Una reunión educativa con el bambu
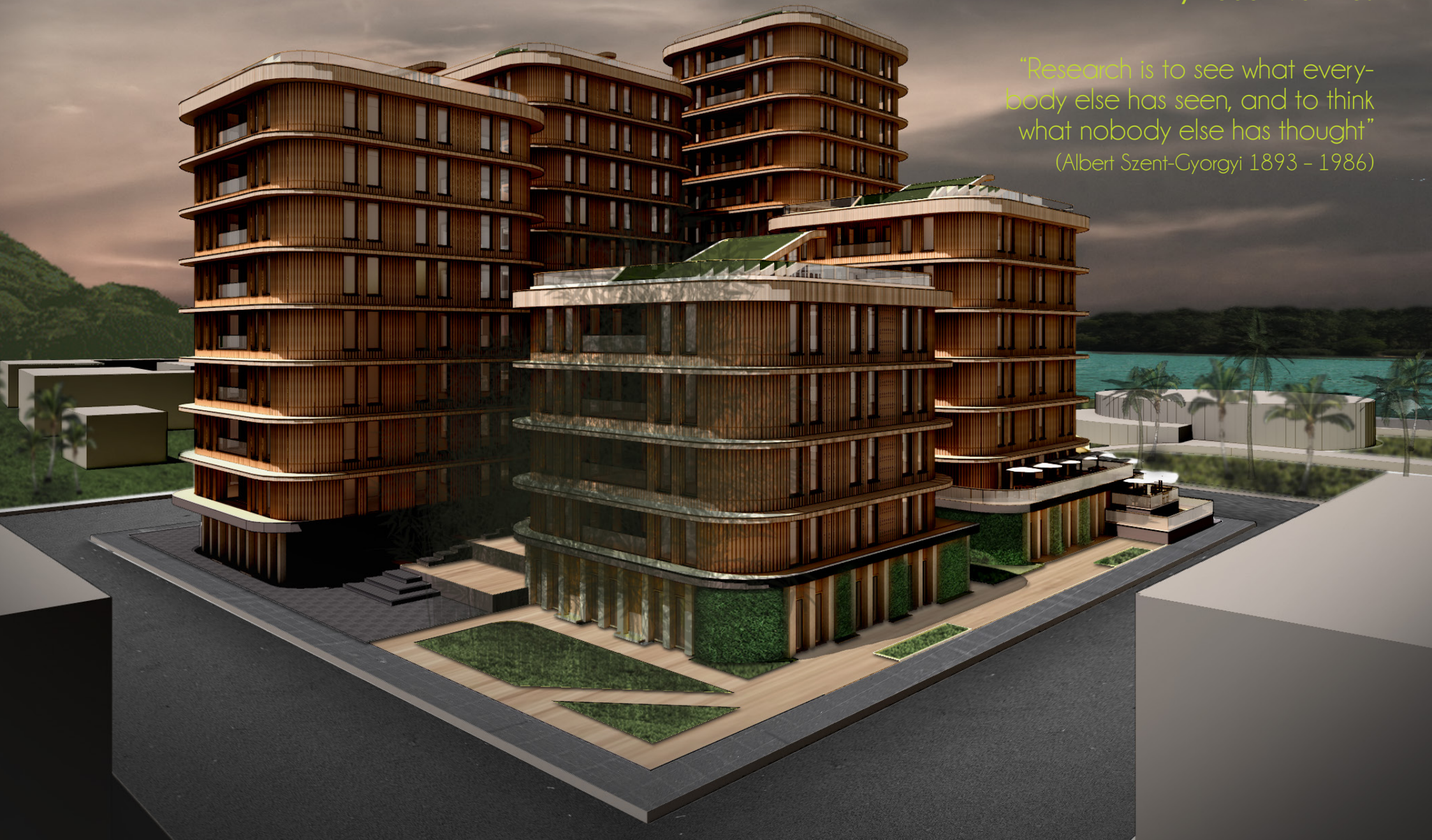
By Robert-Jan Vos
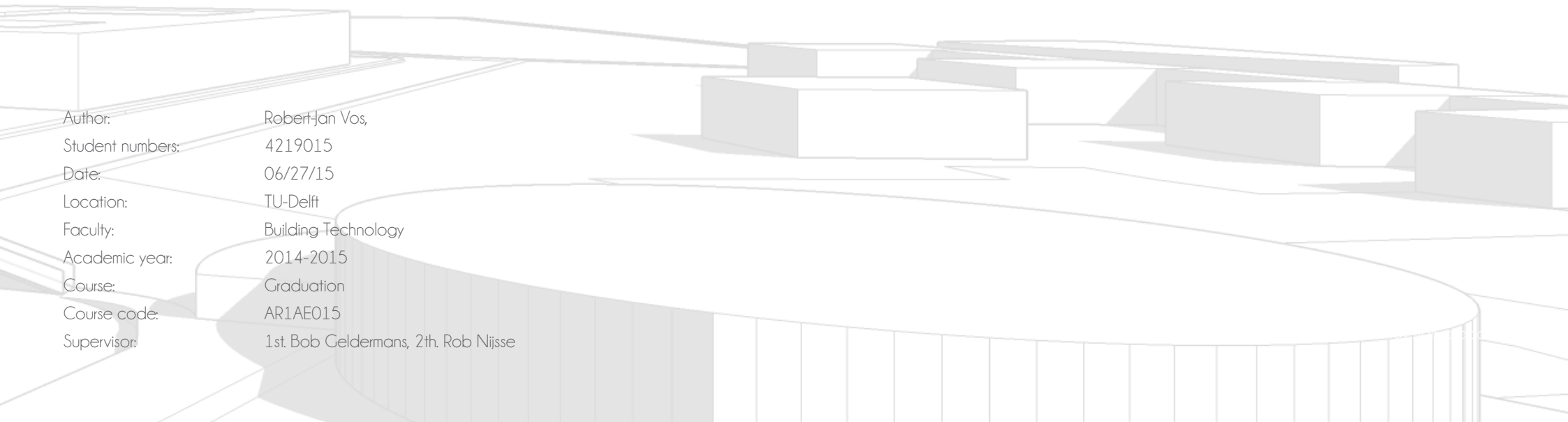
"Research is to see what every-body else has seen, and to think what nobody else has thought"
(Albert Szent-Gyorgyi 1893 – 1986)

"Utilizing today's technology to improve the way we use bamboo as a building material is a way to begin to adopt it into our sustainable way of living"

(S. Rittironk & M. Elnieiri, 2008)

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1.1.   Proem

This thesis has been written as part of the MS4: "Sustainable Design Graduation Project" at Delft University of Technology (TuDelft) within Building Technology graduation studio in the Faculty of Architecture. The aim of this thesis is to research about laminated bamboo, its structural possibilities; to finally propose a design that takes in account a specific urban context. The goal of the design is to show a sustainable solution that could replace mid rise concrete buildings in Ecuador, which is a developing country located South America. The goal of the report is to map the possibilities, the obstructions and the solutions regarding laminated bamboo and its context. The thesis was written in the two semesters of the Sustainable Design Graduation Project. And from the second semester onward the design has started to run parallel with the thesis.

Readers who are interested in the in current state of the bamboo industry and Ecuador are advised to read chapter 3: "*Context*", 4: "*Ecuador*" and 6: "*Bamboo industry*". For those interested in the precedent analysis should have a look at chapter 5: "*Wood industry*". People interested in the structure and material behavior are suggested to read chapter 7: "*Mechanical properties*", chapter 8: "*Other Technical*" and chapter 10: "*Physical testing*". If interested in the impact of the structure of the building and the impact of the structural industry chapter 9: "*Sustainability*" could inform you. If interested in the conclusions, limitations and the suggestions towards further steps chapters 11: "Conclusion" and 12 "Recommendations" should be consulted. To find the source of the images and tables used or on which the images is based on the sub chapter 13.2: Images and 13.3: Tables would provide clarity.

I would like to give my thanks to: Ir. Bob Geldermans, for his support, guidance and ideas. To Dr. ir. Fred Veer, Sebastian Costa, Stalin Armijos, Jos Vos and Gerard Warrens for trying to help me obtain the material and Dr. ir. Fred Veer for helping me test the materials. My thanks goes also to words MSc Arjan ven der Vegte and MSc Luke Schuette for their support and knowledge. For all structural guidence my gradutide goes to prof. ir. Rob Neijsen and ir. Hans Daane.

Robert-Jan Vos

Delft 25-06-2015

Table of Contents

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Abbreviations

ASTM	American society for testing materials
C2C	Cradle to Cradle
C2G	Cradle to Gate
C2S	Cradle to Site
CBI	Centre for the Promotion of Imports from developing countries of the Netherlands
CFC	Common fund for commodities
CIA	Central Intelligence Agency
CLT	Cross Laminated Timber
CO2	Carbon Dioxide (greenhouse gas)
CV	Characteristic value
dB	Decibel
EU	European Union
EOL	End of life
GDP	Gross domestic product
GLB	Glue laminated bamboo
GTZ	The Deutsche Gesellschaft für Technische Zusammenarbeit (German Development Organization)
ha	Hectare
Hz	Hertz
IIC	Impact sound insulation class (Canadian/USA sound isolation class)
INBAR	International Network of Bamboo and Rattan
ISO	International Organization for Standardization and its standards.
kg	Kilogram
LBL	Laminated Bamboo Lumber
LCA	Life Cycle Analysis
LSL	Laminated strand Lumber
LVB	Laminated Veneer Bamboo
LVL	Laminated Veneer Lumber
MC	Moisture Content
m	Meter
MDF	Medium densified Fiberboard
MJ	Mega joules
MPa	Mega pascal the corresponding with N/mm². Says something of force applied on a area.
MOE	Modulus of elasticity (resistance to being deformed elastically)
MOR	Modulus of rupture (bending strength)
NZ	New Zealand
P4	Presentation go/no go face
P5	Final presentation of master thesis
PF	Phenol formaldehyde (Adhesive)
PU	Polyurethane (Adhesive)
SD	Standard diviation
SENA	El Servicio Nacional de Aprendizaje (The National Training Service of Colombia)

SGR	Stress gravity ratio expressed in σ_{rep}
SRI	Solar radiation index
STC	Sound transmission class (Canadian/USA sound isolation class)
UF	Urea formaldehyde (Adhesive)
US	United States
USD	United States dollars ($)

Definitions

Anisotropic materials. Are materials that have different properties along different axes.

Agroforestry — A form of land use management in which trees grow around or in between pasture land.

Basa — The middle part of a bamboo culm in the case of Guadua roughly the part between 5 and 10m of the culm.

Bending strength — Material property about the amount of stress per area a material can have before failure (MPa).

Caramelized — Durability treatment of bamboo using heat treatment with steam to caramelize the sugar molecules in the bamboo.

Carbonized — Durability treatment of bamboo using a lengthy heat treatment with steam, resulting in very durable bamboo, but also a weakened bamboo.

Cepa — Capa is the bottom part of the bamboo the first 5 to 7m of a culm.

Carbon foot print — The amount of greenhouse gases emitted.

Carcinogens — Anything that is a direct agent causing cancer

Char — A chemical process of incomplete combustion leaving a residue called char.

Char rate — The speed in which char is created relating to time, material properties and fire properties

Characteristic value — The value corresponding with the probability were only 5% of the material scores under a certain value, and needed for calculations.

Compressive strength — Material property about how much force per area is needed before a material fails (MPa).

Creep — Phenomenon of permanent deformation over time.

Critical radiant flux — How much energy is needed to ignite a material (W/cm^2)

Culm — The main shaft of the bamboo grass and the equivalent of a trunk of a tree.

Deformation — The displacement of an object under a force given in (mm).

Density — Material property abut the mass per unit volume of a substance (kg/m^3).

Eco-cost — The real cost of a material per unit when one has to pay for the damage done to the ecosystem.

Edge grain — The grain of wood/bamboo seen on the surface of a plate when it is cut parallel the fiber direction.

End grain — The grain of wood/bamboo seen when it is cut parallel the fiber direction.

Energy dissipater — device that absorbs the energy during earthquakes.

Face grain — The grain of wood/bamboo seen when it is cut perpendicular to the fiber direction.

Fiber sheaths — Hollow tubes in the culm tissue providing serving as transportation canals for the sap of the bamboo

Flame spread rate — How fast flames spread by a material, if material needs a low amount of energy the flame spread rate is hight.

Flexural strength — Bending strength also known as modules of rapture (MOR) (MPa)

Giant bamboo — Common name for the bamboo spices with the botanic name Dendrocalamus Asper.

Grain — Term used to clarify in which direction the (main) fibers/vascular bundles run.

Guadua — Bamboo family from South America in construction referring to Guadua Angustifolia Kunth.

Guayaquil — Largest city of Ecuador and one of the biggest ports of the South American pacific.

Glubam — Trade name from China for laminated Moso bamboo.

Glulam — A way of laminating small timber strips in a bigger timber product.

Internode — Part of the culm between the nodes (hollow tubes).

Parenchyma — Weaker and softer cells with thin primary walls remaining alive after plant is mature forming the stuffing between the vascular bundles.

Heavy timber — Describes a timber construction that is at least 2hours fire resistant. Other names used are mass timber and massive timber.

Land-use — The amount land used in the growing face of a regrow able material.

kgCO2 — Unit: of the carbon dioxide emissions.

kgCO2e/kg — Unit: of all greenhouse gases converted to carbon dioxide.

Köppen-Geiger system — A system developed to classify climates.

Lamboo — Trade name/company from US for laminated bamboo.

Las Peñas — Famous hill in Ecuador full with closes packed colorful houses.

Malecón 2000 — Park along the Rio Guayas in Guayaquil, Ecuador.

Malecón Simón Bolivar — Main street in Guayaquil on which the project is located.

Mean — Average values, statistically calculated.

Moment of Inertia — The resistance of a object regarding the rotational acceleration in a axis.

Moso — Trade name/company from the Netherlands dealing in laminated bamboo.

Moso — Is also a bamboo species from china with the botanic name Phyllostachys edulis.

Node — The place were the diaphragm separates the hollow segments of the internodes and were the branches and leaves connect to the outside of the culm.

Periphery — Outer part of the culm wall. Structurally the strongest part.

Physical realm — The world build up out of particles and objects.

Planing — Normally the final step of a (half) product were the beam is sanded to exactly give the right dimensions.

Plantation yield rate — The amount in cubic meter of processed wood/bamboo a plantation offers translated to an annual figure.

Pres-lam — Type of building structure made from pre compressed laminated LVL

Rolling shear — The shear stress resulting in shear strains in the plain perpendicular to the grain direction.

Scrimber — Type of engineered bamboo were culms are split open and pressed together.

Shear strength — Material property referring to the resistants of a material parallel to the internal surfaces (MPa).

Skyscraper — A building of more than 10 stories.

Social interaction — An exchange (verbal and non-verbal) between different individuals (between two people but also large groups).

Spline — Internal connector of the floor elements

Strand woven bamboo — Type of engineered bamboo were not the strips are glued together, but the fibers also known as high density bamboo or extreme density bamboo.

Strip — Half product after the culm is split strips are obtained, and are the base of LVB.

TCC — Timber concrete composite.

Timber — A sawn or engineered product (normally wood based). The term "timber" is also known as lumber.

Tensile strength — Material property about how much force can be applied pulling on the material before it brakes.

Ultimate strength — Maximum stress that a material can withstand before failure.

Vascular bundles — The fibers in the bamboo providing the strength in the material.

A	Area (mm).
d_{char}	Char depth (mm).
d_V	Static deflection calculation in vibration formula's (mm).
D	Depth cross section at the start (mm).
D_{char}	Remaining cross section after charing (mm).
D_{fire}	Depth of remaining effective cross-section (mm).
E	Elasticity modules of an object also referred to as MOE or E-modules (MPa).
$EI^{1,m}_{eff}$	Effective apparent stiffness in the span direction for 1 m wide panel in (N-m²).
Ey	Elasticity modules in the y direction (parallel to the grain) (MPa).
Ex	Elasticity modules in the x direction (perpendicular to the grain) (MPa).
f_v	Fundamental natural frequency in vibration formula's (Hz).
F	Force (kN).
F1	Absolute Force measured in the first point chosen for the ΔF (N).
F2	Absolute Force measured in the second point chosen for the ΔF (N).
F_{max}	Maximum force applied before failure (N).
g	the gravitational force on a object (kN) .
h_{max}	Maximum height possible according the SGR formula (m).
H	Height (m).
I	Moment of inertia (mm⁴).
I_p	Polar moment of inertia (mm⁴).
K	Column effective length factor.
K_b	Stiffness of the pin.
K_{def}	Deformation modification factor.
K_{ox}	Charing rate factor in case of sufficient oxygen.
K_r	Stiffness of the connection.
K_s	Stiffness of an object..
L	Length (mm).
L1	Distance of load from nearest support (mm).
$L_{h.o.h.}$	Length between supports (mm).
M	Moment (Nmm or kNm).
M_{eq}	Moment caused by earthquakes (kNm).
n	Number or population.
P	Deformation measured (mm).
q	Line load (can be wind or other loads).
q_n	The test-average total heat flux (W/m²),
q_w	Wind factor .
r	Radius (mm).
R_v	Reaction force support (kN or N).
t	Time (min).
$U_{fin,P}$	Final deformation by permanent loads (mm).
$U_{fin,Q,1}$	Final deformation by main live loads (mm).
$U_{fin,Q,1}$	Final deformation by accompanying live loads (mm).
$U_{inst,P}$	Instant deformation by permanent loads (mm)..

$U_{inst,Q,1}$	Instant deformation by main live loads (mm).
$U_{inst,Q,1}$	Instant deformation by accompanying live loads (mm).
U_{fin}	Total deformation including creep (mm).
V_s	Shear force (kNm or Nmm).
V_d	Deflection(mm).
V1	Absolute deformation measured n the first point chosen for the ΔP (N).
V2	Absolute deformation measured in the second point chosen for the ΔP (N).
w	Width (mm or m).
W	Section modules (mm³).
W_c	Deformation at center point between two supports (mm).
W_{tot}	Total deformation at center point between two supports (mm).
W_{max}	Maximum allowable deformation (mm).
x	Variable
Xi	Observations
$\underline{X}$	Seismic hazard factor.
$\overline{X}$	Average divided by the mean
Y_g	Force corresponding to the weight of the building (kN).
$	Dollar: American currency also used in Ecuador.
€	Euro: currency shared by many countries in Europe.
%	Percentage
β	Beta: Char rate (mm/min)
$β_{eff}$	Effective charring rate (cm/hour)
Δ	Delta: average of values.
ΔF	Average of force applied.
ΔP	Average of deformation.
$ε_φ$	Epsilon: Creep.
$ε_{be}$	Epsilon: Elastic deformation.
Θ	Theta: Drift
μ	Mu: Mean of population
π	Pi: +/- 3.14.
ρ	Density (kN/M³)
σ	Sigma: Stress.
$σ_m$	Stress caused by bending
$σ_{m,max}$	Maximum stress caused by bending also known as maximum bending strength.
$σ_{rep}$	Maximum allowable stress in user face (kN/m³).
$σ_{SD}$	Sigma: standard deviation.
$σ_{\overline{x}}$	Standard error of the mean
Σ	Sigma: Summation of values.
τ	Tau: Shearing force (N/mm²).
φ	Phi: Creep coefficient.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

1.Framework
1.1.   Introduction

Laminated bamboo, as structural component, is on a breakthrough point. In fact, there has been developed a good amount of research from different areas around the world (USA, China, Colombia, Europe) regarding laminated bamboo, and even a few houses, bridges and other structures are been built. However, it doesn't show all the capabilities of the material. Therefore, the constructing world, and especially, bamboo producing countries still have to acknowledge laminated bamboo as a structural material of equal (if not better) quality than concrete or steel.

Nowadays, it is considered as a poor man's timber. People in developing countries need to start regarding laminated bamboo as a proper building and structural material. Therefore, one of the aims of this thesis is to design a multiple floored building to show the structural and sustainable solutions and possibilities of laminated Guadua bamboo.

In general, the bamboo industry needs more investments and people believing in the product. A high-rise building could have a similar impact as the Eiffel tower had for the steel industry over 100 years ago. It could give a tremendous economic boost to developing countries that have extensive amounts of bamboo available.

Besides, bamboo is also considered as a very sustainable material if it is used in its local context. It could lead to replacing current steel/concrete buildings and replace hardwood applications, reducing land-use, carbon emissions and saving the rainforest.

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

1.2.   Problem, objective and research questions

Problem

Main problem
"Laminated Guadua bamboo could be a sustainable structural solution for multiple floor residential building in Ecuador, but it is regarded unsuited."

Subproblems
- It is unclear how far the laminated bamboo industry has been developed in order to build a multi floor building.
- Nobody knows how to solve technical and structural problems regarding a laminated Guadua building of more than three floors.
- Bamboo has a poor reputation
- It is unclear how sustainable laminated Guadua can be.

Hypotheses about the causes of the problems
- Bamboo is not part of the mainstream building materials, but it is getting closer. However, many people are still unaware about it.
- Nobody knows how to solve the technical and structural problems yet due to the fact that the industry is still young. Firstly, it tries to get a foothold in low rise applications.
- Bamboo is not accepted because of poor handling. It is not from the western world and, in general, the poorest people in the world live in bamboo houses.
- In general, trustworthy information about bamboo is hard to find because many people are not aware of the vast amount of differences between different types of bamboo. Statements are made often in the name of bamboo, but most of the information sources does not explain which type of bamboo or uses different names for the same type of bamboo.

Objective

Designing a multiple floor residential building in Guayaquil, Ecuador. Thus, showing the structural and sustainable possibilities and possible consequences of laminated Guadua Bamboo.

Sub objectives
- Creating an overview of the current status of the market: what products are available? Where are the products from and what is the legislation regarding bamboo?
- Creating an overview of the decisive structural and technical limitations of a residential building with multiple floors using laminated Guadua bamboo and finding out how high a building with structural laminated Guadua can be.
- Creating a building with structural laminated bamboo that improves the image of laminated Guadua bamboo by showing its possibilities, but at the same time accomplishes to the expectation of multiple floor buildings.
- By using the three spheres of sustainability showing the sustainability of the building and comparing the building to similar sized buildings from other materials and compare their environmental performance.

Final products
A report containing information regarding objectives.
Overview of market analyses.
Overview of structural limitations.
A report regarding the sustainability aspects
Technical drawings
Hand calculations for structure
Hand calculations for fire safety
A scaled model.

Hypotheses about the direction of solutions
It will be most likely be heading towards a tower ranging between 20 and 70 meters, depending on the choice to go, either for a full lamboo building or for a hybrid structure. At this moment the preference is for a building between 40 and 70 meters which would result in a hybrid building.

Main research question:

"How to design a residential building (complex) of multiple floors in Guayaquil, Ecuador, showcasing structural and sustainable possibilities and consequences of laminated Guadua bamboo?"

Sub Questions

- Is the world, and especially Ecuador capable of building a laminated Guadua multi floor buildings? In other words: Is the world ready?
- What are the decisive structural and technical limitations of a residential building with multiple floors in Laminated Guadua bamboo and how high the building can be according to those limitations. In other words: Can it be done?
- How to create a building that shows the possibilities of laminated bamboo, but at the same time complies with the current expectations of a building. In other words: How could it look like (and be excepted)?
- In what way does it contribute to the three spheres of sustainability and how does the building preform compared to similar sized buildings regarding environment. In other words: Is it sustainable?

Figure:2. The four pillars of the thesis

1.3.   Boundary conditions

Context
- City center Guayaquil.
- High-end-users.
- Showing laminated bamboo in the building.
- A residential building.
- Climate smart design.
- Guadua laminated bamboo for structure.

Structural
- Basic calculation will be made. No fem analysis.
- Focus on lateral forces and overall system.
- Earthquakes will not be calculated but the general structural proposal will be earthquake aware..
- Lamboo will be used as structural laminated bamboo.
- No calculations regarding Incidental imparts.
- Structure needs to be demountable

Physical

- Floor plan will have a simple geometric form.
- Height weight ration at least 1:1.
- Building will be between 20-50m high.
- Focus will be on Sustainability and Structure, not architectural layout of the apartments.
- No more than basic hand calculation regarding fire performance.
- No more than basic hand calculation regarding sound
- Details will be designed, with a focus on structure.

Sustainability
- Effects of bamboo on the three spheres will only be by literature.
- Land use will be compared to Canadian pine.
- Eco-cost, energy and greenhouse emission calculated with the C2G+C2C.
- Main structural materials used have to be local and "sustainable".
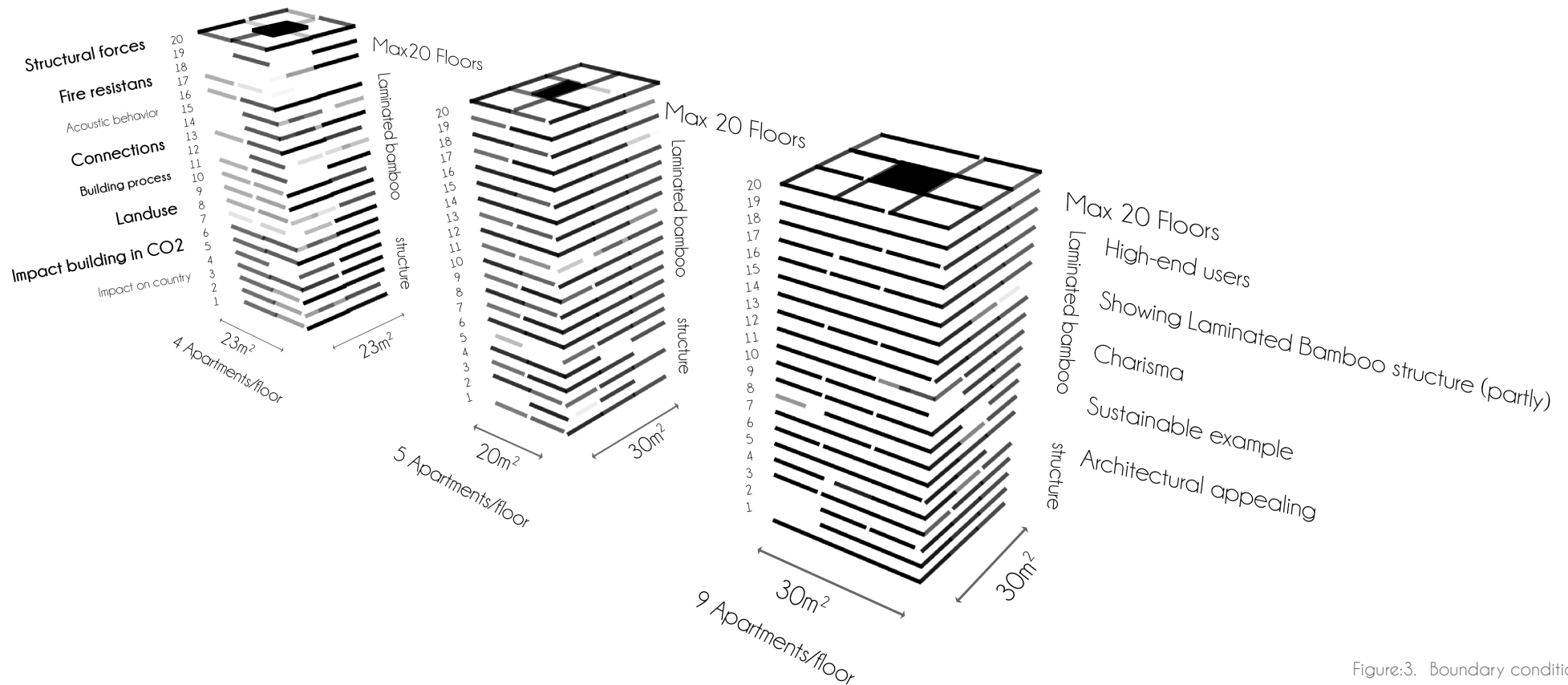- Impact of formaldehyde investigated.

Figure:3. Boundary conditions

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Boundary conditions

Importance of boundary conditions

Not every boundary condition has the same importance. The most important ones for each topic (context, structural, physical and sustainable) will be discussed and explained.

Context.
Regarding context connecting to the surrounding is the most important boundary condition. A sustainable and good design has a strong connection to the surroundings. The second was climate design. A building should always be designed regarding its local context to be sustainable. The point of the thesis is to show a sustainable material, it would not make sense to do this in a unsustainable glass box design with an external structure exposed to the elements.

Structural
Regarding the structural boundary conditions it was essential to find a structural system suitable for laminated Guadua bamboo from Lamboo which could deal with earthquakes. Although solutions will not be completely calculated, system choices are to be made on references using earthquake proof principles. Besides this the second most important aspect is to create a demountable structure. To enhance sustainability, but it also eliminates many options.

Physics
Physically the most important factor is on the structural system and sustainable impact of the structure. Because of the scale of the project and the amount of time available, floor-plans and facade solutions will be generated to give an impression, but are not fully developed and just rough proposals. For the design proposal the width vs. height is also important. For esthetically reasons the design should be oriented vertically, not horizontally

Sustainability
In sustainability all boundary conditions are almost equally important, but with an emphasis on the C2G and C2C.

1.4. Method and Approach

To be able to meet the deadlines a strategy is needed. For that a method has to be used. This paragraph describes the method. At the beginning of the project the problem will be determined and the initial objectives will be set. The research question has been stated to be able to reach those objects.

In the first face the context, the sustainability, the market and the values for the mechanical properties will be investigated. An intensive literature study will be conducted and an overview will be created. This will result in conclusions, regarding the feasibility, prospects and the impact on the three spheres of sustainability.

The next step will be to translate the research into simple basic calculations to determine the bottlenecks per structure type to find out how high a laminated bamboo building can be in the basics. This will be based on literature and estimations. The results will be compared to each other (the objectives, context and environmental impact).

Afterwards one system will be selected and a basic design in the system will be made to show the possibilities in Laminated Guadua. For this system, basic hand calculations will be made for the structural, fire, sound and environmental performance of the building.
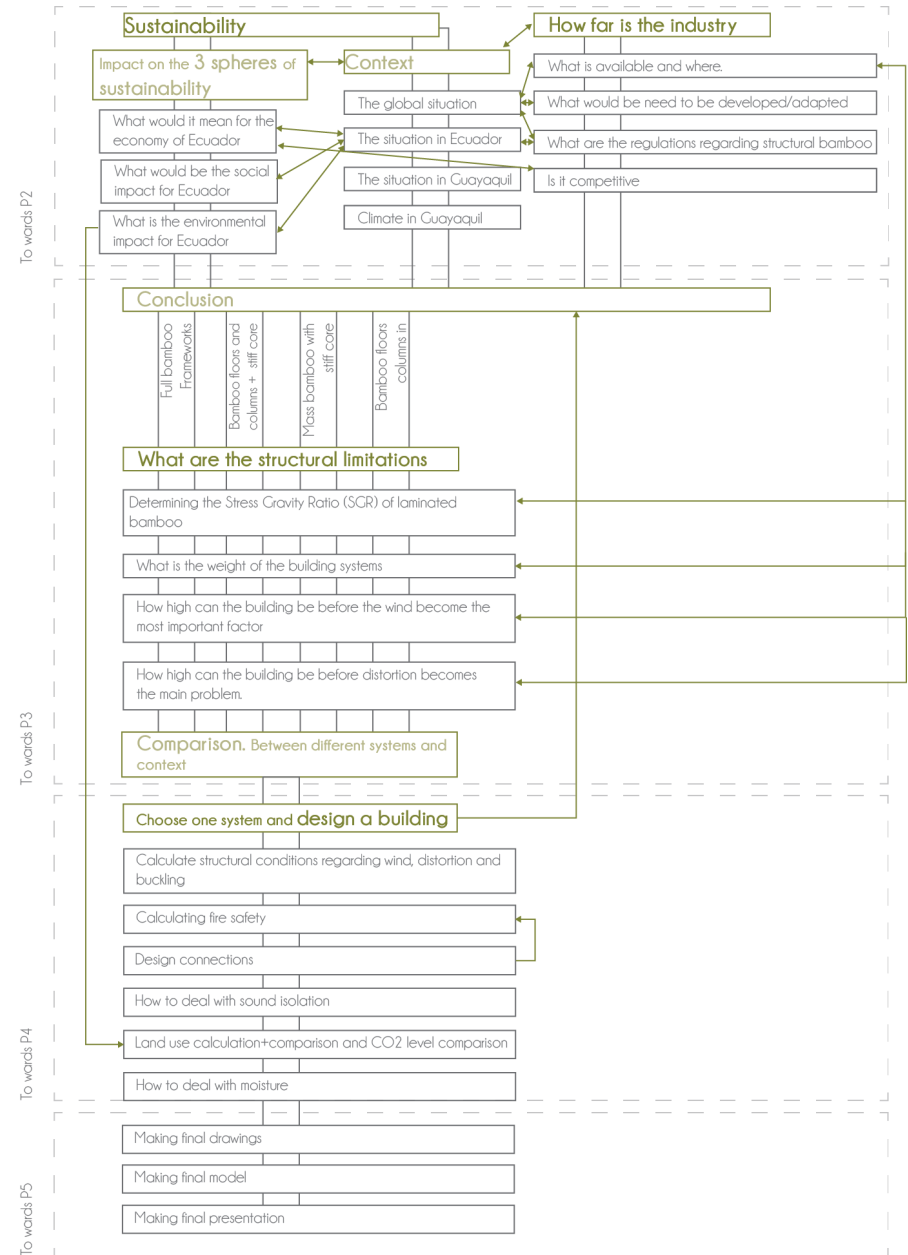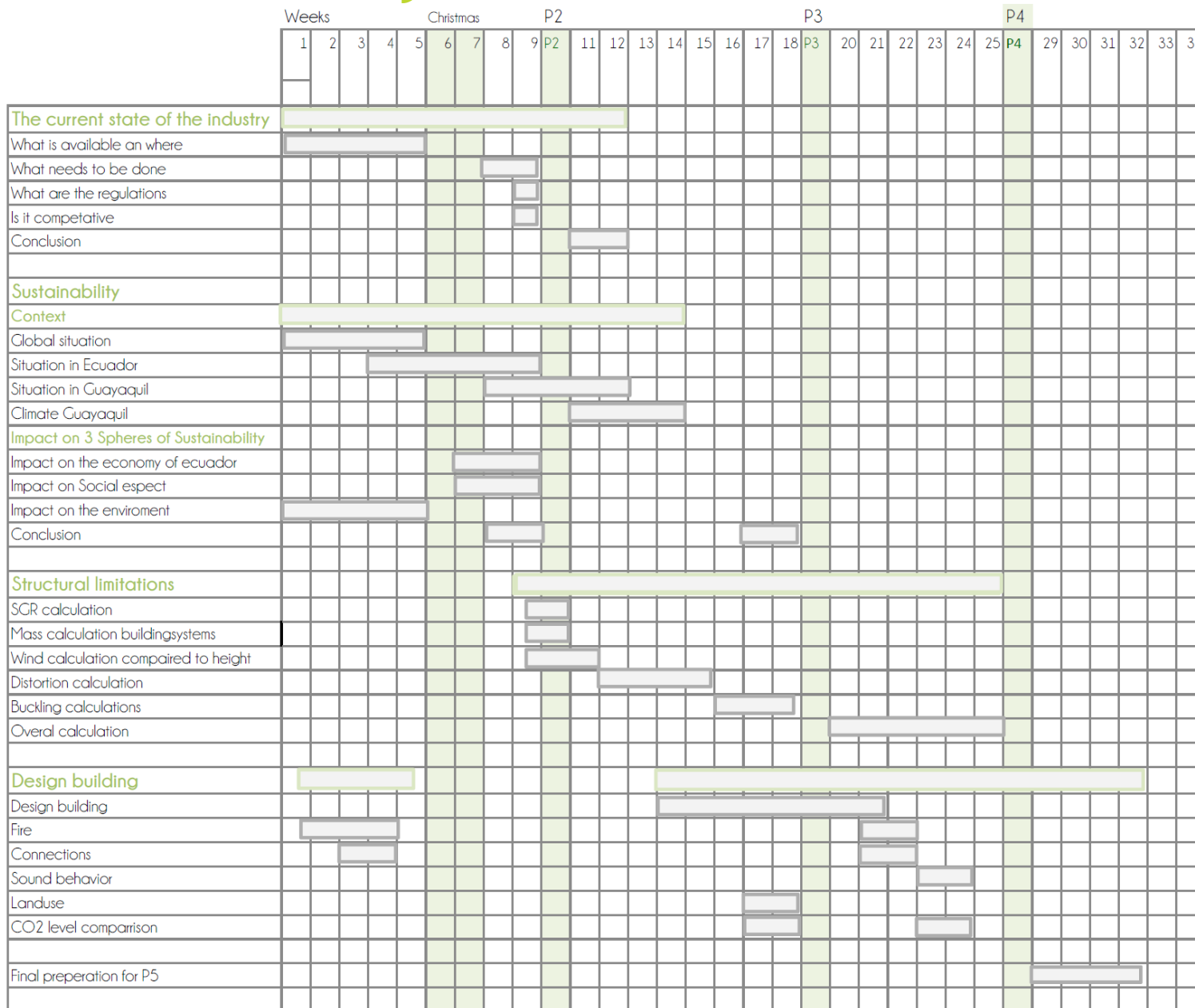

Sustainability

Impact on the 3 spheres of sustainability

Context

How far is the industry

What is available and where.

The global situation

What would be need to be developed/adapted

What would it mean for the economy of Ecuador

The situation in Ecuador

What are the regulations regarding structural bamboo

What would be the social impact for Ecuador

The situation in Guayaquil

Is it competitive

What is the environmental impact for Ecuador

Climate in Guayaquil

Conclusion

Full bamboo Frameworks

Bamboo floors and columns + stiff core

Mass bamboo with stiff core

Bamboo floors columns in

What are the structural limitations

Determining the Stress Gravity Ratio (SGR) of laminated bamboo

What is the weight of the building systems

How high can the building be before the wind become the most important factor

How high can the building be before distortion becomes the main problem.

Comparison. Between different systems and context

Choose one system and design a building

Calculate structural conditions regarding wind, distortion and buckling

Calculating fire safety

Design connections

How to deal with sound isolation

Land use calculation+comparison and CO2 level comparison

How to deal with moisture

Making final drawings

Making final model

Making final presentation

To wards P2

To wards P3

To wards P4

To wards P5

Figure:4. Method and Approach

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

1.5. Planning

This strategy has been translated in to a planning. The planning is visualized on the right.

Figure:5. Planning

The current state of the industry
- What is available an where
- What needs to be done
- What are the regulations
- Is it competative
- Conclusion

Sustainability
Context
- Global situation
- Situation in Ecuador
- Situation in Guayaquil
- Climate Guayaquil

Impact on 3 Spheres of Sustainability
- Impact on the economy of ecuador
- Impact on Social espect
- Impact on the enviroment
- Conclusion

Structural limitations
- SGR calculation
- Mass calculation buildingsystems
- Wind calculation compaired to height
- Distortion calculation
- Buckling calculations
- Overal calculation

Design building
- Design building
- Fire
- Connections
- Sound behavior
- Landuse
- CO2 level comparrison

Final preperation for P5

2. Motivation

"The Future Depends on what we do in the Present" (Mahatma Gandhi 1869-1948)

Figure:6.   Gandhi

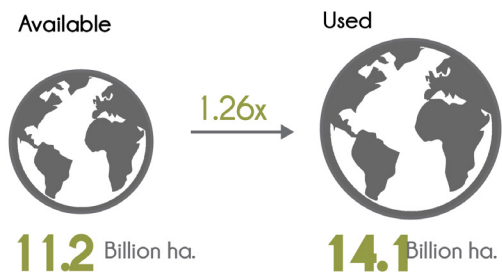How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

2.1. Why Bamboo

Social
Standard of living
Equal Oppertunity
Communication
Education

Economic
Economic growth
Cost saving
Profit

Bamboo
=
Sustainability

Environmental
Environmental management
Use of natural resource
Pollution prevention

Figure:7. The 3 spheres of sustainability

World population

2000

1.45x

2050

6.1 Billion

8.9 Billion

Ecological Footprint (Annually 2003)

Available

1.26x

Used

11.2 Billion ha.

14.1 Billion ha.

Market (Millions US $)

18000
16000
14000
12000
1000
8000
6000
4000
2000
0

US $ 16.8 Billion

Other
Panels

Flooring   45%

Laminated Furniture

Traditional Furniture

Chopsticks
Bamboo shoots

Blinds   55%

Handicrafts

US $ 6.8 Billion

Other   5%
Traditional Furniture

Chopsticks
Bamboo shoots

Blinds   95%
Handicrafts

Zero growth of Global market in
2017 (equal to 2007)

Mid-level growth
Global market in 2017

Growth scenario
Bamboo sector

Figure:8. Bamboo prospects

(De)Forestation

Annual

2,15x

Surface NL

7,3 Million ha.

3,4 Million ha.

Plantation yield rate

Bamboo

4x

Canadian pine

15 m³/ha annual

3.55 m³/ha annual

Figure:9. Why bamboo

Why should people build with an unknown material such as bamboo? This chapter will explain why people should consider building with bamboo.

The global world population is on the rise, growing from 6,1 billion people in 2005 to 8,9 billion people in 2050. The majority of development will occur in the developing world (Economic and Social Affairs 2004). Three billion new houses need to be constructed in the next 20 years, increasing the percentage of people in urban areas from 50% to 75% and in addition, one out of three people living in city's today live in slums and therefore also in need of a better home (Green 2013 July 9). This shift will mainly take place in Africa, Asia Central- and South America to which bamboo is a native building material, providing potentially the most sustainable material while at the same time offering an opportunity to develop their industry, increasing independency of the developed world. In 2007 several scenarios were developed for the global bamboo sector. Mid-level growth could mean an increase from $6,8 billion in 2007 to $16,8 billion in 2017 as the image: "*Bamboo prospects*" shows. The main improvement is in high end products, which need extensive processing, like flooring, laminated furniture and panels (Marsh and Smith 2007).

