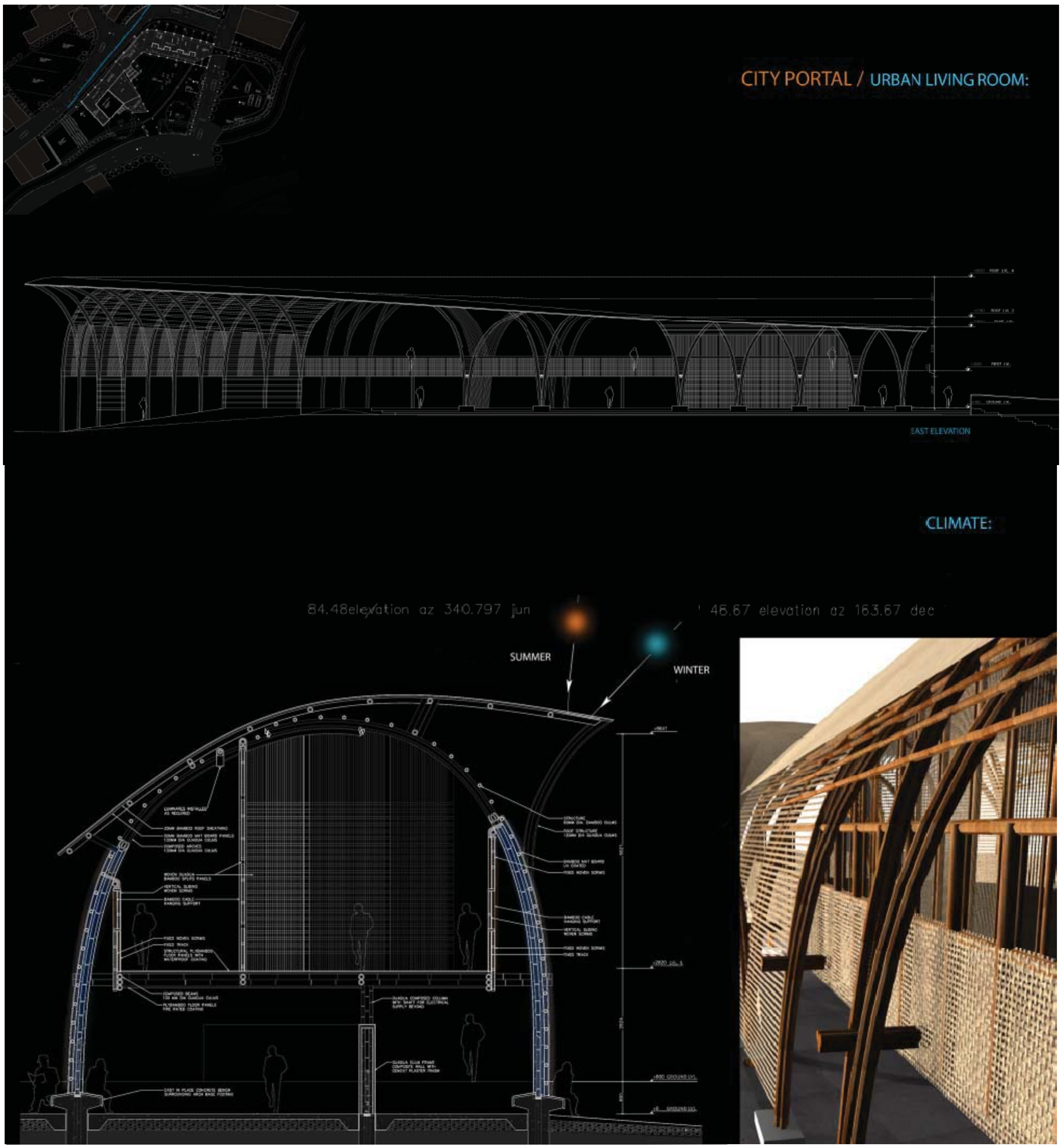


Fig.100 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012)
a:East Elevation, b:Cross section and facade rendering.

3.1 BUILDING DESIGN_MATERIAL STRATEGY WITH GUADUA BAMBOO

The materialization of the building will unfold under the following guises:
Cured Guadua culms:
The natural curvature of cured Guadua culms will be utilized and enhanced primarily for the design of an arched structural system, forming a three dimensional truss supporting the roof and floor platforms. The high arches composed of 3-6 culms will reduce the resulting moments and reactions at the footings, while the cross bracing resulting from the woven design of the arches in each branch will efficiently counter lateral forces (wind or earthquake loads), and will also distribute live and dead loads efficiently throughout the structure while minimizing efforts.
The proposed curvature of each culm will merely exaggerate its natural curvature during growth. And since the curvature will take place during the culms' natural growth cycle, the microstructure of the poles will inherently be shaped and strengthened at the most critical points along the curve. Since the maximum culm length available is 25 meters long, the culm length utilized will be between 10-15 meters, in a series of composed arches which will be formed to resist vertical and horizontal loads and where necessary the columns will increase the number of culms used in order to resist greater forces. For instance, at the point where the arches cross each other, the culms are interconnected by 12mm steel bolts, galvanized threaded rods and are stacked in a diamond shape in order to enhance vertical and lateral stability. Joints in the composed arches will be staggered to ensure further stability,

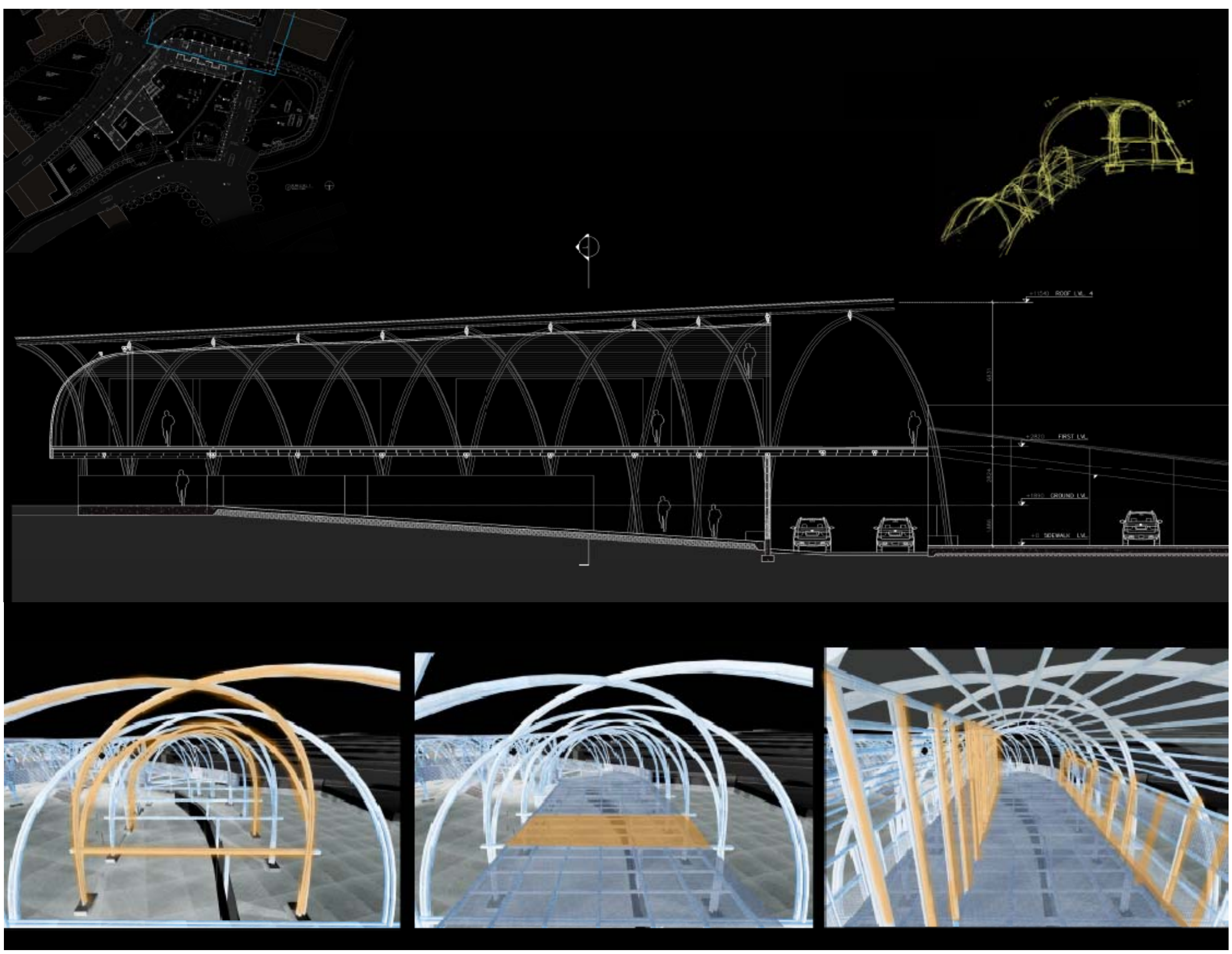


Fig.101 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012)
a: Section and structural system diagram through retail branch