Main reasons for deforestation in Ecuador are agricultural expansion, demand for hardwood and oil (of which vast amounts are used in the steel and concrete industry) (Zambrano-Barragán 2010). Bamboo could replace steel and concrete and therefore reduce the CO2 emissions and the need for oil. Laminated bamboo can also reduce the demand for hardwood since it mechanical properties are comparable. Bamboo is a renewable material with an exceedingly yield rate, outgrowing softwoods even after processing (Flander and Rovers 2009), see image: "*Why bamboo*", this could help stopping deforestation. It is even used to counter deforestation since it grows almost anywhere and improve water management and prevents erosion (INBAR 2014a). The study of Marsh and Smith (2007) shows the potential of engineered bamboo to counter poverty in developing countries. Therefore, bamboo has the potential to add to all three pillars of sustainability (Economy, Social and Environmental).
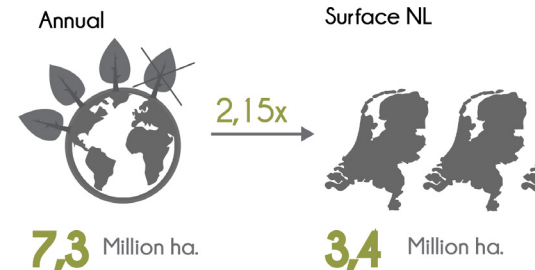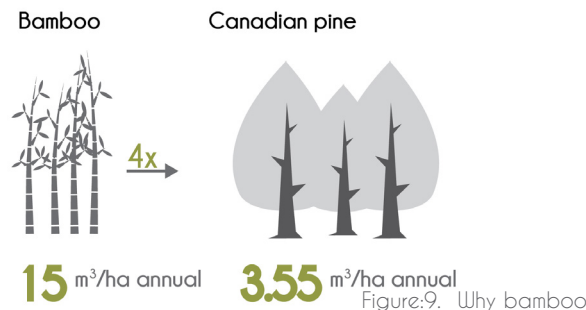
There are around 1500 different types of bamboo, vastly different in characteristics and mechanical properties. This paragraph will explain why Guadua is chosen from 1500 other kinds of bamboo and why it needs to be laminated.

Guadua

This report focuses on Guadua Angustifolia Kunth, in this report referred as Guadua. Guadua is the third tallest bamboo in the world. The tallest is Dendrocalamus giganteus (Schröder 2010, January 23). Guadua is well documented in comparison to many other bamboos. Guadua grows rapidly. It reaches its height in 6 months and needs only 4 to 5 years to mature (Schröder. S, 2012). Its sequestration rate per ha. is twice that of a Fir forest or Moso forest (Yiping, Yanxia et al. 2010) (Moso is a well-documented Chinese bamboo, which is often used in lamination bamboo products). Guadua is the strongest documented bamboo regarding MOR and MOE (Guadua Bamboo n.d. B, de Vos 2010). Guadua is also native to Ecuador (the location of the project).

Laminated Guadua

Raw Guadua can be used as building material and has been used for many years in South America (Takahashi 2006). It is estimated that 1.8 million houses in Ecuador are built with bamboo culms, but its use is limited and has too much the image of a poor man's timber (Flander and Rovers 2009). It has a poor behavior in fire (because its thin wall and shape). Every culm is unique and has imperfections,. Therefore, making proper connections are difficult and time consuming (van der Lugt. 2003), in comparison to wood. Wood can be applied as a log, which can be very sustainable, but economically not feasible on a large scale. To reach the masses and to build higher and higher, logs have been altered by processing them and even laminating them. To reach the masses of the modern world and to help local people to become part of the modern world, bamboo needs to undertake a similar process. The Ecuadorian and South American market in general would profit greatly if the Laminated Guadua industry is developed. High end bamboo products create wealth for the poor, it could strengthen the position of woman in the countries and bamboo has a cultural value (Marsh and Smith 2007). It would help, to a lesser extent, the global market by offering an alternative to the Chinese market providing an even stronger product for the most extreme applications.
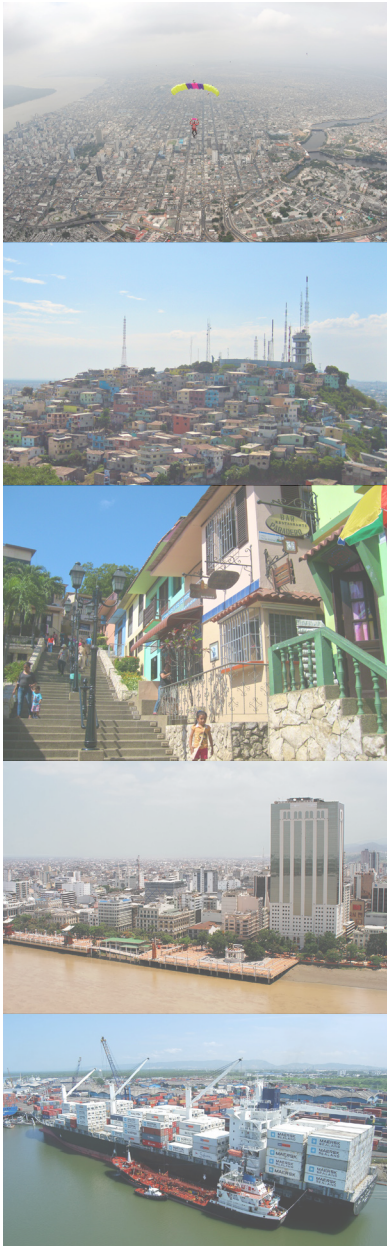

Figure: 10. Glue laminated Guadua (GLG) form Colombia

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

2.3. Why Guayaquil

Figure:12. Pictures of Guayaqyui

COLOMBIA

Esmeraldas

Carchi

Imbabura

Pichincha

Quito

Sucumbios

Manabi

Cotopaxi

Napo

Orellana

Tungurahua

ECUADOR

Los Rios

Guayaquil
Guayas

Chimborazo

Pastaza

Canar

Morona - Santiago

Azuay

El Oro

Zamora -
Chinchipe

Loja

PERU

Figure:11. Location Guayaquil in Ecuador

Climate zones Equador

La Costa (Coastal lowlands)
La Sierra (Andean Mountains)
El Oriente (Amazon Region)
← Galapagos Islands

Housing shortage Ecuafor (2014)	Rural	Urban
Total housing stock	1.357.420	2.391.499
Qualitative housing shortage	480,108 (35.4%)	761.526 (31.8%)
Quantitative housing stock shortage	436.750 (32.3%)	271.051 (11.3%)
Total housing stock shortage	916.858 (67.5%)	1.032.577 (43.2)

(Klaufus and Cedrés Pérez 2014)

Table:1. Housing need Ecuador

Why in Guayaquil? Why Ecuador? This paragraph will give answers to those questions.

Ecuador

Ecuador is a developing country in South America. Existing out of four regions: Costa, Sierra, Oriente and Galapagos Islands. In 2014 it marked it 40st year of civilian governance, but until 2007 Ecuador was considered to be unstable. Nowadays Ecuador is considered stable (CIA 2014) and has an annual growth of 4.5% according to the world data bank (2014). It holds many resources and one of them is Guadua. Guadua has been used in Ecuador for many thousands of years (Takahashi 2006) and slowly Ecuador is discovering the potential of Guadua as a high-end product and starts developing the industry for laminated Guadua. However, the last technical step to be competitive with China still have to be made (Takahashi 2006). Potentially the Bamboo industry of Ecuador and Peru could be worth 100 million USD within 10 years (INBAR 2008). It also could help in the Ecuador's demand for new qualitative housing.

Guayaquil

To develop the bamboo industry Guayaquil plays a key role. Guayaquil is Ecuador's largest city, with a population of 2.279 million (UNdata 2010) and a predicted population of 2,8 million in 2015. Of which 60% lives in poverty (Solano de la Sala 2003). The poor people live in extremely dense low-rise neighborhoods. It is the biggest port of Ecuador and one of the major ports of the Pacific. Guayaquil is also the most industrialized city of the country (Wikipedia 2014b). On top on that, the city is boxed in geographically resulting in a densification of the city, demanding for high rise. Guayaquil has vast amounts of bamboo resources nearby. 60.2% of the houses in Guayaquil are made of bamboo (INBAR 2014b). This is also the bottleneck of developing the bamboo market. The vast majority of the bamboo houses is of poor quality and owned by the poorest people. Ecuadorians see bamboo as a poor man's timber. Living in steel or concrete buildings is seen as a status symbol. The middle class and rich live in unsustainable, energy consuming concrete houses. To become more sustainable peoples view regarding Guadua needs to change and because of Guayaquil strategic position and history it is a good starting point to start changing the mind of the people.

2.4. Why a tall building

According to the best of the authors knowledge there has never been a structure of laminated bamboo of 4 stories or more. This paragraph explains why someone should want to build higher with laminated bamboo.

There are two main reasons. First of all Guayaquil has a significant housing shortage with a surplus in population and substandard housing. However, The city is limited in its expandability, because of its geographical position. On the north-west there are steep mountains, on the southwest and south are the protected mangroves and swamps, in the north is the river Rio Daule and to the east is the river Rio Guayas. That leaves only one possibility and that is up. In downtown, Guayaquil buildings are becoming taller and taller. Ten of the fifteen tallest buildings in Ecuador are located in Guayaquil, ranging between 21 and 33 floors (Wikipedia March 20, 2013).Those buildings are typically built out of concrete. To do it sustainable, it needs an alternative to concrete. Laminated Guadua can be that alternative.

The second reason is because bamboo is suffering from the image being a poor man's timber (only good to make small houses) it potentials are not reached, its industry not developed and a big opportunity to reduce poverty is left unused. Tall buildings have always been a symbol of power, wealth and engineering ingenuity. The economy of Ecuador has more than doubled in the last 7 years. It has grown from $4.68x10^{10}$ in 2006 to $9.45x10^{10}$ in 2013 (world data bank 2014). In the last 9 years, Ecuador has had a growth average of 4.6% annually. A laminated bamboo structure in the form of a tall building could symbol of the new upcoming economy, and while doing that showing the potentials of laminated bamboo and change the mindset of people, resulting in people to accept laminated bamboo as a building material for the 21st century.

The author is aware of the negative impact of tall buildings on the environment. However, this thesis doesn't focus on the difference between low rise and tall buildings, but between tall buildings.

"High-rise buildings have always triggered major debates and aroused emotion. That is hardly surprising, considering that this type of building radiates more symbolic power than almost any other."
(Münchener Rück and Munich Re Group, 1993)

"Building high-rises with bamboo will be building for the rich and wealthy, but creating wealth for the masses." (Robert-Jan Vos 2014)

Top 15 Highest buildings in Ecuador

135m heights building   **10**/15 tallest buildings in Guayaquil

Rank	Name	City	Height	Floors
1	Banco La Previsora	Guayaquil	135m	33
2	Basilica del Sagrado Voto Nacional	Quito	117 m	38
3	Edificio MAGAP	Guayaquil	102 m	28
4	Torres de La Merced	Guayaquil	97 m	27
5	El Forum	Guayaquil	93 m	30
6	San Francisco 300	Guayaquil	86 m	26
7	Finansur	Guayaquil	86 m	25
8	El Fortín	Guayaquil	83 m	27
9	Edificio CFN	Quito	82 m	23
10	Induauto	Guayaquil	81 m	23
11	Consejo Provincial de Pichincha	Quito	80 m	23
12	Torres del Rio	Guayaquil	78 m	21
13	Huancavica	Guayaquil	77 m	23
14	Hilton Colon Quito Hotel	Quito	75 m	21
15	Edificio El Tiburón	Salinas	74 m	23

Source: http://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Ecuador
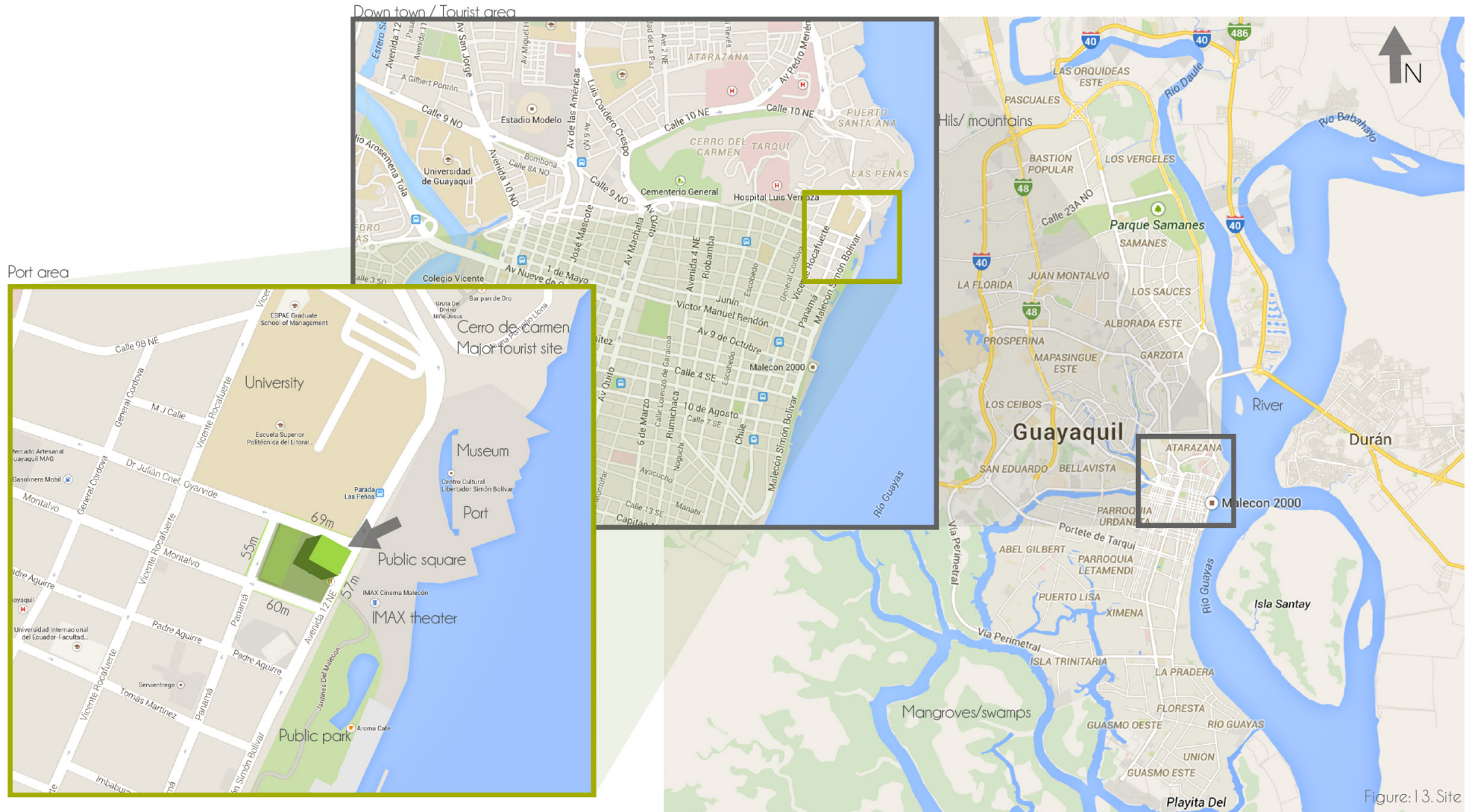
Table:2. Top 15 highest buildings in Ecuador

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

2.5.   Site

In Guayaquil, a site has been chosen for the project. This paragraph will explain why this site.

The site is an urban block roughly 65x56m in downtown Guayaquil. The site is close to the water, port, university, hospital, public park, several museums and other entertainments. This makes it a very good location. A place where wealthy people (target group of the design) would like to live. It is also a place where the building will be seen by a lot of people (locals and tourists) and; therefore, creating the opportunity to create a lot of free publicity. It would make sense to use the plot creating a strongly present tower on the front edge of the plot to the back to off set it from the other tall buildings along the Malecón Simón Bolivar (the streets runs in a slight curve). The site has significant contextual input guiding and shaping the design. A design in this location should only be suited for the chosen location.

Figure: 13. Site

3. Global Context

Figure: 14. Natural growing zone of bamboo

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?
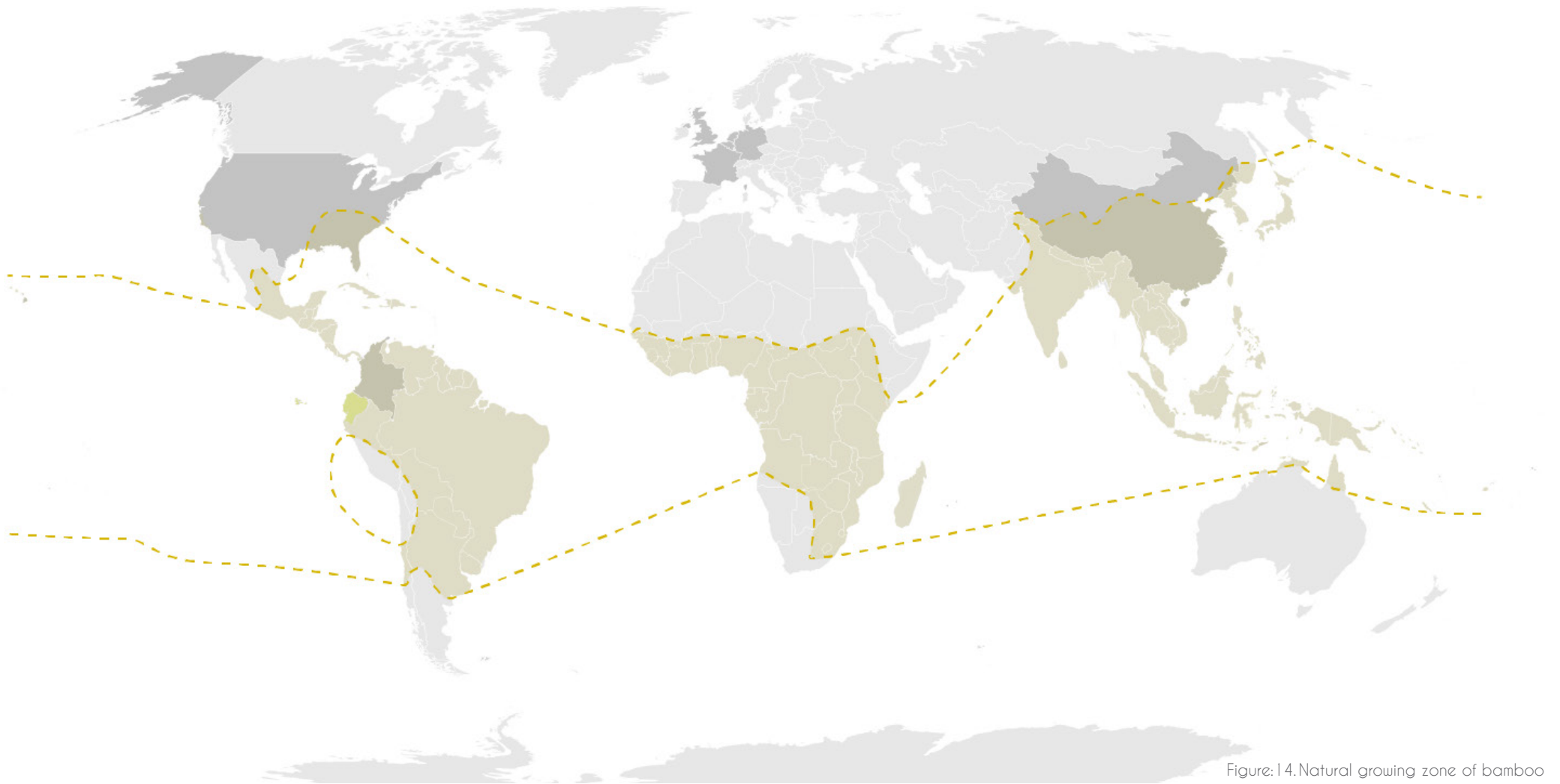
3.1.   Global Context

When proposing a bamboo tall building, the first objection is: "the market is not ready yet". People haven't even started with normal housing. It is a fact that there is no high-rise building in laminated bamboo. However, it is not as far fetched as some believe. This chapter will show the current state of the laminated bamboo market.

The image: "*Bamboo global overview*" summarizes major players in the current market. The major players are USA, Europe, China, Colombia and to a lesser extent Ecuador. Japan is also an important player, since has the largest number of patterns on processed bamboo (Zhang, Yang, and Yu 2008) and significant bamboo resources.

The wages in Japan however are too high to harvest the local bamboo (Dewancker 2008). Furthermore English literature regarding structural bamboo in Japan is difficult to find. India, Indonesia and Central Africa also possess structural bamboo, but literature is too trivial and therefore excluded.

€   GBP per Capita

🏭   Advancement of wood/bamboo industry

🍃   How sustainable is it to use bamboo in this region

A⁺   University research rate

Ⓟ   Patents on processed bamboo products
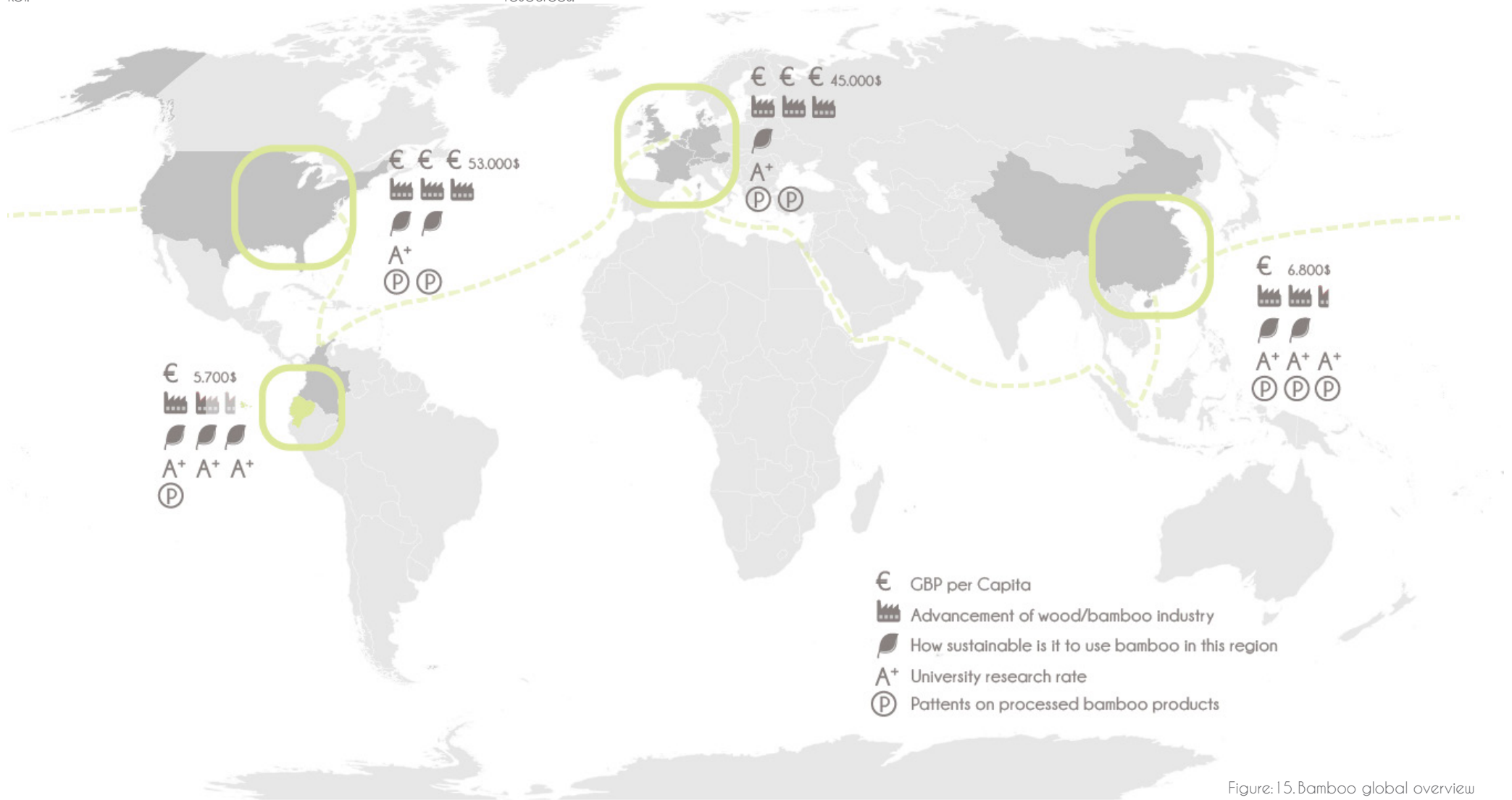
Figure: 15. Bamboo global overview

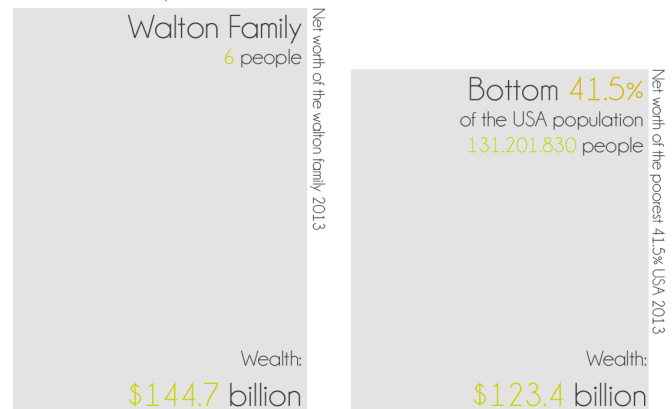## Europe and the United States.

The industries of Europe and the United States (US) are at the moment the most advanced, especially regarding the wood industry. In both Europe and the United states the race has started to create sky scrapers made out of wood.

Based on the data from the world data bank (2014) EU and US are the wealthiest regions in terms of GDP. US has a 9,3x higher income than Ecuador. But some side notes have to be made regarding this. In the United States the Walmart's founding family Walton (existing out of 6 persons) owns more than the 131 million poorest US citizens combined that is 41,5% of the US population (Swanson, 2014 November 5). US is one of the most unequal countries on the planet where 10% of the population owns more than 74% of the wealth (Swanson 2014, October 22).So the life of the average American is not that bright as the GDP suggests.

Studies have been carried out to determine the sustainability of (laminated) bamboo in Europe (Vogtländer, Van der Lugt et al. 2010, 2012; van der Lugt 2000b;) and the US (Lamboo 2012). These studies show a homogeneous result. It indeed preforms better than steel, concrete and tropical wood, however local soft wood is in most applications more sustainable. This is often caused by the impact of transportation. Bamboo, at the moment, is shipped from China and sometimes from South/Central America, Indonesia or India. Although bamboo is not native to Europe and the majority of the US, EU and US do have bamboo plantations. The Netherlands have a successful bamboo plantation that provides foot for panda's in nearby zoo's (Bamboe Gigant 2012 January 20) and also in the US serious efforts have been made to create bamboo plantations (Rittironk and Elnieiri 2008).

However, the bamboo species used are not suited for the structural applications. The interest in growing structural bamboo is growing and is theoretical possible (Vos, Armijos Moya and Vongsingha 2014; Hitchcock Becker 2013). Therefore, it theoretically could become a local product in the future.

During the search for literature on laminated bamboo, only a small amount came from US/ European sources. However, US and Europe do hold a surprising amount of patterns and the only fully recognized structural laminated bamboo product comes out of the US. It goes by the trade name Lamboo and is recognized by American and European standardization institutes (Lamboo 2014). Multiple buildings have been builds and structures have been build in the USA ranging from Church to showrooms to offices to houses. At least that are the claims by Lamboo. In Europe MOSO has also introduced laminated beams and testing results and certification are expected in the first half of 2015 according to A. van der Vegte , Project Manager & Senior Manager Quality Control, Research and Development (personal communication November 17, 2014) results of this will be included in the chapter physical testing. This shows that the market is moving, developing and that laminated bamboo slowly being accepted as a building material in Europe and the US.

Figure:17. Bamboo farm for Panda's in European zoo's the in Asten Netherlands

Figure:18. Two global players: Lamboo (US) Moso (Europe) in Laminated bamboo

Walton Family
6 people

Net worth of the walton family 2013

Bottom 41.5%
of the USA population
131.201.830 people

Net worth of the poorest 41.5% USA 2013

Wealth:
$144.7 billion

Wealth:
$123.4 billion

Ishai Evers of Dadaviz created this chart, which contrasts the wealth of six prominent members of the Walton family with the bottom 41.5 percent of Americans, or more than 131 million people. The results or the bottom 41.5% are so low in part because many Americans have negative net worth, i.e. carry more debt than their assets
Figure:16. Unevenly distributed wealth in the USA

Figure:19. Lamboo church in US

Global Context
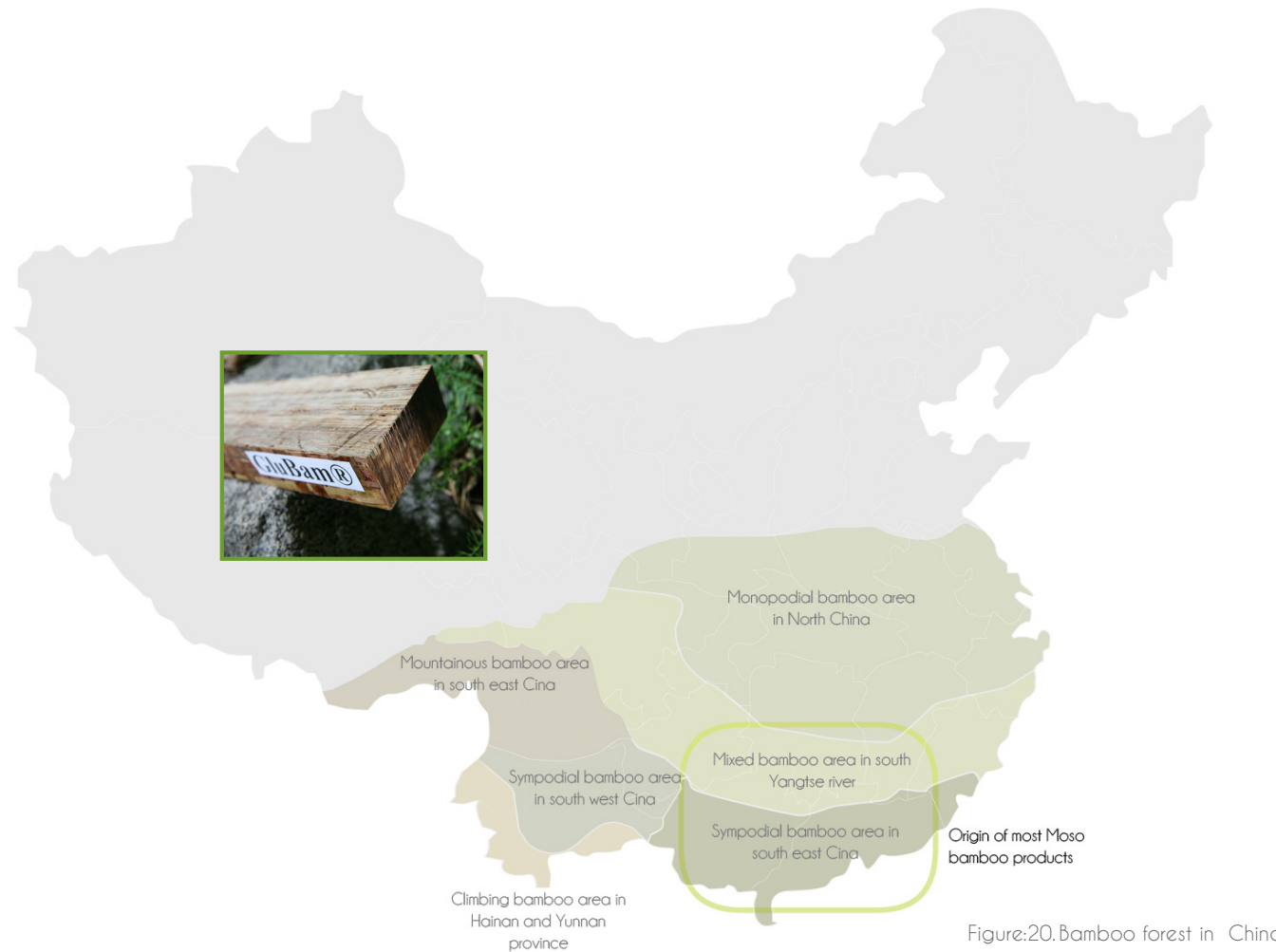
China

Chinese bamboo forest exists out of 5.444.000 ha and is the third biggest bamboo country (after India and Brazil) measured in forest area, counting for 14% of the total amount of bamboo forest worldwide and growing (FAO, 2005). China has 626 natural bamboo species of which four are used in construction. Best known is Moso. The Botanical name for Moso is Phyllostachys edulis. Moso comes from the south eastern part of China and if you live in Europe or US and you have a laminated piece of bamboo it is most likely Moso. China is market leader in processed bamboo products, because of extensive effort from the government, good infrastructure, high knowledge (Zhang, Yang, and Yu 2008) and cheap labor (world data bank 2014).

After Japan, it has the largest amount of patent applications in bamboo. In concordance with WIPO, patents contain 40% of the new products, which is only 10% of the total amount of research. Therefore China is an important player on the global market. Bamboo patent applications contain: furniture, handicrafts, bamboo paneling, healthcare applications and medicines, Bio-fuel, food, crude bamboo, cultivation processes, processing methods and fibers (Zhang, Yang, and Yu 2008).

China has a patented structural laminated bamboo product on the market, known as Glubam®. Glubam is developed in cooperation with University of Southern California (USA) and College of Civil Engineering, Hunan University (China). The first project using Glubam as a structural application is a pedestrian bridge at Hunan University in China. Glubam also made the first truck-load roadway bridge in Leiyang (China 2007) (Xiao, Zhou et al. 2009), First, two story house in laminated bamboo in Changsha (Hunan Province in China 2009) (Chen, Xiao et al. 2008), and many more bridges and houses since. Glubam have done all test required (fire, systemic, connection and strength tests) for operating on the Chinese market meeting the Chinese standards (Y. Xiao, B. Shan et al. 2014).

Monopodial bamboo area in North China

Mountainous bamboo area in south east Cina

Mixed bamboo area in south Yangtse river

Sympodial bamboo area in south west Cina

Sympodial bamboo area in south east Cina

Origin of most Moso bamboo products

Climbing bamboo area in Hainan and Yunnan province

Figure:20. Bamboo forest in China

Materials	In plane tensile strength (MPa)	Elastic Modules E_y (MPa)	Elastic modules E_x (MPa)	G_{xy} (MPa)	G_{yx} (MPa)	In-plane compressive strength (MPa)	Bending strength (MPa)	Density (kg/m³)
Glubam	82	10400	2600	4.6	7.2	51	99	800-900

Table:3. Mechanical properties Glubam according to the Chinese timber structure design standard

Colombia

Colombia is a country with a strong bamboo tradition and home of the famous bamboo architect Simon Velez. For structural use Colombia depends on Guadua. Colombia's Guadua forest area is estimated on 51.500 ha. Including 5.260 ha of Guadua plantations (Guadua Bamboo n.d. C). About 44% comes out of the central provinces from Colombia, see image: "*Guadua growing area in Colombia*". The world data bank considers Colombia as a developing county and has a GDP of $7.500,- (World data bank,2014).

Colombia is the leading county in South and Central America regarding research to bamboo and laminated bamboo. Compared to other countries there is a high amount of cooperation between different actors in the bamboo field (Van Der Lugt 2005). In Colombia there were already three big parties pushing the bamboo industry forward: Universidad de los Andes (Laminated bamboo research), Universidad Nacional de Colombia (Laminated bamboo research) and Guadua bamboo (plantation managers). Recently another influential party has joined. Lamboo has announced a partnership with Guadua bamboo. At current, Lamboo only buys Guadua culms from Colombia and Ecuador, however Lamboo agreed on co-development of the laminated manufacturing industry in Colombia. Providing trainers and cutting edge technology from weave-core to its structure-line (Lamboo, 2014 September 8).

Universidad de los Andes under the leading of Juan F. Correal Daza and Universidad Nacional de Colombia (both located in Bogotá) provide a large academic database regarding Guadua bamboo. Resulting in the first prototyped houses in laminated bamboo in Pasuncha and Ibama (Universidad Nacional de Colombia 2013, July 19) (Luna and Takeuchi 2014). At the same time Universidad Nacional de Colombia is investigating the production process. The research of Universidad Nacional de Colombia apparently is being translated to new building codes regarding laminated Guadau. The New building codes will be placed in "norma NSR-10, capitulo G12" (standard NSR-10, Chapter G12) (Universidad Nacional de Colombia 2014, May 29).

Figure:21. Guadua growing area in Colombia

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

3.2. Legislation

Counrty	Code	Standard
China		JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007)
Colombia	Reglamento Colombiano de Construcció n Sismoresistente – chapter G12 Estructuras de Guadua (Guadua structures) (ICONTEC, 2010)	NTC 5407: Uniones de Estructuras con Guadua angustifolia Kunth (Structural unions with Guadua angustifolia Kunth) (ICONTEC, 2006) NTC 5525: Mé todos de Ensayo para Determinar las Propiedades Fí sicas y Mecá nicas de la Guadua angustifolia Kunth (Methods and tests to determine the physical and mechanical properties of Guadua angustifolia Kunth) (ICONTEC, 2007)
Ecuador	Norma Ecuatoriana de la Construcció n – chapter 17 Utilizació n de la Guadua Angustifolia Kunth en la Construcció n (Use of Guadua angustifolia Kunth in construction) (INEN, 2011)	INEN 42: Bamboo Cañ a Guadua (bamboo cane Guadua) (INEN, 1976)
India	National Building Code of India, section 3 Timber and bamboo: 3B (BIS, 2010)	IS 6874: Method of tests for round bamboos (BIS, 2008) IS 15912: Structural design using bamboo – code of practice (BIS, 2012)
Peru	Reglamento Nacional de Edificaciones, Section III. Code E100 – Diseñ o y Construcció n con Bamboo (ICG 2012)	
USA		ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013)
International		ISO 22156: Bamboo – structural design (ISO,2004a) ISO 22157-1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b) ISO 22157-2: Bamboo – determination of physical and mechanical properties – part 2: laboratory manual (ISO, 2004c)

Table:4. Legislation world wide (2014)

EN 408: 2010 (CEN, 2010)
Timber structures. Structural timber and glued laminated timber.
Determination of some physical and mechanical properties

EN 1193: 1998 (CEN, 1998)
Timber structures. Structuralt timber and glued laminated timber. Determination of shear strength and mechanical properties perpendicular to the grain

EN 380: 1993 (CEN, 1993)
Timber structures. Test methods. General principles for static load testing

ISO 8375: 2009 (ISO, 2009)
Timber structures. Glued laminated timber. Test methods for determination of physical and mechanical properties

Bamboo structures.
Glued laminated bamboo.
Determination of physical and mechanical properties

1   Determination of local (shear free) modulus of elasticity of the beam in bending
2   Determination of global modulus of elasticity of the beam in bending
3   Determination of bending strength of the beam
4   Determination of the modulus of elasticity in tension paralell to the grain
5   Determination of tension strength parallel to the grain
6   Determination of modulus of elasticity in compression parallel to the grain
7   Determination of compression strength parallel to the grain
8   Determination of tension and compression strengths perpendicular to the grain
9   Determination of the modulus of elasticity in compression and tension perpendicular to the grain
10 Determination of shear modulus of the beam – single span method
11 Determination of shear modulus of the beam – variable span method
12 Determination of shear strength parallel to the grain – smallspecimen test
13 Determination of shear strength parallel to the grain – fullsize beam test
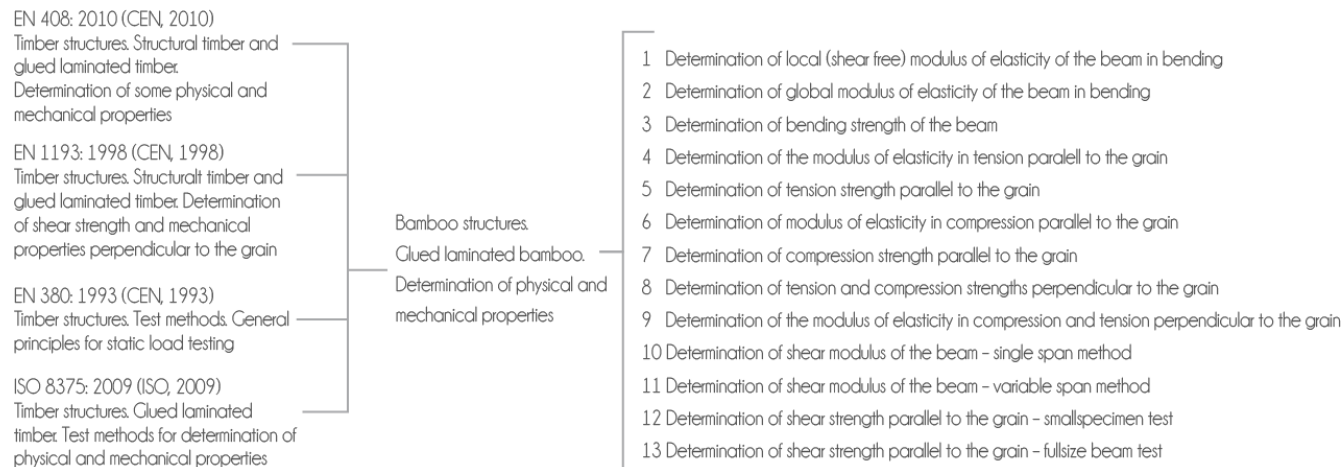
Figure:22. Relevant European norms and ISO timber standards and their application to bamboo

One of the major obstructions for building in structural laminated bamboo is legislation. Legislation is always behind on development also in the bamboo industry. However, also on this field there is movement. This chapter will give a over view of the current stat, see image: *"Legislation world wide (2014)"* and what can be expected.