and will be filled with cement mortar which can transfer sheer loads to culm's diaphragm where fiber cells are interwoven and can avoid splitting. Also, beams composed of straight culms will increase their load bearing capacity when their static height is increased as per design load. The secondary structure will be built up from straight culms through a unitized panel system. The cladding along the arches will further strengthen the structure and provide the necessary protection against local climatic conditions as previously discussed.

Material Density:

In addition to the use of guadua culms, the proposed design will truly showcase the great versatility that is achievable with bamboo. Essentially, from the floor to the roof, the building will exemplify the diversity of building materials this grass can produce: floor panels, cable for hanging supports, split culm panels for translucent scrims, and composite panel systems with resin for the roof and plastered panels that create massing for a series of enclosed spaces.

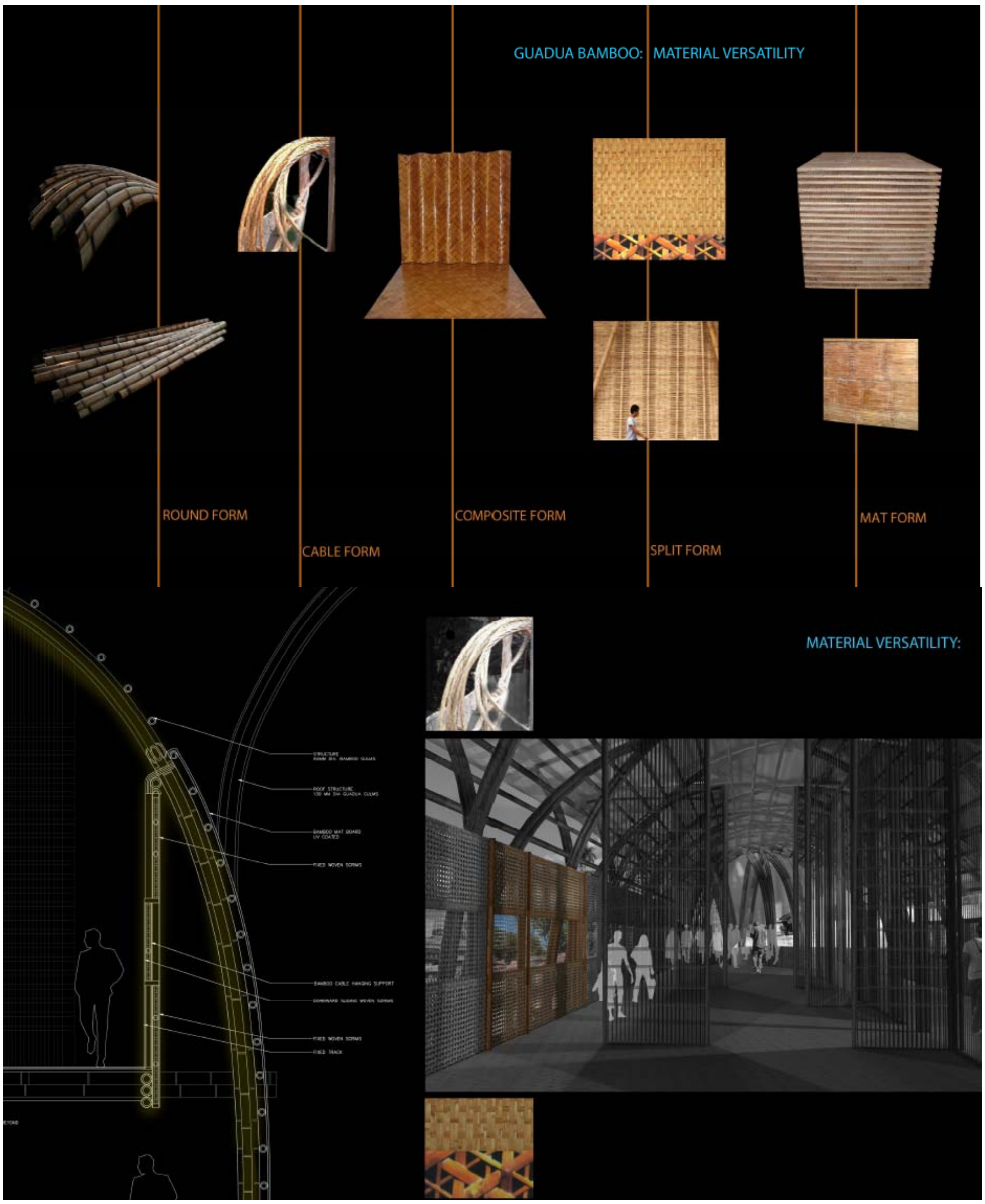


Fig.102 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012).
a: Bamboo material versatility diagram b: Section and rendering of materials utilized

Fig.103 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012).
a: Rendering Exhibit space_ Bamboo plastered walls with woven ceiling panels at center
b: Rendering retail space_ Facade system with diverse woven scrims fixed and movable, and spatial dividers throughout retail