Most of the countries regulations and standardizations only available for the culm. Only China and USA have regulations regarding laminated bamboo and soon Colombia (Universidad Nacional de Colombia 2014, May 29) and Europe (personal communication June 1, 2015). Ecuador has only regulations for the culm, similar to the Colombian regulations (Gatóo, Sharma et al. 2014). Ecuador tents to follow Colombia with its bamboo industry (Van Der Lugt 2005); therefore, it is likely that Ecuador in the near future also will have codes for structural bamboo.

There are also international standards; current ISO standards are outdated and inadequate and need to be revisit. Another pathway to future standardization is linking the bamboo testing methods to the timber industry, making it easier to use them and allows architects and engineers more easily to engage in the standardization and testing (Gatóo, Sharma et al. 2014). Researcher of the University of Cambridge also created a overview of the rules and codes that could be used to standardize laminated bamboo on the European market see image: *"Relevant European norms and ISO timber standards and their application to bamboo"*.

In the near future further standardization regarding structural laminated bamboo products will be realized. The speed and the efficiency of this process will depend on the cooperation between the different stakeholders(Gatóo, Sharma et al. 2014).

For tall buildings another obstruction is that the building can not contain combustible materials in its structure (SOM 2013). The rules are slowly being revisit as more knowledge becomes available about the behavior of wood in fire. However in current tall wood buildings the codes are just over ruled, by adding extra safety measures and providing physical proof.
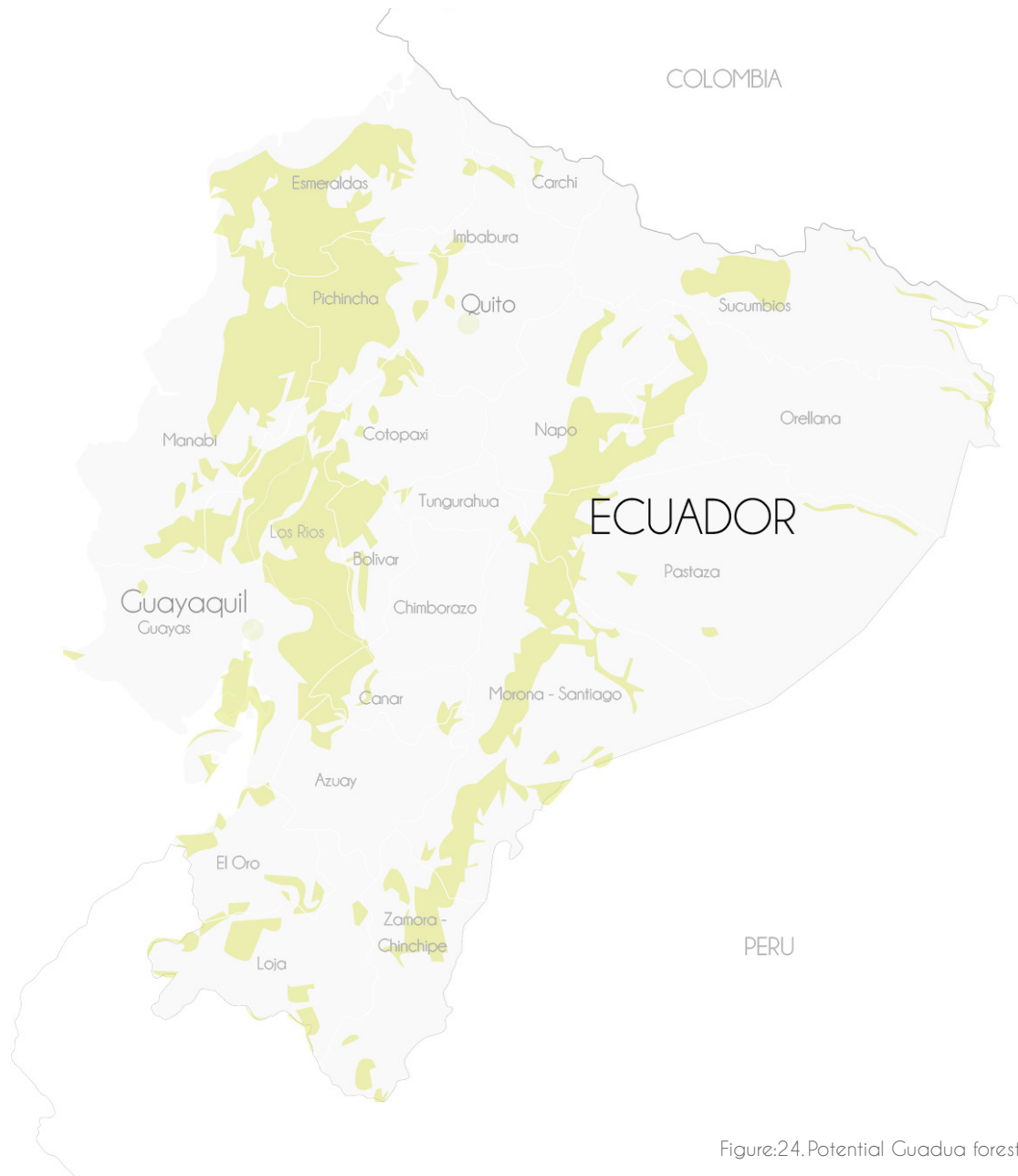
4. Ecuador

Figure:23. Cuenca (Ecuador)

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

4.1. Intro

COLOMBIA

Esmeraldas
Carchi
Imbabura
Pichincha
Quito
Sucumbios
Manabí
Cotopaxi
Napo
Orellana

ECUADOR

Tungurahua
Los Rios
Bolivar
Pastaza
Guayaquil
Guayas
Chimborazo
Cañar
Morona - Santiago
Azuay
El Oro
Zamora - Chinchipe
Loja

PERU

Figure:24. Potential Guadua forest.

Summed up some countries around the world are close or already have started to build houses, bridges, offices and big open spaces out of structural laminated bamboo. The question is how far is Ecuador?

Guadua forest

Ecuador has a long tradition in bamboo similar to Colombia. The most important structural bamboo is Guadua (Parsons 1991). The estimation of Guadua bamboo is that Ecuador has 30.000 ha of productive Guadua forest/plantations (Guadua n.d. D). Potentially the Guadua forest could be a significantly larger (Klop, Cardenas and Marlin 2003), however much of the original Guadua forest has disappeared, because of deforestation. For example the Guayas river basin near Guayaquil (2002 July 27) has been deforested to provide homes/shelters for the poor. Some researchers in the past (Vogtländer, Van der Lugt et al. 2010) stated that it would be better to focus on Moso, because the biodiversity in Ecuador is about 2,5 times higher than the region where Moso comes from. A counter argument is that a large part of the deforestation in Ecuador is caused by the national and International demand on hard wood (Zambrano-Barragán 2010). Guadua can replace this demand and has a two times higher yield rate when compared with Moso (Vogtländer, Van der Lugt et al. 2010). Besides the area with the highest potential for Guadua plantations (in the coastal area) have already been deforested (Zambrano-Barragán 2010). Why not reforest these areas with Guadua? Offering a more sustainable solution than the current land use of the region (Biofuel from palm trees, which is ineffective and absorbed a lot less carbon).

The ministry of Environment of Ecuador plans to reforest 1 million ha before 2028. 750.00 ha are intended as industrial plantations, 150.000 ha are intended as agroforestry and only a 100.000 ha for conservation and protection (Zambrano-Barragán 2010). Until 2010 the plan has only been able to create 7.371 ha of new forest. In the coastal region 343 ha have been planted for industrial use (logging), excising mainly out of balsa, laurel, chucho, pine and eucalyptus. Compared to Guadua all of them have lesser mechanical properties, yield rates and CO2 fixation. In potential there is a large role for Guadua to play in the reforestation.

4.2. Guadua production chain

Situation in 2003

Klop, Cardenas and Marlin have published in 2003 the results of a study to the Guadua production chain (Klop, Cardenas and Marlin 2003). It shows that Ecuador could become an important player in the bamboo market, however, first numerous problems have to be overcome throughout the production chain. To create clarity the production chain has been divided in five: production (growing bamboo), commerce, construction, agricultural sector and the industry, see image: *"Market streams and actors in Ecuador"*. The challenges for these will be discussed separately.

Production (growing bamboo).

- Lack of knowledge/no technical assistance. Farmers don't know how to maintain a Guadua plantation and when Guadua is mature There are some international cooperation programs, but are not efficient.
- Asexual reproduction in nurseries is the most efficient way of creating plantations. Nurseries are scarcely available in Ecuador.
- It is seen as a side business for most producers.
- Small amount of Guadua available from plantations, although investors are interested in investing in plantations.

Commerce.

- The quality of Guadua products. Almost no production control. Bamboo is cut (often) immaturely and there is no control on the drying process. This decreased the mechanical properties and durability of Guadua.
- Sustainability of activity. Guadua commerce is seen as a site activity and an additional source of income for most actors.
- Lack of transparency in price fixation. A large part of the Guadua commerce has an informal character.
- It is considered a "not wood" product therefore higher taxes have to be paid over Guadua compared to wood, increasing unsustainable illegal activities.

Construction.

- The main obstruction is mixed quality used in the construction. There's no quality control throughout the chain (in most cases), leading to a shorter lifespan of the buildings.
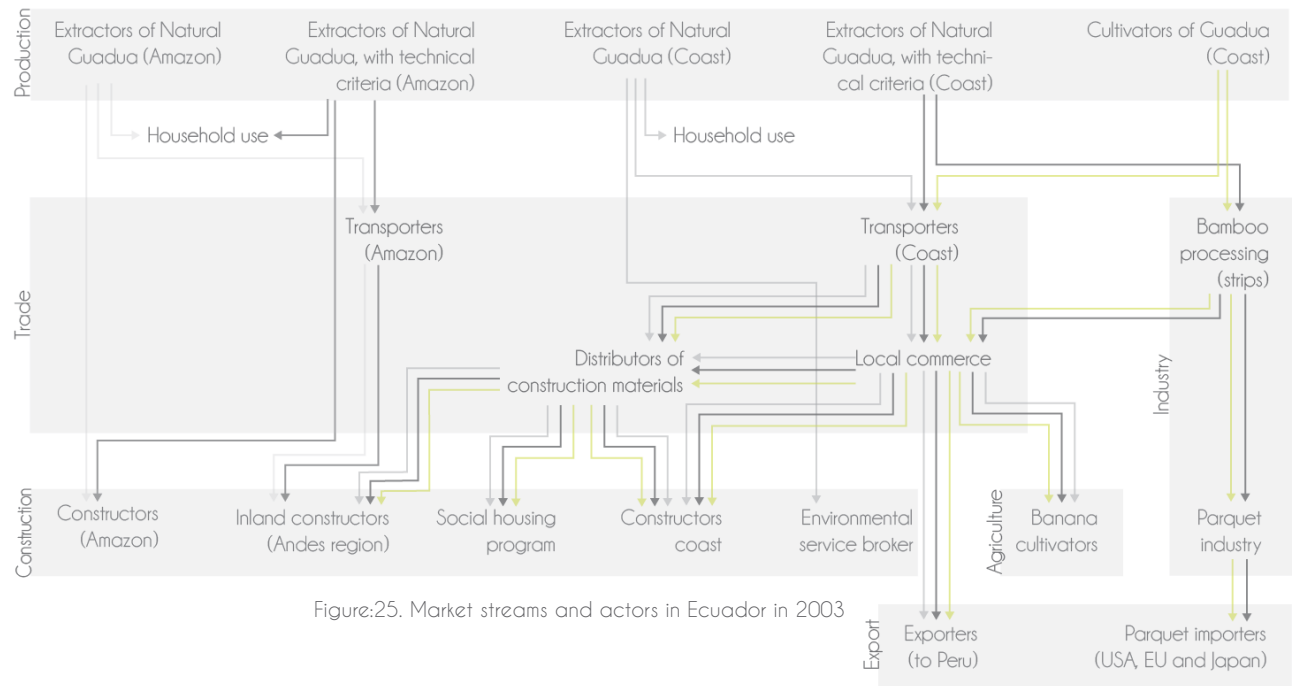
Figure:25. Market streams and actors in Ecuador in 2003
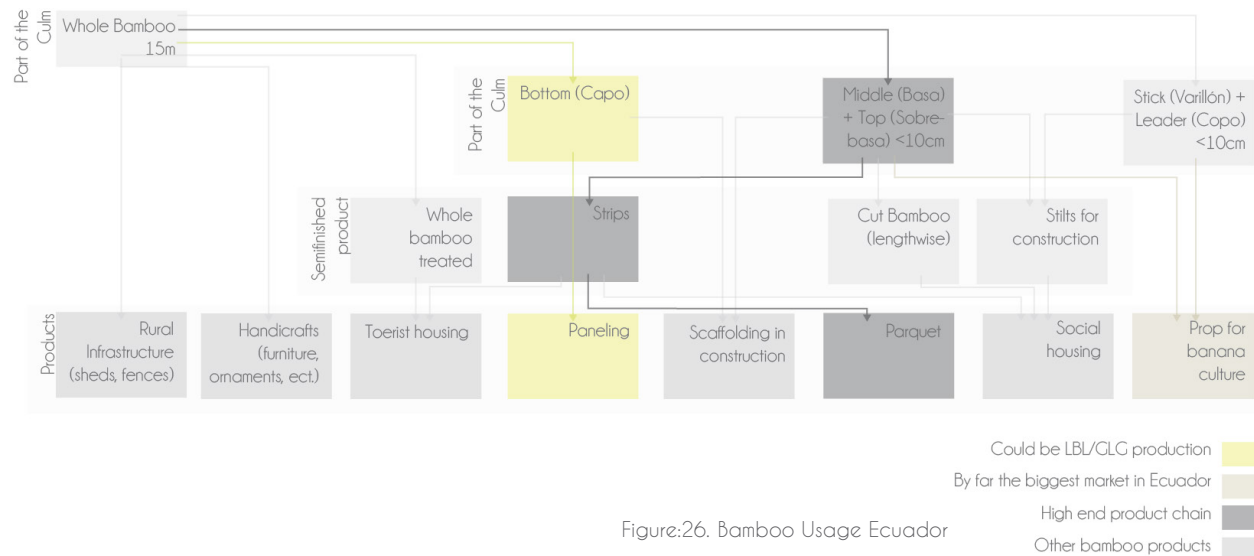
Figure:26. Bamboo Usage Ecuador
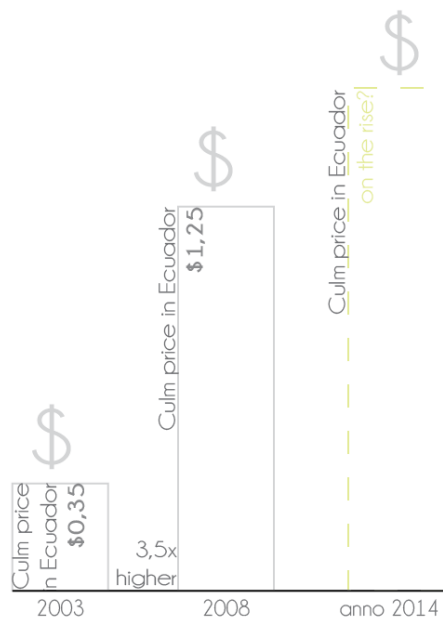
Could be LBL/GLG production
By far the biggest market in Ecuador
High end product chain
Other bamboo products

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
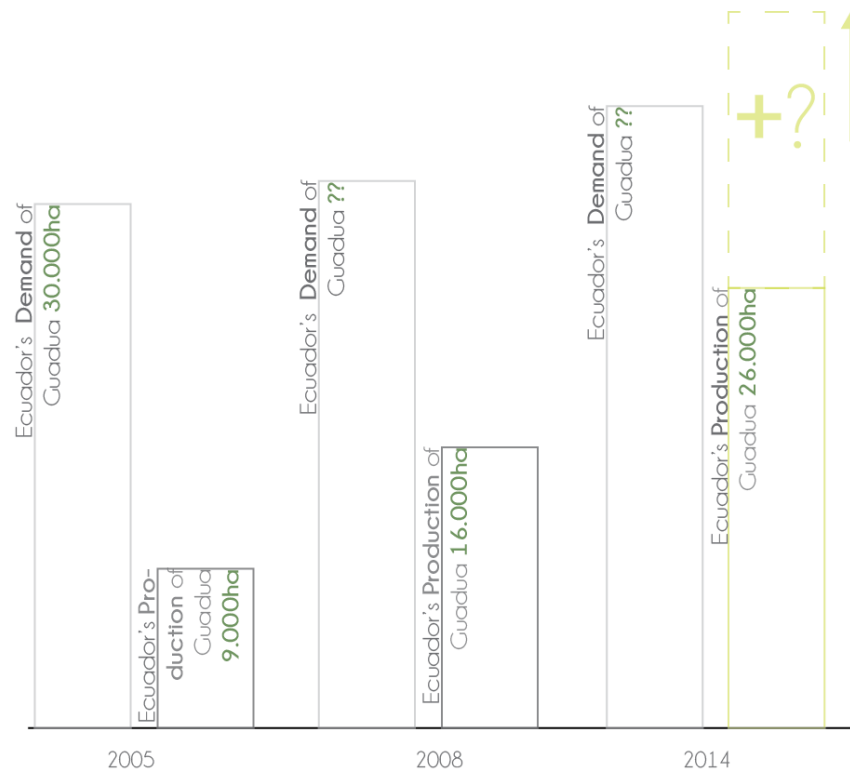
Guadua production chain

Agricultural sector.

- There is a high demand for the upper part (normally seen as a by-product) of Guadua to use as props for banana plants. The demand increased because of a growing fair trade market. Fair trade markets prohibit plastic ties. For the banana industry in Ecuador 30.000 ha of sustainable, well managed bamboo plantations would be needed. In 2003 only 3.000ha of Guadua plantations where available.

Industry (strip makers and floors and panel makers).

- Technologies are copied/adapted from China, without having spare parts and technical assistance.
- Bamboo is seen as an artisanal product and not as an industrial product witch needs regulation.
- Although the Guadua industry is only beginning to develop there is already a problem with getting high quality materials.

2003- Present

Through schooling and support from international organizations like SENA, INBAR, GTZ and CBI the first part of the production chain, plantation, harvesting and strip making was improved, but their where very few high-end products available from the Ecuadorian market in 2005 (Van Der Lugt 2005). The main reasons according to van der Lugt are: for this Lack of commercial skills of local people, insufficient knowledge of how the market works, poor designing skills and inadequate product developing skills.

INBAR has continued to school people in Ecuador and help local people develop knowledge, commercial and product developing skills to improve the processing of bamboo, creating more valuable products. Also creating income for Ecuadorian womans. Several reports show that bamboo provides an income not only to males but also to females especially in high end products like furniture and flooring (Bansal and Presad 2004), (Marsh and Smith 2007) and (INBAR 2008). Between 2003 and 2008 the price farmers get has become 3.5x times higher, providing the farmers with a good income, making it interesting to grow Guadua. In cooperation with locals INBAR planted 7.000ha of Guadua forest/plantations and a forest in the same region of 10.000 ha is on its way. (INBAR 2008).

Figure:27. The price a farmer receives per culm

- Culm price in Ecuador $0,35 — 2003
- Culm price in Ecuador $1,25 — 2008
- 3,5x higher
- Culm price in Ecuador (on the rise?) — anno 2014

Figure:28. Guadua production on the rise

- Ecuador's Demand of Guadua 30.000ha — 2005
- Ecuador's Production of Guadua 9.000ha — 2005
- Ecuador's Demand of Guadua ?? — 2008
- Ecuador's Production of Guadua 16.000ha — 2008
- Ecuador's Demand of Guadua ?? — 2014
- Ecuador's Production of Guadua 26.000ha — 2014
- +?

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Page 34

One of the problems INBAR faces is the lack of recognition from the Ecuadorian people towards Guadua, the Ecuadorians fail to see the possibilities Guadua has (INBAR 2008). This is slowly changing, but still is a problem. So not only the world has to be convinced of the prospects of Guadua, but also the local people. A 20 story well made building could open up the eyes of the locals and the world and drive the Ecuadorian bamboo industry forward. The building could be the 21st century equivalent of the Eiffel tower in France, witch was the catalyst of the steel building industry (Green 2013 July 9).

Besides INBAR, CFC (common fund for commodities) is also investing in the development of a bamboo industry in Ecuador. Together with partners, CFC invested $2.007.300,- in Ecuador and Peru and is fully operational since April 2011 (Common fund for commodities n.d.). The USA company Lamboo has plantation in Ecuador and Colombia. At the moment Lamboo is moving factories towards Colombia providing Colombia with machines and knowledge. This could also happen in Ecuador, however, actors have to start working together because, the big difference between Colombia and Ecuador is that Ecuador misses a strong cooperation between actors in the bamboo market. This was the case in 2005 (Van Der Lugt 2005) and still is the case in 2014.

There is one other group of actors that plays a role on the Ecuadorian market: the Chinese investors. Chinese investors have successfully started a company called Bigbamboo. Bigbamboo makes floors, decking and beams by pressing bamboo strips together using hydraulic pressure and heath. This is known as Strand Woven Bamboo. (Bigbamboo n.d.). A mark has to be made. Giant bamboo doesn't use Guadua, but uses Dendrocalamus Asper also known as Giant bamboo.

To sum up the Guadua forest is growing, The quality of the culms on the market are improving, Farmers receive better prices, the demand is increasing and forest management has also improved. Few high end products produced (most of it for the US and European market) although the number is increasing. However, exact numbers of the current situation are not available yet.

Strand woven bamboo Floor

Strand woven bamboo Column

Strand woven bamboo Floor

Figure:29. Strand woven bamboo from BigBamboo

Page 35

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

4.3. Economy

GDP growth (annual %)
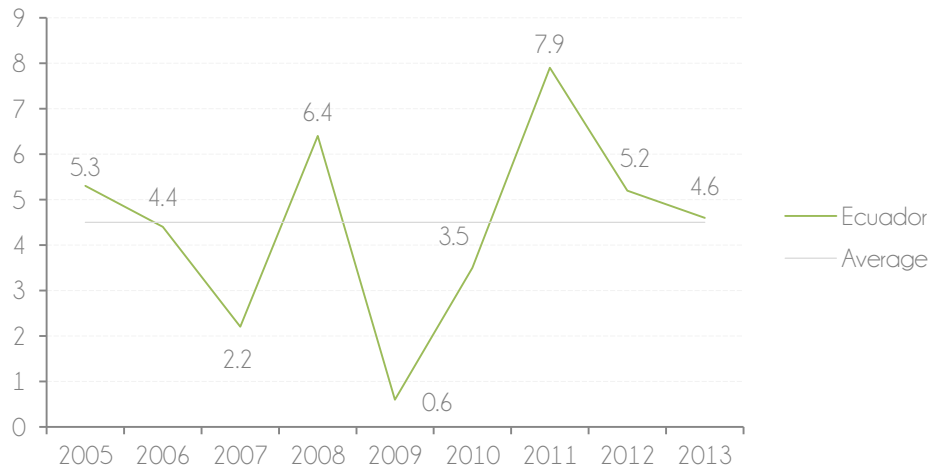
Figure:30. GDP growth past 8 years

GDP growth forecasts (annual %)
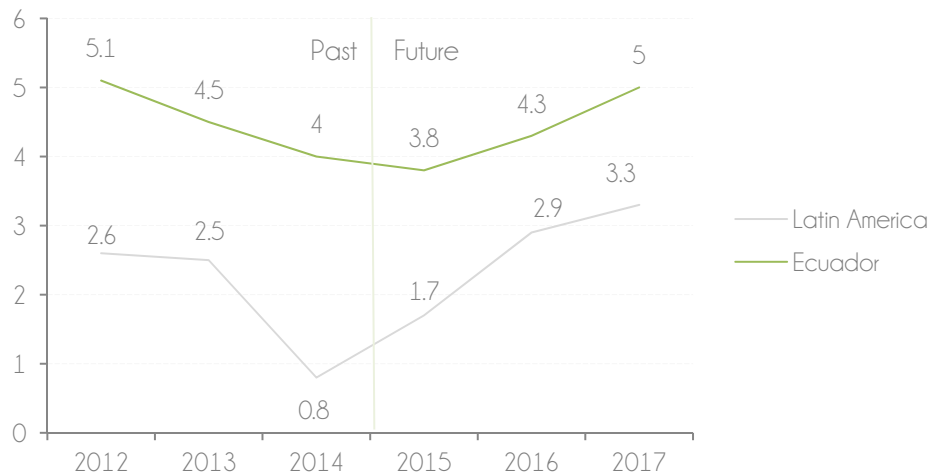
Figure:31. Predicted GDP growth

For the feasibility a rough understanding of the economy is important. This sub-chapter will explain.

Ecuador is a socialist country. The Heritage Foundation monitors the 10 pillars of freedom and rates countries across the world recording to the results from the 10 pillars. Ecuador only scores a score of 48/100 for comparison the Netherlands score 74.2/100. The major issues for Ecuador are corruption, governmental spending, investment freedom and property rights (The Heritage Foundation 2014). Investment freedom and corruption are serious obstacles for this project. Only with extensive cooperation between local municipalities from an early stage onwards could make this project feasible.

Governmental spending has been on the rise since President Rafael Correa has been appointed. Vast amounts have been spent on education, energy production/transportation and infrastructure. It already has drastically reduced poverty, from 37,6% down to 24,5%. The gap between poor and wealthy people has been successfully reduced. The economy has also drastically increased in the last 10 years, with an average growth of 4,6% and a predicted average growth above 4.5% till 2017 (World data bank, Nov 05, 2014).

Ecuador has two economic centres. Guayaquil and Quito and is primarily a farming country (world largest exporter of bananas). Its industry is mainly focus around the two centres. The industry is mainly for the domestic market, but with the harbor Guayaquil is more internationally orientated.

The project is mainly focus around the sustainability of the structure, however to design a sustainable building more aspects have to be taken in to account and one of those is the climate its designed for and witch climate strategy is applied. This chapter will explain the kind of climate and the strategy options

Climate

According to the Köppen-Geiger system Guayaquil has a As climate also known as a Tropical Savannah climate with wet winters and dry summers. The raining period is from January till April with an precipitation of almost 200mm a month compared to almost no rain between July and October. Temperatures throughout the year are stable, monthly averages ranging between 28.6°C and 31.5 °C during the day and 22.7°C and 19.6°C at night (climate data n.d.), see image: "Guayaquil monthly temp. and precipitation".

Guayaquil is located at 2°9'S, 79°53'W. Because Guayaquil is located very close to the equator the daylight hours per day are about 12 hours throughout the year. On average Guayaquil receives about four hours of sunlight a day throughout the entire year regardless of wet or dry period. Like many tropical coastal cities the wind in Guayaquil has a prime direction. The primary direction is from the South/West. 33% of the time the wind blows from this direction, see image: "Guayaquil wind rose". The total percentage in the image is 75% of the time, this is because windless times are not included. The strength of the wind is on average a light breeze, hovering around 3m/s (Weather base 2015 February 9) see image: "Monthly wind speed avg." On average there might be a light breeze, but occasionally during storms wind gusts can reach speeds up to 18m/s. This is considered a fresh gale on the Beaufort scale (Beaufort number:8).

Guayaquil monthly temp. and precipitation
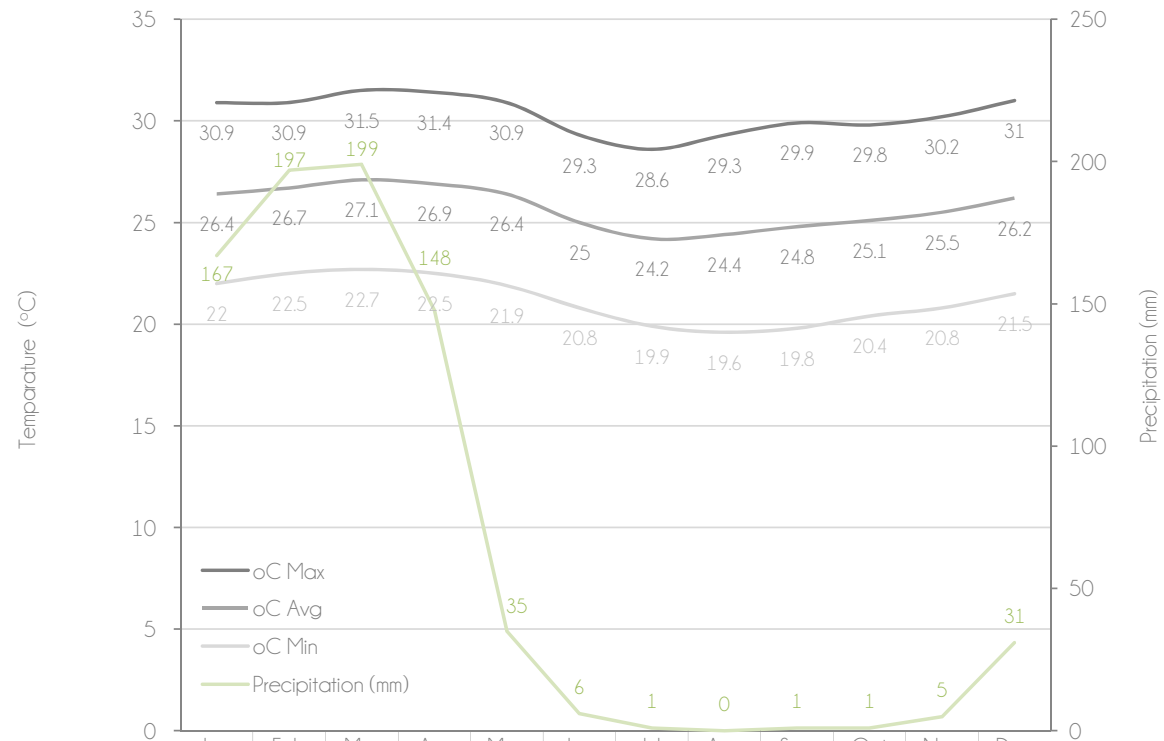
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
oC Max	30.9	30.9	31.5	31.4	30.9	29.3	28.6	29.3	29.9	29.8	30.2	31
oC Avg	26.4	26.7	27.1	26.9	26.4	25	24.2	24.4	24.8	25.1	25.5	26.2
oC Min	22	22.5	22.7	22.5	21.9	20.8	19.9	19.6	19.8	20.4	20.8	21.5
Precipitation (mm)	167	197	199	148	35	6	1	0	1	1	5	31

Figure:32. Guayaquil monthly temp. and precipitation

Monthly wind speed Avg (m/s)
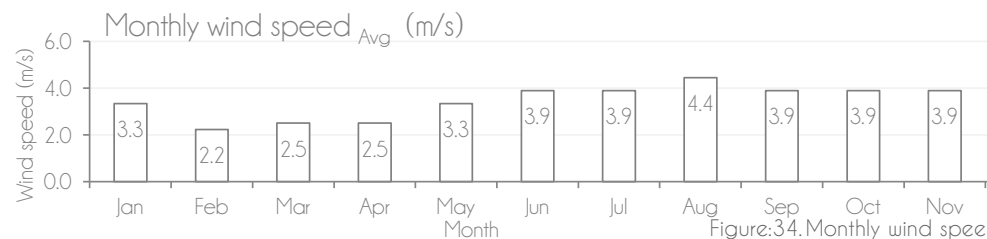
Figure:34. Monthly wind speed avg.

Figure:33. Guayaquil wind rose

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
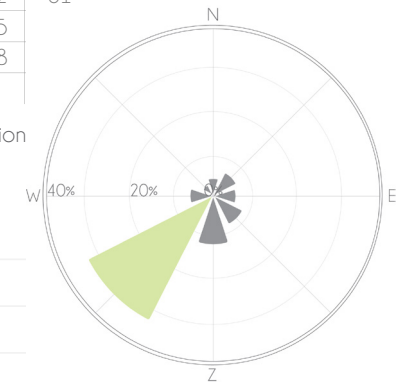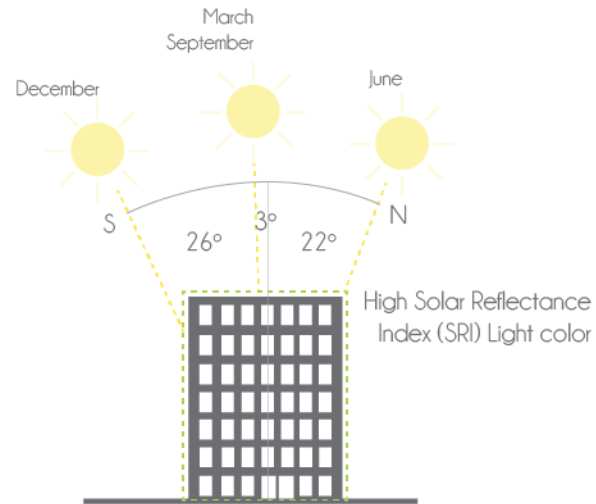
Climate of Guayaquil
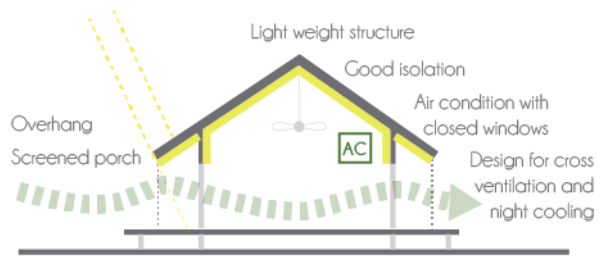

Figure:35. Solar angles and SRI

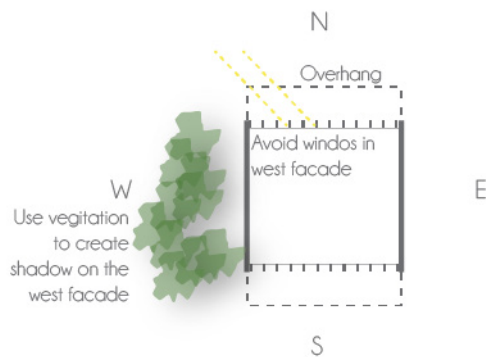Figure:36. Basic design essentials in hot humid climates

Figure:37. Basic design essentials in hot humid climates 2

Climate strategies

To determine the climate strategies the program Climate consultant 5,5 has been used. A data file for Guayaquil was not available, therefore a data file for a similar climate has been used. Bangkok has a similar climate and is also classified as an As climate. The main difference is in the solar angles, since Guayaquil is closer to the equator. The solar angles of Guayaquil are shown in the image: "*Solar angles and SRI*". Climate consultant offers a couple of solutions for a hot and humid climate of Bangkok.

The main challenge is limed the heat load on the building. Temperatures are so high that air conditioning in buildings large buildings can not be prevented. However their are several design solutions to reduce the heat load of a building and with that reduce the cooling demand of the building. Resulting in lower energy consumption.

The first solution is to uses a SRI. A white facade will reflect the solar heating better than a black facade, therefore a light colored facade/roof and reflective glass has a positive effect on the heat load of the building. However a side note has to be made. In an urban context using a high SRI on the facades and applying reflective glass has an negative effect on the urban heat island, and can be the cause of glare. So it is important that a good balance is found in the design.

In hot humid climate using light weight structures is also beneficial especially in combination with night cooling. Thermal mass will heat up during the day and release its heat during the night and reducing the colling effect of night cooling. However a certain mass is needed to prevent tension in the structure caused by wind. Night cooling can be a very effective passive way of cooling the building. This strategy release on the wind and cross ventilation and have a large impact on the layout and orientation of the building.

Good insulation is needed to prevent the heat to penetrate the building and heat up the interior and when the air conditioning is running the windows should be close.

An other essential design solution is to create overhangs on the to prevent direct sunlight on the facade and from entering the building through the windows. Because of the location all sides of the building will benefit from an overhang, but the north and south profit the most the overhangs see images "*Basic design essentials in hot humid climates*" and "Basic design essentials in hot humid climates".

The porches and balconies would also benefit from screened porches. Letting the wind to ventilate the space, but reducing the solar radiation.

The heat load can also be reduced by using vertical blinds on the north and south side to prevent the low morning and evening sun from entering the building. It is needed on both sides because depending the time of the year the sun will be in the north or in the south during noon.

In the west facade windows should be avoided. The evening sun at the warmest part of the day will create a large heat load in the building and overhangs can not shade the windows sufficiently. Climate consultant 5,5 also suggest adding vegetation to the west wall or use trees to shadow the wall.

The east wall has similar problems to the west facade, but the morning sun is less strong than the evening sun. So the same solutions can be applied, but will be less effective than on the west facade.

For the design of the multi-floor residential building these climate design rules need to be incorporated in the building together with the structural, functional and contextual rules.

5. Wood industry

Figure: 38. Wood industry

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

5.1.   Precedent analysis

Figure:39. Yingxian Pagoda
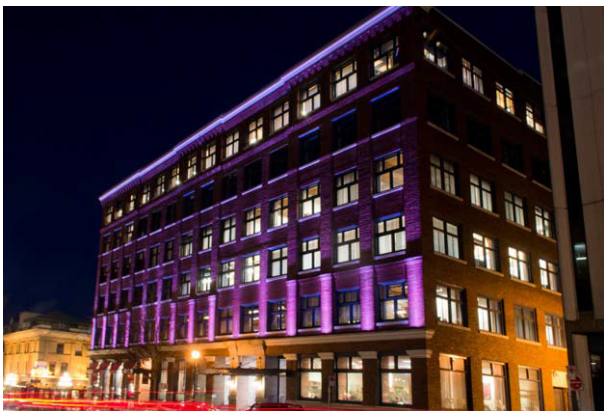

Figure:40. Urnes Stavkirke

Figure:41. Leckie Building

Figure:42. Perry House

Figure:43. Limnologen

A bamboo skyscraper is new, however, wooden skyscrapers are existing and many lessons can be drawn from tall wooden buildings. This chapter will give a overview of the worlds tall wooden buildings

Yingxian Pagoda

Location:	China, Shanxi
Building Year:	1050
Seismic active:	Yes
Number of stories:	9
Construction system:	Fully wood
Base:	Stone foundation (1 level)

Urnes Stavkirke

Location:	Norway, Sogn og Fjordane
Building Year:	1132
Seismic active:	No
Number of stories:	6*
Construction system:	Fully wood
Base:	Stone foundation (few layers)

Leckie Building

Location:	Canada, Vancouver
Building Year:	1908
Seismic active:	Yes
Number of stories:	6
Construction system:	Brick and beam structure
Base:	Brick foundation

Perry House

Location:	Australia, Brisbane
Building Year:	1913
Seismic active:	Yes
Number of stories:	9
Construction system:	Heavy timber structure with bricks
Base:	Brick foundation

Limnologen

Location:	Sweden, Vaxjo
Building Year:	2009
Seismic active:	No
Number of stories:	8
Construction system:	Timber frame
Base:	concrete foundation

Stadthaus

Location:	United Kingdom, London
Building Year:	2009
Seismic active:	No
Number of stories:	10
Construction system:	Cross laminated timber (CLT)
Base:	Concrete foundation (1 level)

Bridport House

Location:	United Kingdom, London
Building Year:	2011
Seismic active:	No
Number of stories:	8
Construction system:	Cross laminated timber (CLT)
Base:	Concrete foundation

H8

Location:	Germany, Bad Aibling
Building Year:	2011
Seismic active:	No
Number of stories:	8
Construction system:	CLT +concrete core
Base:	Concrete foundation

Life Cycle Tower One

Location:	Austria, Dornbirn,
Building Year:	2012
Seismic active:	No
Number of stories:	8
Construction system:	CLT
Base:	Concrete foundation

Forté Building

Location:	Australia, Melbourne
Building Year:	2013
Seismic active:	Yes
Number of stories:	10
Construction system:	CLT +concrete core
Base:	Concrete foundation

Figure:44. Stadthouse

Figure:46. H8

Figure:47. Life Cycle Tower One

Figure:45. Bridport House

Figure:48. Forté Building

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Precedent analysis

Figure:49. Via Cenni

Figure:50. Bullitt center

Figure:51. Wood Innovation Design Center

Figure:52. Bergen Project

Figure:53. Feasibility study of a 20 story wood skyscraper by MGA

Via Cenni

Location:	Italy, Milan
Building Year:	2013
Seismic active:	Yes
Number of stories:	9
Construction system:	Cross laminated timber (CLT)
Base:	Concrete foundation

Bullitt Center

Location:	United States, Seattle
Building Year:	2013
Seismic active:	Yes
Number of stories:	6
Construction system:	Glulam post/beam + concrete slaps
Base:	Concrete foundation

Wood Innovation Design Centre

Location:	Canada, Prince George
Building Year:	2014
Seismic active:	No
Number of stories:	7
Construction system:	Glulam post/beam + concrete slaps
Base:	Concrete foundation

Bergen Project (in construction)

Location:	Norway, Bergen
Building Year:	2014
Seismic active:	Yes
Number of stories:	14
Construction system:	Glulam beams + CLT
Base:	Concrete foundation

This summary is based on 3 sources. For the projects till "Wood Innovation Design Centre" two sources have been used (Gerard, R. Barber, D. Wolski, A. 2013) and (Gerard 2014, Augustus 5). For "Bergen Project" one source has been used (Vest Cran 2014, n.d.) This research shows that the wood industry has developed at a staggering rate in recent years and feasibility studies, by different cooperations spread over the world, have been done pushing the envelope up somewhere between 20 and 42 stories. Either in a hybrid or a pure wood construction for example SOM (SOM 2013), MGA (Green and Karsh 2012), CEI (CEIArchitecture 2011) and Timmer (Timmer 2011).