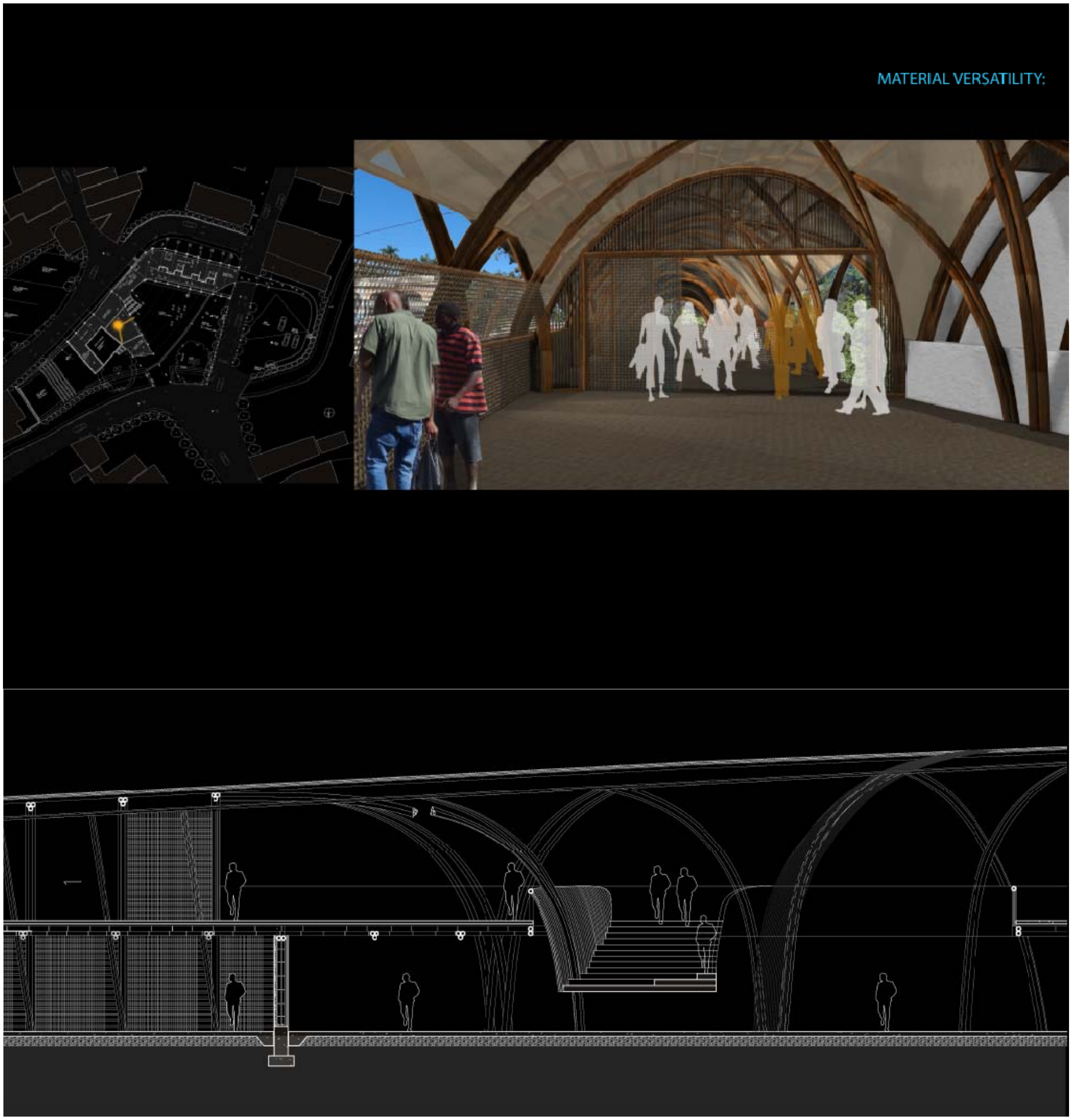


Fig.104 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012).
a: Rendering_ Tourism displays and City of Jacmel information office- varied application of bamboo based materials visible
b: Section_ Main access to first level functions of Urban Living Room

Fig.105 Design Proposal Drawings Jacmel City Portal/Urban Living Room (© Roitman, 2012).
a: Rendering_ Retail entry from pedestrian bridge b: Section_ Outdoor cinema and exhibition space

APPENDICES

A. HAITI'S GEOGRAPHIC OVERVIEW

The Republic of Haiti is located in the Caribbean Sea, and shares the Hispaniola Island with the neighboring Dominican Republic. Haiti's total land mass area is 27,750 km^2, including four smaller islands; Ile de la Tortue, Ile de la Gonave, Ile a Vache, and Iles Cayemites.

Geography:

Haiti's geography is characterized by five main mountain ranges which run east to west along the northern peninsula, across its central mass, and along its thin and long southern peninsula, listed as follows: the Massif du Nord, Montagnes Noires, Chaine des Mathux, Chaine de la Selle, where the highest point of the island is found (Pic de la Selle 2,680 meters), and the Massif de la Hotte. Additionally, the Chaine du Trou d'eau and the Cordillera Central mostly located in the Dominican side of the island end in the Haiti's western border.

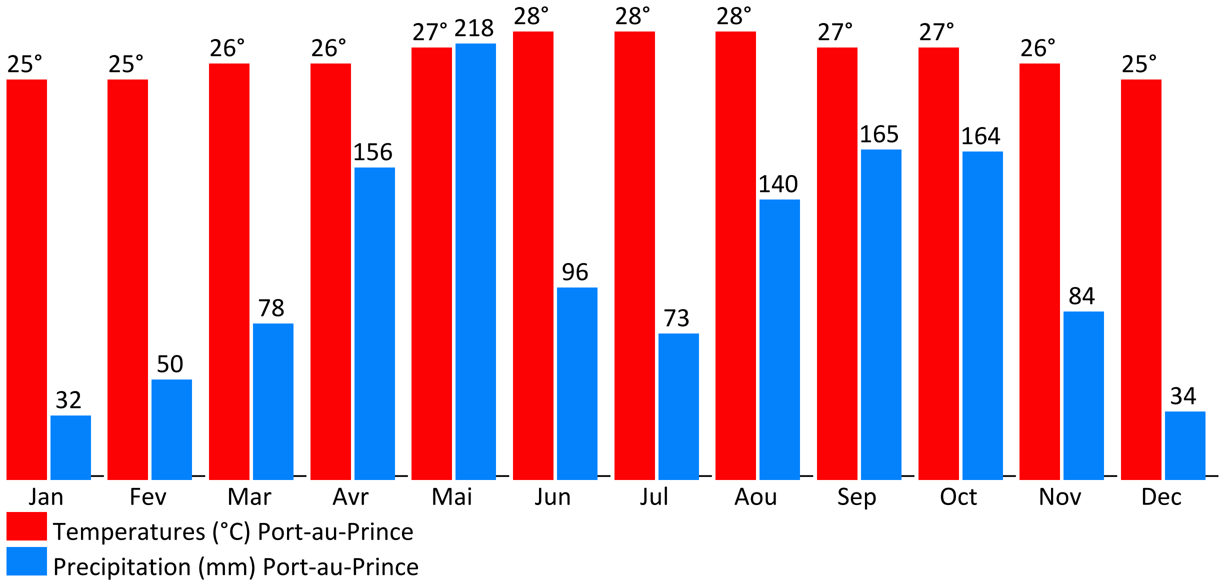
A network of rivers flow throughout the island and empty out at the Atlantic Ocean along its northern coastline, or at the Caribbean Sea along its eastern and southern coastline. Haiti has one main lake, Etang Saumatre, and two smaller lakes Lac de Peligre and Trou Caiman.

In essence, the nation's terrain can be summarized as steep and mountainous with valleys, and *extensive* coastal plains which used to be covered by humid tropical forest (a point which will be elaborated later).

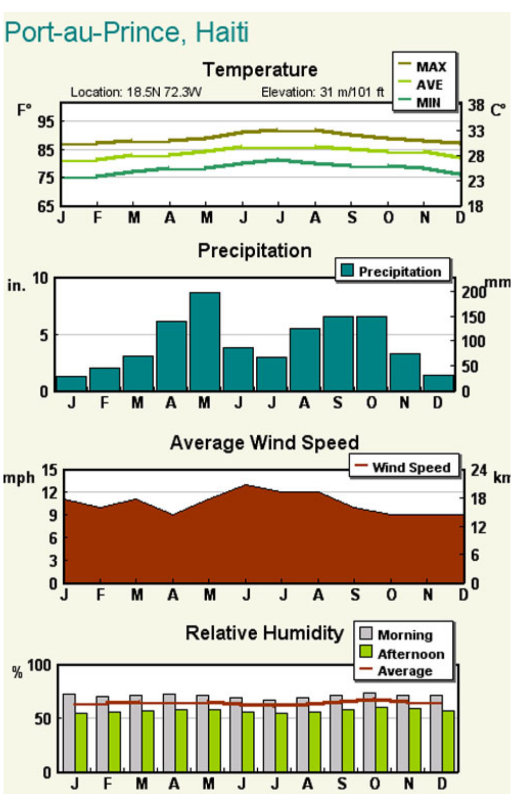
(http://commons.wikimedia.org/wiki/Atlas_of_Haiti,2012).

B. HAITI'S CLIMATE OVERVIEW

The climate in Haiti is tropical and has some slight variations due to changes in elevation; for the most part however it can be characterized as hot and humid. The leeward side of the mountains, which cut off the trade winds are characterized as semiarid. On average the expected range of temperatures are as follows: Jan 23°C (73°F)-31°C (88°F), Jul 25°C (77°F)-35°C (95°F). Temperatures are almost always high in lowland areas (15-25 in winter) and (25-35 in summer), where the highest concentration of inhabitants remain.