5.2. Lamination Types

There are a couple of ways to build tall wood buildings. From Solid hard wood, to Glulam (Laminated timber), to CLT (Cross Laminated Timber) to LVL (Laminated veneer lumber). The hard woods are not relevant for a laminated bamboo structure, but from CLT, LVL and Glubam lessons can be learned.

General

Strength of the laminated products consist on a couple variables. The properties of the lumber used, the direction timber is used, the layup, the conditions the product is used in, the properties of the adhesive and its binding strength to the lumber (Gagnon and Pirvu 2011).

Glulam

The oldest form of laminating wood is Glulam. This type of laminating dates back to the mid 19th century. It is basically gluing planks or strips of wood in to beams or panels, although normally beams. Glulam is capable of increasing the performance from soft wood considerably, but the grains keep running in one direction and therefore as a floor or wall element it is not able to take te lateral forces applied to it. Therefore, it is not suited for multistory buildings in earthquake areas or tall buildings exposed to wind (Gagnon and Pirvu 2011). Besides, it has a high spill rate of adhesives in comparison to LVL Glulam (Faculty of Forestry 2013).

CLT

In CLT panels are laminated in a 90 degree angle. Normally the other layers are orientated to the load bearing direction, witch is in case of walls normally vertical. The edge and/or face of the wood panels are glued with an adhesive and pressed in a hydraulic press (most common) or pressed using a vacuum press (Gagnon and Pirvu 2011). The dimensions of individual wood strips differ between 16mm-51mm in thickness and 60mm-240mm in width. The final product can be as thick as 500mm, a height of 3m and a length of 18m (Gagnon and Pirvu 2011). These limitations are strongly related to transportation limits. The advantages of CLT are: increased dimensional stability, increased splitting resistance, relative high stiffness, the possibility to selects the best planks and in and out of plane stiffness. The wood panels in the CLT are considerably larger than the bamboo strips (Rittironk and Elnieiri 2008). CTL systems are well suited for prefabrication of elements (Gagnon and Pirvu 2011).
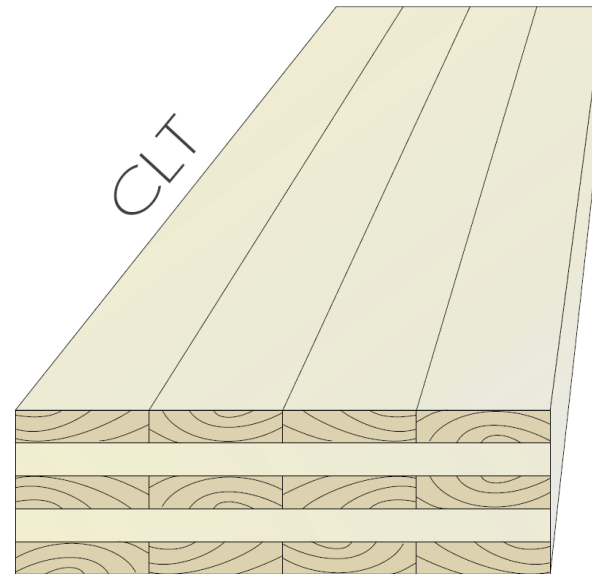
CLT

Glulam

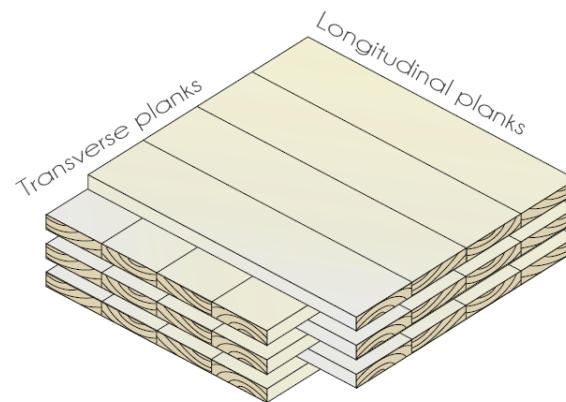Figure:54. CLT vs. Glulam

Transverse planks

Longitudinal planks
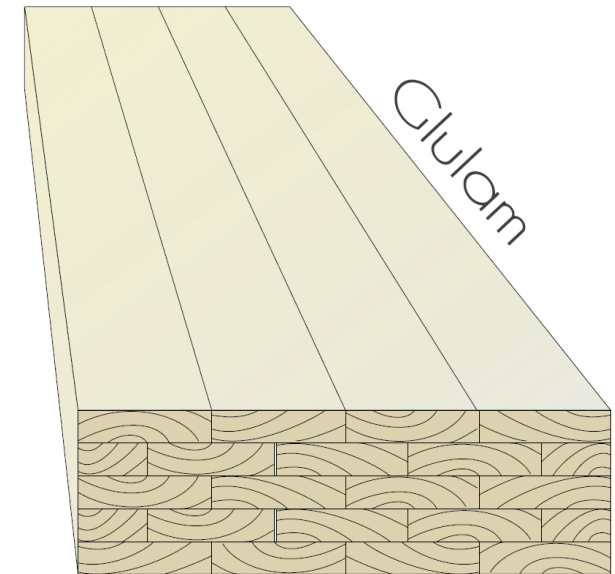
Figure:55. CLT build-up

Figure:56. Different lay-up possibilities in CLT

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
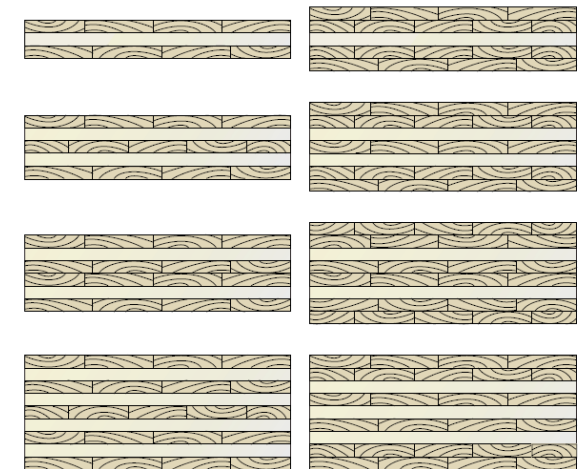
Lamination types

Figure:57. Laminated Veneer Lumber (LVL)

LVL

Laminate Veneer Lumber (LVL) is used in large prefabricated wood wall and floor elements comparable with CLT and LSL (laminated strand lumber) (BSLC and FFI 2014). LVL consists out of thin sheets known as Veneer, with a thickness variating between 1.5mm and 6mm (Faculty of Forestry 2013) and then pressed to gather. The fibers can be orientated either parallel or crosswise. Crosswise LVL is commonly known as plywood. Plywood therefore behaves similar to CLT and can be used in Earthquake areas or in multistory buildings. Compared to the other wood products LVL has an advantage, because the defects of the wood are more homogeneously spread through out the plate (Faculty of Forestry 2013).

The standard size of the panels differs per country, in Canada the standard size LVL plate goes up to 89mm thick and 2.44m wide and 19.5m long (Green and Karsh 2012). The beams and columns are made by cutting the LVL plate in to smaller sections. Commonly per layer 180 g/m² of Adhesive is used resulting in a total usage that is two times higher than of Glulam or CLT. The adhesives are at the moment the most (Faculty of Forestry 2013). Although studies show that LVL emissions of formaldehyde (0.02 ppm. - 0.04 ppm.) are comparable to CLT (0.015-0.05) (Green and Karsh 2012).

Lessons from laminated wood

All these timber products have increased properties compared to their base materials. Defects can be randomized or left out, strips can be selected for their quality. Smaller tries can be used to make bigger wood products can be made. The shapes can be customized and prefabricated as large elements. Overcoming or reducing the limitations of wood and pushing wood buildings up to the sky. For a 10 floor building in Ecuador using Guadua, the most promising technique is CLT. CLT can be produced in the largest dimensions, is strong in earthquakes and instead of randomizing defects, only the best strips can be used for making structural products. Using the other parts in non structural applications like cutting boards.

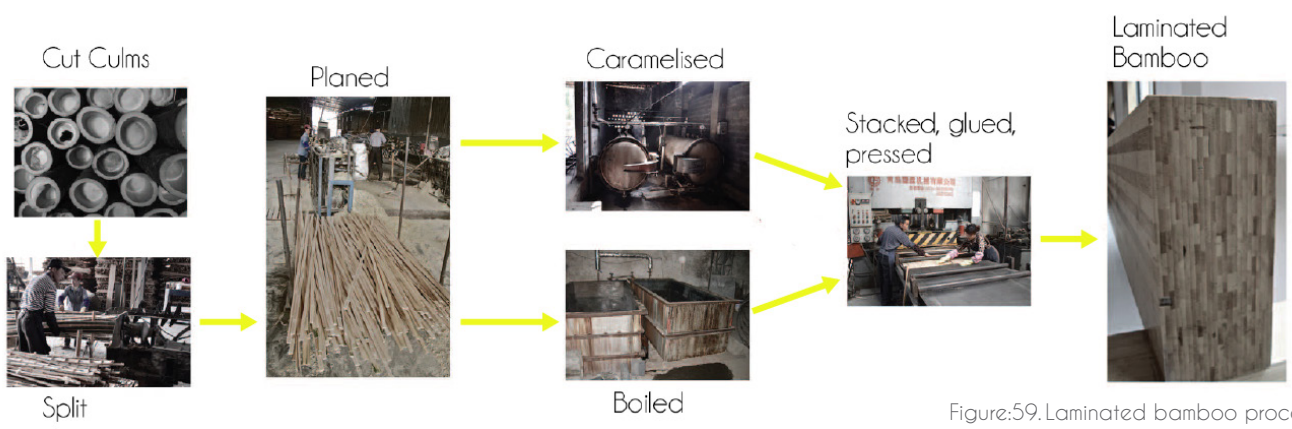# 6. Bamboo industry

Figure:58. Bamboo splitting machine

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

6.1. Laminated bamboo products

Cut Culms

Split

Planed

Caramelised

Boiled

Stacked, glued, pressed

Laminated Bamboo

Figure:59. Laminated bamboo process

To make standard sizes and straight products out of laminated bamboo it needs to be processed. Processed bamboo beams can be made in different ways. Three of them will be discussed in this chapter.

Laminated Veneer Bamboo LVB

Laminated bamboo from Lamboo has been classified as LVB. LVB stands for Laminated Veneer Bamboo an other term frequently found in litarature is LBL (Laminated bamboo Lumber). Under this name it has been included in to the US ASTM building codes in the section D5456 - 14a (ASTM International 2014A). The codes regard LVB as a LVL product although it could also be considered as scaled down version of CLT or Glulam depending on the layup. The reason for regarding LVB as LVL is the strip sizes. LVL/Plywood consists out of 1.5-6mm thick layers, Guadua strips have a thickness up to 5mm (Universidad Nacional de Colombia 2014,February 14). Therefore LVB is comparable to LVL. There is another similarity in the way a beam is made. Bamboo strips are normally first pressed in to plates before the plats are cut at the beam size and glued together in a beam.

Process of Laminated bamboo

After harvest the bamboo culms are dried and cut in different parts for different usage. For structural applications only the first 9-10m (Basa+ cepa) is used of a 12-14m Guadua culm (Flander and Rovers 2009). The rest can be used for other applications. Of the total amount of basas and capas harvested (+/-26.6m³/ha) about20% (5.325m³) can't be used for lamination because of imperfections and damages. Another 24% (6.3m³) is lost in the processing method. About 56% is used in the final structural product. If the process is optimize none of the bamboo is wasted just used for a different purpose. The biggest variation in the mechanical properties is caused by the base material, the glue, the orientation and the pressing of the bamboo.

Strand woven bamboo

In strand woven bamboo the first step is to make small strips. The strips are put through a machine that beats them in to fibers (see image: "*Machine making bamboo fibers*"). The fibers are then drenched in an adhesive put in to a mold and pressed in to a board or beam.

Figure:60. Machine making bamboo fibers

6.2. Price Comparison

Scrimber bamboo

In scrimber the bamboo is cut open and the flattens. The pieces are then caramelized. Caramelizing is similar to heath-treating also known as carbonizing only it is steamed for a shorter period of time and at a lower temperature. It enhances the durability of bamboo by transforming sugar molecules (Grant, n.d.). The bundles are then put in a bath with glue till the bamboo absorbed the glue. The next step is to compress them and then press them. The pressure delivered by the press determines the weight of the product since it compresses its base material. The stronger the press the denser the product will be come and the stronger the product will be (Shangguan, Zhong et al. 2014). Chinese research showed a significant increase in compression strength see image: *"Relation between densification and ultimate compression strength"* to the side. Increasing the density could be useful in a high rise, since in increases the weight and therefore the resistance to wind. This way of producing also allows more material to be used. About 80% of the Basa and Cepa (the first 9-10 meters) can be used for the structural beams.

Price of Manufactured bamboo

For a typical 5x10 (cm) the price for LVB is about 4x that of spruce and about 1.4 times the price of normal laminated timber. With hard wood however it is comparative. The structural laminated bamboo industry needs to solve this price difference. The difference is caused by the lamination process, the size of the industry and the strip selection. In LVB strips have to be more carefully selected and it needs a different form of laminating (Rittironk and Elnieiri 2008). Added to this is the fact that the flooring industry is more advanced and the construction industry still has to cope with the start-up cost and legislation cost making it less compative at the moment. Also the organization, marketing and distribution infrastructure needs to be improved to increase its comparativeness
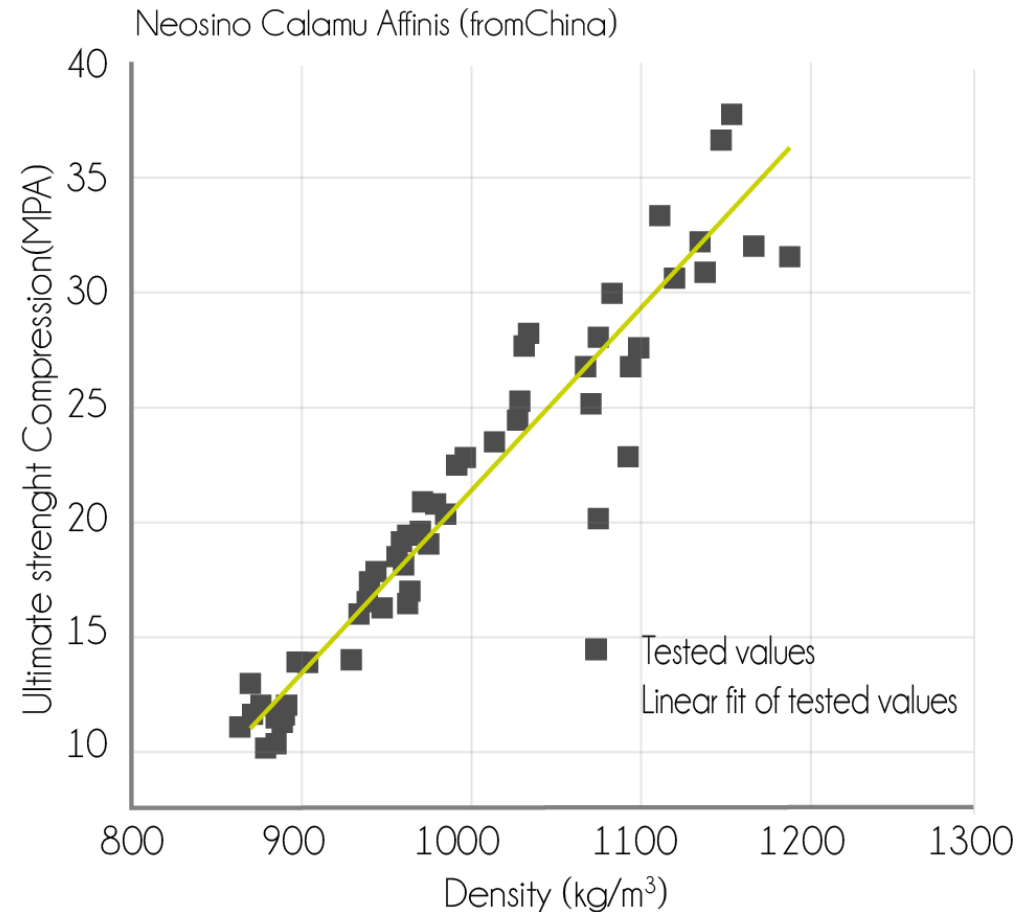

Figure:61. Relation between densification and ultimate compression strength.

Figure:62. Scrimber process

80% used for structural elements the rest for other applications

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

6.3.   Near future advancement

Figure:63. Guadua growing in a adjustable metal frame

Figure:65. Cross laminated panels become thicker and larger

Figure:64. Triangular Guadua compared to round creates larger strips to be laminated

Figure:66. Scrimber beams from China

The structural laminated bamboo industry is operating in a niche market and is relatively young. But the market is growing and laminated bamboo products have high potential to replace the demand for hard wood (van der Lugt and Lobovikov 2008). The bamboo market could be compared to the solar industry 10 years ago. Panels were on the market, but not yet cost effective, but more people start buying it for its sustainable advantages, which resulted in a increase of investments, a decrease of production cost and acceleration in technology development resulting in a comparative product now a days. It could go the same way with laminated structural bamboo.

For example, Colombian market has adopted a Japanese method for shaping the bamboo. Putting in a metal frame one node big ensures that the bamboo will take the form of the frame. Creating a triangular section has as mayor benefit that it creates largest pieces of strips. It can be twice the size of the normal strip size reducing the amount of labor and making it more cost effective (Motta 2014, February 20).

Panel sizes and thickness of panels and beams are ever increasing. Panels are already cross laminated and therefore it seems that in the near future this could result in structural cross laminated load baring floor and wall elements.

Also further development of the scrimber industry can result in a more economical and effective land use where waste is reduced and structural performance is improved. One of the biggest limitations is at the moment is the size of the press, standard presses used can only reach a length of 2.4m according to A. van der Vegte , Project Manager & Senior Manager Quality Control, Research and Development (personal communication June 1, 2015), which is not very uses full in buildings as a construction material, often longer sizes are needed. However there are already some presses on the market that can go longer and in the future this will probably increase further, because of the demands of the industry.
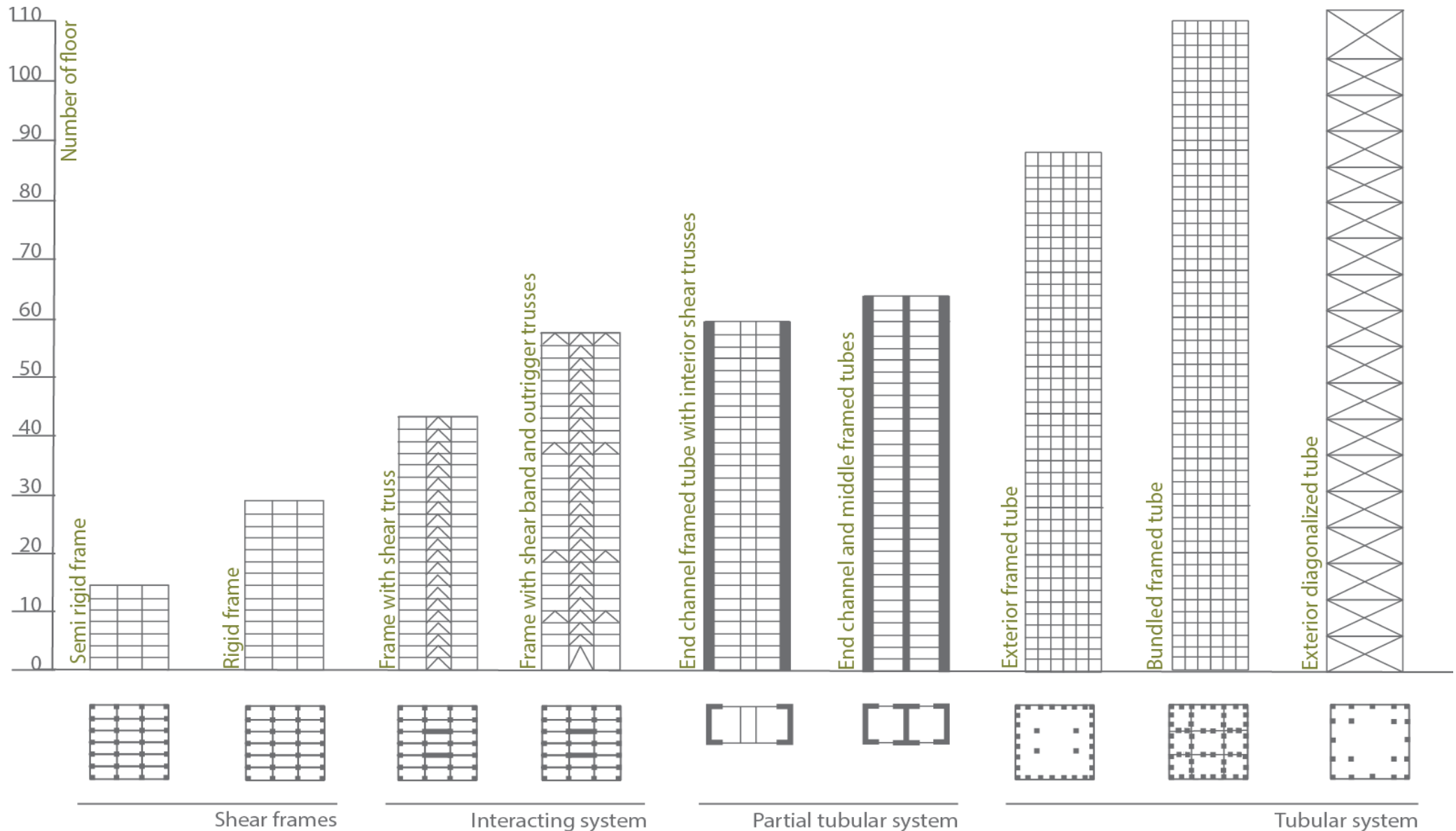
7.Mechanical behavior

Number of floor

- Semi rigid frame
- Rigid frame
- Frame with shear truss
- Frame with shear band and outrigger trusses
- End channel framed tube with interior shear trusses
- End channel and middle framed tubes
- Exterior framed tube
- Bundled framed tube
- Exterior diagonalized tube

Shear frames

Interacting system

Partial tubular system

Tubular system

Figure:67. Different high rise systems

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

7.1. Mechanical overview

Stiffness=3,8e5n/mm²

Size needed to prevent buckling:

Wood Material use:140%
Lamboo Material use:100%
Concrete Material use:62%

3m / 3m / 3m

35cm / 35cm
30cm / 30cm
23cm / 23cm

Figure:68. Size vs stiffness

Density (kg/m³)

Moso MC 10.5% — 605
Guadua MC 12.6% — 690
English Oak MC 13% — 695
Meranti MC 15% — 700
Douglas MC 11% — 530
Spruce MC 12% — 460

Bambooes — Woods

MC=moisture content

Figure:69. Density of common wood like species

To get a better feeling about the material an overview is created comparing Lamboo and GLG form Columbia with oak, soft woods and veneer products.

The overview shows that Lamboo is stronger in every aspect compared to Douglas and LVL and is comparable or stronger than oak. However, a note has to be made, the LVL used is the normal LVL. Not the ones used in tall wood buildings (which are normally densyfied to enhance its mechanical properties).

Important is the Modules of Elasticity (MOE) it is the property of a material that determents the stiffness of an object. The formula is: Stiffness of a element

$$K_s = \frac{A \times E}{L}$$

K_s= The Stiffness
A= The cross-sectional area
E= Modules of Elasticity
L= The length of the object

Buckling

$$F = \frac{\pi^2 \times E \times I}{(K \times L)^2}$$

F = maximum/critical force (vertical load on column),
E = MOE,
I = area moment of inertia,
L = (unsupported) length of column,
K = column effective length factor.
For both ends pinned (hinged, free to rotate), K = 1.0.
For both ends fixed, K = 0.50.
For one end fixed and one end pinned, K = 0.699....
For one end fixed and one end free to move laterally, K = 2.0.
L = is the effective length of the column

The stiffness of a floor is important to be able to create large spans. Large spans means fewer, but bigger columns, creating more freedom in the floor plan and bigger columns are safer in a fire (SOM 2013) and therefore preferable in a bamboo multi storey. The impact of the material for the column size is visualized in figure "*Size vs stiffness*". Buckling is important especially in tall buildings it determines the fore a large part the size of the columns. Both are determined by the MOE and the MOE Lamboo is higher when compared to the wood species and about 62% of concrete.

Material	Laminated bamboo			Wood			Laminated Veneer		Concrete	Steel	
Properties	Guadua Lamboo	Guadua Colombia	Moso still to receive	American Red Oak	Douglas Normal	Douglas structural	LVL Pine	LVL Douglas	C25/30	S235	
Compression parallel	93	60	34.4	46.6	9.2	11.7	20.1	18.8	16.7	235	Mpa
Compression ⊢	21	21.6	9.2	6.1	4.3	4.3	3.6	3.3	16.7	235	Mpa
Tensile Strength	148	61.4	31,8	5.1	4	6.9	12.4	12.1		360	Mpa
Flexural Strength	24.1	85	50.8	25.5	6.2	10.3	19.3	20.1			Mpa
Shear Strength	20	4.7	2.3	7.72	1.2	1.2	2	2			Mpa
Modulus of Elasticity	19305.3	14000	9721-8866	12548	11031.6	13100	13789.5	13789.5	31000	210000	Mpa
Density	690	730	650-700	700	480	480	-	-	2400	7800	kg/m³
Thermal Conductivity	0.14	-	-	0.14	0.12	0.12	-	-			W/m·K (Btu·in/h·ft2·°F)
Thermal Resistivity	7.9	-	-	6.9	8.5	8.5	-	-			W/m·K (h·ft2·°F/Btu·in)
Moisture Content (MC)	4.9	6 to 8	7.7 to 9.8	12	12	12					%
Hardness	12455	-	5687	4200	1868	2669					lbf (Janka Ball test)

Table:5. Overview mechanical properties

To try and see what are the limitations of the material a closer look to the SGR is needed. The results are presented in this paragraph.

Formula

Formula:
$$h= \sigma_{rep}/g$$

SGR=   Stress Gravity Ratio expressed i n (σ_{rep})
σ_{rep} =   Maximum allowable stress in user face (kN/m²)
g=   The gravitational force on a object (kN/m³)
h_{max} =   height

The formula describes the maximum height a building in one material can have if it only has to carry its own weight. All information base on Jellema part 9 except Lamboo(Brinksma, Hofkes et al. 2011).

Lamboo

σ_{rep} =?
g_{Lamboo} =6.90kN/m³
$\sigma_{rep\,Lamboo}$ = 93.000kN/m² (compression parallel)

Ratio between fd and σ_{rep} wood = 10>7 N/mm²
It is unlikely to be the same for bamboo, but likely comparable.
Therefore 93.000x0.7=65.100kN/m²
If Lamboo only had to carry its own eight the hight of the structure could be:
$$h=65.100kN/m²/ 6.90kN/m³=9.4x10³m=9.4km$$

Steel

S235
g_{steel} =78kN/m³
$\sigma_{rep\,steel}$ = 160.000kN/m²

$$h_{max} =160.000/78=2.0km$$

Prestressed Concrete

C40/50
$g_{C40/50}$ =25kN/m³
$\sigma_{rep\,C40/50}$ = 19.000kN/m²

$$h_{max} =19.000/25=760m$$

Wood

C18
g_{C18} =5.5kN/m³
$\sigma_{rep\,C40/50}$ = 7.000kN/m²

$$h_{max} =5.500/7=1.2km$$

Brick

g_{Brick} =18.kN/m³
$\sigma_{rep\,Brick}$ = 2.000kN/m²

$$h_{max} =2.00018=111m$$

Conclusion

Lamboo (laminated Guadua) is by far the strongest in this comparison. It is this weight to strength ratio that leads to a common quote of bamboo enthusiasts: Bamboo is stronger than steel. However this is too simple. There is more to take in to account, and for highrise steel and concrete have strong advantages.

Figure:70. Material's max height considered its stress to weight ratio

Material's max height considered its stress to weight ratio

Lamboo: 9400, Steel S235: 2051, Wood C18: 1273, Concrete C40/50: 760, Brick: 111

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
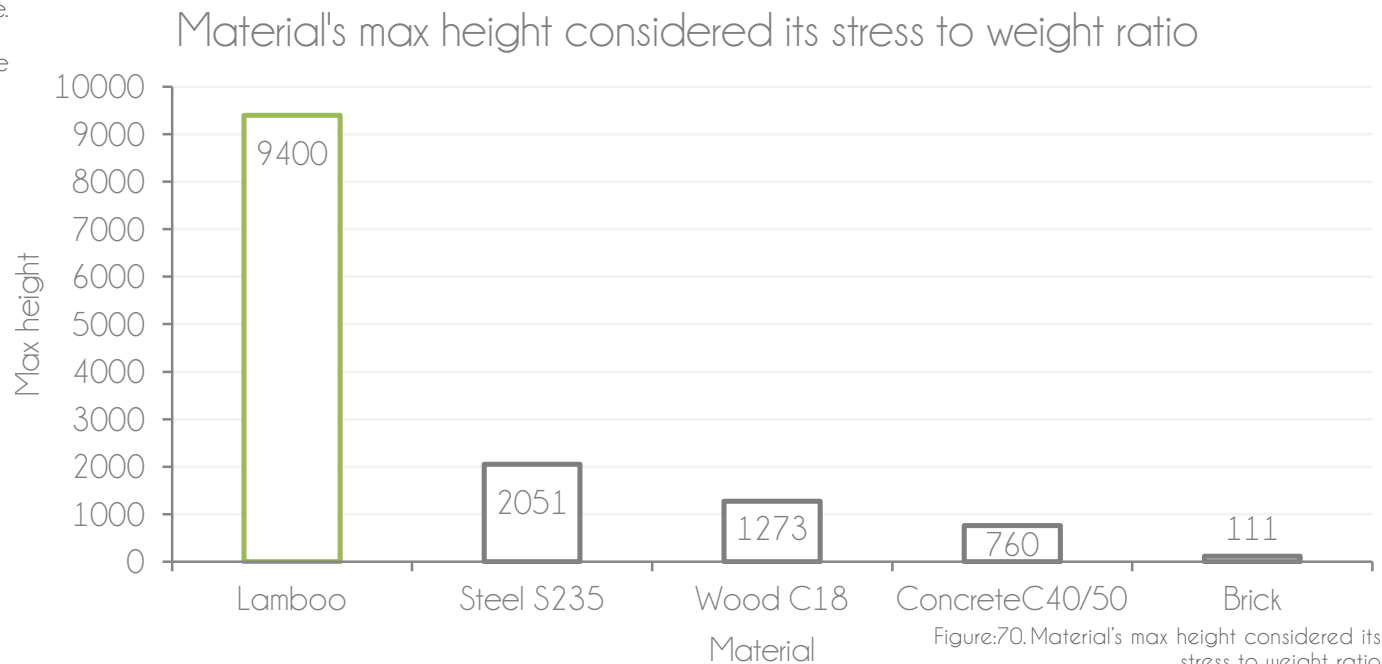
7.3. Flipping point weight/wind

Height Z_e (m)	Zone I			Zone II			Zone III	
	Coast	Rural area	Urban area	Coast	Rural area	Urban area	Rural area	Urban area
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10

Table:6. Wind factor regarding certain height of building adapted form the Dutch standards

Often weight is described as something negative. Often its better to build light weight. This is not the case for high-rise. In multiple story buildings there is a point were weight is needed to counter the moment created by the wind to prevent tension in the foundation. This can be roughly described with the formula:

$$\frac{g}{A} >= (1/8) \times q \times h^2$$

g= the gravitational force on a object
A= area (m²)
q_w = wind factor
h= height of the building

For factor q Dutch standards will be used. Since Guayaquil is in a Delta in a similar position as Rotterdam, Zone I is used. The project will be in an urban area so the values of the urban area will be used.

The first simple calculations will be with values received from A Visual Life Cycle Analysis (Kulik 2014).

$g_{concrete\ structure}$: 14,00 kN/m²/floor
$g_{wood\ structure}$: 4,40 kN/m²/floor (stick and beam)
$g_{bamboo\ structure}$: 4,20 kN/m²/floor (stick and beam)

Kulik assumes that because of the higher strength of bamboo less material has to be used. Next to a stick and beam a mass timber and a hybrid structure will be compared.

100% Bamboo (stick and beam structure)

Number of floors: 4
Height: 12m
Floor height: 3m
q: 0,728
$g_{bamboo\ structure}$: 4,20 kN/m²/floor
$g_{building}/A=$ 4,20 kN/m²/floor x 4 floors = 16,8kN/m²
$M_{wind} =$ (1/8)x 0,728x(12²)=14,04kN/m²
16,8kN/m² > 14,04kN/m²

Maximum of 4stories in normal stick and beam bamboo buildings.

100% Lamboo (mass timber)

For mass bamboo the weight is estimated on:

$g_{structure} =$ 3,7 kN/m²/floor

$g_{foundation} =$ 1 kN/m²/floor

$g_{finish} =$ 2 kN/m²/floor

$g_{tot} =$ 6,7 kN/m²/floor

Number of floors:	6
Height:	18m
Floor height:	3m
q:	0,86

$g_{building}/A=$ 6,7 kN/m²/floor x 6 floors = 40,2kN/m²

$M_{wind} =$ (1/8)x 0,86x(18²)=34,83kN/m²

At 19m q=0.88

$M_{wind} =$ (1/8)x 0,88x(19²)=39,71kN/m²

$g_{building}/A$ > M_{wind}

40,2kN/m² > 39,71kN/m²

Limit in this system is just below 20 meters and 6 stories

Hybrid structure example

Number of floors:	10
Height:	31m
Floor height:	3.1m
q:	1.04

$g_{bamboo\ structure}$: 11,83 kN/m²/floor+1x24 for ground floor

$g_{building}/A=$ 11,83 kN/m²/floor x 9 floors+24 kN/m²/floor = 130kN/m²

$M_{wind} =$ (1/8)x 1,04x(31²)=131kN/m²

16,8kN/m² > 14,04kN/m²

A maximum of 10 floors before the wind becomes stronger than the weight of the building and tension in the connections occurs. A solution could be to density the bamboo from 690kg/m³ up to 1300kg/m³ and using a scrimber method or prestressed the lamboo.

So to go up in the air without reaching the flipping point a hybrid structure is needed.

$G_{construction/floor}/FLOOR$

$g_{Material} = \rho_{Material} x$ m³/floor

CONCRETE

$\rho_{concrete} =24kN/m³$

m³/floor $_{concrete} =62,5m³/floor$

$g_{concrete} =24x62,5=1.500kN/floor$

LAMBOO

$\rho_{Lamboo} = 6,9kN/m³$

m³/floor $_{Lamboo} =543m³$

$g_{Lamboo} =6,9x543=3747kN/floor$

$g_{constructionfloor} =g_{Lamboo} +g_{concrete} =$

$g_{construction/floor} =1.500+3747=5247kN/floor$

Lamboo/floor
Shearwalls
T=0,4m
L=10m
H=3,3m
St=8st
V=0,4x10x3,3x8=105m³

Lamboo/floor
Facades
T=0,4m
LxB=30x30m
H=3,3m
Openings=60%
V=0,4x30x4x3,3x0,4=158m³

Lamboo/floor
Floors
T=0,35m
LxB=30x30m
Openings=10x10m
V=0,35x(30x30-10x10)=280m³

Lamboo/floor
Tot=shearwalls+facadse+floors
105+158+280=543m³/floor

Concrete ground floor
V_{Tot}=Lamboo/floor+core/floor
534+62.5=596,5m³/floor
$\rho_{concrete} =24kN/m³$
$g_{constuction ground floor} =24x596,5=14.316kN/floor$
A=LxB=30x30=900m²
$g_{construction} =14316/900=16kN/floor$
$g_{fundation} =4kN/m²/floor$
$g_{finish} =2kN/m²/floor$

g/a/floor=$g_{constuction ground floor} +g_{fundation ground floor} +g_{finish ground floor}$
=16+4+2=24kN/m²

Concrete core/floor
Walls
T=0,4m
LxB=10x10m
H=3,3m
Openings=10%
V=0,4x10x4x3,3x0,9=47.5m³

Concrete core/floor
Floors
T=0,3m
LxB=10x10m
Openings=50%
V=0,3x10x10x0.5=15m³

Concrete core/floor
Tot=walls+floors
47.5+15=62.5m³/floor
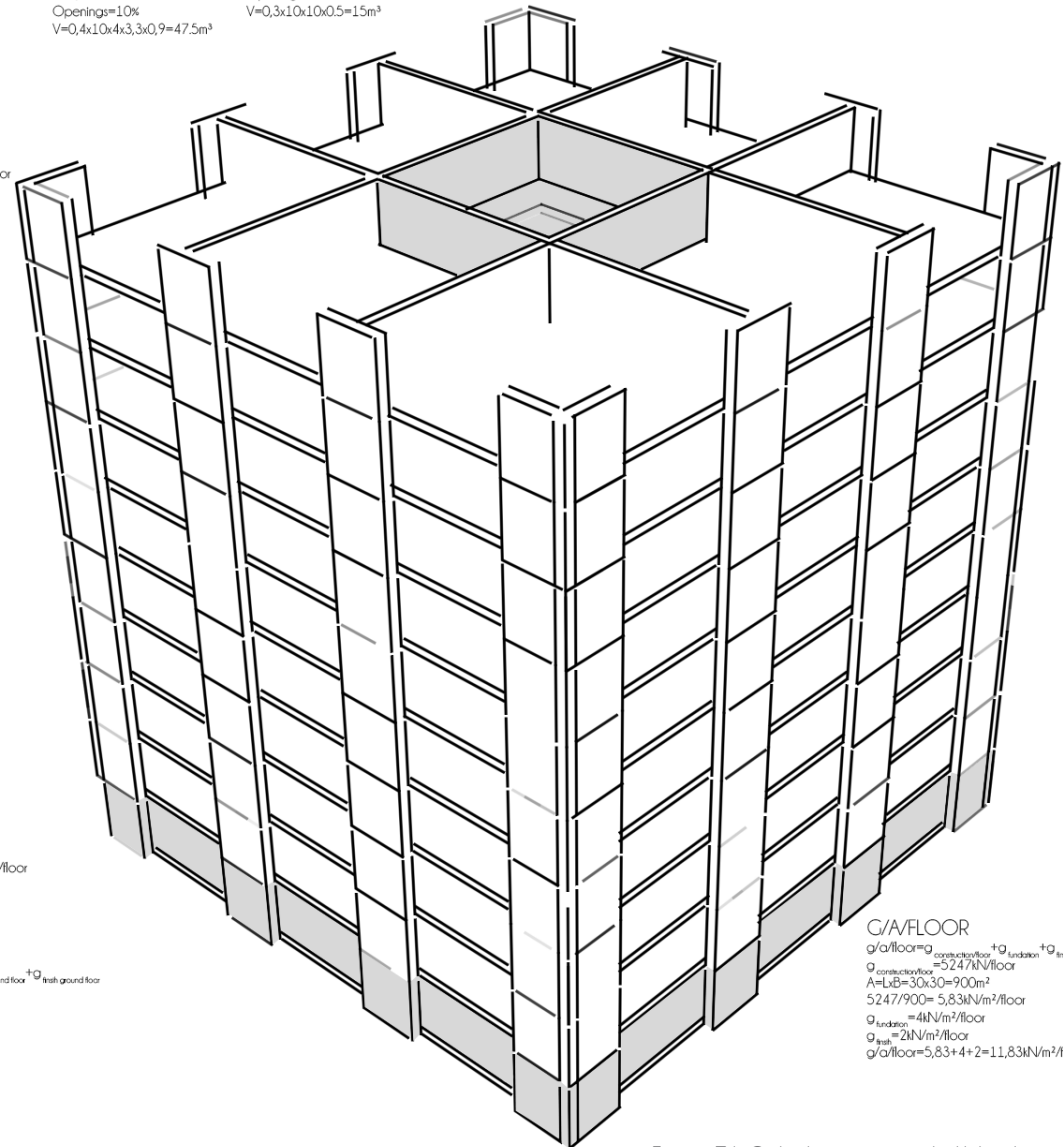
G/A/FLOOR
g/a/floor=$g_{construction/floor} +g_{fundation} +g_{finish}$
$g_{construction/floor} =5247kN/floor$
A=LxB=30x30=900m²
5247/900= 5,83kN/m²/floor
$g_{fundation} =4kN/m²/floor$
$g_{finish} =2kN/m²/floor$
g/a/floor=5,83+4+2=11,83kN/m²/floor

Figure:71. Calculation example Hybrid structure

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

7.4. Creep

Material (Standard)	Service Class 1	Service Class 2	Service Class 3
Solid timber[1] (EN 14081-1)	0.60	0.80	2.00
Glued-laminated timber (EN 14080)	0.60	0.80	2.00
Plywood (EN 636[2])			
Part 1	0.80	-	-
Part 2	0.80	1.00	-
Part 3	0.80	1.00	2.50

Table:7. Deformation modification factor, $_{kdef}$ (table 3.2. EN 1995-1-1)

Material/Load Duration Class	Service Class 1	Service Class 2	Service Class 3
Glued-Laminated Timber			
Permanent	0.60	0.60	0.50
Long term	0.70	0.70	0.55
Medium term	0.80	0.80	0.65
Short term	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90
Plywood[1]			
Permanent	0.60	0.60	0.50
Long term	0.70	0.70	0.55
Medium term	0.80	0.80	0.65
Short term	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90

Table:8. Strenght modification factor, K_{mod} (table 3.1. EN 1995-1-1)

For tall buildings with mixed materials it is important to consider the effects of creep. Creep(ε_φ) is a permanent deformation caused by permanent loads (dead loads) under the influence of time and can be related to elastic deformation (ε_{be}). The creep coefficient (φ) is the connection between the elastic deformation and the deformation caused by creep.

$$\varphi = \frac{\varepsilon_\varphi}{\varepsilon_{be}}$$

φ = Creep coefficient
ε_φ = Creep
ε_{be} = Elastic deformation

The larger the creep coefficient the larger the deformation over time. Larger deformation could lead to failure. However the biggest problem is a different deformation in different parts of the structure. This results in tension in the connections and could lead to failure in the connections which could lead to an overall failure of the building.

Creep coefficient (φ):
Steel   0
Concrete   2-3
Wood   1
Bamboo   1*
(Brinksma, Hofkes et al. 2011)

Bamboo behaves similar to wood, but the precise value for laminated Guadua still has to be determined, however for this report the value of wood will be used for LVB plywood will serve as reference. However, TU Delft is trying at the moment to obtain the Lamboo material to test it regarding creep. The building will be designed for 50 years or more, therefore the dead loads will be considered permanent. Permanent loads are load present on the building for 10 years or more, see next page. For glue laminated timber (GLT) the k_{def} and k_{mod} are 0.60, see table to the side. These values are from the Canadian CLT handbook (Gagnon and Pirvu 2011).

For CLT panels and Plywood creep values are about 30-40% higher than that of glue laminated timber, because of the crosswise layers (Gagnon and Pirvu 2011). Assumed will be that this ratio also will be valid between LVB beams(100%) and LVB walls/plates (130%-140%) (CLB). This is an additional design challenge. To calculate the deformation of timber structures the Eurocode 5 prescribes the following formula's in clause 2.2.3 of EN 1995-1-1 (Porteous and Kermani 2013). These guidelines will be used to calculate deformation of bamboo columns and floors.

If it is allowed to translated it one to one is the question, further research is needed but some research hints towards a better creep behavior of laminated bamboo when compared to wood. In other words less deformation over time (Ma, Wang et al. 2014). Therefore, it seems safe to use wood values although it might have a negative impact on the costs because more material is needed.

Deformation by permanent loads including creep
$$U_{fin,P} = U_{inst,P} * (1+k_{def})$$

$U_{fin,P}$ = The final deformation by permanent loads
$U_{inst,P}$ = Instant deformation by permanent loads
k_{def} = Deformation modification factor (0.8 for LVB / 0.6 for GLB)

Deformation by main live loads including creep
$$U_{fin,Q1} = U_{inst,Q1} * (1+ \psi_{2,1} *k_{def})$$

$U_{fin,Q1}$ = The final deformation by main live loads
$U_{inst,Q1}$ = Instant deformation by main live loads
$\psi_{2,1}$ = Factors for main live loads that are semi permanent applied. For residential buildings ψ_2=0,3 with permanent floor loads (2.5 kN/m²), For wind ψ_2=0.
k_{def} = Deformation modification factor (0.8 for LVB / 0.6 for GLB)

Deformation by accompanying live loads including creep
$$U_{fin,Qi} = U_{inst,Qi} * (\psi_{0,i} + \psi_{2,i} *k_{def})$$

$U_{fin,Qi}$ = The final deformation by accompanying live loads
$U_{inst,Qi}$ = Instant deformation by accompanying live loads
$\psi_{0,i}$ = Factors for combination value of live loads (its unlikely that all floors are occupied to its maximum capacity). For residential ψ_0=0,4
$\psi_{2,i}$ = Factors for accompanying live loads that are semi permanent applied. For residential buildings ψ_2=0,3 with

permanent floor loads (2.5 kN/m²), For wind ψ_2=0.
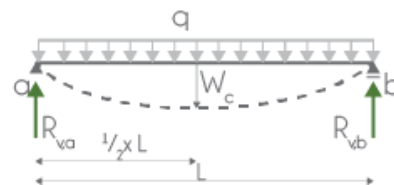k_{def} = Deformation modification factor (0.8 for LVB / 0.6 for GLB)

Total deformation including creep
$$U_{fin} = U_{fin,P} + U_{fin,Q1} + U_{fin,Qi}$$

U_{fin} = Total deformation including creep
$U_{fin,P}$ = The final deformation by permanent loads
$U_{fin,Q1}$ = The final deformation by main live loads
$U_{fin,Qi}$ = The final deformation by accompanying live loads

Example
Both sides supported beam with hinged connections

Dead loads
· Solid cross laminated bamboo floor with a span of 5.7 m and a thickness of 25 cm (17cm Lamboo and 8cm recycled wood) with a density of 6,9 kN/m³. Own weight of 6,9x0,25=1,7 kN/m²
· Separation walls= 1,2 kN/m²
· Installations: 0,5 kN/m²
· Concrete floor (50mm) = 1,2 kN/m²
Total 1,7+1,2+0,5+ 1,2 =4,6 kN/m²

Life loads
· Floor load of 2.5 kN/m² (Office load used to increase possibilities of reuse (dwelling 1.75kN/m²))

q load including live and dead loads with creep effect:
$U_{fin,P}$ =4,6x(1+0,8)=8,3 kN/m²
$U_{fin,Q1}$ =2,5x(1+0,3x0,8)=3,1 kN/m²
$U_{fin,Qi}$ =Non present
U_{fin}=q=8,3+3,1=11,4kN/m²=11,4 kN/m

Deformation can then be expressed in:

$$W_c = \frac{5 \times U_{fin} \times L^4}{384 \times E \times I}$$

W_c= W_{tot}
U_{fin}=q= 11,4 kN/m=11,4 N/mm
L=5400 mm
E=19305 GPa
I=(1/12)xbxh³= (1/12)x1000x(170)³=4.09x10⁸mm⁴
$$W_{tot} = \frac{5x11,4x(5400)^4}{384x19305x4.09x10^8} =16.0mm$$

W_{max}=0,004xL
W_{max}=0,004x5700=22,8mm
W_{tot} < W_{max} Maximum deformation floor is adaptable

The strength of the recycled wood is not included when added this decreases the creep significantly. It is the fire protection layer, it's thickness in accordance with Gagnon and Pirvu (2011) values for CLT. A site note has to be made, special care has to be taken regarding the selection of adhesives to create adequate fire safety see the chapters *Fire behavior* and *Adhesives*. In the appendix structure, the full calculation can be found regarding the proposal.

Service Class	Climatic Condition
Service class 1	Moisture content (MC) of material @ 20°C and > 65% relative humidity (RH) for a few weeks per year (softwood timber MC < 12%; panels MC < 8%)
Service class 2	Moisture content (MC) of material @ 20°C and > 85% relative humidity (RH) for a few weeks per year (softwood timber MC < 20%; panels MC < 15%)
Service class 3	Condition leading to higher MC than Service class 2 (softwood timber MC > 20%; panels MC > 15%)

Note: CSA O86-09 defines dry service conditions as climatic conditions at which MC of solid wood is less than 19% per year (equilibrium MC ≤ 15%). Wet service conditions correspond to all conditions other than dry.

Table:9. Service classes (clause 2.3.1.3. EN 1995-1-1)

Load Duration Class	Accumulated Duration of Load
Permanent	> 10 years
Long term[†]	6 months - 10 years
Medium term	1 week - 6 months
Short term	< 1 week
Instantaneous	N/A

Note: [†]Standard term for load duration factor in CSA O86-09 exceeds 7 days but it is less than almost continuous loading throughout the life of the structure.

Table:10. Load duration classes (table 2.1. EN 1995-1-1)

7.5. Shear

Shear

Shear force can be described as a force perpendicular to the extension of the element. Resistance against shear forces is often called shearing force or viscosity and it given the letter τ (Tau). The shear force can be determined by the formula:

τ=F/A

τ= Shearing force (resistance factor against shear)(N/mm²)
F= Force applied (N)
A= Area (mm²)

The shearing force will be largest in the bottom part of the design and need to be checked. The are verified with hand calculations. The calculations are included in the appendix under structure, the results are shown here.

$$F_{Shear\,(point\,x)} < \tau_{l\,amboo} \times A_{core}$$

$$894\ kN < 0.02 \times 6.84 \times 10^6 = 1.37 \times 10^5$$

Based on the calculations it seams that shear is no problem in the design.

Rolling shear

There is one other kind of shear which plays a role in laminated beams/strips it's called rolling shear. In wood it's believed that wood with edge gluing could have higher load carrying values, because of reduced chance of rolling shear, although no research has been constructed jet. With bamboo this is not the case, LVB will always be edge glued. For CLT lumber the rolling shear is estimated to be between 40 and 80 MPa (Gagnon and Pirvu 2011), depending on width to thickness ratio, wood species, adhesives used and how applied (edge glued or not). At least a width to height ratio of 4 to 1 is recommended, and European codes demand verification at a ratio of less then 3.5 (Gagnon and Pirvu 2011). Rolling shear is normally caused by internal stresses caused by bending. In this report the rolling shear is not included in the calculations. This could be a further study.
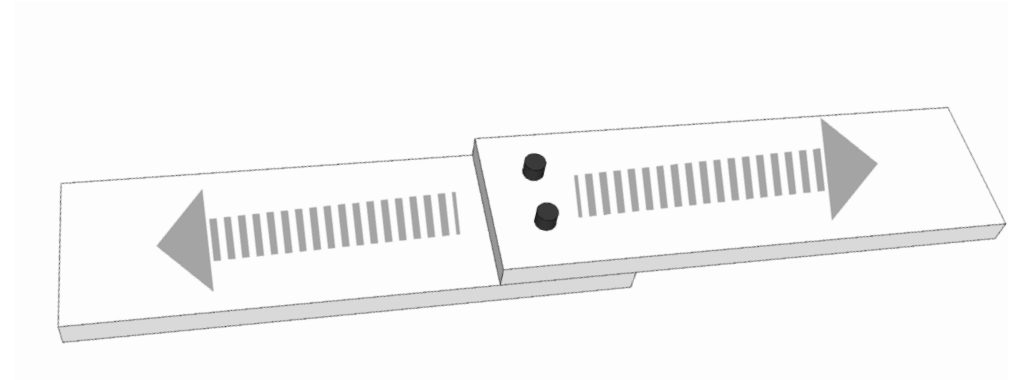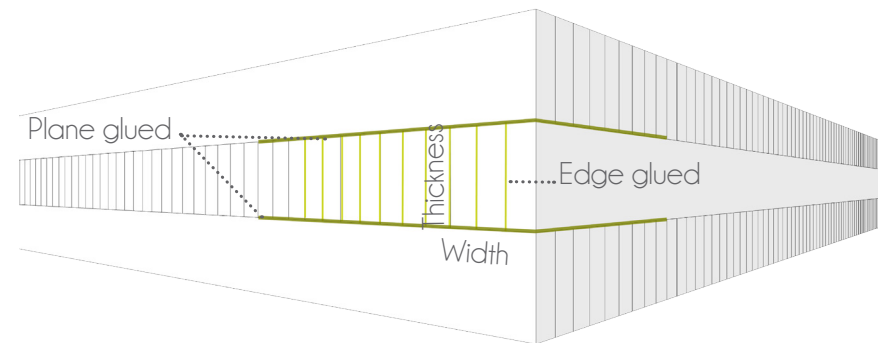

Figure:72. Shear principal

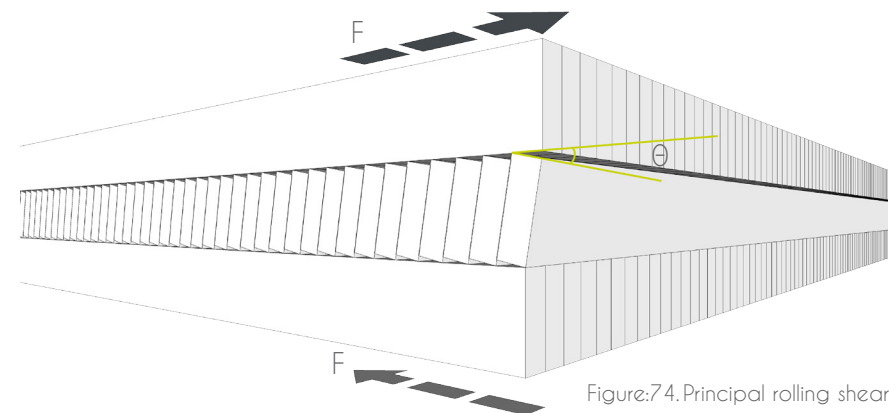Figure:73. Difference plane and edge glued

Figure:74. Principal rolling shear

7.6. Deformation

Deformation

For high buildings it's not only about the ultimate state of the vertical elements, equally important is the deformation caused by horizontal forces. In this paragraph the fundamentals will be explained.

In case of only using a stiff core to withstand the lateral forces the top floor will deform the most. See it as it is a tree, if the wind blows at the tree the top will deform further than the bottom trunk. The core is basically a big beam that is clamped at the foundation, the further away from the base the bigger the forces become. The biggest problem of this is the usability. Having floors that are tilted gives people an unsafe feeling.

In a stiff frame work the bottom columns will deform the most and potentially create dangers situations since the bottom columns are no longer loaded in their central axes and leaning over. The reason that the top deforms less is because each moment connection can take a certain amount of moment. On the top floor it only has to take care of the moment created in the top floor. The floor underneath the top floor has to withstand its own moment and the moment created on the top floor, and so on to the base were the forces are the strongest.

The two systems can also be combined. See the system as two springs resisting a force. The core is stiffer than the frame work and could therefore be seen as the stiffer spring. A stiffer spring will absorb more of the force than the weak spring; the core is normally significantly bigger than a stiff frame. Looking at it this way it doesn't seem logical to combine the two, but there is more. The big advantage comes from the fundamental difference in reaction towards lateral loads (Brinksma, Hofkes et al. 2011). A stiff core will reduce the deformation in the bottom and a stiff frame will reduce the deformation in the top.

The maximum amount of deformation is set on 1/500 of the height of the building and its maximum axial tilt also known as maximum obliquity 1/300 of the height of the building.

For example a building of 50m height cannot be deformed by more than 10cm and can only have an angle twist of 0.16o.

Although the proposal uses shear walls and a stiff frame it is calculated as if only a stiff core is used. In the appendix the full calculations can be found regarding the performance of the proposal, in this sub-chapter only the final step is shown, see calculation on the side. It shows that the building can with stand the forces.

Moment fixed frame

Distortion by lateral force

+

Stiff core

Distortion by lateral force

Combi core and moment fixed frame

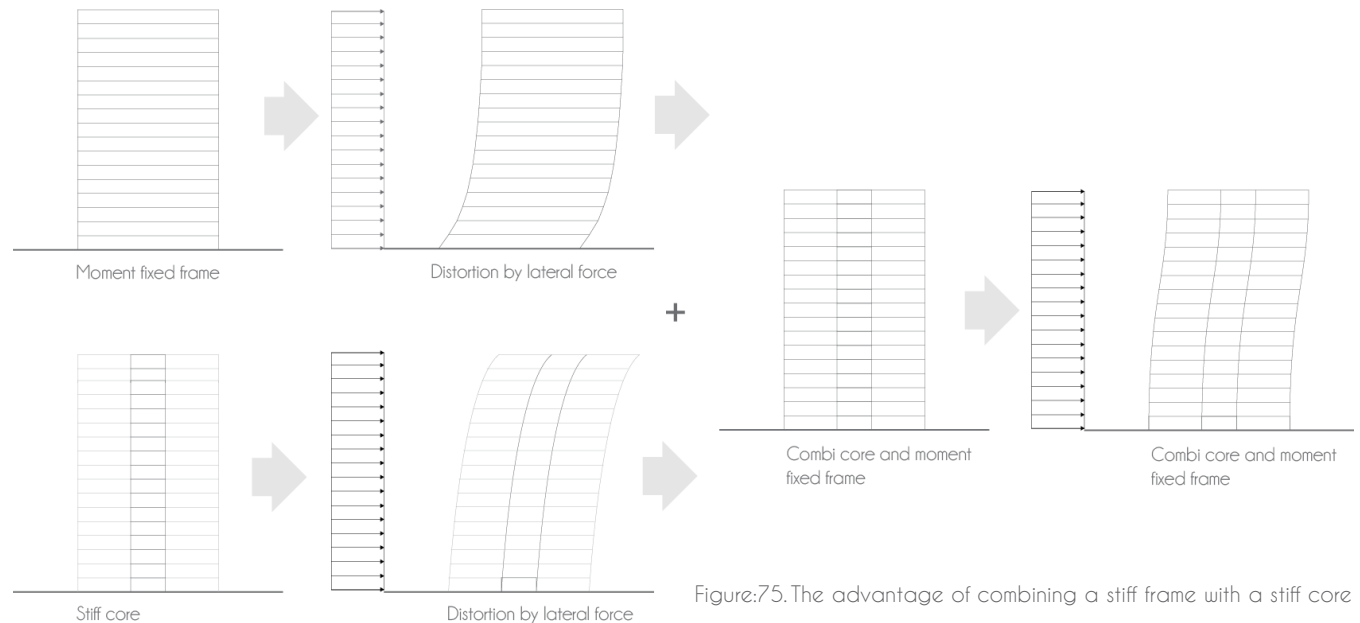Combi core and moment fixed frame

Figure:75. The advantage of combining a stiff frame with a stiff core

$$E \times I > 62.5 \times Q_{rep} \times l^3$$

$$19305 \times 3.71 \times 10^{13} > 62.5 \times 22.32 \times (3.96 \times 10^4)^3$$

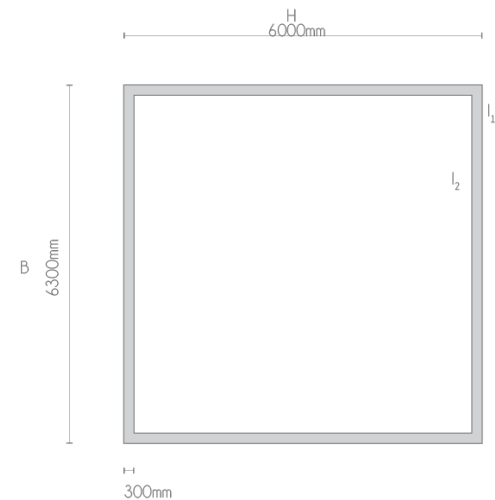$$7.16 \times 10^{17} > 8.28 \times 10^{16}$$

H
6000mm

B
6300mm

l_1

l_2

300mm

Figure:76. Dimensions core

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

7.7. Building system

Figure:77. Different high rise systems

Bar chart labels (left to right):
- Semi rigid frame
- Rigid frame
- Frame with shear truss
- Frame with shear band and outrigger trusses
- End channel framed tube with interior shear trusses
- End channel and middle framed tubes
- Exterior framed tube
- Bundled framed tube
- Exterior diagonalized tube

Y-axis: Number of floor (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110)

System groupings: Shear frames | Interacting system | Partial tubular system | Tubular system

Figure:78. Different kind of stiff core configurations

Split core | End core | Atrium core | Multiple core | Multiple core 2

System overview

Building a high building can be done using various building systems. Each system has it advantages and disadvantages which determine the possible height of a building. The image: "*Different high rise systems*", is an image which often can be found in literature as for example in Buyukozturk and Gunes (2004).

However there are more options and a lot of combinations. Shear frames or shear resistant portals are simple and effective with a lot of freedom and flexibility; however when a certain height is achieved the moments in the connections becomes too great. Adding shear trusses or shear walls (stiff cores) reduce the moments in the connections and allow the building to become higher. When shear bands or stiff frames are added the stiffness of the overall system can be drastically increased allowing for the height to be increased. The limitation is the position of the shear walls/trusses. The closer to the center the less effective the elements are. When the shear walls are moved to the outside the resistance against the wind increases (the same principle as using a higher steel profile to increases the stiffness) allowing for a higher building. To build beyond the limits of a partial tubular system is to build with a load baring facade also known as an exterior framed tube. When one tube is not enough a bundle of tubes can be used to push the height up even further and the system that allows the greatest heights is a super triangular frame on the outside.

For the proposal a couple of systems were considered a rigid frame making use of portals, a frame with shear trusts (or in the case of the proposal a core), partial tubular system using a load bearing facade and a triangular super frame on the outside. The last option seems to make sense if you want to build high and showcase the structural opportunities of LVB, however it has been discarded because exposing the laminated bamboo to the hot humid climate and therefore reducing the lifetime of the structure was not preferable because of sustainable reasons. A partial tubular system has also been considered. However the results during designing were not satisfying. The system would allow higher buildings, but the chosen 12 story building is fitting in the context an already a structural challenge. On the other hand the rigid portal frame building allows all wood connections but is limited to 7 or 9 stories. But if you have a staircase why not use it, staircases are not flexible in designs and to make the walls around it structural makes sense, allowing the rest of the building to be more open and allowing the building to be higher than 9 stories.

Hybrid or not?

Beside the choice for a certain structural overall system it was also necessary determine if the building would be hybrid and if the building needs to be hybrid to what extend?

Proposals from SOM (2013), Green and Karsh (2012), Timmer (2011), Buchanan, Deam et al. (2008), Shigeruban (2013), Vest Cran (2014) and the buildings summarized in Babrauskas, (2004) all have been studied. Full wood was too limited, but in combination with steel and concrete it could make a very competitive and resilient system.

An impression of the different systems:
1. CLT mass Timber buildup Fixed layout and small rooms (Babrauskas, 2004)
2. All wood portal connections with massive wood elements, with concrete floor topping (Shigeruban 2013)
3. Vertical wood elements and wood floors clamped between reinforced concrete beams (SOM 2013).
4. Mass space frame with boxes stacked in to it (fully wood)(Vest Cran 2014) .
5. External wooden space frame. with steel connectors (Timmer 2011),.
6. A combination of horizontal steel beams and timber floors and vertical elements with a concrete topping to add weight. (Green and Karsh (012).
7. Press lam, structure. Wooden beams with an embedded steel tendon and concrete floor toppings (Buchanan, Deam et al. 2008).

The system proposed in this research is somewhere between the press lam and the proposal from Green and Kash. And will be structurally explained on the next pages.
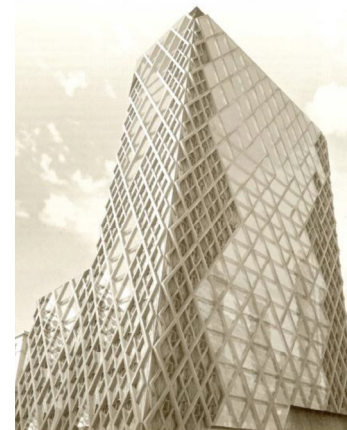

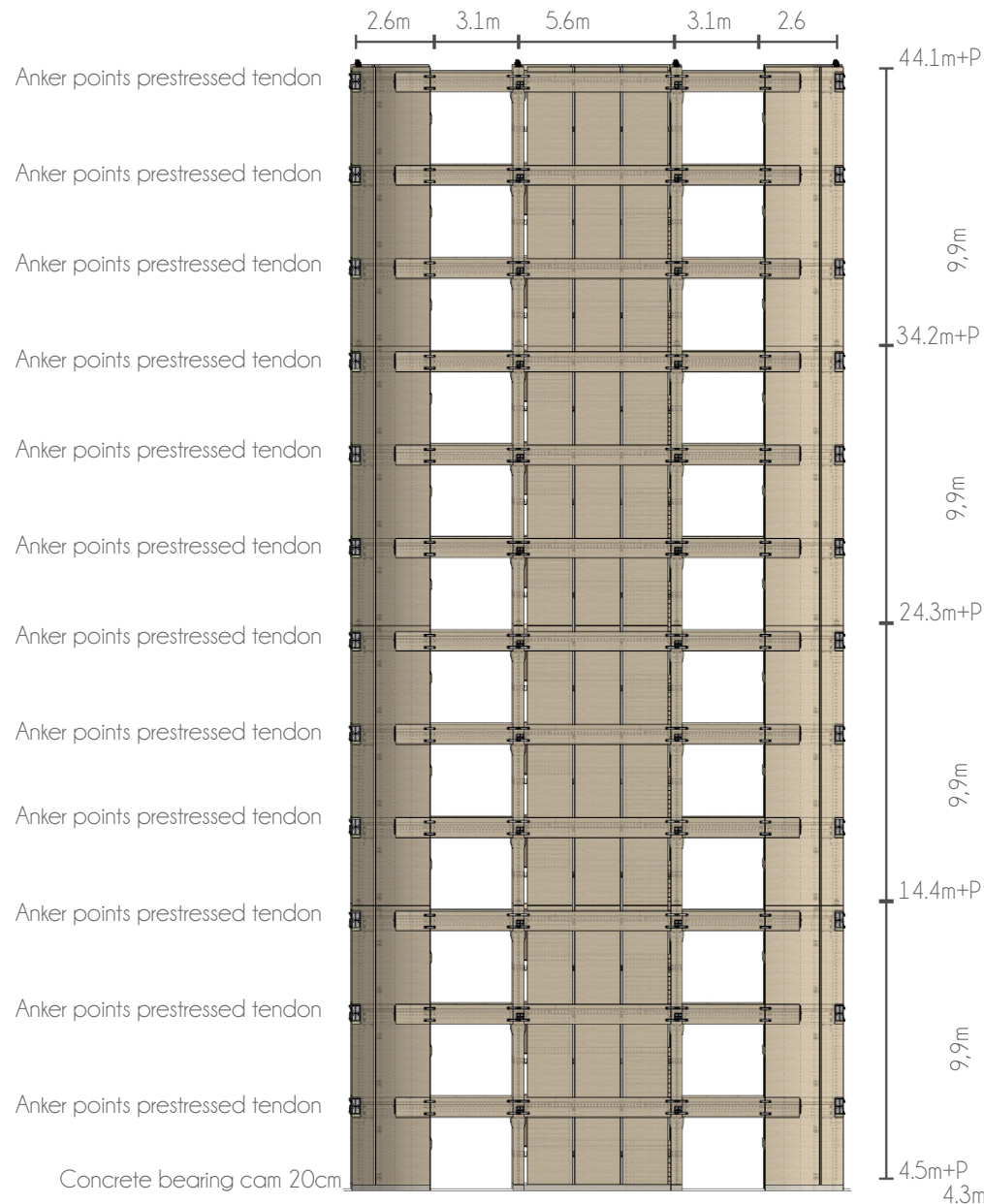Figure:79. Overview different Tall timber buildings/proposals

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Building system

2.6m	3.1m	5.6m	3.1m	2.6

Anker points prestressed tendon — 44.1m+P

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon — 34.2m+P

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon — 24.3m+P

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon — 14.4m+P

Anker points prestressed tendon

Anker points prestressed tendon

Concrete bearing cam 20cm — 4.5m+P
4.3m+P

9,9m / 9,9m / 9,9m / 9,9m

Figure:80. Proposal, North/south elevation

2.6m	3.1m	5.6m	3.1m	2.6

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Anker points prestressed tendon

Concrete bearing cam 20cm

Figure:81. Proposal, West elevation

The system

The 12 story tower is buildup out of vertical elements staked 4 times. Each element is 9.9m long and less than 2.5m wide allowing easy transport. The vertical elements are dominant to improve the earthquake behavior. The horizontal beams are squeezed between the vertical elements. Floors span (were possible) multiple spans reducing the working time and reducing the necessary thickness caused by deformation.

If this is possible depend on the shrining rate of the different elements. If the columns shrink less than the core in a certain amount of time or the other way around the tensions in the floor could become too great. This is not investigated and depends on building height, ground conditions and creep factor of materials and the size of the elements. This is considered further research but for now it is presumed that it is possible.

The core makes use of two connected timber elements with a sound isolation material in-between. This could be rock wool or any other soft isolation material as long as the material is fire resistant.

To support the two ventilation shafts the corresponding floor have been strengthened by adding additional beams.
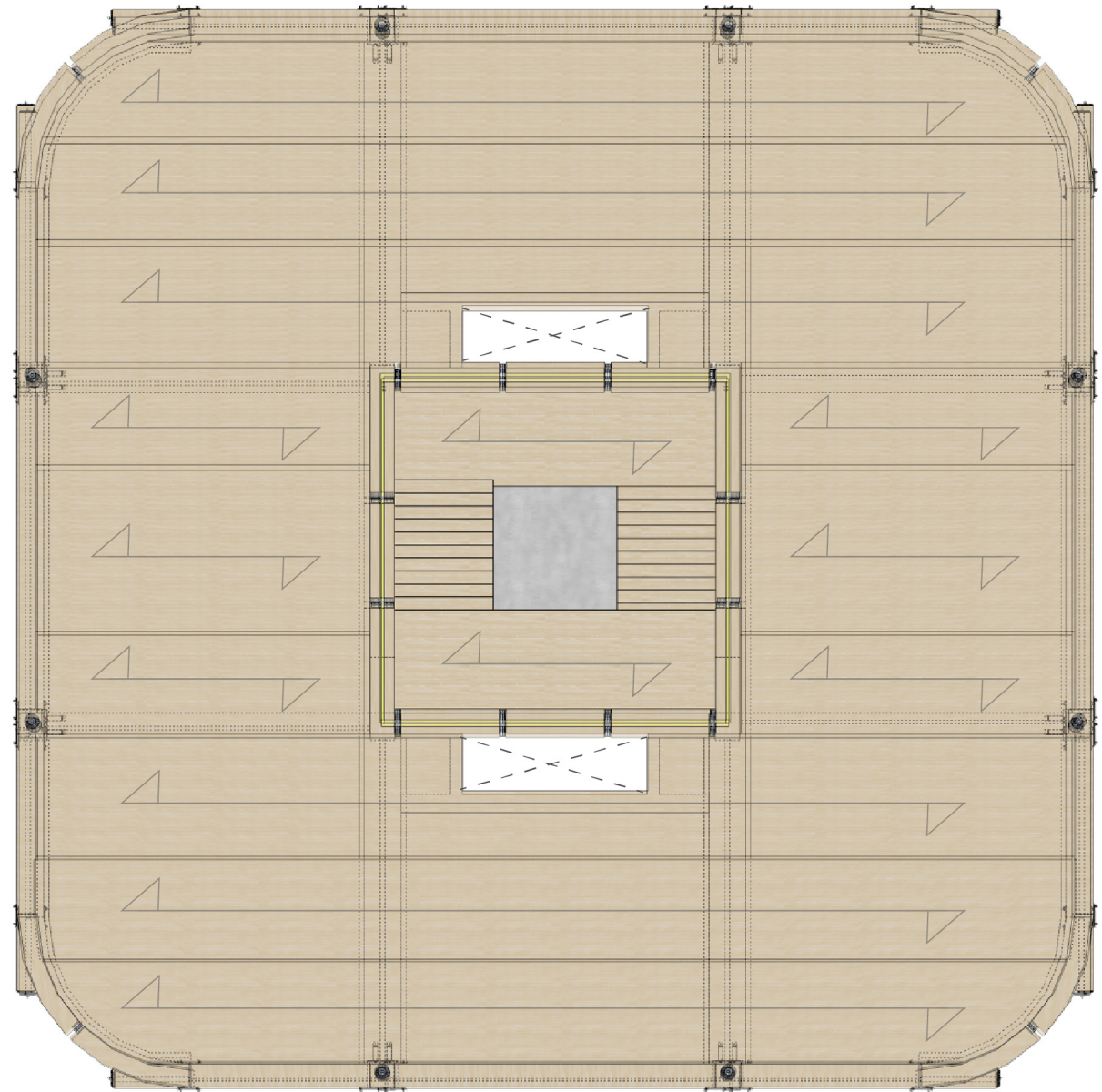
Figure:82. Proposal Span direction floors

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

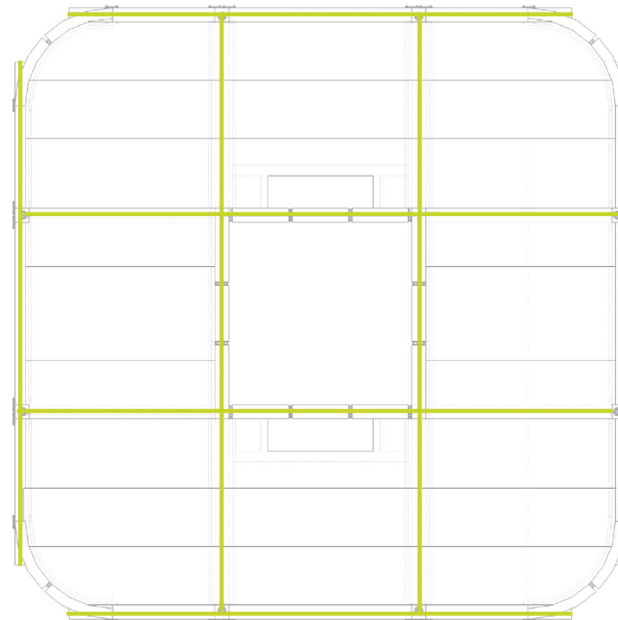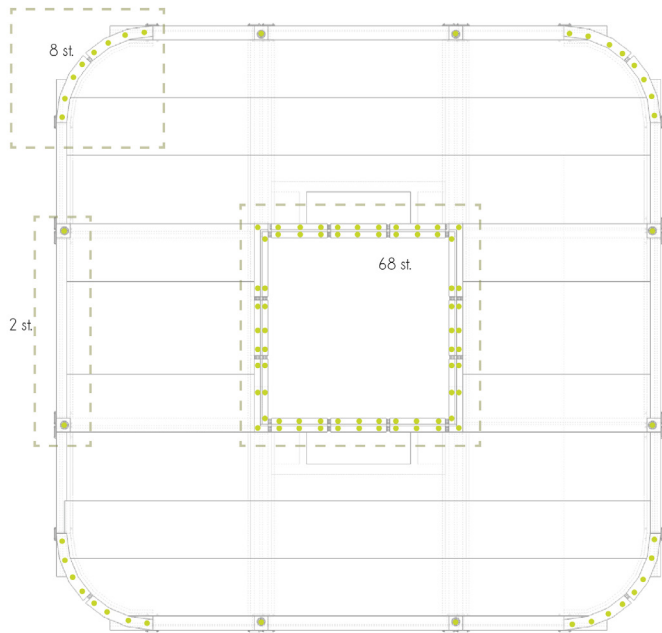# Building system

8 st.

68 st.

2 st.

Figure:83. Orientation of tension cables

Tendons

Per floor there are 108 vertical steel tendons and 8 vertical tendons. 30 of the vertical cables only run in the wall elements them self, the others run from the top floor to the concrete base level. The elements that only run in one element are to prevent tension on elemental level in the elements. The cables running all the way do the same but then on building level by adding extra compression force. The wall elements and have each two tendons running down. Having two tendons running down also improves the stability during earthquakes.

Pre- compressed LBV

Forces cause by wind
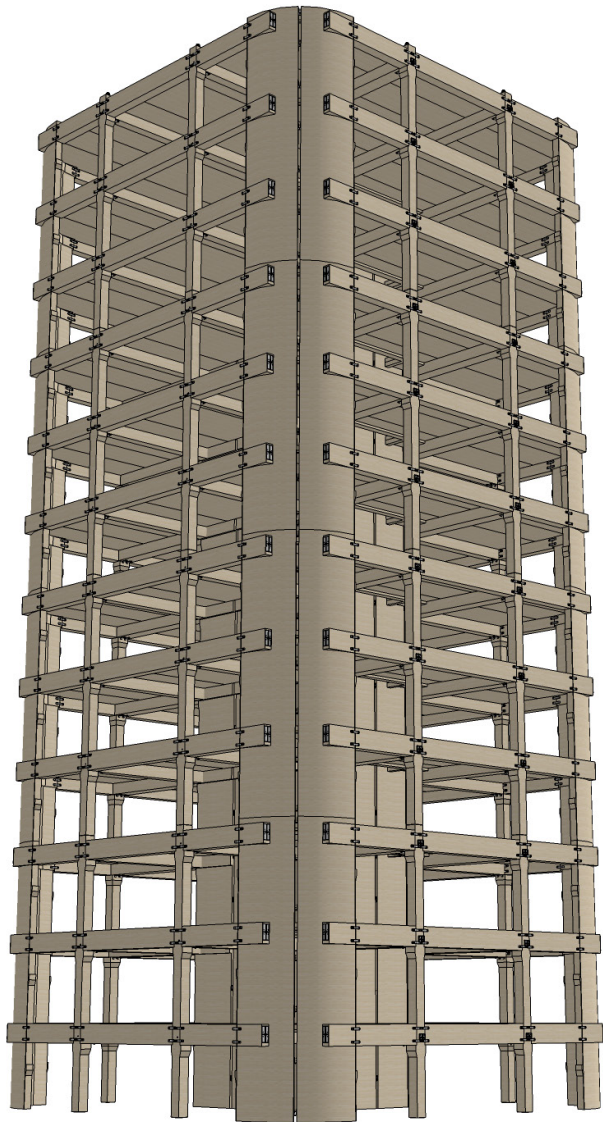
Because of extra compression by tension cables no tension in the elements/structure
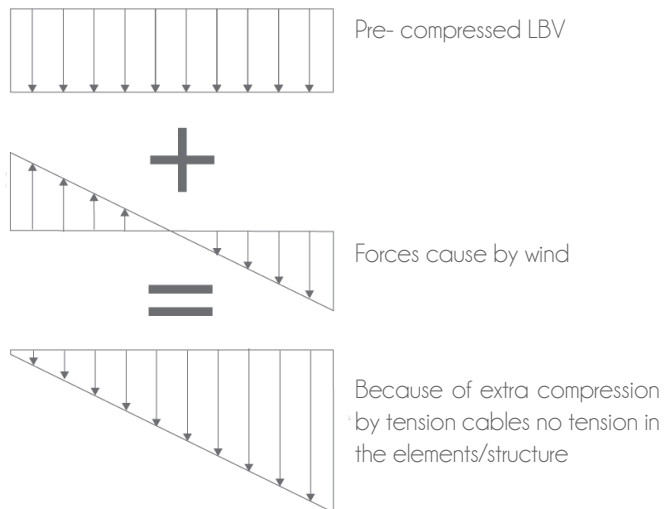
Figure:84. Principle diagram system

Figure:85. 3D structure of proposal
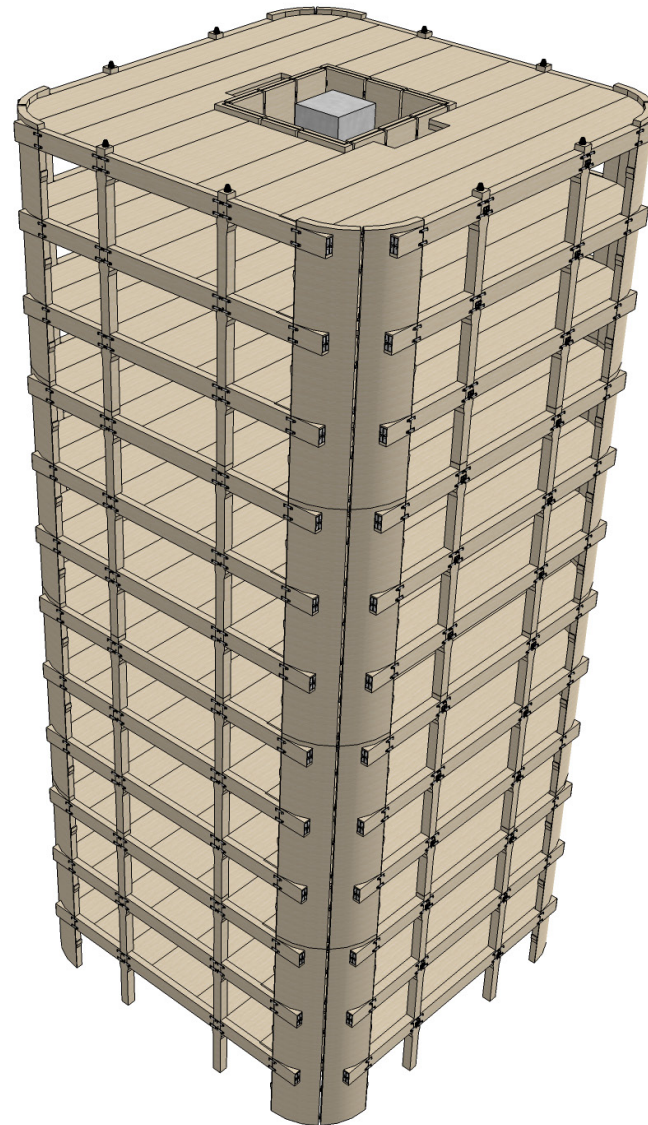
Figure:86. 3DStructure of proposal 2

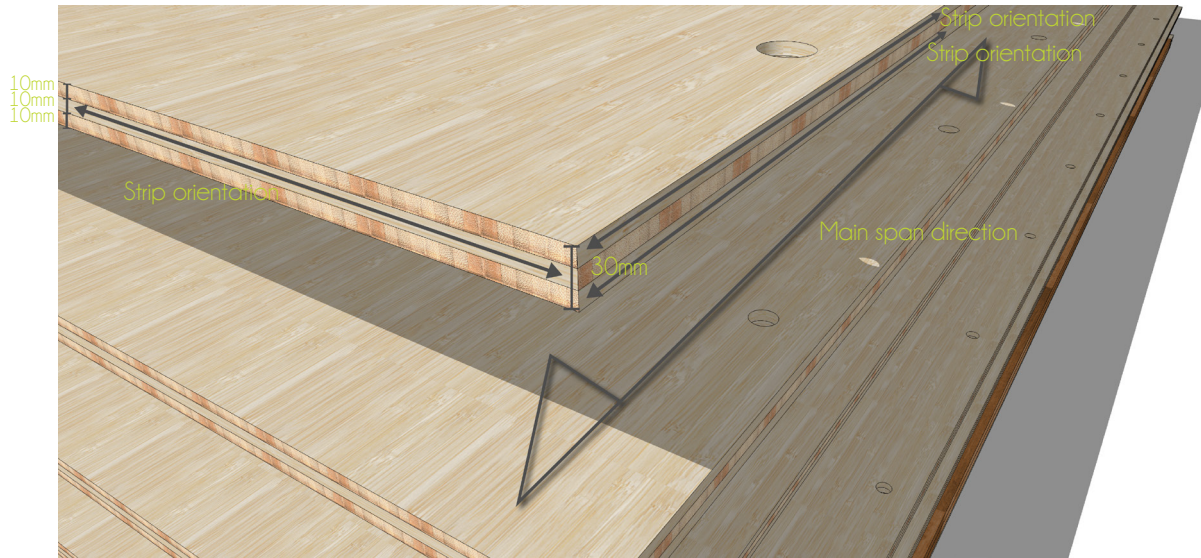How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

7.8. Elements

10mm
10mm
10mm

Strip orientation

Strip orientation
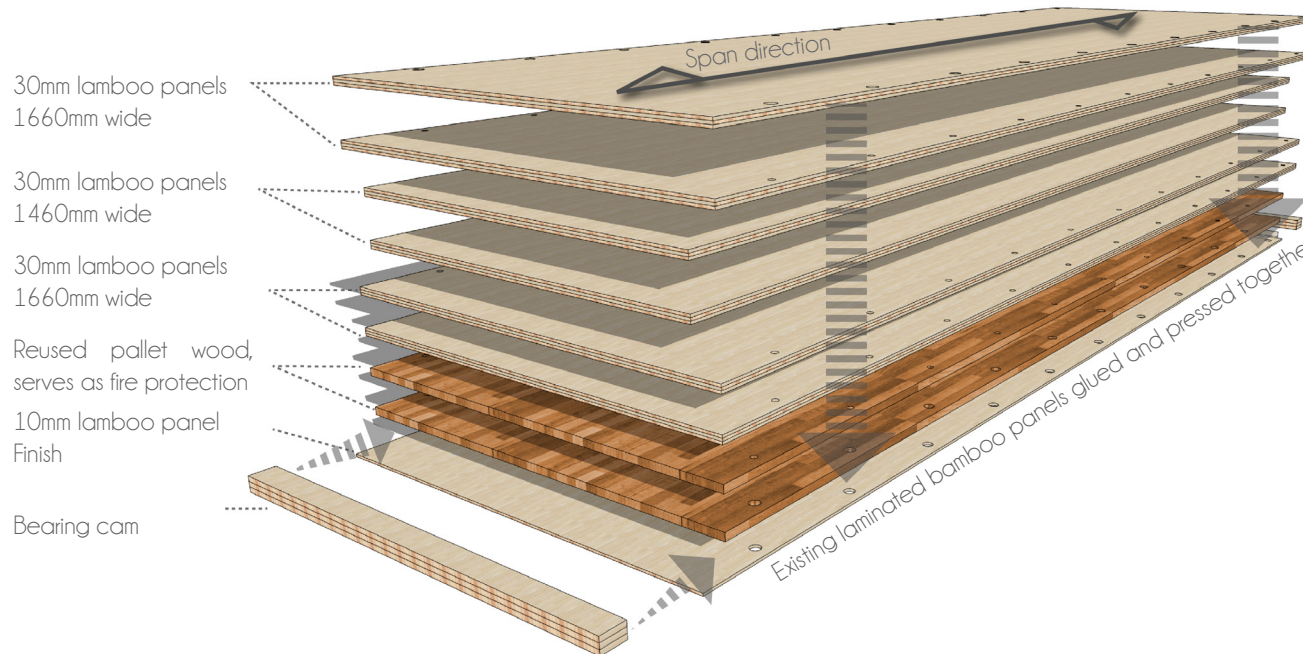
Strip orientation

30mm

Main span direction

Figure:87. Close up of one 3 ply bamboo element

In this sub chapter different elements of the design are shown and how the elements are build-up / connected.