(Valeurs moyennes mensuelles) [Average monthly values]
(http://www.studentsoftheworld.info/informations_pays.php?Pays=HAI&Opt=climat, 2012).



Wind:

North winds with fog and drizzle usually interrupt the dry season which runs between November through January. The wet season, on the other hand, between February until May is ushered in by the northeast trade winds bringing heavy rains.

Rainfall:

On average about 140-200cm of uneven distribution of rainfall can be expected annually. Heavier rainfall usually takes place in the southern peninsula, the northern plains and mountains.
Rainfall decreases however from east to west across the northern peninsula. Along the eastern central region there is only moderate amount of precipitation. While on the western coast, from the northern peninsula towards Port-au-Prince it is relatively dry.
The rainy seasons usually take place between [April-June] and [October-November] (southtravels.com/america/haiti/weather.html, 2011).

Natural Hazards:

Haiti is located along a hurricane belt path, which makes it quite vulnerable to severe storms during hurricane season which runs from June until October. Flooding throughout the rainy seasons and during and after storms has also become a major problem, and its impact is only increasing due to deforestation.

As seen in Figure 3, there are two main fault lines that run through Haiti, the Enriquillo-Plantain Fault running right through Port-au-Prince, and the Septentrional fault running at the northern extreme of the country. Historically, Haiti and the surrounding area have experienced a series of disasters due to the active tectonic plates of the surrounding area.

Deforestation:

As of 1925 the forest cover in Haiti was around 60%, presently Haiti has only 2% forest cover remaining. The wood is primarily being used for cooking fuel, while land is being cleared for agricultural use (Reliefeweb, 2009).

Due to such extensive deforestation, a series of environmental problems have been introduced with severe consequences for the population. For instance, due to the decrease in forest cover the soil is no longer stable making erosion an extensive nuisance and hazard. The erosion of topsoil not only makes cities vulnerable to landslides and flooding, but it is the main contributor to desertification. Since the topsoil of the land is washed into the ocean more and more fertile land is increasingly lost throughout out the island, which in turn decreases its possible use for agricultural purposes.

C. HAITI'S HISTORY

[Sources: (Stouter, 2010), (Schwartz, 2011), (Buschschluter,2010), (Amos, 2010)].

HISTORIC TIMELINE

5000 BC-1492-Taino chiefdoms
1492-Columbus discovers 'New World' landing at Môle Saint-Nicolas
Colonial period-exploitation of the island for gold/exploitation and maltreatment of natives/introduction of foreign diseases and African slaves
French pirates-exploitation through trade
French colonial period-plantations and slavery
1697-Treaty Rijswijk
1791-1804-Haitian revolution
1804-(January 1)- Independence from France declared
1804-Dessalines (Emperor Jacques I)
1806-Henry Christophe/Alexandre Sabes Petion
1818-Jean-Pierre Boyer
1825-France recognizes Haiti's independence
1833-Britain recognizes Haiti's independence
1847-Faustin-Elie Soulouque (Faustin I)
1859-Fabre Geffrard overthrows (Faustin I)
1862-US recognizes Haiti's independence
19th century-Gap between French speaking mulatto elite and black Creole-speaking majority deepens
1843-1915- 16 rulers overthrown or assassinated
1915-1934-US occupation by US Marines (Monroe Doctrine)
1930-Stenio Joseph
1937-Massacres Dominican Republic border
1941-Elie Lescot
1941-US maintains fiscal control
1946-Student strikes and violent demonstration against Lescot
1947-US maintains indirect control
1950-Military coup by Dumarsais Estime
1950-Paul E. Magloire

1956-Francois Duvalier –Papa Doc—end mulatto domination extend political and economic control to black masses while Tontons Macoutes-paramilitary group terrorize population
1964-Duvalier re-elects himself as president for life [Haiti under Duvalier becomes a police state], increases international isolation, expedites exodus of Haitian professionals, and regime is characterized by corruption, contracting economy, and withdrawal US aid/decline in tourism
1971- Jean Claude Duvalier—Bebe Doc—
1975-1980-African swine fever outbreak- mass eradication of pig population
1980's- AIDS becomes widespread issue/tourism virtually collapses
1986- Jean Claude Duvalier exiled to France
1987- Lieut. Gen. Henri Namphy (three dozen voters killed)
1988- Leslie Manigat (Jan. elections considered fradulent/overthrown in June)
1988- Lieut. Gen. Prosper Avril (unstable government)
1990- Jean-Bertrand Aristide (First free elections in Haiti's history/reforms alienate wealthy elite)
1990- Gen. Raoul Cedras opposes Aristide/US and other nations impose trade embargo/mass exodus attempts to Florida
1994- US occupation/Aristide returns to power, dismantles Haitian army/oppositions go to exile/country benefits from international aid and loans/ farmers fail to compete with cheap imports/UN forms new Haitian police-inadequate preparation/criticized for corruption and violence
1995-Rene Preval (first peaceful transfer of power/faced political infighting)
2001-Jean-Bertrand Aristide (faced economic/political problems after re-election/international sanctions impoverished population further/HIV-AIDS rose/lawlessness and violence rose/
2004-Street demonstration against Aristide/ Aristide flees country/remittances from Haitians abroad becomes main source of income/ MINUSTAH –United Nations Stabilization Mission in Haiti assumes power—confesses pressured to use violence
2005-Crime/kidnappings/gang activity delay presidential elections
2006-Preval claims presidency by 51% of the vote/ food and fuel price increase led to protests/government instability
2008-Violent riots against government and MINUSTAH–high costs of living/ Senate dismisses prime minister replaced by Michele Pierre-Louis first female prime minister
2008-Aug.-Sept. series of hurricanes ravage nation/floods destroy crops/country relies on international relief efforts/rebuilding hampered by lack of government action/violence from Haitians and MINUSTAH
2010-Jan. 12- 7.0 Earthquake/Epicenter near Leogane/Massive damage/considerable loss of life and capital/Collapse of homes, public buildings-hospitals, schools, National Palace, Parliament building, Main post office, several Ministries, City Hall/ nearly one third of the population affected by the quake/International aid flooded Haiti to provide relief
2010-Oct. Cholera outbreak
2010-Nov. 28- Michel Martelly

HISTORY OVERVIEW

Haiti has faced a tumultuous history that has vacillated from vast richness to extreme poverty, from violent exploitation to revolutionary independence, from unstable governance to emphatic dictatorial rule, from misguided humanitarian aid to over-dependence on foreign intervention, from violent social unrest to violent natural disasters.

The history of a nation is not a simple progression of events that can be easily summed up. Yet for the sake of grasping what has happened along the development the state, we are obliged to take a sweeping look through the corridors of time in an attempt to decipher what series of events and weighty factors have driven the rise and fall of a nation's social, economic, and *natural* prosperity. In Haiti's case, the disparity from its past glory as the "The Pearl of the Antilles" to its present identity as the "poorest nation in the western hemisphere" is quite shocking.

In order to give a brief overview of Haiti's history, the events that transpired will be grouped under the following historical eras: pre-colonial, colonial, post-colonial, US occupation period, police state period, post-dictatorial period, Aristide/Trade embargo period, Natural disasters period.

PRE-COLONIAL:

Present day Haiti and the Dominican Republic were ruled by the Taino and Arawak Amerindian tribes. The Island was divided into five main chiefdoms.

Pre-Colonial architecture:

The architecture during this era was characterized by circular buildings, mainly constructed with native wood and thatched roofs.

COLONIAL [1492-1804]:

The arrival of Columbus in 1492 to St. Mole Nicolas, introduced the colonial era in the Hispaniola Island and later spread it throughout 'the New World'. Unfortunately, the self seeking motives of the explorers brought on numerous woes to the Taino natives. Along with the exploitation of the Island and maltreatment of the indigenous people, the population was virtually decimated through foreign disease outbreaks. African slaves were therefore brought to work for Spanish exploits and later for French colonial plantations established primarily by French pirates. By 1697 tensions had began to grow between the Spanish and French rule, which gave rise to the Rijswijk treaty of 1697 effectively dividing the Island between Spain and France (Dominican Republic and Haiti).