Floor elements

The floor elements have a maximum single span of no more than 5.2 meters and are typically 1660 wide. The system is build up with 3-ply bamboo plates for the structural part. On the bottom extra wood is added consisting out of two layers of recycled wood (3cm each) and underneath that is a single layer laminated bamboo for creating the bamboo look. The 3 ply bamboo plates are cross laminated. The middle layer is oriented perpendicular to the main direction. Each layer is 10mm making the total thickness of each plate to 30mm. Six plates together form the structural part of the floor element. The plates are first predrilled were needed and then glued and pressed together. Near the supports bearing cams are used to support the floor with a thickness of a 100mm. Reason for this is the unknown state of the quality of the wood since it is being recycled and near the supports the structural integrity is important, more "flesh" is also beneficial because it helps to spread the peak stresses in the material near the support.

Connecting the elements can be done in several ways, see image: "*Different floor connection option*". The connection chosen is the internal split connection. It's a bit more difficult and requires more accurate building, but gives a very beautiful result and is a stronger connection as the half lapped connection. Instead of screws, bolts will be used to allow easier disassembly and complete reuse.

The internal spline will also be made of LVB but will be 5mm smaller than the available gap to allow a bit of clearance to construct it. The connections could be further strengthened with adhesives, but this will not be done, because it makes it harder to disassemble. The holes for the bolts will be covered with caps made of recycled plastic. The caps create as smooth surface to apply the insulation mat to disconnect the structure from the topping floor on the upper side.
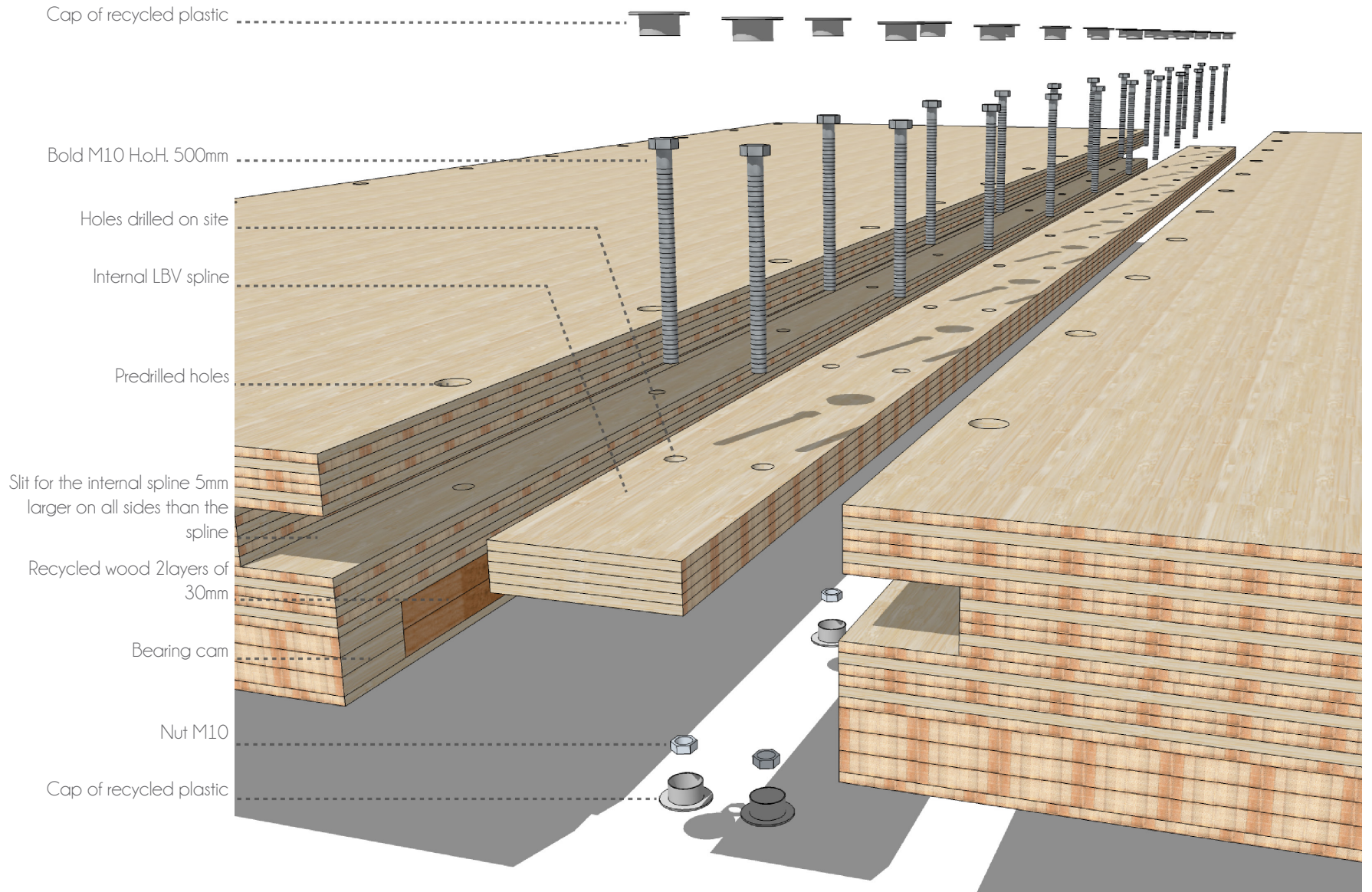

30mm lamboo panels 1660mm wide

30mm lamboo panels 1460mm wide

30mm lamboo panels 1660mm wide

Reused pallet wood, serves as fire protection

10mm lamboo panel Finish

Bearing cam

Span direction

Existing laminated bamboo panels glued and pressed together

Figure:88. Exploded view floor element

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Page 64

Elements

Cap of recycled plastic

Bold M10 H.o.H. 500mm

Holes drilled on site

Internal LBV spline

Predrilled holes

Slit for the internal spline 5mm larger on all sides than the spline

Recycled wood 2layers of 30mm

Bearing cam

Nut M10

Cap of recycled plastic

Figure:89. Close op of connection exploded view

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Elements

Figure:90. Connecting two panels using a internal spline
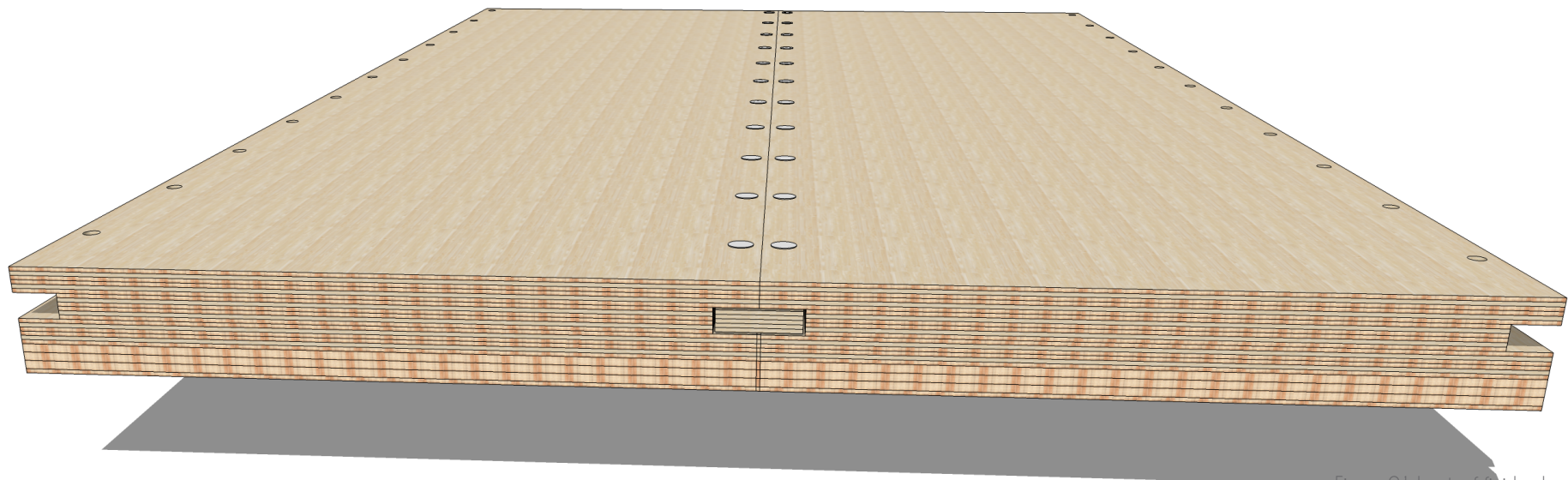
Figure:91. Look of finished connection

Single surface spline

Screws

CLT floor

CLT floor

Plywood

Single internal spline

Screws

CLT floor

CLT floor

Plywood

Double surface spline

Screws

CLT floor

CLT floor

Plywood

Half lapped joint

Screws

CLT floor

CLT floor

Figure:92. Different floor connection option

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
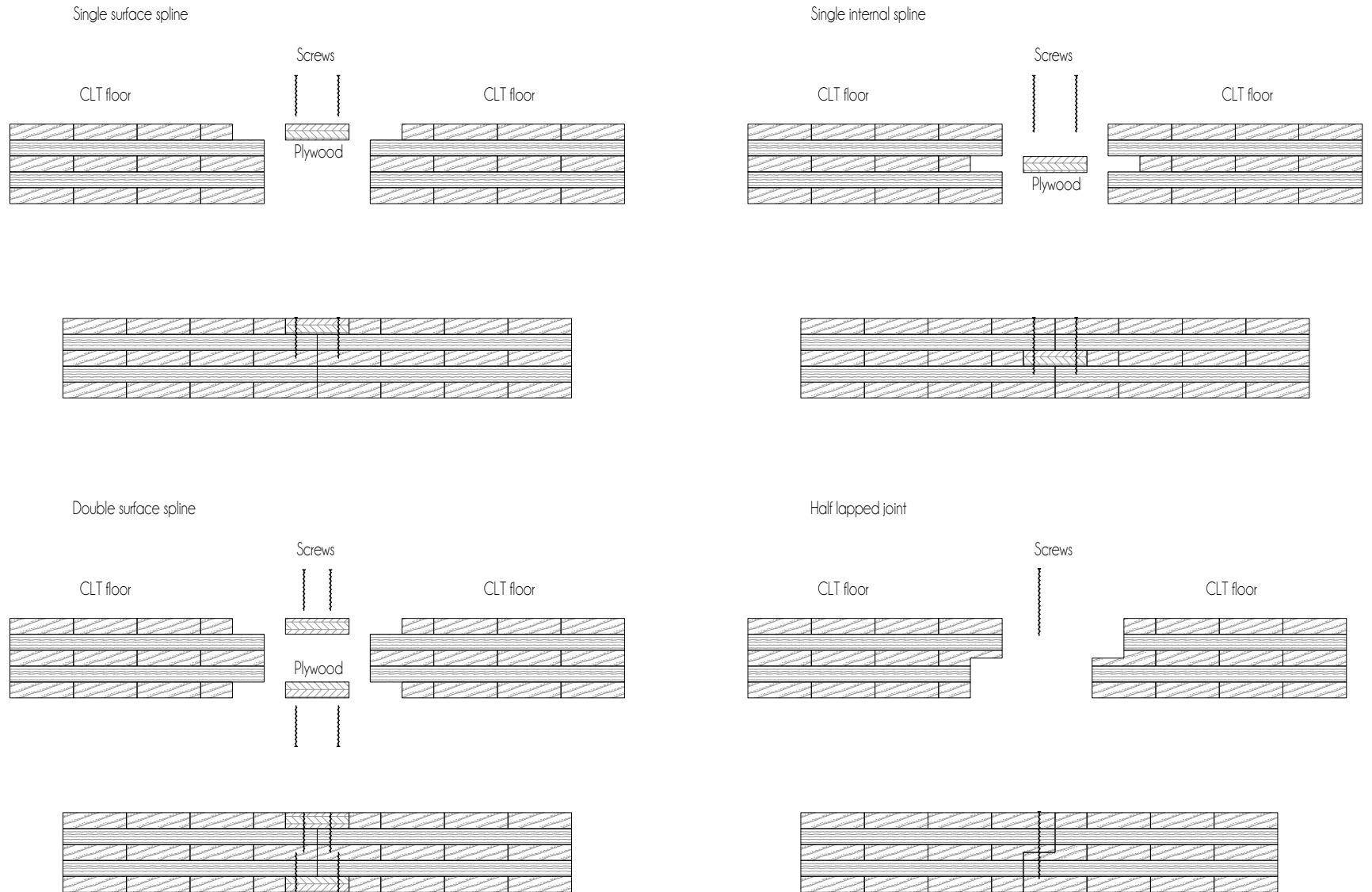
Elements

Wall element Core

There are two types of wall elements. The core wall elements and the Curved facade wall elements. The curved elements are bigger, have two one element spanning tendons instead of one and are curved 45 degrees. The curved elements also have an extra wing to tension the beams and have no separation for acoustic performance.

The core wall is build up out of 3 layers all pressed together in the factory. The steel connectors are there to allow easy installment and together with temporary support system described in the chapter assembly keeping the elements upright till connected to each other and then tensioned. The Sound isolation could be rockwool but doesn't have to be, but it should be soft and fire resistant. The elements are vertically orientated and so are the fibers.

The elements consist out of two sub elements consisting out of 6 layers of 3 layered plywood (180mm thick in total) and to prevent the isolation to be compressed spacers of LVB have been used between the elements. The sub elements are connected in the factory. The steel plates are added on site, because milling techniques are within accuracies of 1mm the wooden gaps are only slightly oversized to have a bit of room during construction on site.

For structural reasons further explained in the sub chapter: "connections" the walls need to be separated to let the U shaped energy dissipaters do their work. It was however an architectural choice to accentuate the connections between the elements in the horizontal direction, to show the people how the building works, to add to the bamboo cultural heritage and to decorate the interior providing a vibe of nature.
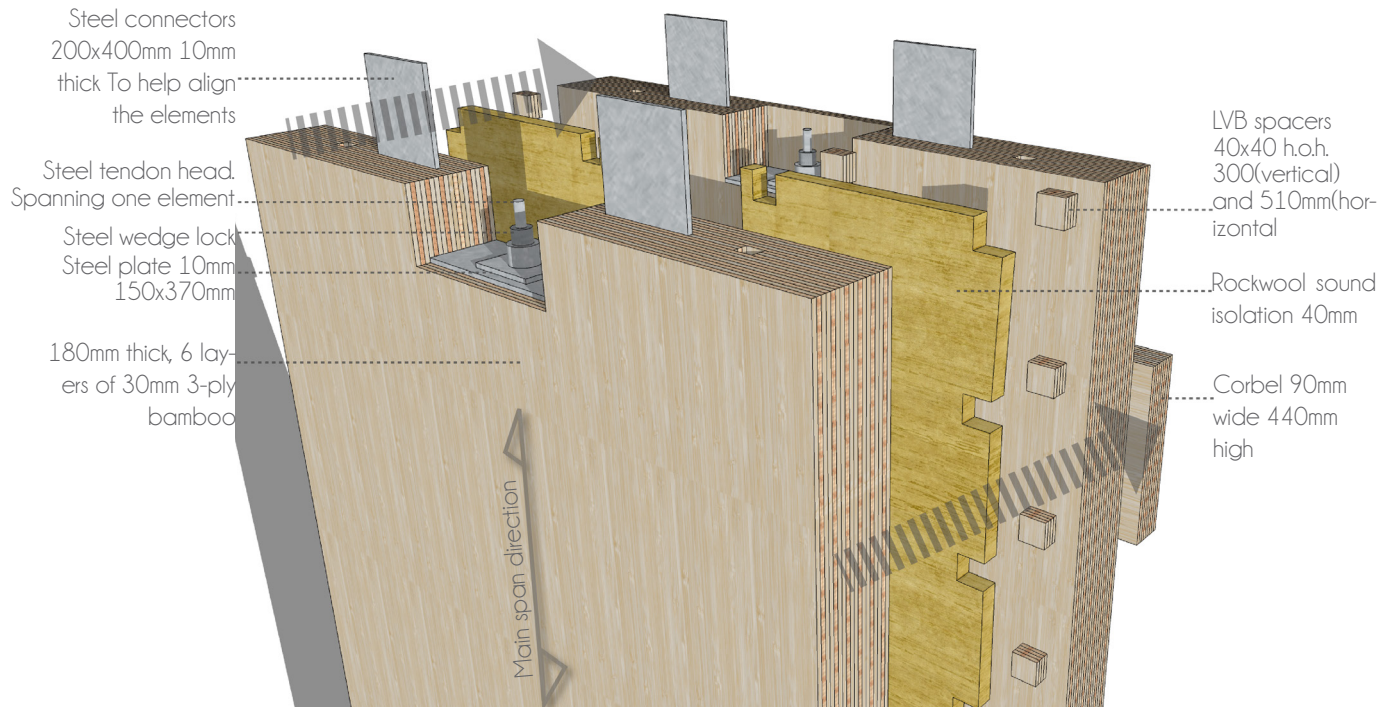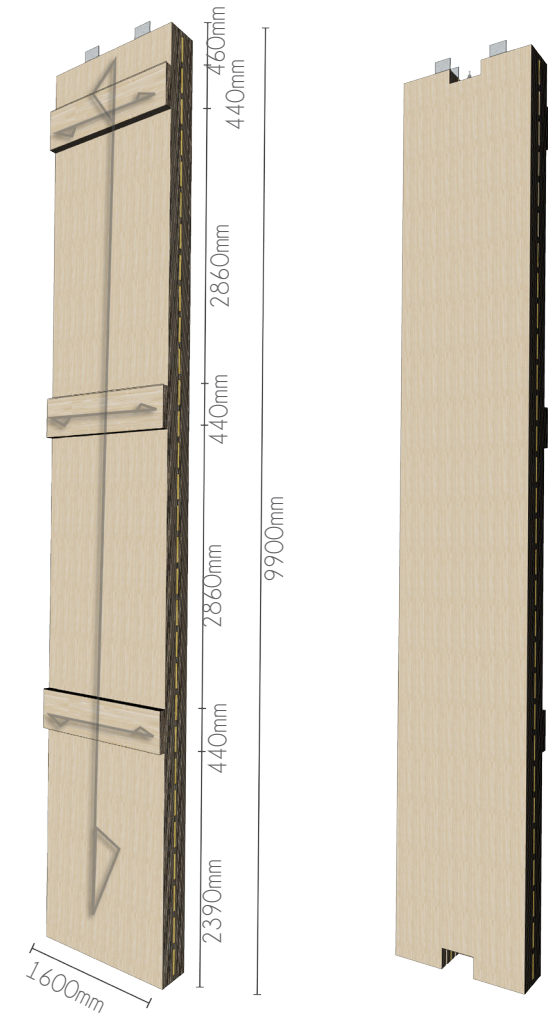
Steel connectors 200x400mm 10mm thick To help align the elements

Steel tendon head. Spanning one element

Steel wedge lock Steel plate 10mm 150x370mm

180mm thick, 6 layers of 30mm 3-ply bamboo

Main span direction

LVB spacers 40x40 h.o.h. 300(vertical) and 510mm(horizontal

Rockwool sound isolation 40mm

Corbel 90mm wide 440mm high

Figure:93. Build-up of one wall element located in the core

460mm
440mm
2860mm
440mm
2860mm
9900mm
440mm
2390mm

1600mm

Figure:94. Apartment side and staircase side
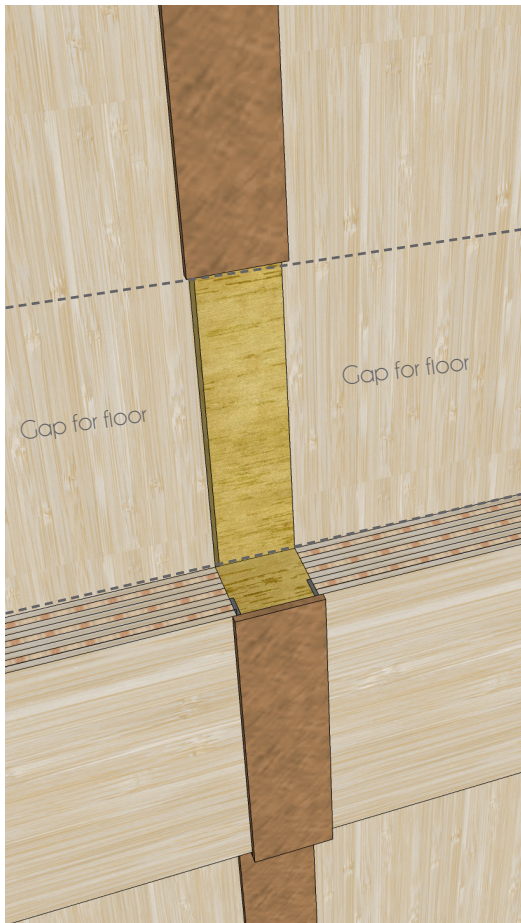
Fire proof sound isolation

Click on covers strip

Self tapping screw 550mm long
h.o.h. 900mm

UFP energy dissipater100mmx-
100mmx8mm with sliding slots

Self-tapping bolts 8x per
dissipater

Nuts 8x

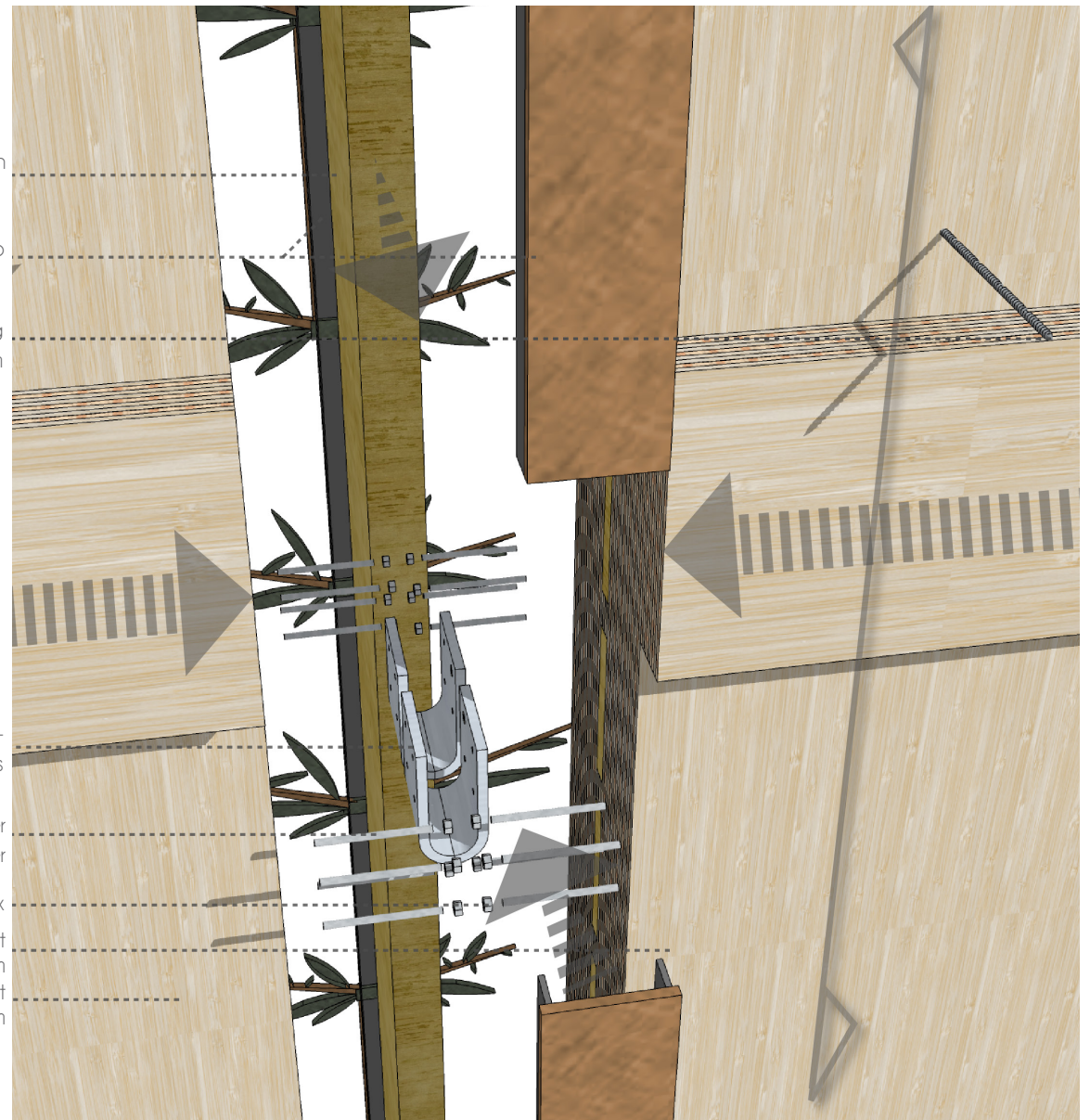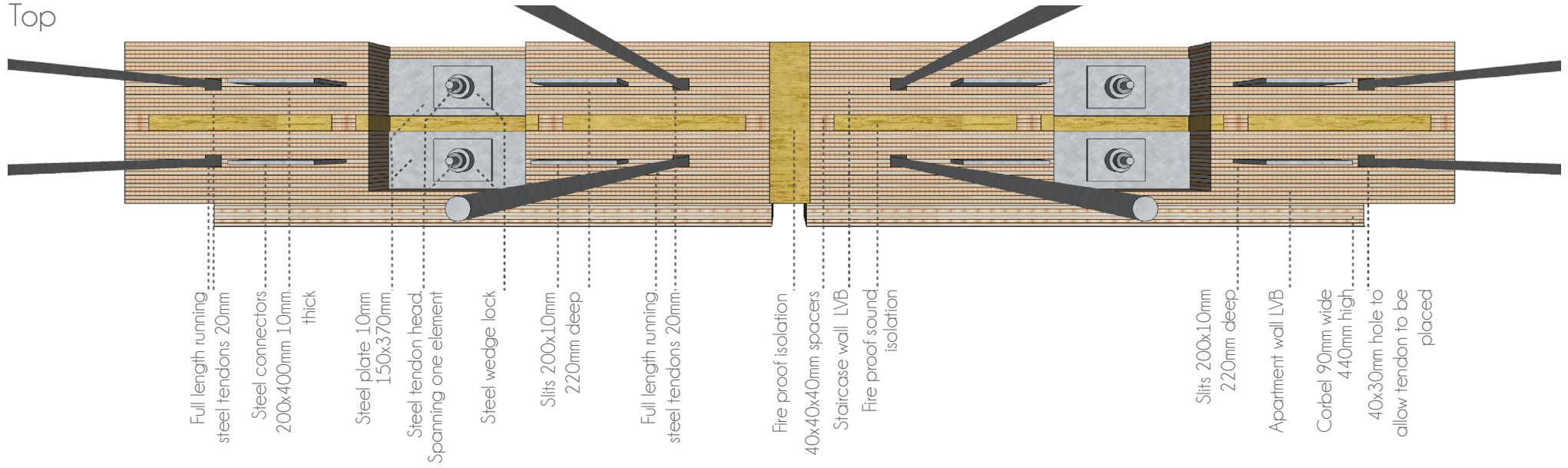Core wall element
9900x1600x400mm
Core wall element
9900x1600x400mm

Gap for floor

Gap for floor

Figure:95. Wall elements horizontal connection finished

Figure:96. Horizontal connection wall elements

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Elements

Top

Labels (top view, left to right):
- Full length running steel tendons 20mm
- Steel connectors 200x400mm 10mm thick
- Steel plate 10mm 150x370mm
- Steel tendon head. Spanning one element
- Steel wedge lock
- Slits 200x10mm 220mm deep
- Full length running steel tendons 20mm
- Fire proof isolation
- 40x40x40mm spacers
- Staircase wall LVB
- Fire proof sound isolation
- Slits 200x10mm 220mm deep
- Apartment wall LVB
- Corbel 90mm wide 440mm high
- 40x30mm hole to allow tendon to be placed

Bottom

Labels (bottom view, left to right):
- 40x30mm hole to allow tendon to be placed
- Staircase wall LVB
- Notch 370x390mm and 230mm deep
- Sound isolation
- Apartment wall LVB
- 40x40x40mm spacers
- Fire proof isolation
- Click on covers trip fire resistant
- Full length running steel tendons 20mm
- Slits 225x20mm 200mm deep
- Node welded to end-point tendon
- Steel plate 10mm 150x370mm
- Slits 225x20mm 200mm deep
- Full length running steel tendons 20mm

Figure:97. Top and bottom view wall elements core

Elements

Top LVB element

Steel plate 10mm 150x370mm acts as power distributor.

Continuous steel tension cables 20mm

Steel connection plates to help align elements

Fire proof sound isolation to fill cavity

LBV door self clamming with rubbers to improve sound resistance, with bamboo decoration

Example of stressed tendon to clamp element and reduce tension

Bottom LVB element

One element steel tension cable before tensioning

Steel wedge lock

Steel plate 10mm 150x370mm acts as power distributor.

Corbel for floor

Figure:98. Top bottom connection wall elements core

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Elements

The horizontal elements are connected 20cm above the floors. This because of the amount of elements joining in the facade. The structural reason is not to have more the joints (read weak points) in the connections. The core elements have six steel cables running through them. The four outer cables are vital in the seismic control of the building and run from the concrete ground floor to the top floor. On the top floor at eye height all the three cables are linked to a steel plate to help spreading the load over the surface. Because it is supposed to be a show case building the connection is placed behind fire proof glass and the steel elements are treated with a paint to protect them in fire (The paint is very unsustainable, and a concession is made to be able to show case the possibilities). For the central cables (which only run through one element) a wooden door is provided and the cavity is filled with fireproof isolation material. The reason for the little door is that it should be possible to further tension them when the steel becomes longer over time because of creep or is elongated because of extreme forces during an earthquake when the steel starts flowing.
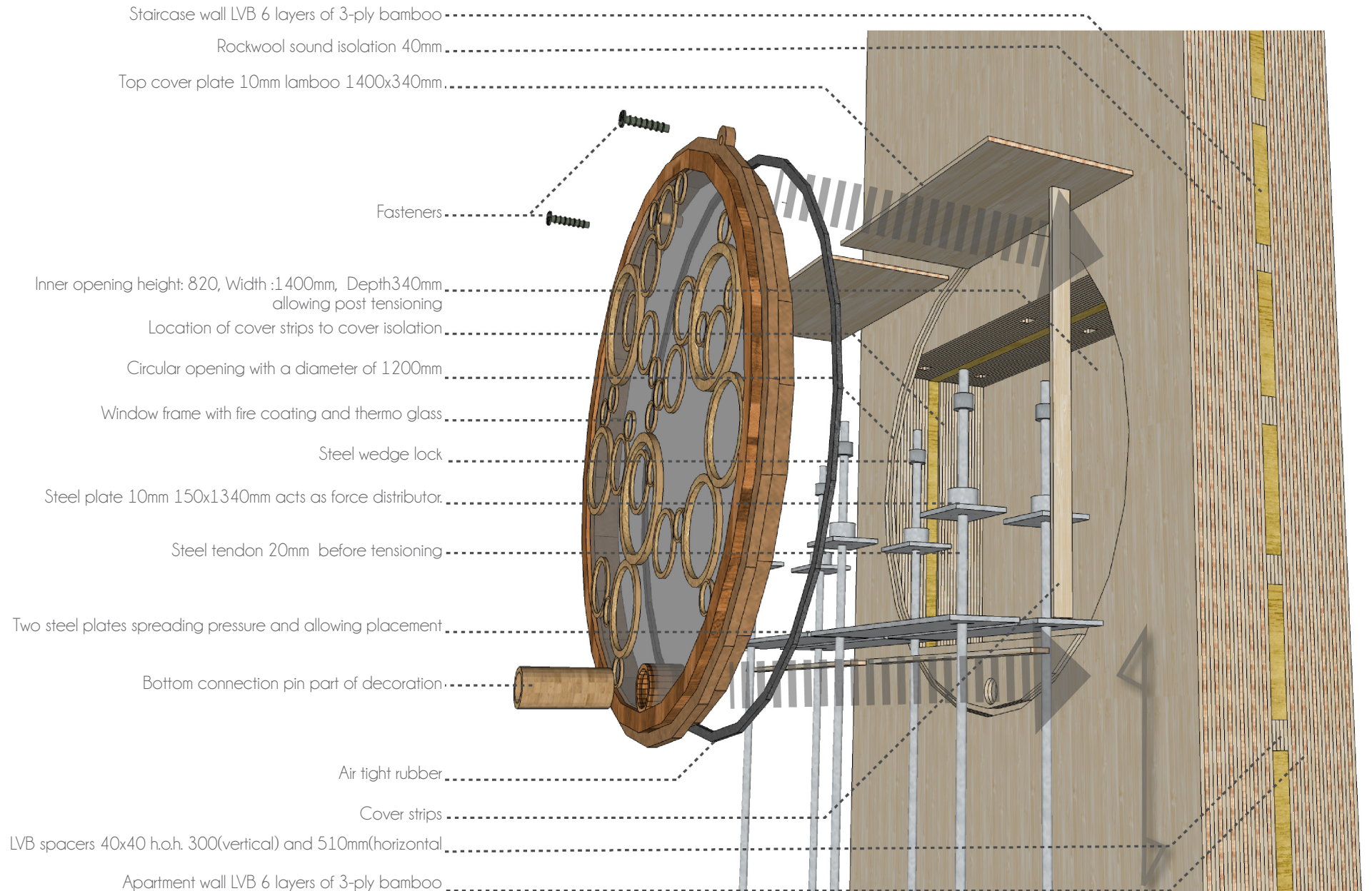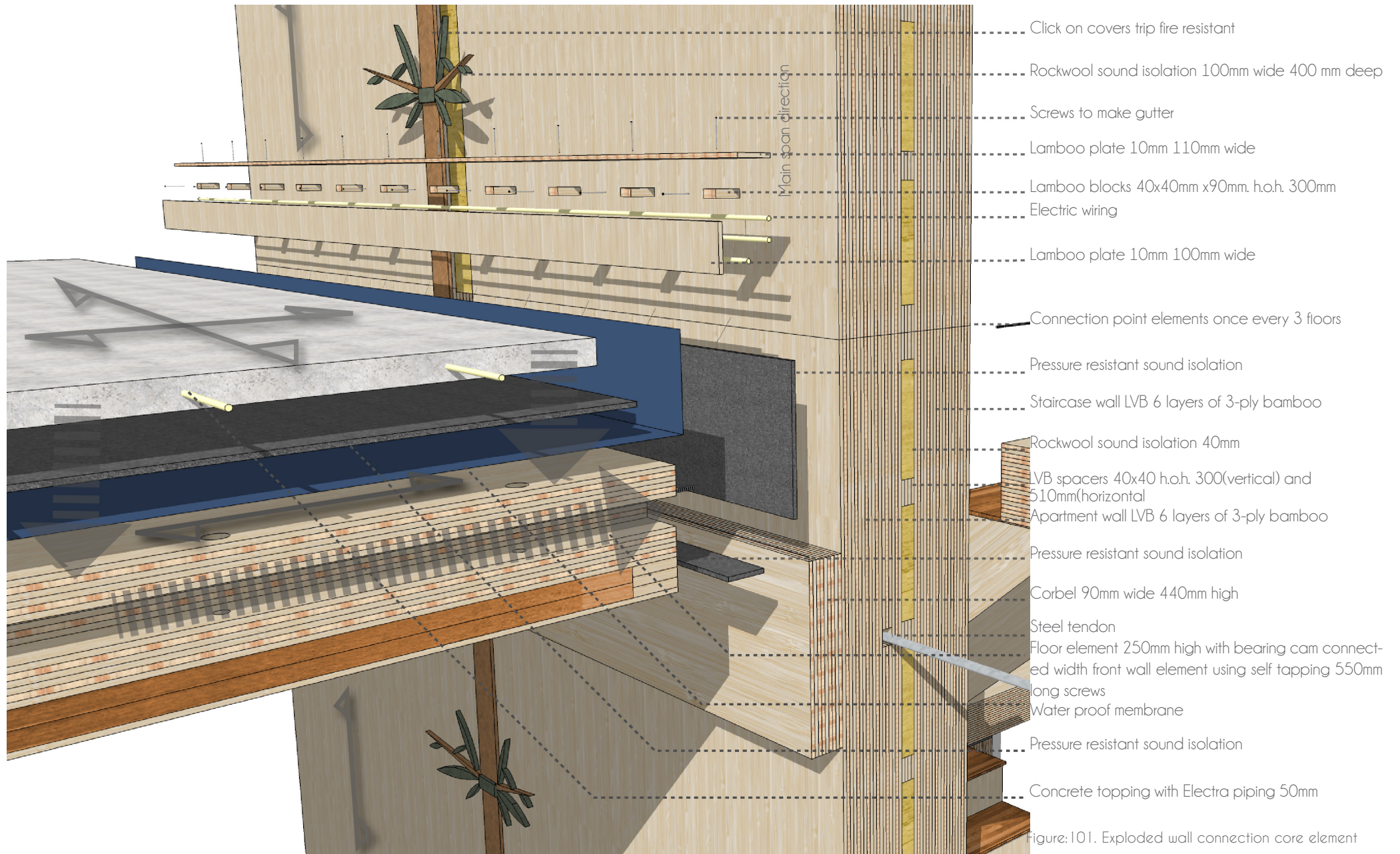
Figure:99. Top bottom connection wall elements core connected

Elements

Staircase wall LVB 6 layers of 3-ply bamboo · · · · · · · · · · · · · · · ·

Rockwool sound isolation 40mm ·

Top cover plate 10mm lamboo 1400x340mm · · · · · · · · · · · · · · · · · ·

Fasteners ·

Inner opening height: 820, Width :1400mm, Depth340mm · · · · · · · · · · · ·
allowing post tensioning

Location of cover strips to cover isolation · · · · · · · · · · · · · · · ·

Circular opening with a diameter of 1200mm · · · · · · · · · · · · · · · · ·

Window frame with fire coating and thermo glass · · · · · · · · · · · · · · ·

Steel wedge lock ·

Steel plate 10mm 150x1340mm acts as force distributor. · · · · · · · · · · · ·

Steel tendon 20mm before tensioning · · · · · · · · · · · · · · · · · ·

Two steel plates spreading pressure and allowing placement · · · · · · · · · ·

Bottom connection pin part of decoration · · · · · · · · · · · · · · · · ·

Air tight rubber ·

Cover strips ·

LVB spacers 40x40 h.o.h. 300(vertical) and 510mm(horizontal · · · · · · · · · ·

Apartment wall LVB 6 layers of 3-ply bamboo · · · · · · · · · · · · · · · ·

Figure:100. Top floor buildup of tension cabbing

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Elements

Click on covers trip fire resistant

Rockwool sound isolation 100mm wide 400 mm deep

Screws to make gutter

Lamboo plate 10mm 110mm wide

Lamboo blocks 40x40mm x90mm. h.o.h. 300mm

Electric wiring

Lamboo plate 10mm 100mm wide

Connection point elements once every 3 floors

Pressure resistant sound isolation

Staircase wall LVB 6 layers of 3-ply bamboo

Rockwool sound isolation 40mm

LVB spacers 40x40 h.o.h. 300(vertical) and 510mm(horizontal

Apartment wall LVB 6 layers of 3-ply bamboo

Pressure resistant sound isolation

Corbel 90mm wide 440mm high

Steel tendon

Floor element 250mm high with bearing cam connected width front wall element using self tapping 550mm long screws

Water proof membrane

Pressure resistant sound isolation

Concrete topping with Electra piping 50mm

Main span direction

Figure:101. Exploded wall connection core element

Another important connection is where the floor connects with the wall element. To keep the concrete separated from the wood floor and therefore could be removed without damaging the wood a waterproof membrane is place. The membrane also helps in the hardening process of the concrete and provides safety in case of a leakage, preserving the wall and the floor elements from getting wet. Next to the wall on the bottom a gutter runs with electric cables. From time to time the cables spit of and run through the concrete floor. This way the LVB elements are kept free from slots for the cable (when a cable has to be brought up it can be in the connection strips or with a horizontal gutter. This way the structures stays untouched which improves the chances of reuse and lets the char layer do its work.

The structural roof consists out of wood again, for weight concrete is added. On top of which isolation is placed and roof proof membrane on which modules are placed with plants.

More details will be added in the appendix: "Other technical: details".

Figure:102. Wall connection core element

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Elements

Modular green roof system 130mm thick

Waterproof membrane

Pressure resistant Isolation layer on slope

Concrete topping

Floor element 250mm high with bearing cam

Steel tension cable (horizontal)

Corbel 90mm with 440mm height

UFP energy dissipater100mmx100mmx8mm

Open stair 850mm wide

Ornamented window with fire coating and thermo glass

Click on covers trip fire resistant

Platform

Elevator shaft, executed in LVB (kept transparent in this image to show elements behind it.

Concrete topping with Electra piping 50mm

Main span direction

Main span direction

Figure:103. Upper floor with Tension cabin and green roof build up

Guayaquil is highly seismic active. Although it plays an important role in the design choices it has not been calculated, because of its complexity it could be a separated graduation project. But a small calculation has been made.

For the calculation a simple formula is used to see if tension occurs and if so how much the structure has to be pretensioned and what are the sizes of the columns in that case.

The formula:
$M_{eq} = (X \times Y_g) \times 1/2H$
M_{eq}= moment by earthquake near the facade
X= seismic hazard factor
Y_g = weight of the building
H= height of the building

It calculates the generated moment by and earthquake witch than can be used in the load combinations to determine the tension and the compression on the foundation. The big unknown in Ecuador is the seismic hazard factor, therefore the factor 0.4 from the United states have been applied (Münchener Rück and Munich Re Group, 2000). The 0.4 factor is a heavy factor compared to for example New Zealand were the factor 0.3 is used (it used to be 0.22 but it has been increased after the earthquake in Christchurch) (Baird, Palermo et al. 2012).

The formula is added in the appendix structural calculations

Figure:104. Visualization of ornamented hallway showing structural dissensions

8. Other Technical

Figure: 105. Problems like Fire, Sound, Vibration and connections needs to be solved in a building

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

8.1.   Fire behavior

1) Structural resistance

Heat

T(C°)

Smoke

Flames   Fire

2) Intergarty

Heat
ΔT=140°C

T(C°)

Smoke

Flames   Fire
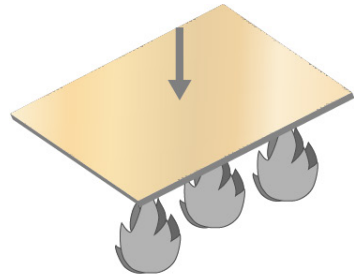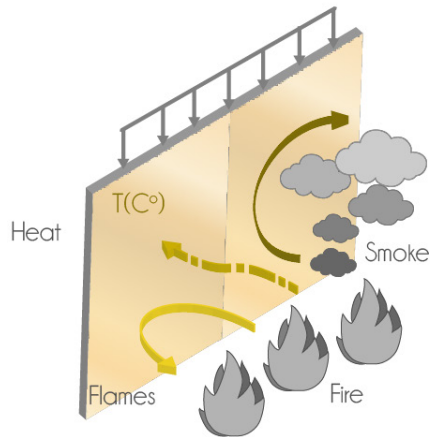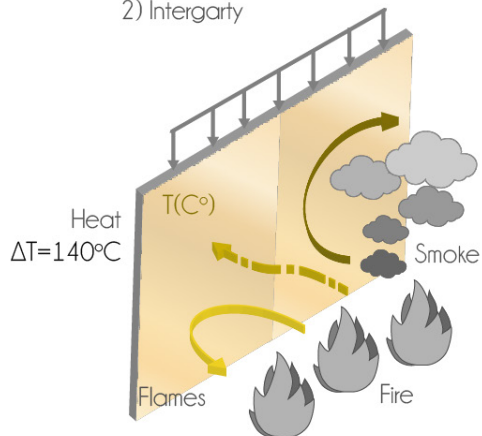
3) Insulation
Figure:106. The 3 fire resistance criteria

Flame spread rate

Figure:107. Flame spread for different materials.

The amount of energy needed to ignite a material
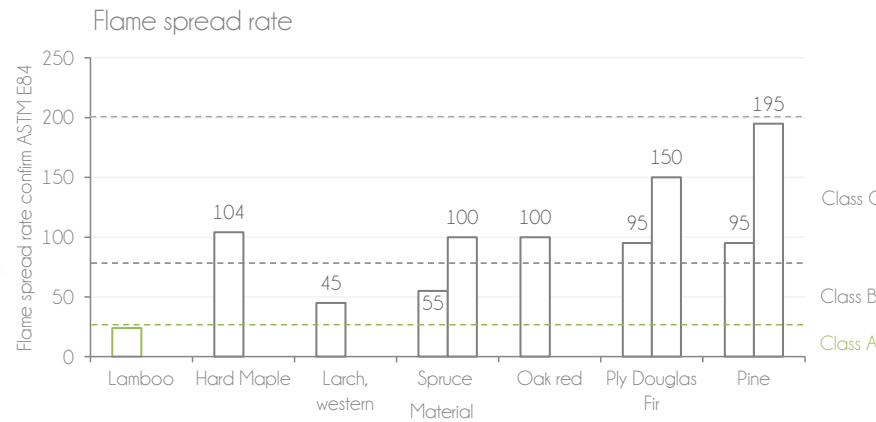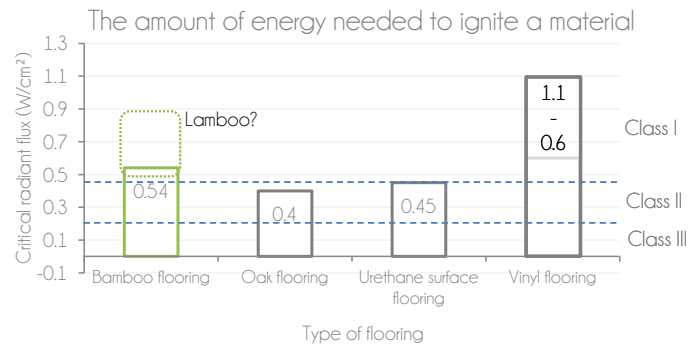
Figure:108. Critical radiant flux

When proposing a multistory building in wood/bamboo the first objection is often fire safety. This chapter will show that it is possible to make a multistory building out of lamboo meeting the fire regulations.. There are basically three strategies regarding fire safety of timber structures: Covering it with noncombustible materials. Prevent ignition under all circumstances. Or design the structure in such a way it is self-extinguishing and oversizing the members to keep them functioning after charring (SOM 2013). Because it is a show case building the strategy will be oversizing the members in combination with a sprinkler installation.

Fire resistance

The fire resistance to wards a fire is related to time, and density of a wood like material. The main structure for a residential building (+/-10 floors) Has to be at least 1 hour fire proof and it is advised to create a building that is two hours fire proof. For a construction to be fire proof it needs to meet three different standards. First it must remain structurally strong enough despite the fire for at least two hours. Secondly it is not allowed to catch fire, also known as integrity of a structure. And last it has to isolate adjacent rooms from smoke, flames and heat (less than 180°C our an average <140°C) (Gagnon and Pirvu 2011).   Lamboo offers two values regarding fire resistants. The flame spread index and the critical radiant flux (Lamboo 2014).

Flame Spread Index

Lamboo is classified in the 'Flame Spread Index' as a class A material using the ASTM E84 (code regarding Surface Burning also known as Flame spread) (Lamboo 2014). Class A has a flame spread index between 0-25. Anything below 450 passes and class A can be used in enclosed vertical exits. The fire resistance is therefore extremely high and surpasses wood products (Sweet 1993, American Wood Council 2010). Although not mentioned it seems assumable the bamboo of Lamboo has been specially treated to achieve- these values

Critical radiant flux

The critical radiant flux says something about the flammability of a material and is represented as (W/cm²). The higher the value the more energy is needed to ignite the material. In US and Europe it is used in standards regarding flooring (EN ISO 9239-1, ASTM E 648, ASTM E 970). Lamboo claims it's product meets class 1 standards using the ASTM E648. It seems possible others also claim similar results and Bamboo Flooring Imports inc. claim a Critical radiant flux of 0.54W/cm² (Bamboo Flooring Imports 2011). For ex-

ample oak flooring has a class 2 and a critical radiant flux around 0.4 W/cm² (Lawson and Dalton).

Char rate

Using the Cone Calorimeter more trustworthy results have been obtained over the last decades. From these test a formula has been derived showing the correlation between the char rate, density and exposed time (Babrauskas 2004).

$$\beta = 113k_{ox}\frac{(\overline{q^n})^{0,5}}{\rho \times t^{0,3}}$$

q'' = the test-average total heat flux,
k_{ox} = 1.0 for charring in plentiful oxygen (e.g., in the Cone Calorimeter) and kox = 0.8 for furnace tests.
ρ = density (690 kg/m³)
t = time (60 min)
β = Char rate (mm/min)

Test-average total heat flux:
q''= $18,0 \times t^{0,4}$
q''= $18,0 \times 60^{0,4}$=92.6 kWm^{-2}

Charring rate Lamboo:
$\beta = \frac{113 \times 1 \times 92.6^{0,5}}{690 \times 60^{0,3}}$= 0.46mm/min
In case of a two hour safety requirement:
q''= $18,0 \times 120^{0,4}$=122.2 kWm^{-2}

$\beta = \frac{113 \times 1 \times 122.2^{0,5}}{690 \times 120^{0,3}}$= 0.43mm/min

To calculate required thickness the Canadian Standard for Engineering Design in Wood (CSA O86) is used which uses the same methodology as the Eurocodes (EU) or the ASTM (USA) for calculating laminated and heavy timber Gagnon and Pirvu (2011).

Char depth at a given time:
d_{char}= $\beta \times t$

d_{char} = depth of char in mm
β = char rate in mm/min
t = duration of fire exposure in min.

The remaining cross-section depth:
D_{char}=D - d_{char}

D_{char} = depth remaining cross-section in mm
D = depth cross-section at the start in mm
d_{char} = depth of char in mm
tThe remaining effective cross-section depth:
D_{fire}=D_{char} - d_{heat}

D_{fire} = depth remaining effective cross-section in mm
D_{fire} = depth remaining cross-section in mm
d_{char} = Loss of strength factor due heat. In tension 10mm in compression 16mm (is a wood norm, might need to be altered for Lamboo)
The remaining effective cross-section depth can also be written as:
D_{fire}=D-($\beta \times t$)-d_{heat}

Calculation Example

For a column in compression all sides exposed with a 60min fire safety and a structural need of 350mmx350mm results in a column:
350=D-(((0,46x60)-16)x2)
D=350+2(27,6+16)=350+2x43,6=437,2mm
On all sides 4,4cm has to be added to create sufficient fire safety.

In case of a two hour fire safety:
350=D-(((0,43x120)-16)x2)
D=350+2(51.6+16)=350+2x67.6=485,2mm
On all sides 6,8cm has to be added to create sufficient fire safety.

There is one side note to be made. Depending on the adhesives used delamination can occur. Some of the structural adhesives will delaminate when temperature of 300 C° is reached. Structural adhesives are almost always synthetic and can be further classified as thermosetting and thermoplastic. Both transform and create bounds under heat. A thermoplastic process however cannot be reversed and therefore are suitable for structures that have to be fire proof (AF&PA. 2007). Most likely Phenol formaldehyde is used (see sub chapter Adhesives). Phenol formaldehyde is a thermoplastic and therefore delamination is unlikely to be a issue.
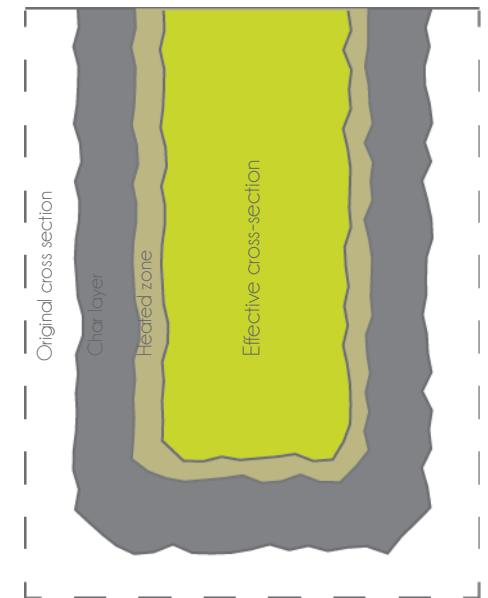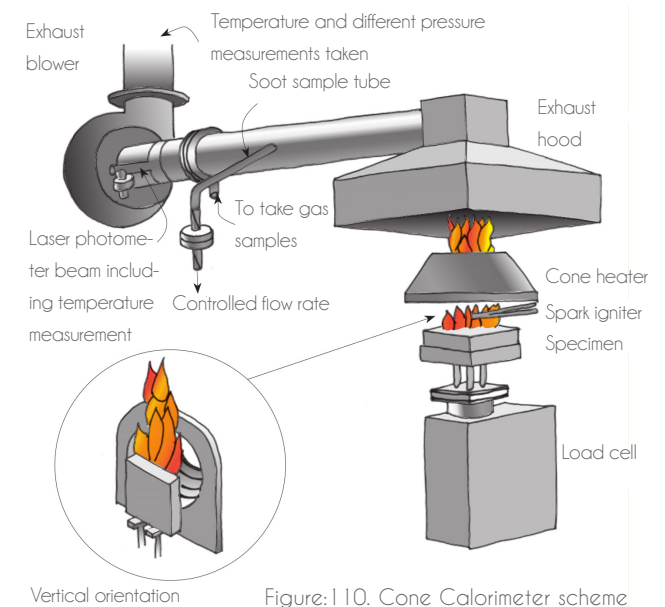

Original cross section
Char layer
Heated zone
Effective cross-section

Figure:109. Heavy timber behavior in fire

Exhaust blower
Temperature and different pressure measurements taken
Soot sample tube
Exhaust hood
Laser photometer beam including temperature measurement
To take gas samples
Controlled flow rate
Cone heater
Spark igniter
Specimen
Load cell
Vertical orientation

Figure:110. Cone Calorimeter scheme

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Fire behavior

Thickness for loadbearing applications

+7cm

Char thickness

Wall
2 hour fire proof
exposed on one sides

Thickness for loadbearing applications

++14cm

Char thickness
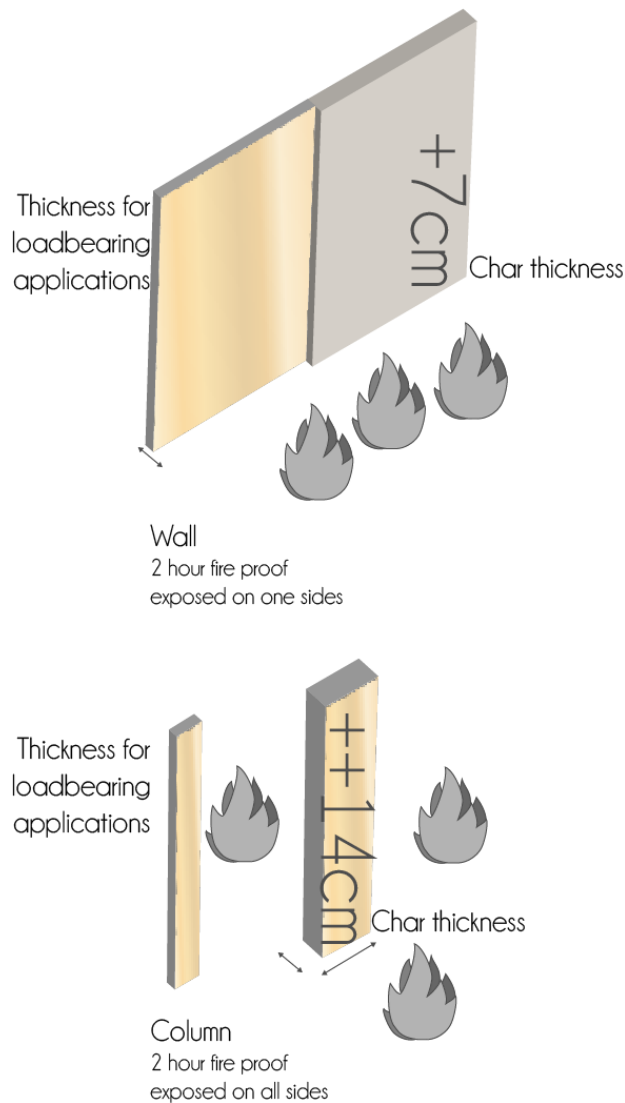
Column
2 hour fire proof
exposed on all sides

Figure:111. Consequences of structural resistance regarding fire

Effective charring rates and char layer thickness per the NDS methodology

Required Fire Resistance	Effective Charring Rate β_{eff} (cm/hour)	Visual Char Layer Thichness (cm)	Zero strenght Layer (cm)	Effective Char Layer Thickness a_{char} (cm)
45min	4.8	3.0	0.6	3.6
60min	4.6	3.8	0.8	4.6
90min	4.2	5.3	1.1	6.4
120min	4.0	6.7	1.3	8.0

Table:11. Charing speed of CLT lumber
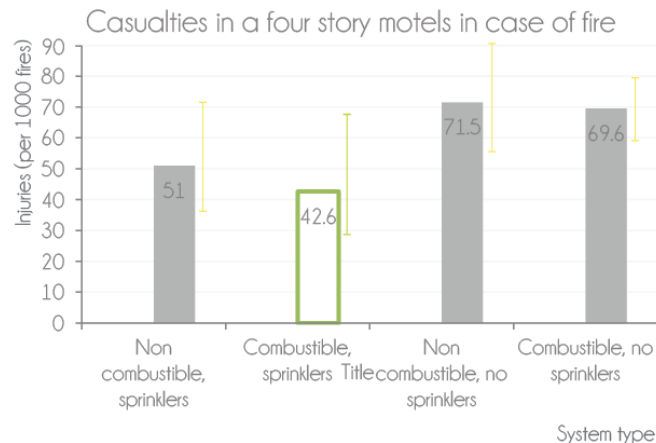
Figure:112. Casualties in 4 story motels in case of fire comparing (non)/combustible materials and (no)/sprinkler buildings

Lamboo outperforms the most common wood products, but it also outperforms the heavy timber products. According to the (ASTM International 2014B) the CLT panels have been tested (Gagnon and Pirvu 2011). The results show that the charing thickness in a two hour fire safety requirement is 1cm more than that of Lamboo (7cm vs. 8cm).

System testing

To the best knowledge of the author there hasn't been a test conducted on a building scale. Although it has been suggested in (Gerard, Barber et al. 2013). A full scale system test could improve understanding the behavior of heavy timber/Lamboo construction. It could capture structural responses as: load redistribution, Interaction between structural framing elements, the ductility of the connection, failure modes, structural restrains and continuity. Proposals how ever have been made to start up research (Gerard, Barber et al. 2013). These test could help improve the acceptance and knowledge of tall timber buildings as it has done for steel buildings. In steel research as that of Pakala and Kodur (2013) have increased the knowledge of steel building and therefore also increase the acceptance of steel.

Another important aspect that needs further research is post earthquake fire performance. Timber building normally perform well in earthquakes but damage in the fire separations and structural elements could be devastating in case of fire (Gerard, Barber et al. 2013). Especially if cities would have a large amount of timber buildings (think of the famous Chicago fire 1871.
The last interesting fact is that timber buildings with a sprinkler installation have a lower on average casualty rate than non combustible buildings with a sprinkler installation (Maxim, Plecas et al. 2013). This could be because the rules regarding timber buildings are stricter, or it could be that people are more cautious in a timber building.

Although further research is needed research done it seems very possible to build in Laminated bamboo in tall building if a heavy timber method is used.

Sound is an issue in timber construction. Although solid timber has an advantage. It can be solved. This report will show some basic strategies for solving these problems for the floor and roof.

Rules

For the rules regarding sound isolation Canadian/American norms will be used. Elements between residential units should have a STC of at least 50 dB, and next to an elevator walls should have at least 55 dB. In case of bare floors a IIC of at least 55 dB is recommended (there are no codes in Canada regarding this) (Gagnon and Pirvu 2011).

This can not be directly translated to the Dutch norms but are around the same order of magnitude. When the Dutch norm is used section 3.4 has to be used. Regarding airborne sounds between apartments a reduction of >52 dB is required. For contact sounds a reduction of >54 dB is needed (Rijksoverheid 2012).

Wall

In a solid wall the mass is the insulator. More mass means more sound absorption. In timber frame and mass timber construction mass alone is not enough low. A 11.5 mm CLT panel (+/- 500kg/m³) a sound reduction of ~32-34dB(Green and Karsh 2012). It can be calculated using the formula sound transmission and using the A-weighting factor (this factor takes the human hearing in to account). Solid Bamboo elements would be slightly heavier than normal wood panels however this will not be sufficient. As rule of thumb an increase of 5 dB can be expected when the weight is doubled using the STC calculations (Acoustics.com 2004).

To reach a sound reduction of 50dB for 500Hz the solid bamboo wall has to be more than 2m thick. However, for light weight constructions there is another option following the mass-spring-mass principle. Where high absorption material, like stone wool is used to absorb the vibration created in the first mass. This is the spring in the system. The softer the spring (the thicker the isolation material) the better the sound is absorbed and the higher the mass the better the sound is absorbed in this system. Doubling the isolation will increase the STC between 4 and 6 dB.

A system like this has one side effect and that are the bad performances when reaching its own frequency and sows a sound reduction in correlation with the image: "*sound reduction Index*". A solution can be making the mass elements of different thicknesses as is done with glass.
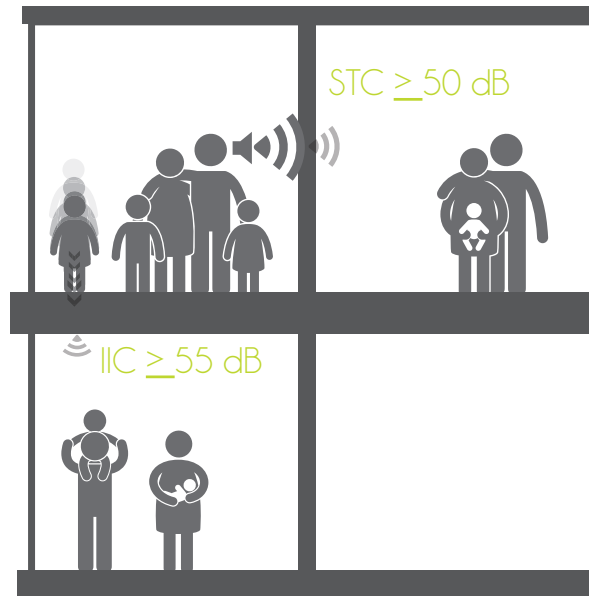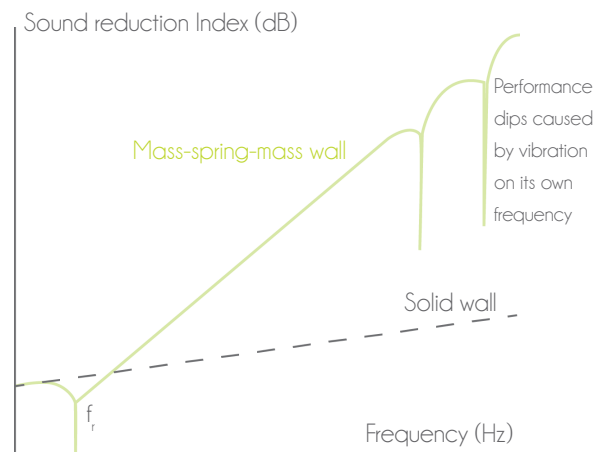

Figure:113. USA/Canadian building standard demands

STC ≥ 50 dB

IIC ≥ 55 dB

Sound reduction Index (dB)

Mass-spring-mass wall

Performance dips caused by vibration on its own frequency

Solid wall

f_r

Frequency (Hz)

Figure:114. Sound reduction Index

STC ≤ 32~34 dB

Lamboo wall 11.5mm thick

STC ≤ 50 dB
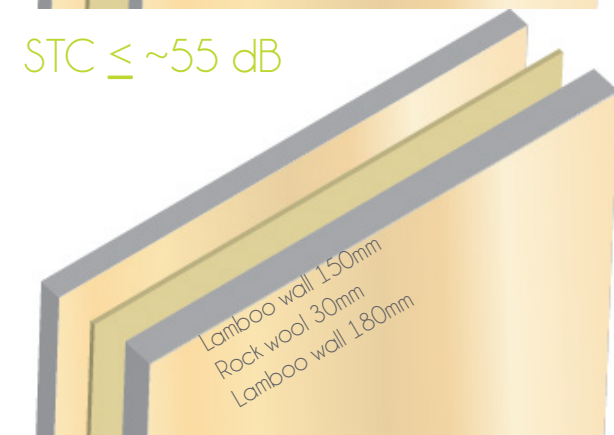
CLT 11.5mm
Rock wool 30mm
CLT 11.5mm

STC ≤ ~55 dB

Lamboo wall 150mm
Rock wool 30mm
Lamboo wall 180mm

Figure:115. Acoustic build up wall

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
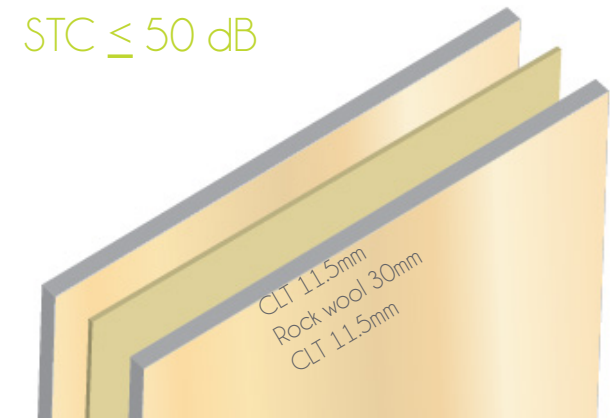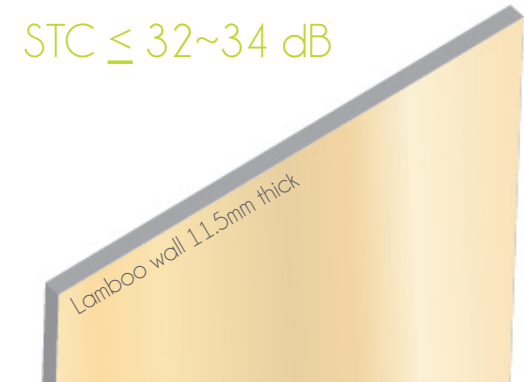
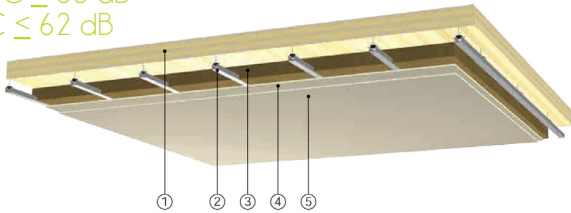# Sound

Floating floor
STC $\leq$ 52 dB
IIC $\leq$ 45dB
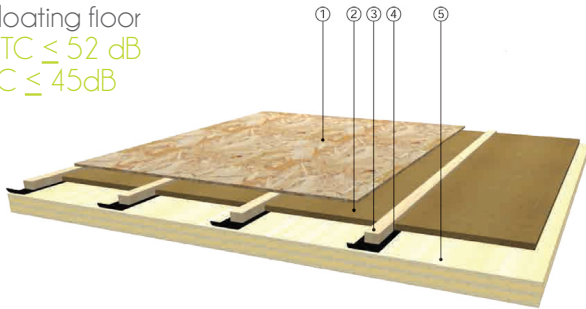
Floating floor
1. Particleboard panel 22 mm
2. Sound insulation material ($\approx$ 40 mm)
3. Lumber sleepers
4. REGUPOL underlayment
5. 5-layer CLT panel 146 mm

Suspended ceiling
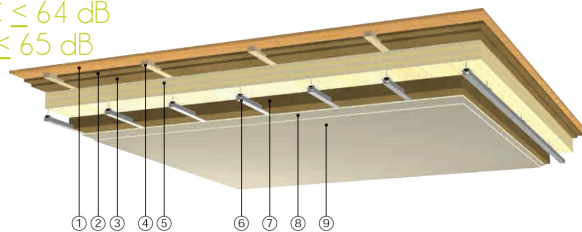STC $\leq$ 63 dB
IIC $\leq$ 62 dB

Suspended ceiling
1. 5-layer CLT panel 146 mm
2. Resilient supports and rails (100 mm)
3. Sound insulation material (100 mm)
4. Gypsum board 13 mm
5. Gypsum board 13 mm

Concrete topping
STC $\leq$ 64 dB
IIC $\leq$ 60 dB
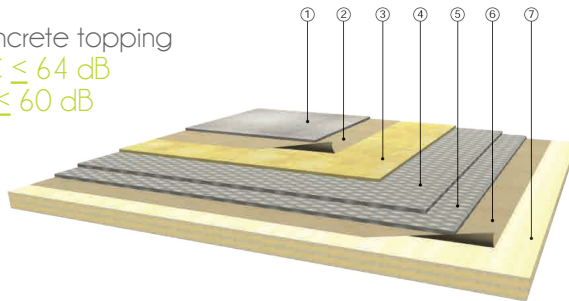
Concrete topping
1. Prefabricated concrete topping 20 mm
2. Kraft paper underlayment
3. Sub-floor ISOVER EP2 25 mm
4. Honeycomb acoustic infill FERMACELL 30 mm
5. Honeycomb acoustic infill FERMACELL 30 mm
6. Kraft paper underlayment
7. 5-layer CLT panel 135 mm

Double enclosure
STC $\leq$ 64 dB
IIC $\leq$ 65 dB

Double enclosure
1. Floorboards nailed to sleepers
2. Low-density fibre board THERMISOREL 20 mm
3. Low-density fibre board THERMISOREL 20 mm
4. Lumber sleepers
5. 5-layer CLT panel 146 mm
6. Resilient supports and rails (100 mm)
7. Sound insulation material (100 mm)
8. Gypsum board 13 mm
9. Gypsum board 13 mm

Figure:117. Different solid wood floor buildups and acoustical performance

Floor

For the floor system there are several option that can full fill the asked requirements of reduction >50 dB STC (airborne sound) and can meet the proposed 55 dB IIC (impact sound).

A floating floor system can meet the requirements although not all of them. However when a concrete floating topping is used as presented in the image *"Different solid wood floor buildups and acoustical performance"* the acoustical performance of the flooring system is very good. A floating floor system has the advantage that beams can run under the floor without creating possible floor leaks and can show the laminated wood/bamboo on the ceiling.

A double enclosure scores best in acoustics (and in fire). Allowing for systems to run under the ceiling. The system is however the thickest, most expensive solution that completely hides the solid wood/bamboo product, which would be a shame and not in accordance with this project to showcase the possibilities and the sustainability of laminated bamboo.

A suspended ceiling can fulfill the requirements allowing the clt to be used as floor surface. This could be a problem for wood because it is not that hard-wearing/durable as bamboo. However, bamboo is very hard-wearing; therefore, it would not only show its possibility as a structure, but at the same time its well known durability as flooring. At the same time it would allow installation run along the ceiling. A risk is however the spilling of liquids on the floor (in large quantities).

Details

The most crucial part will be the details where the wall meets the floor. How to prevent that the structural elements create a so called flanking sound.
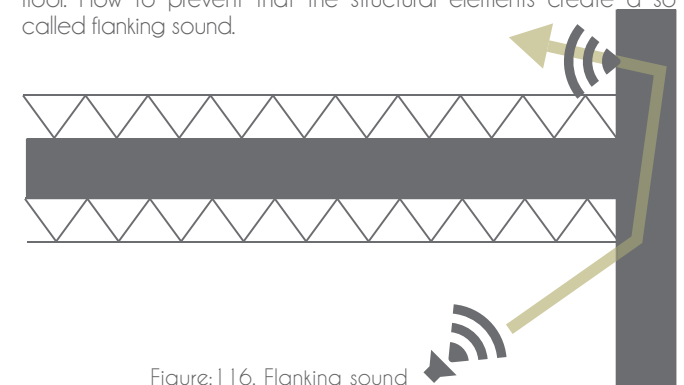
Figure:116. Flanking sound

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

8.3. Vibrations

Activities on a floor always create vibrations and every floor has its own frequency. Depending on the frequency (Hz) people notice them or do not. Humans are normally sensitive for a frequency between 4 and 8 Hz. The further away the natural frequency of a floor is the safer a floor feels for people (Gagnon and Pirvu 2011). The frequency of a floor is determent upon its properties (mass, stiffness and the absorption of excitation energy, i.e., damping of the floor system. Codes and regulations if any, normally deal with the floor response to a walking person also known as the Footstep force.

Footstep Force

The force of a footstep is dependent on a few factors the weight of a person, the gait and the footwear of a person. The force of a footstep can basically be divided in two kind of vibrations which both can create a vibration in the floor system. A footstep basically creates two kind of vibrations which have to be taken in to account. The vibration is either a transient vibration or resonance, which is decisive depends upon the properties of the floor. A floor with a fundamental natural frequency above 8-10 Hz, far above the footstep frequency and its predominant harmonics the design should most likely focus on the transient response caused by the impact of the heel in each footstep. Below 8-10 Hz the design will most likely have to take care of the harmonics. Bare CLT floors which are comply normally have a natural fundamental frequency above 9Hz (Gagnon and Pirvu 2011). Adding mass like a concrete topping normally reduces the fundamental natural frequency to below 9Hz. Which results in the need of extra measurements. For example absorbing material could be added, or dampers could be used. Previous research suggest that the connections between different CLT floor elements have no significant result on the performance regarding vibrations (Gagnon and Pirvu 2011)..

Normal CLT floors the natural frequency ranges between 6.5 and 8.5hz. This is depended on the density, the structural layup an structural behavior (SOM 2013).

The mass timber industry have proposed a calculation method to calculate the frequency in coloration to the floor thickness, mass, span and the static deflection. An attempt to calculate (with the information available) if CLB floors has been made and is included in the appendix: Apendix "*Other technical Vibrations*".

Design Criterion

$$\frac{f_V}{d_V{}^{0.7}} \geq 13 \; or \; d \leq \frac{f^{1.43}}{39}$$

f = fundamental natural frequency calculated using equation [2] in Hz

d_V = 1 kN static deflection calculated using equation [3] in mm

Fundamental natural frequency

$$f_V = \frac{3.142}{2l^2} \times \sqrt{\frac{EI_{eff}^{1m}}{\rho A}}$$

f_v = fundamental natural frequency of 1 m CLT panel simply supported in Hz

L = CLT floor maximum span in meter

EI_{eff}^{1m} = effective apparent stiffness in the span direction for 1 m wide panel in N-m²

ρ = density of CLT in kg/m3

A = area of cross-section of 1 m wide CLT panel, i.e. thickness x 1 m wide in m²

Static Deflection

$$d_V = \frac{1000Pl^3}{48EI_{eff}^{1m}}$$

d = static deflection at mid-span of the 1 m wide simply supported CLT panel under 1 kN load in mm

P = 1000 N

Simple design method

$$l \leq \frac{1}{9.15} \times \frac{(EI_{eff}^{1m})^{0.293}}{(\rho A)^{0.123}}$$

Figure:118. Proposed Formula's from the mass timber industry

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

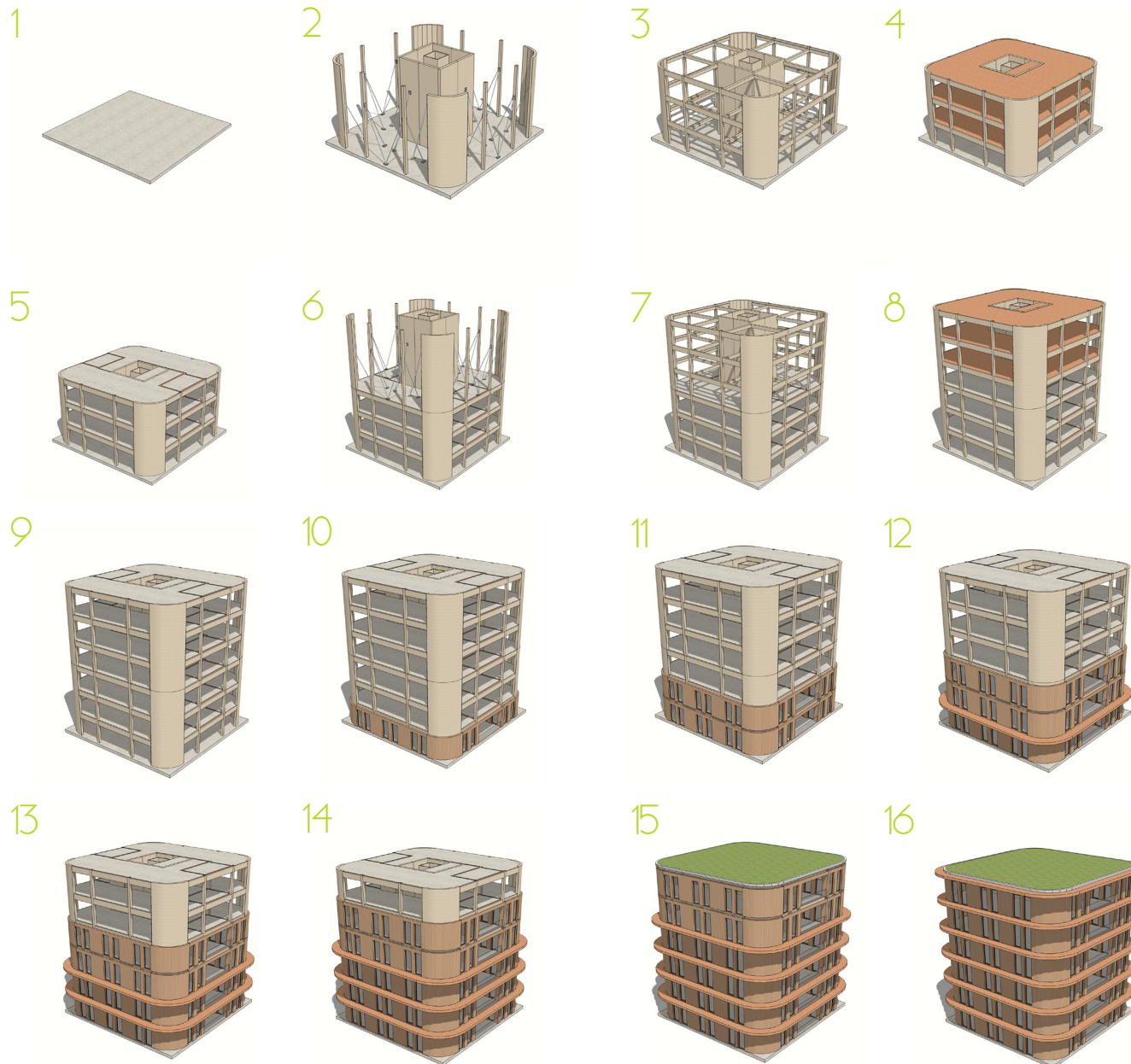# 8.4. Assembly

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Figure:119. Possible assembly for a 6 story building

Assembly or in other words construction on site is an important cost and risk factor. The longer the time the more cost for fees have to be paid and the more risk of damage to the structure by bad weather conditions.