Colonial Architecture:

The establishment of plantations and the influence of Spaniard architecture can clearly be seen in the vernacular architecture of Haiti even to this day. Kay houses typically found in plantations, were erected by slaves who seamlessly merged typical African and Taino architectural traditions into a hybrid style. These 'shacks' were later symbolically elevated to signify an architecture of defiance after the liberation from colonial rule. Presently, most Haitian housing resonates the essential typology of this simplistic shelter literally in form and spatial pattern. The Creole house, which is another significant historic style presently built, was derived from the Spanish colonial style. In this case, the building's frontal façade is more elongated.

POST –COLONIAL [1804-1915]:

From 1791-1804 freedom from French plantation owners was fiercely contested by Haitian slaves. Led by Toussaint L'Overture, Haiti effectively became the first black republic to gain independence from colonial powers on January 1, 1804. Although, this cry for independence was heard around the world it was slowly recognized by the reigning powers, French recognition came by 1825, Britain by 1833, and the U.S. by 1862. The century following this independence was filled with extensive instability. The newly established governance suffered with seventeen different rulers being overthrown or assassinated, and the disparity between the French speaking mulatto elite and the black creole speaking majority began to grow deepening societal tensions.

Post-colonial Architecture:

This era brought about a picturesque and elaborate style, predominantly represented by European styled houses, which were nicknamed "gingerbread" houses, by visiting *American* tourists. The style arose as the exchange and travel between Europe and the Haitian elite grew during this period. Currently, the remaining houses that have been preserved and those which have fallen badly into disrepair and are all being targeted as cultural icons that deserve attention.

U.S. OCCUPATION[1915-1934]:

By 1915 Haiti was suffering from a century old cyclical pattern of unstable governance and social unrest.
This volatility in the nation was disapproved by the neighboring US, who at this point sought to secure this region from external European intervention, while extending its power. Essentially, what had characterized foreign policy for the US through the Monroe Doctrine was again applied, and this time enforced by the US Marines. The formal occupation period took place from 1915-1934, however US fiscal control remained until 1941, and the overall governance of the state was indirectly controlled by the US until 1947.

Architecture during US occupation:

During this period there was no particular style that arose, but rather a major material shift toward concrete begun as construction in timber was officially banned in 1925 in order to prevent fires.

The question that arises at this point is whether this shift in building materials did not derive from the US occupation of the island and the preferred and customary building practices of the US Marines which is more permanent and largely developed and utilized in the US for housing and public works. The main highways and presidential Palace and Cathedral were also built during this period under the tutelage of the Marines. The question remains how the housing and development could have naturally grown without this foreign intervention and interruption. Could the traditional building methods continued to be employed and valued? Or possibly elevated to a new level?

POLICE STATE [1956-1986]:
As the US let its grip on the Haitian state relax, the seemingly established rule shortly swung back to disarray and overall instability. This breach in governance opened unhealthy tensions that had been present years earlier. This gave Francois Duvalier, also known as Papa Doc, a clear path toward leadership, as the platform of his campaign was based on ending mulatto domination and redirecting control of the country's power centers to the black masses. This populist agenda served him well and allowed him to rise to power in 1956. Unfortunately, his desire for power and violent enforcement of it essentially created a police state with Duvalier proclaiming himself as "President for life". Papa Doc's dictatorship was characterized by a terrorized citizenry, corruption, international isolation, and foreign investment withdrawals. After his death in 1971, his son Francois Duvalier –Bebe Doc-, inherits the Haitian state but is unable to maintain control. After a series of disease outbreaks including African swine flu, epidemic cases of HIV/AIDS, which also drove the small economic sector in tourism to virtually collapse, Duvalier is exiled to France in 1986.

U.S. / UN / ARISTIDE [1990-2008]:
Once again as the nation oscillated from an iron-fist type of governance to loose attempts at governance with a handful of military coups, Jean Bertrand Aristide seems to end this wave of unrest, and is elected through Haiti's first free elections in 1990. After a short lived victory, his political reforms alienate the wealthy elite and what appears as corrupt ruling is castigated by the US by imposing trade embargoes. Soon after a series of mass exodus attempts began by Haitians who attempted to escape to surrounding nations, especially the coasts of Florida. By 1994 the UN and the US occupied the island for peace keeping and humanitarian aid attempts. The first peaceful transfer of power takes place between Aristide and the newly elected Rene Preval in 1995. Aristide is once again re-elected in 2001, this period is characterized by widespread violence and more international sanctions forcing Aristide to flee the country. By 2004 the UN stabilization mission forces or MINUSTAH (Mission des Nations Unies pour la stabilisation en Haiti) seize control. The ensuing four years climax in violent riots in 2008 against the government and the UN due to the rising costs of living.

DISASTERS [2008-2010]:
In addition to the economic and social woes, 2008 also brought a series of hurricanes and deadly floods, which devastated the country further by destroying crops and cities alike. Haiti's government could not mobilize sufficient aid, so relief was necessary from international aid. And one of the most devastating natural disasters strikes Haiti with a 7.0 Earthquake January 2010. Once again the island is flooded with international aid.

D. HAITIAN URBANIZATION

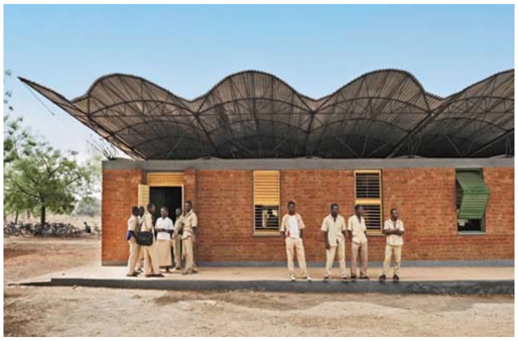
Haitian settlement patterns in general have the most densely populated areas in the plains, but some settlements along with cultivated plots are also found in the hills or steep mountains. From 1982 onward the population of Port-au-Prince has increased from 750,000 to more than 2.5 million, with an estimated average of 75,000 people moving to the city annually. This phenomenon is mostly due to the lack of investment in Haiti's rural economy over the past three decades thus culminating in unplanned rapid expansion of surrounding cities and primarily Port-au-Prince. The main problems that arise with this lack of planification are overcrowding, inadequate infrastructure, and proliferation of slums containing poorly built homes (BBC_1, 2010).

Despite these problems the neighborhoods in and around Port-au-Prince that continue to sprawl have several things in common. Firstly, the inhabitants remain in the same area on average for seventeen years, thus creating quite a stable residential base mostly from countryside migrants. The materials used for construction are concrete and tin, which tend to reflect the longevity or permanent investment of residents in an area seeking to own a home. Common building materialization is broken down as follows: "100% have cement floors, 99% have cement walls, and 62% have cement roofs. The typical building is one story with two to four rooms...70% of those interviewed believe they own the house and 60% believe they own the land (Schwartz, 2011). After the 2010 earthquake land tenure became one of the most significant issues that needs resolution, as a lack of clear land ownership has stalled many projects from moving forward.

Additionally, due to the local and traditional building techniques relying on masonry bricks which are made by inhabitants in their own backyards and dried in the sun, owner built houses were largely destroyed during the quake (BBC_1, 2010). Since there has been no national enforcement of building codes and most of these building materials when not manufactured properly or reinforced once built, have potentially catastrophic results. Furthermore, the priority of most housing built has been on hurricane proofing, rather than earthquake proofing which is usually more costly and complex, "Most buildings are like a house of cards, they can stand up to the forces of gravity, but if you have a sideways movement, it all comes tumbling down," Roger Musson, head of seismic hazard at the British Geological Survey (BBC_2, 2010).

Clearly, as rebuilding efforts take place focus should be on the need to upgrade building standards and an overall enforcement of national building codes. It is essential that informal and unregulated construction before long-term measures can be set forth, that the citizenry become informed of good building practices. However, a larger perspective should be taken into consideration, and that is whether it makes sense to rebuild Port-au-Prince in the first place. Economists Paul Collier and Jean-Louis Warnholz both advocate a decentralized approach to urbanization in Haiti. They wrote in the Financial Times, "Done right, international intervention can deliver immediate jobs through construction, and longer-term jobs through new enterprises. Done wrong, it will only pour relief into Port-au-Prince, luring in rural migrants from the impoverished central plateau, and further diminishing local food production at a time when it is most needed". Essentially, reducing the population density in the capital, will take the burden off this centralized location and will allow the expansion and development of the state as a whole. Therefore, the construction of new homes should be linked with the potential to generate new economic opportunities with a sustainable and holistic perspective. It is therefore of prime importance that secondary cities become focal points in development strategies and modernization of agricultural methods takes place (BBC, 2010).

E. TROPICAL CLIMATE DESIGN PRINCIPLES



Dano secondary school in Burkina Faso built in 2007 consists of 615 square feet classrooms, 560 square feet computer room was designed by Francis Kere, which he describes as "reflective of, if not dictated by, the local environment and economy." The school is located in West Africa and utilizes natural ventilation, local labor and local materials. The building overall is quite innovative and elegant with the use of simple construction methods. The distinctive split-level roof and ceiling structure utilizes the stack effect which draws air in by removing warm air through ceiling slits in the scalloped shaped roof above. Also, the tall windows throughout the facades have shading system which control light levels while drawing fresh air into room.

Overall, the building is design utilizing local materials: corrugated tin roofs, hand-pressed sand and earth bricks from locally cut laterite, a clay that contains iron allowing it to harden when exposed to the air. The added benefit to the use of this clay is its effective insulative properties, thus keeping the building cooler despite high temperatures. Also to note is Kere's focus on utilizing the local labor for the building efforts thus simplifying the design in order to use non-industrialized construction techniques (Dumiak,2012).

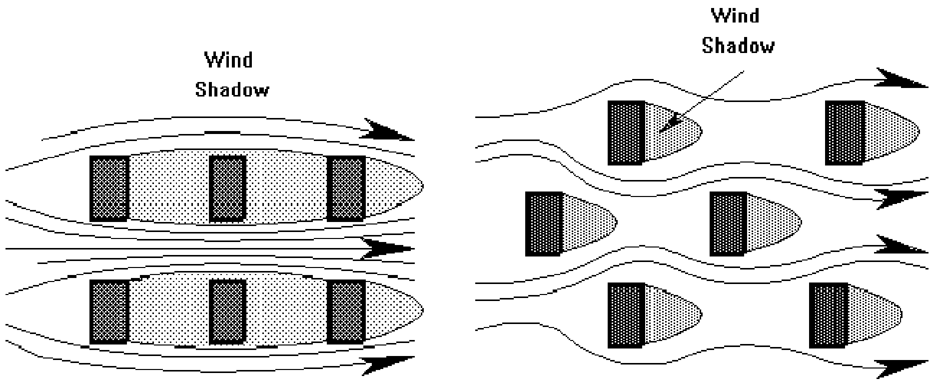
Climate Design guidelines:

Air movement

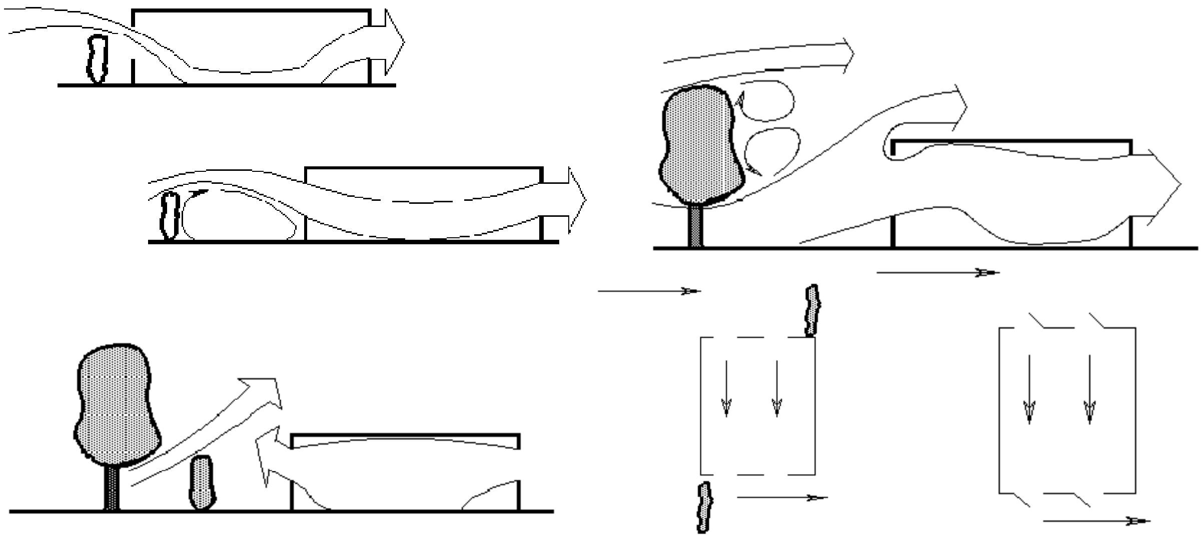
- Long horizontal barriers reduce wind speed 25-50% at distance 20 times the height
- Wind speed is lower at ground level or uneven terrain in addition to frictional effects
- Cyclones usually penetrate 50km inland after which wind speed is reduced
- Diminution of wind speed at leeward side
- Valleys provide shelter depending on wind directions or may funnel wind intensifying effect

Ventilation:

- Greatest pressure on windward façade when elevation is perpendicular to wind direction
- Wind incidence 45 degrees could reduce pressure up to 50%, if large openings are on leeward side suction or Venturi effect could increase internal airflow
- If there is a conflict between the optimum orientation for sun shading, and the direction of the prevailing wind, it is probably preferable to give priority to orientation relative to the sun
- Regular grid of buildings could reduce effect of wind



- It is preferable to stagger buildings, space buildings 50m apart, reducing wind shadow effect



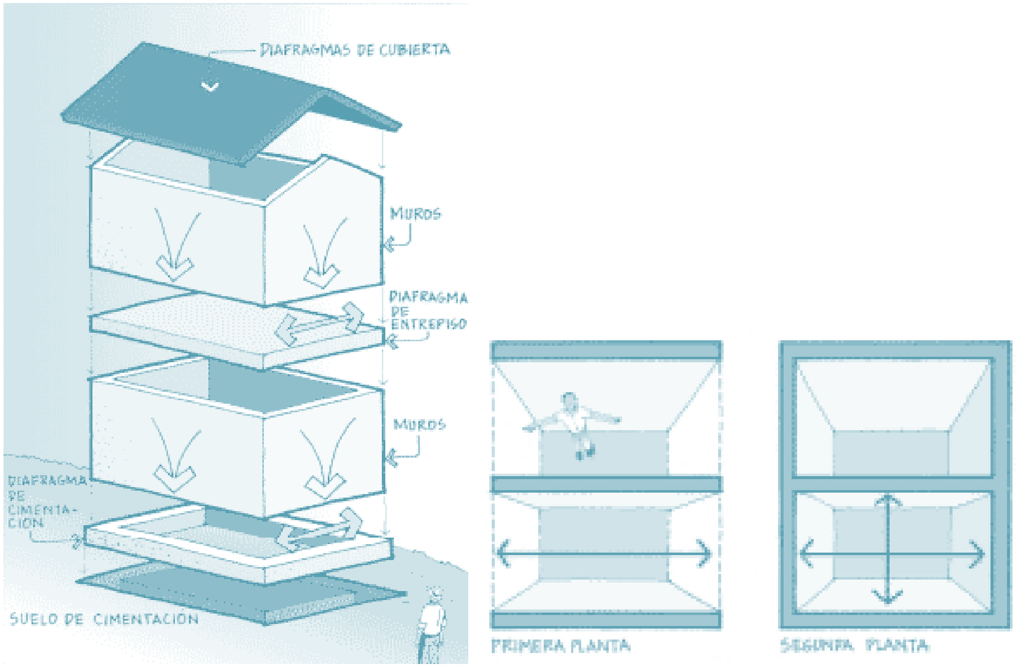
- Effect of obstructions and wind flow (Clark, 2010).

Guidelines from vernacular architecture:

Example Palace of Bandjoun, Cameroon:

- Internal spaces enclosed by solid walls, infilled with clay, surrounded by buffer veranda space
- Deep overhangs and row of columns protect from sun, allow translucent light
- Dark internal spaces generally 100sm lit with top roof light
- Allows open free flowing intermediary spaces, residential courtyards, natural ventilation

F. ANTI-SEISMIC DIAGRAMS



In order to have a safe structure that can adequately respond to seismic forces the following systematic design principles should be observed.

Load bearing or stability walls:

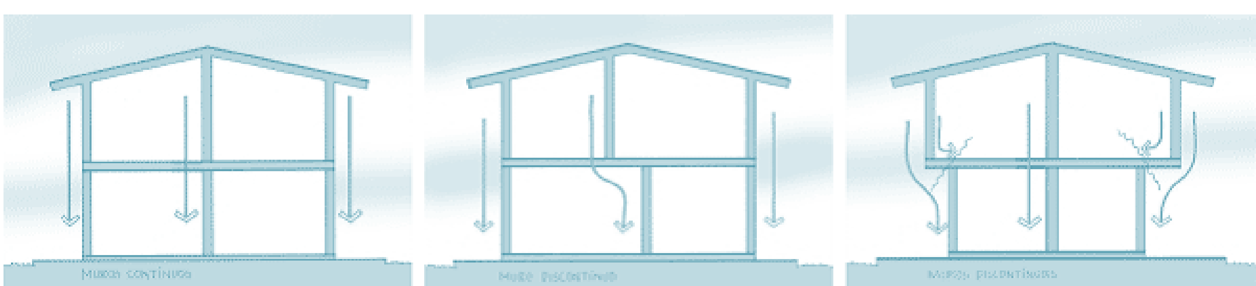
- Should resist horizontal forces in both primary directions in plan and rigidity should exist in the same plane as each wall. Structural walls transfer forces parallel to their own plane, from origin to the floor level. Load bearing walls support their own weight, and vertical loads from subfloors.

Diaphragm system:

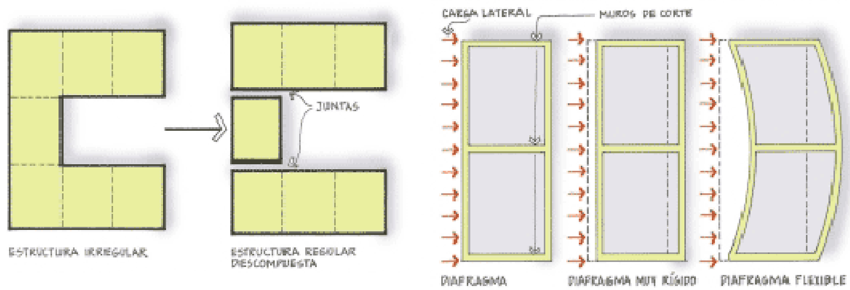
- *A*llows load bearing walls to work as one unit by ties that transfer horizontal loads

Footings

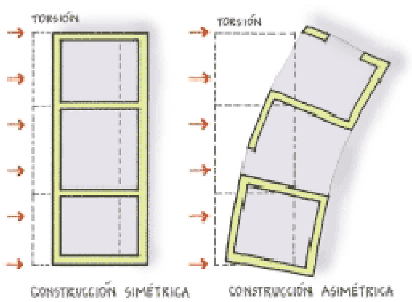
- As load is transferred from walls, the foundation slab must prevent diverse settlement of the structure. The foundation must also form a diaphragm connecting foundation walls and footing with structural ties.
- The effectiveness of the ties in the diaphragms will be affected by the vertical and horizontal continuity of the structural walls and by the irregularity of the structure in plan and elevation.

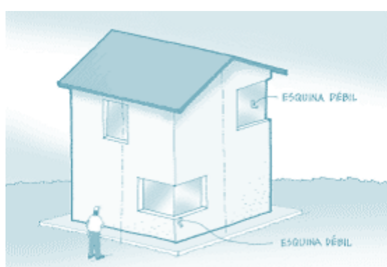


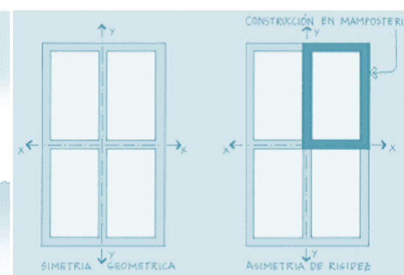
- In order for walls to be considered structural they must have continuity from the top loading point all the way to the foundation.
- If walls loose this vertical connection between diaphragms, it is no longer structurally continuous.



- Irregularities in plan should be avoided in geometry and rigidity, by isolating elements that would create irregular shapes.
- Regular forms can be assymmetric in rigid terms, which should be avoided by redistributing them appropriately.
- Since wood diaphragms are quite flexible, plans with an elongated shape loaded horizontally, are more likely to behave like beams, presenting large deformations relative supported points.
- It is advisable that structural walls resisting horizontal loads should not be spaced more than twice the longitudinal length of structure. The more rigid and least elongated the diaphragm is, the loads can be transferred more adequately between walls.
- If the diaphragm is too flexible or elongated, the load is distributed on each wall according its area of influence, without taking into account its rigidity.

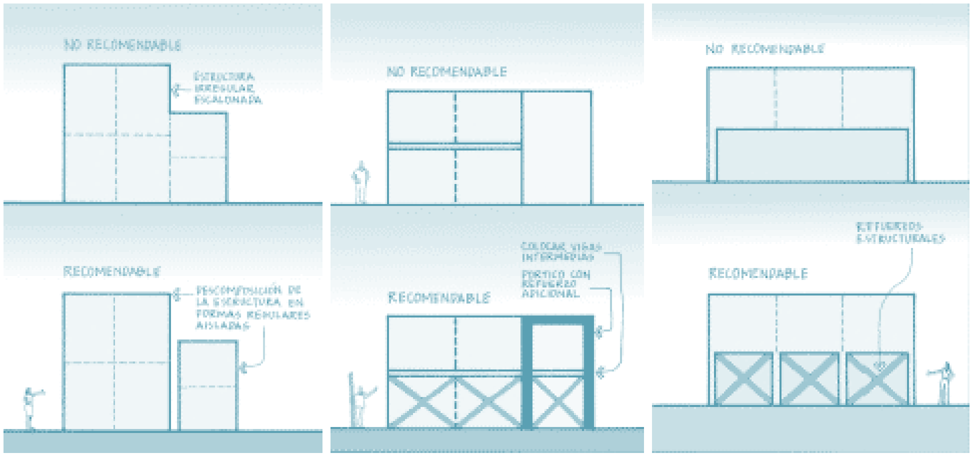




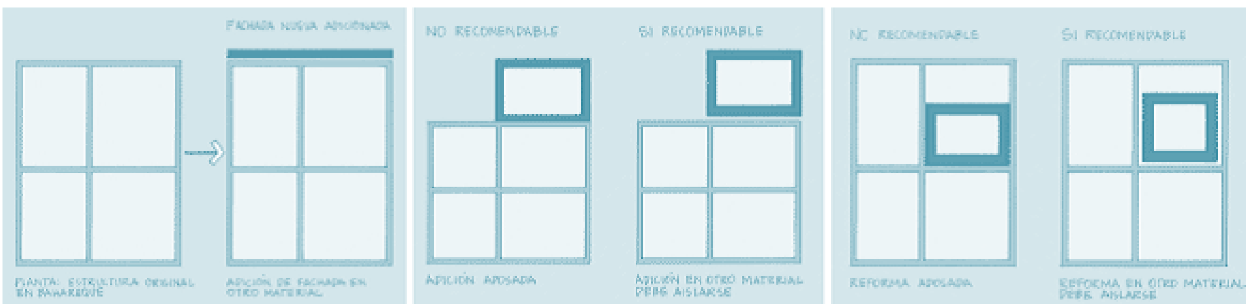


Torsion in structures:

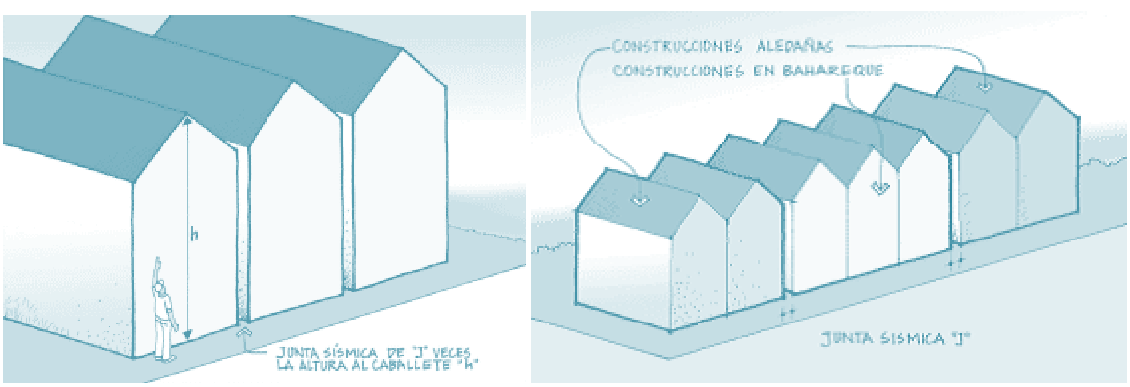
- With a lack of symmetry in plan torsional effects can take place throughout the structure
- Some elements can become more resistant than perimeter walls, making the design inefficient
- To minimize torsional effects, wall configuration should change or rigidity of shorter walls must increase, and resultant forces must be close to center of stability of the structure in plan.
- Symmetrical plans can result in torsion if there is an irregular distribution of rigid walls (rigidity not based on apertures but rather location in overall structure).



- Irregularities in geometry or rigidity should be avoided in elevation
- If structures do vary in height it is better to have to said structures isolated from each other
- Double height spaces should be reinforced increasing rigidity and resistance of the overall structure



- It is not recommended to mix materials with diverse rigidity characteristics or resistance
- Bahareque structures should therefore be constructed with the same material
- If a different material is utilized on a façade or additions, each should be isolated to work independently from bahareque structure

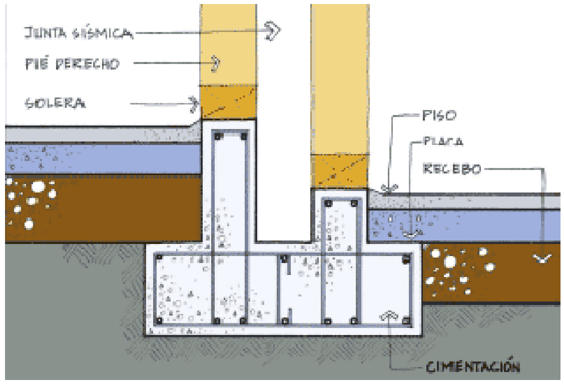


- Where a series of houses of different materials are closely built, seismic joints must be incorporated between each independent structure
- Sufficient separation can be determined by the following, with an average j of 15-20 (mm/m)

$$j \times altura\ al\ caballete = 15\frac{mm}{m} \times 3{,}5\ m = 52{,}5\ mm$$

- Seismic joints should also be applied in bahareque constructions with shaded walls (3 times its length).

- Constructions that are separated by seismic joints can have shared foundations, but they must become separate above ground level so each structure can act independently.



[Excerpt translated from Colombian Association of Antiseismic Construction Guidelines with Bamboo Construction, 2001].

G. BAMBOO ANATOMY

In order to fully grasp the implications of using a “prefabricated” organic material for construction purposes it is necessary to understand the different components that give bamboo its shape and resilience.

ROOTS and RHIZOMES:

a-b.(marcelovillegas.com,2010), c. Root System Seen in the Phyllostachys Genus (completebamboo.com/bamboo_behaviors.html,2010)

Even though bamboo has quite a large variety of species, they can all be classified into to types of root systems: running or clumping type. The main distinction lies in how widely the giant grass can spread through its root system.

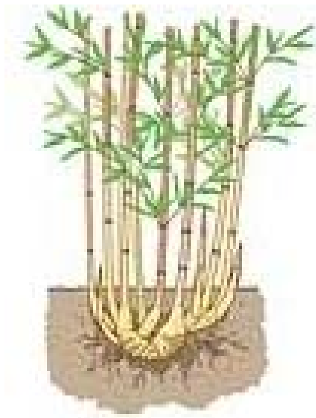
"RUNNING" type:

This type is primarily found in temperate climates or in the high mountains of the tropics. The root system is a long horizontal shoot that can spread quite effortlessly and is in fact quite hard to limit growth.

RUNNER: Giant Running Bamboos (galagarden.com/bamboo-multitalented-macken.html, 2010).

”CLUMPING“ type:

In contrast the clumping type of bamboo variety is more restricted in spread and tends to produce larger diameter culms with thicker-walls which are usually better for construction purposes. The rhizomes for these varieties are quite short, therefore the bamboo plant stays contained in a clump (Adams, 1998).




CLUMPPER: Bambusa multiplex. (Photo: KENPEI completebamboo.com/bamboo_behaviors.html, 2010).

CULMS + BRANCHES:


a. Moso Bamboo Culms and branches (completebamboo.com/bamboo_behaviors.html, 2010).

LEAVES + FLOWERS:



a. Bamboo leaves (Photo:E. Silversmith) b. Close up of a Bamboo Flower (Photo: M.Engelund) c. Mass bamboo flowering. (Photo: Joi Ito)

Bamboo reproduces mostly from its rhizomes, however sporadic flowering will occur, when some of the plants bloom. Blossoming tends to occur in cycles of 10-145 years, which largely depends on the species. After flowering occurs, the existing culms die off, which could threaten those dependent on a constant supply of culms (Hidalgo,2003).

H. NATURAL DURABILITY/ PRESERVATION

Since Bamboo is an organic material much care should be taken in order to maintain its durability and increase its longevity. Although bamboo fibers are vulnerable to the environment, insects, and mold, its susceptibility can be largely reduced by proper conservation, treatment, and curing. In fact, many farmers have speculated that even the point when a bamboo culm is cut from the grove must be taken into account. It is believed that harvesting bamboo should take place during full moon and before sunrise, when the starch content of the culms is at its lowest
This becomes of prime importance since there is a strong relationship between insect attacks, humidity, and starch content of bamboo culms.

Therefore, after harvesting, curing and drying processes are essential to protect bamboo against rot and insect attacks. One method is to spot cure bamboo while its left standing cut on a stone for a period of a month alongside living culms. The leaves must be left on the culm in order for them to continue removing the remaining starch from the walls. If air curing is employed however, it is best to leave the bamboo in a vertical position since its drying out time is reduced by half. Curing by immersion is another method of reducing starch, where the culms are soaked in water for up to four weeks and are then soaked in fumes of caustic soda solution. Overall, one of the most effective methods thus far for treating bamboo is to force a solution of 3-10% of half borax and half boric acid through the culm by using an air compressor creating 20-30 lb of pressure. While leaving the culm on a slight incline with the base closest to the tank the chemicals gradually move through the vascular system (Adams,1998).

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