Heavy timber has proven to have the opportunity to have a fast assembling time. Many of the tall wood building constructors call it on of the biggest advantages. (Buchanan 2011, December 4, Zumbrunnen 2012, Creebyrhomberg 2012, October 30, Collins 2013). It has the potential of a high degree of prefabrication, providing optimal workspace for the workers, and resulting in mere a few weeks on site to erect a 7-10 story building. Wood builders also point out advantage of the weight difference. A timber/bamboo tower would have significant lighter elements than a concrete proposal, resulting in lighter cranes and therefore saving money in time and equipment compared to concrete (only the material is significantly more expensive). Thus, making it possible to compete with concrete buildings. Heavy timber can be made in large panels or beams, allowing the reduce of elements. The limitation is transportation. Truck sizes vary, but a normal big truck has a load capacity of 2.13m x 2.13m x 15.5m (Truckads 2015). Because of the behavior of the structure (creep) different experts suggest to make the vertical elements continuous (Green and Karsh 2012, Karsh 2013, 20 September). Making structural elements that are tall rather than wide will improve the structural behavior under lateral loads (wind / earthquakes) (Winter, Tavoussi Tafreshi et al. 2010, Buchanan 2014, October 12).

The structural vertical elements should therefore first be erected, Because of their size it needs temporary support which can be removed when the beams are placed, followed by the floors. On the floors a concrete topping (for sound insulation and mass) is added. If a prestressed system is used (similar to prestressed concrete) this is the face where the vertical elements should be tensioned. Then the facade is mounted, which will hang from the floor above.

To sum it up. A proper designed wood building will lead to a fast erection time and lighter equipment. The focus of order should be on the vertical elements to be able to deal with the lateral loads.

Anisotropic

Bamboo and wood are both anisotropic materials. Anisotropic materials have a strong and a weak direction. Wood and bamboo are strongest in the grain direction. The weakest direction is perpendicular to the grain direction. For wood and bamboo goes that the main threat is splitting. Splitting is caused by tension parallel to the grain. The resistance of wood against splitting (shear strength) is about 8 to 20 times smaller than its compression capability parallel to the grain (Hoadley 2000). Lamboo claims a shear strength about 5 times smaller than its compression strength (20,002 KN/m² vs. 92,966 KN/m²). Which is higher than soft woods in compression.

A anisotropic material is more likely to split when a single big connector is used than when several small pins with in total an equal service area is used. More pins results in a bigger contact area and therefore a better load spreading and a reduced chance of splitting. An example of this are the nail plate connectors, it spread the load over a bigger area reducing the chance of splitting the wood. If it is esthetically pleasing is another topic. Besides steel plates solutions including embedded steel can be chosen to take care of perpendicular tension and moments.

Rotational stiffness

To be able to transfer moments a connection needs a high Rotational stiffness. The stiffness depends on the distance from the center of the connection, the number of connections, the strength per section and the kind of connector and can be calculated using the following formula's.

Stiffness of pin connections:

$K_r = K_b \cdot I_p$

K_r = Stiffness of connection I_p = Polar moment of inertia

K_b = stiffness pin

$$I_p = \sum_{i=1}^{n} r_i^2$$

I_p = Polar moment of inertia
n= Number of connections
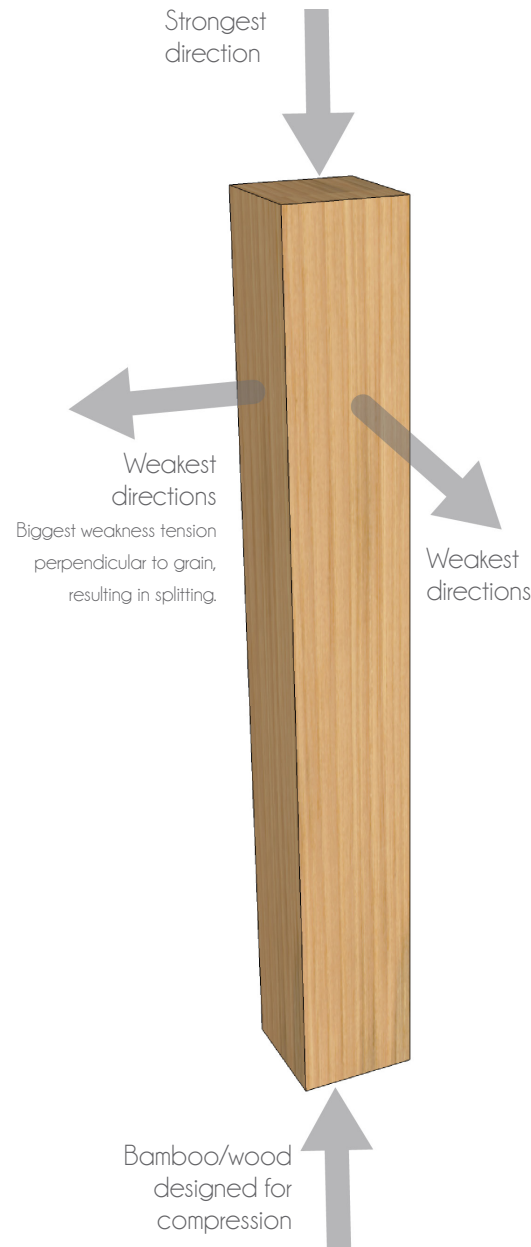r= Distance to connection center
(Verweij, 2005).

8.5.   Connections

Strongest direction

Weakest directions
Biggest weakness tension perpendicular to grain, resulting in splitting.

Weakest directions

Bamboo/wood designed for compression

Figure:120. Strong and weak points of Anisotropic materials

Beam of laminated bamboo

Connector

Splitting

Tension perpendicular to the grain

Figure:121. Problem with end connections

Figure:122. Example of moment stiff connection, by adding steel plates

Figure:123. Example of a moment stiff connection in wood with bolds

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Connections

Figure:124. First prestressed timber building in Europe (near completion)
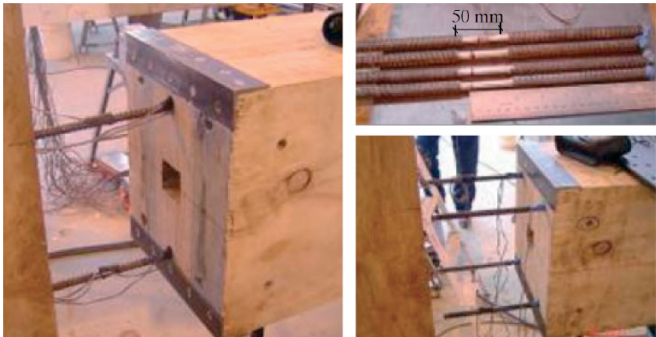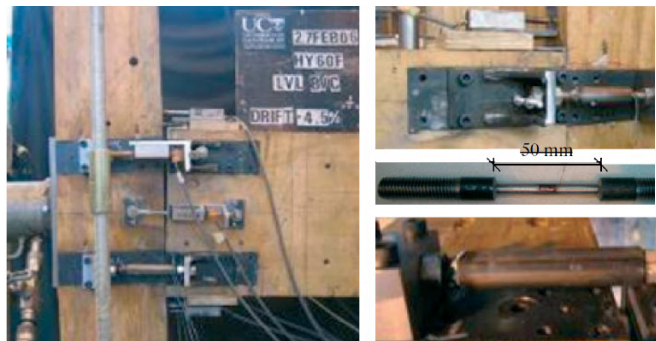

Figure:125. Internal dissipative devices in LVL
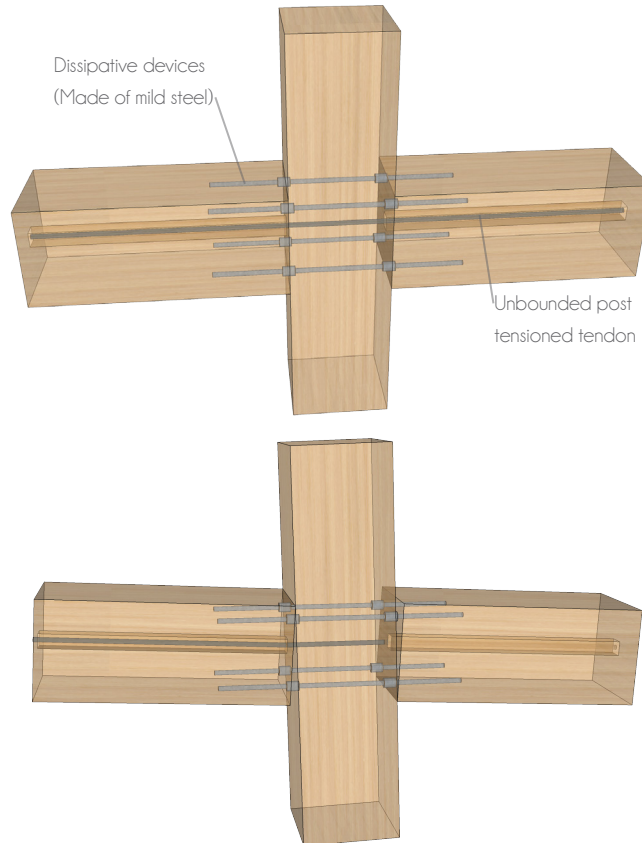

Figure:126. External dissipative devices in LVL

Dissipative devices
(Made of mild steel)

Unbounded post tensioned tendon

Figure:127. Functioning of Hybrid system in Earthquake

Self-Centering   Energy dissipation   Hybrid system

Unbonded post tensioned   Dissipative devices

Figure:128. Energy behavior n Earthquake

In New Zealand an interesting development has taken place. At the university of Canterbury a multi storey prestressed timber building system has been developed to deal with earthquakes.

It basically adapted a concept that has been used in the concrete industry since the 1990's known as jointed ductile connections or PRESSS-technology. Their solution is to clamp the beams between the columns. These solutions can undergo a inelastic displacement comparable to traditional concrete structures, assuring the structures capability to re-center after seismic events and limiting the structural damage. The inelastic demands of the earthquake are absorbed by the opening and closing of the existing gap and the structural elements are kept in the elastic range resulting in very little damage. A combination between dissipation devices and unboned post tensioned tendons creates the best results. Canterbury made a design proposal for a 6 story all woof building using this system and multiple lower buildings haven been realized (Buchanan, Deam et al. 2008).

This hybrid system shows a flag-shape hysteresis behavior, see image: '*Energy behavior in earthquake*'. The mild steel is used because it is ductile when compared to for example stainless steel. This ductility allows a larger amount of energy absorption. On the next page are several graphs showing the amount of drift and the fewer lines means a higher absorption and a better earthquake performance. The hybrid system clearly preforms better. The next page shows vertical orientated prestressed shear walls and their earthquake behavior. The tendons are stressed by using a jack and hold in place with a steel anchor which is basically a reinforced steel plate.
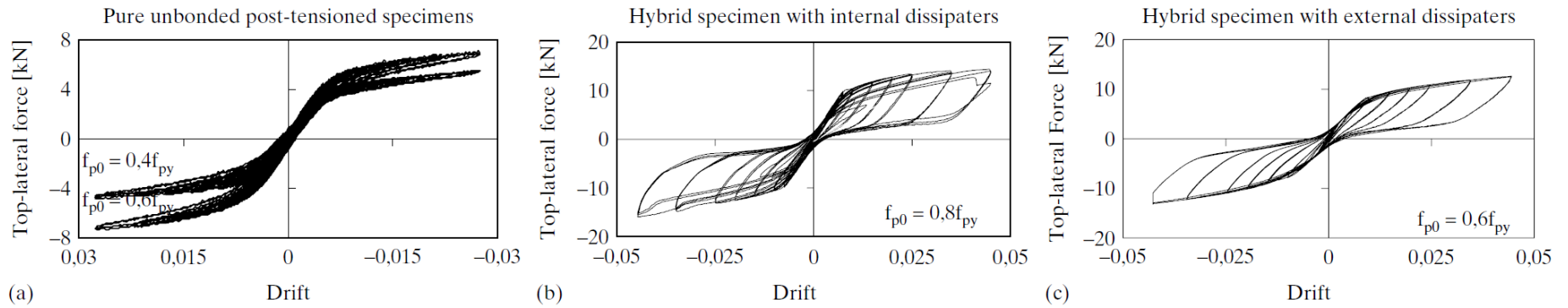
Fig. 5: Lateral force-drift curve: (a) pure unbonded post-tensioned solution; (b) hybrid solution with internal dissipaters; (c) hybrid solution with external dissipaters (modified from Refs [9,10])
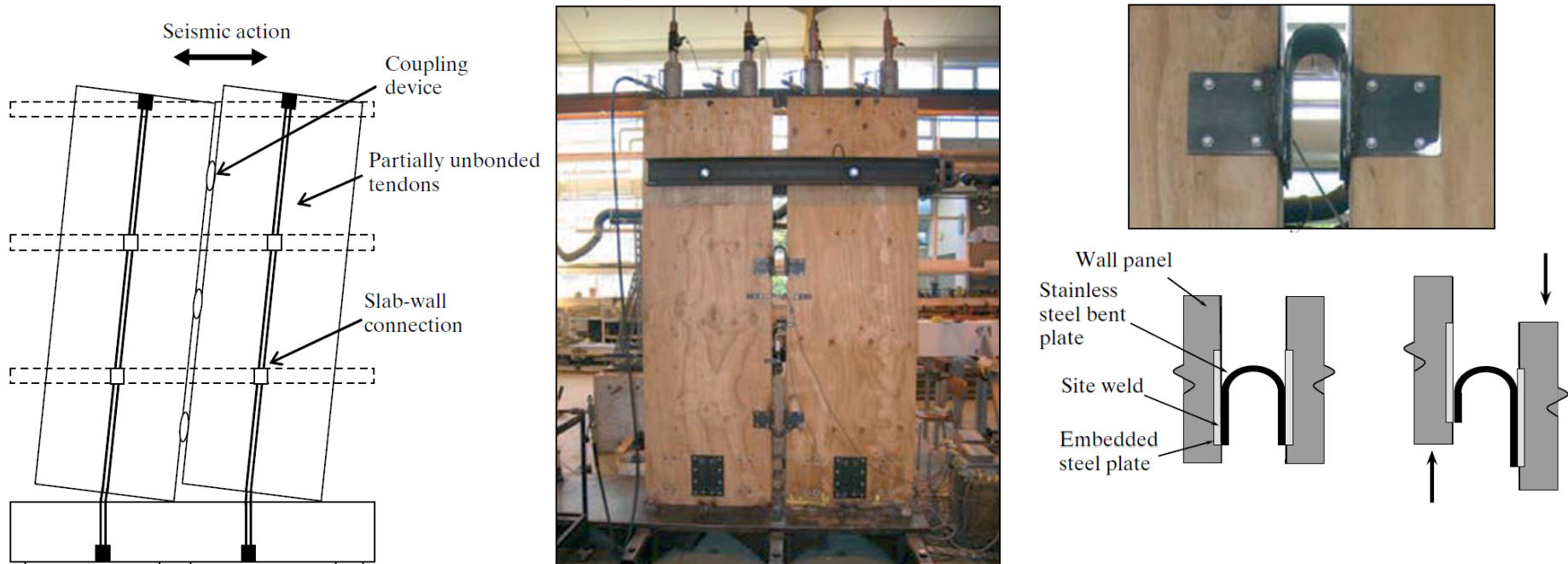

Fig. 6: Mechanism of coupled hybrid walls and set-up using U-shape flexural plate dissipaters[16]
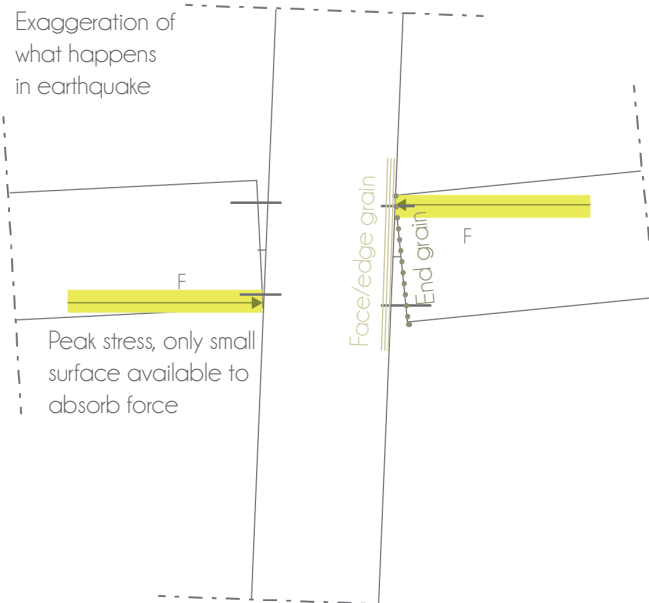
Figure:129. Canterbury prestressed LVL research.

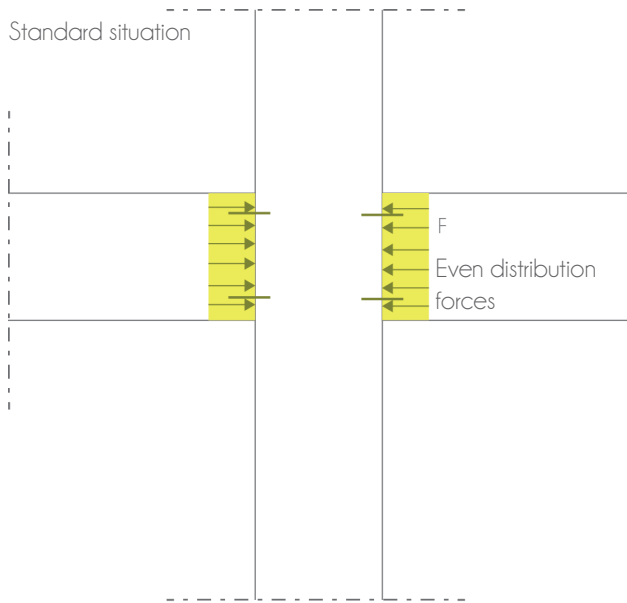How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Connections

Standard situation

Even distribution forces

Exaggeration of what happens in earthquake

Peak stress, only small surface available to absorb force

F

Face/edge grain

End grain

F

Figure:130. Structural challenge regarding edge grain face grain

Knife

Cutting

Fibers split

Edge grain or face grain

Knife

Cutting

Fibers spring back

End grain

Figure:131. Splitting or springing of fibers

Face grain

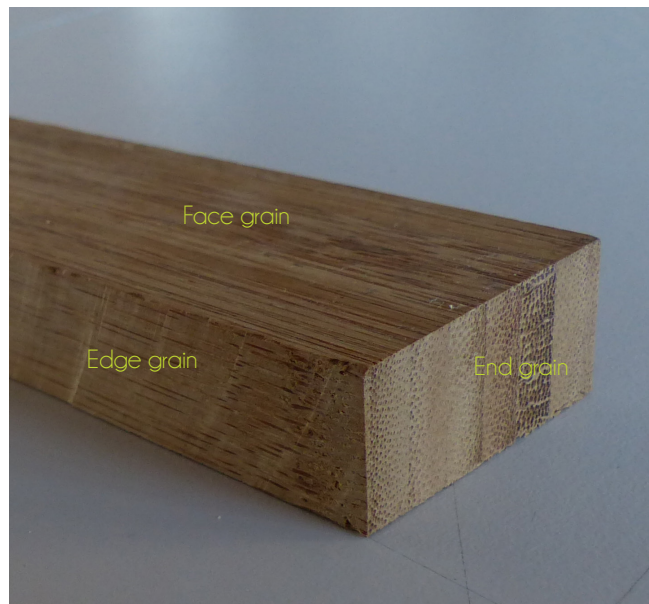Edge grain
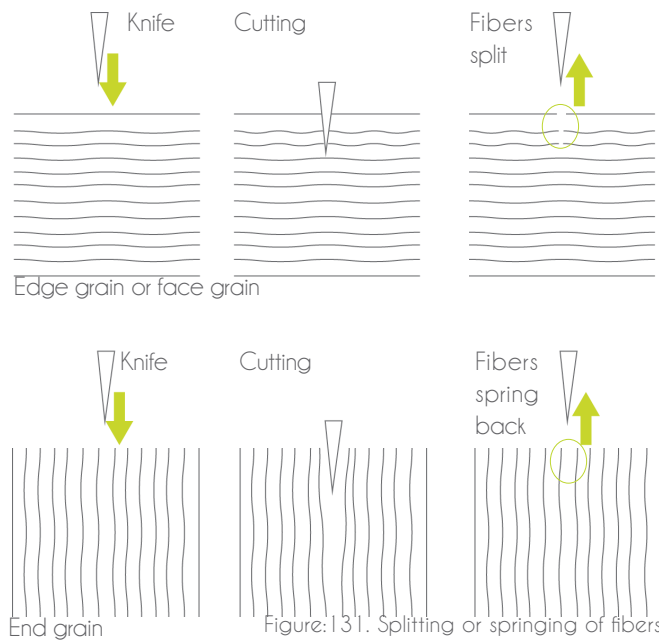
End grain

Figure:132. Face, edge and end grain

Important is that the steel connector spreads the force of the tendon over a larger surface area. The columns can be placed on a steel foot and the shear walls normally are connected by either using brackets or steel profiles and depending on the requirements can be nailed, screwed (new screws are available with lengths over 50cm) hooked or bolted (Gagnon and Pirvu 2011).

Important is to understand the material. Bamboo is known for its hardness (Janka hardness: Moso: +6000, Guadua: 3000-4000). Guadua is only half as hard compared to Moso or European oak, however it is still more than twice as hard as European spruce (often used in CLT or LVL) (Guadua Bamboo n.d. E). However the bamboo is anisotropic (like wood). The hardness differs when comparing end grain to edge/face grain, see image: "*Face, edge and end grain*". Edge grain wood is harder and more durable than face grain and for its durability it often has been used in factory floors, or floors dealing with heavy traffic. It is also the preferred choice for butcher blocks because the fibers don't split but bend back. It absorbs energy and noise (Smith). Edge or face wood splits were end grain bends back see image: "*Splitting or springing back of fibers*". The rule of thumb is that end grain is about 10x harder than edge grain (The Grothouse Lumber Company 2015). The rule of thumb applies for woods species and assumed is that it also applies for bamboo species. This could be an issue to the structure.

During an earthquake the structure will rock start rocking. The rocking is mineralized by the energy dissipative devices, however the beam column connection will move. This results in higher peak forces in the edges of the beam and also in the column opposite of the peak forces in the beam. The beam (+/-10times harder) acts like a knife and the column (which is edge/face grain) could get cut (dented) if the forces become to high. This would decrease the structural integrity and increase movement in the next earthquake. Assumed is that the material is hard enough and the energy dissipaters absorb enough energy to prevent it from occurring. This however needs to be verified in further research. A solution to the issue could be to place a metal strip near the edges of the beam spreading the force over a larger area.
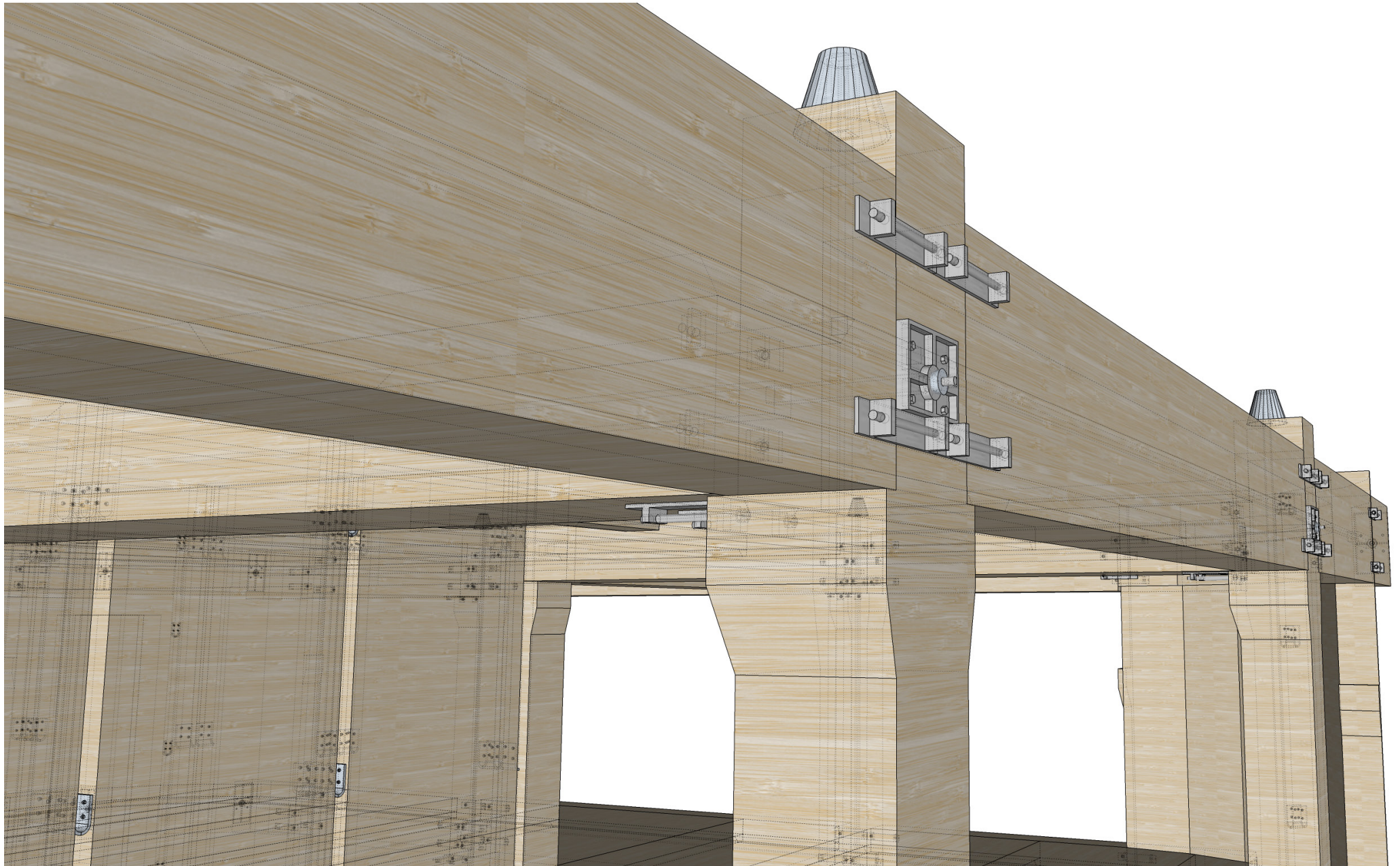
Figure:133. A 3D design suggestion in Lamboo for a 3 point node with anchor

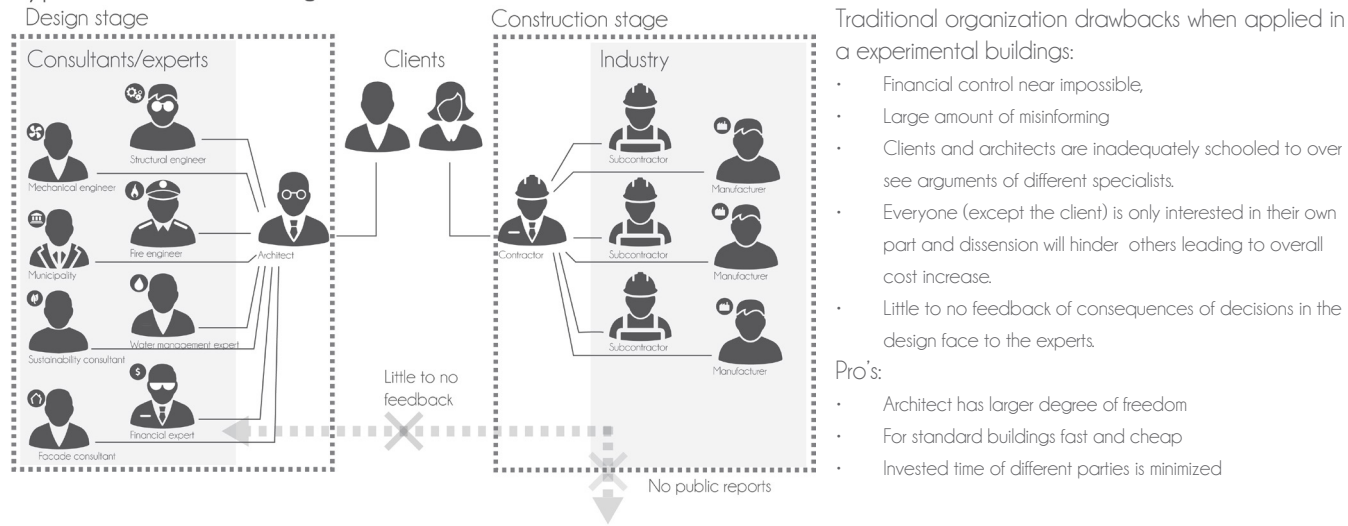How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

9. Sustainability

Figure:134. Bamboo forest

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

9.1.   Social sustainability

Typical traditional orginisation

Traditional organization drawbacks when applied in a experimental buildings:

- Financial control near impossible,
- Large amount of misinforming
- Clients and architects are inadequately schooled to over see arguments of different specialists.
- Everyone (except the client) is only interested in their own part and dissension will hinder others leading to overall cost increase.
- Little to no feedback of consequences of decisions in the design face to the experts.

Pro's:

- Architect has larger degree of freedom
- For standard buildings fast and cheap
- Invested time of different parties is minimized
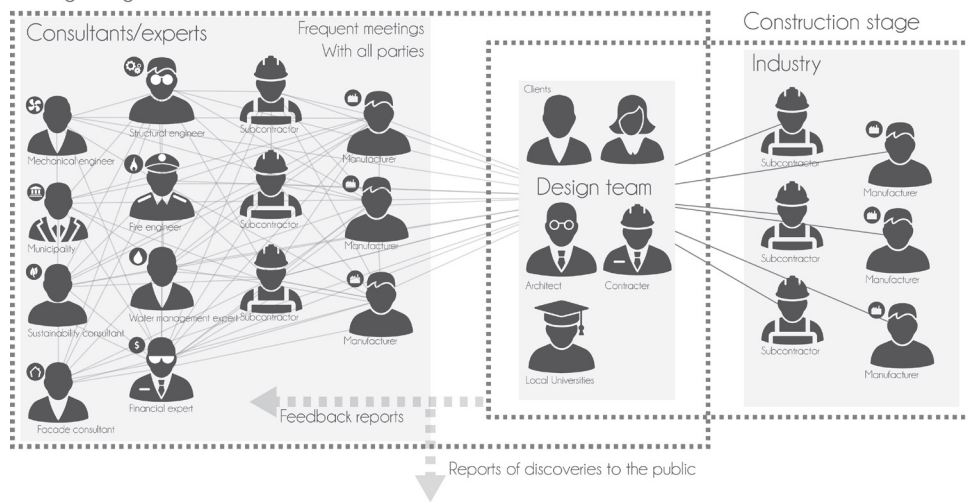
Proposed orginisation

Figure:135.   A traditional organization vs the proposed organization

Proposed organization drawbacks:

- All parties have to be fully committed.
- Most information is irrelevant to different parties, but all have to attend for that small part that is relevant leading
- Vast amount of decisions have to be made in an early stage
- Time consuming meetings
- Goals can differ
- Industry will not be happy to shear knowledge

Pro's

- Allows better cost control
- Reduces miscommunication
- Increases understanding the building process for all parties
- Involving the executing parties to the design table allows them to optimize the design to their specialties and helps them understand the overall goals of the project.
- Could boost the entire industry

Sustainability can be divided in three pillars and one of them is social sustainability. Social sustainability is maybe the poorest defined pillar of sustainability. The definition for social sustainability used for the thesis is: The improvement of social structures in the physical realm. The social structures are education, interaction, expression of culture, standard of living and equalization of rights and prospects. Each will be discussed in this chapter regarding the design proposal or industry or both.

Education

Education is an important part of the design. First of all the aim is to produce all products locally, creating knowledge for producers, designers, developers, constructors, users and regulators in how to deal with a bamboo structure. Luke Schuette the director of Lamboo admitted that Lamboo is working towards creating more factories in South America with a focus on Colombia and Ecuador, because of the difficulties that are common in developing countries Lamboo prefer to keep a low profile regarding the specific details, but soon Ecuador will most likely have high tech bamboo factories (personal communication March 31, 2015). To make this to a success, help from experts in different fields are needed. Some have to come from abroad to shear there knowledge. An established player on the market like Lamboo could play a key role in this.

The proposal is a proposal, to make the building a success all the different parties have to be involved and together have another look at the design to fine tune it. To further enhance the creation of knowledge Local universities will be included throughout the process and the vast majority of the reports made will open to the public. Building tall in wood/bamboo is relatively new, other pioneers also underline the importance of involving different parties in an early state to keep the cost and quality under control (Green and Karsh 2012, Zumbrunnen 2012). The building process wouldn't benefit from a traditional organization. Although architects don't like to admit, architects are insufficiently schooled in the technical complexities.

A better solution would be to use a design team and let specialist meet on frequent base to educate each other and reduce costs.

From the combined meetings all participants would benefit from an increased understanding of the overall process. Increased specialization has resulted in alienation between specialties, leading to extra costs reintegrating specializations. The building industry could benefit from reintegration (Cacciatori and Jacobides 2005). When extensive documentation is collected and reflected throughout the process valuable lessons could be learned, helping to improve further laminated bamboo designs in earthquake zones increasing the social sustainability of the design proposal.

The design proposal is not only about educating the industry, it is also about educating the community and tourists. To show the beauty and possibilities of laminated bamboo. To help to remove the negative stigma of being a poor mans material inferior to concrete and steel (Flander and Rovers 2009) and to show that bamboo is suited for more than feeding panda bears or making kitchen utilities (van der Lugt and Otten 2006). To show what kind of solutions are possible and how it could provide safe environmental friendly alternative to the mainstream solutions. The restaurants and shops are designed to draw people to the area. This in combination with a strategic location enchants the chance of people seeing and visiting the building and therefore learn about laminated bamboo.

Interaction

Social interaction is an exchange (verbal and non-verbal) between different individuals (between two people but also large groups). Social interaction is important for the human wellbeing (Argyle 1969, Rook 1984, Bloomberg, Meyers et al. 1994) and most social problems (racism, discrimination, bulling, etc.) comes from a lack of communication, interaction and cooperation between different groups of people (Argyle 1969).

Architects are often over estimating the influence of design. A good design is no warranty for social interactions. According to Teerds (2008) architecture is part of the artificial world of objects it merely creates some of the boundary conditions needed for social interaction. It creates a podium for public life to occur. So it could be stated that a good design provides an excellent podium for interaction and social sustainability, therefore a good de-

sign cannot be social sustainable regarding interaction, it creates a good podium for interaction the people themselves have to create the 'real' social sustainability. To create space for social interaction in the physical realm the design uses spaces that should function as meeting places. A meeting place is a place/location that stimulates/encourages interaction, communication and cooperation between individuals/groups respecting the norms and values of the socializer's and non-socializer's. Interaction is encouraged when people slow down/arrive somewhere and not when moving to wards a destination. The Dutch architect H. Hertzberger quoted: *"If a street-form is more suited to movement, the square-form is more likely to encourage lingering. You are under way in a street, whereas you arrive in a square. The square is the spatial capacity for gatherings and encounters."* (Hertzberger, 2008, p. 132).

The design takes those things in to encounter, creating public places for people to slow down and interact, creating shadow and greenery to make people more comfortable in the hot climate of Guayaquil and allows them to take a break. The plan provides 3 different restaurants with the purpose of further stimulating interaction. Some of the previous buildings were restaurants. The location is well suited for restaurants. It's next to the university, the tourist port, IMAX theatre, 2 national museums and the "Malecón 2000 Park". On top of that 500m from the project is the most famous neighbor hood and hill located "Las Peñas" attracting millions of tourists every year.

Public space

Restaurant

Shops

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
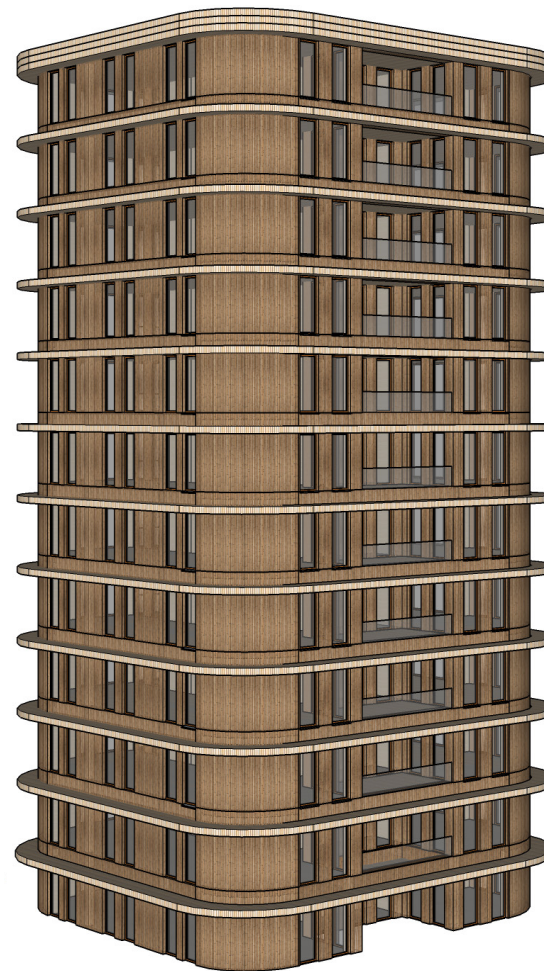
The building could offer space for tourists who want to have a break and see something unique (a bamboo structure of 35m with is earthquake proof). For students and teachers it offers a place to lunch, or just to take a break. IMAX and museum visitors can have a drink or have lunch/dinner in the restaurants. By creating these possibilities the design creates a platform for the social interaction to occur and therefore adding to the social sustainability.

Expression of Culture

Ecuador and especially Guayaquil has a long tradition with bamboo (Takahashi 2006, INBAR 2008). Now a day's bamboo is no longer a popular material and regarded as a poor man's material. This threatens the bamboo traditions of Ecuador. The old way is on the other hand no longer suited to house people, the density of cities and modern comforts are increasingly difficult to combine with the modern standards of living. The design proposal however shows a new chapter to the rich bamboo tradition of Ecuador.

The building has the layout of a common modern building with a focus on flexibility (facades, and internal layouts can be modified easily). On the outside it tries to show its sustainable character but at the same time to present itself as a normal building. The design tries to balance sustainable and notable look with a conservative more excepted look. In architect terms the aim was to create a "I like my neighbor" kind of building. A "I love my neighbor" kind of appearance is not wanted. One of the problems of identities of metropolitan cities is that the international style of high-rise is without identity. The buildings can be placed anywhere, informing the modern metropolises (Wood 2010, Korotich 2011). The proposed building complex is fit for its location. The from comes from the boundary conditions prescribed by the site of the building. The design respects the climate conditions and is not just a glass box, it symbolizes the material it is made from (bamboo) and it uses local materials. Besides it would be the first tall building in bamboo in the world and potentially it could be the first of many more laminated bamboo buildings in Guayaquil, creating a stronger identity for the city escaping the main international style of uniform glass boxes. Together this creates a stronger identity for Guayaquil and therefore strengthening the culture and social sustainability. Therefore it adds to identity of the city.

I love my neighbors

F* my neighbors

I like my neighbors

Figure:137. The preferred architectural strategy: I like my neighbors

Figure:138. Possible look of the proposed building

Standard of living

The building itself does little to improve the standard of living of the people. Prices are likely slightly higher then compared to a comparable concrete structure (although could be cheaper in the long run), see sub chapter: Economic sustainability. However er the proposal aims at producing the material local, very local. The main ingredient (bamboo) can be harvest just outside of the Guayaquil witch has the main bamboo industry of Ecuador. This will not only benefit the environmental sustainability, but also the social sustainability.

The second effect is also known as the pro-poor financial impact (Marsh and Smith 2007). Ecuador has an bamboo industry which is mainly low tech. Based on the data from Mash and Smith (2007) going to a high-tech bamboo industry could provide Ecuador with 5x (from 0,2 job/ha to above 1 job/ha) more jobs in the bamboo industry and the pro poor financial impact per ha could increase from less than $500,- to around $2500,- (an increase around 500%). The proposed building could be the catalyst of that process. The actual number compared to the projected number of jobs per ha is likely to be higher, since the bamboo analyzed by Mash and Smith is Moso and not Guadua. The biomass of Guadua is almost 2 times higher (Yiping, Yanxia et al. 2010). The building itself will not increase the standard of living of the general population, but if it is able to catalyze the industry towards a high-tech industry it will increase the standard of living for the poor and therefore at to the social sustainability.

Equalization of rights and prospects

More jobs and better paid jobs, means more opportunities for poor people and more money to get better homes with electricity, pluming, etc. It also allows for better education. Out of the researcher of Marsh en Smith (2007) it can be also concluded that high tech bamboo products provide more equality for womans. It offers them jobs and therefore financial Independence. So the building doesn't directly improve the rights and prospects of the poor, but the development of the industry needed does.
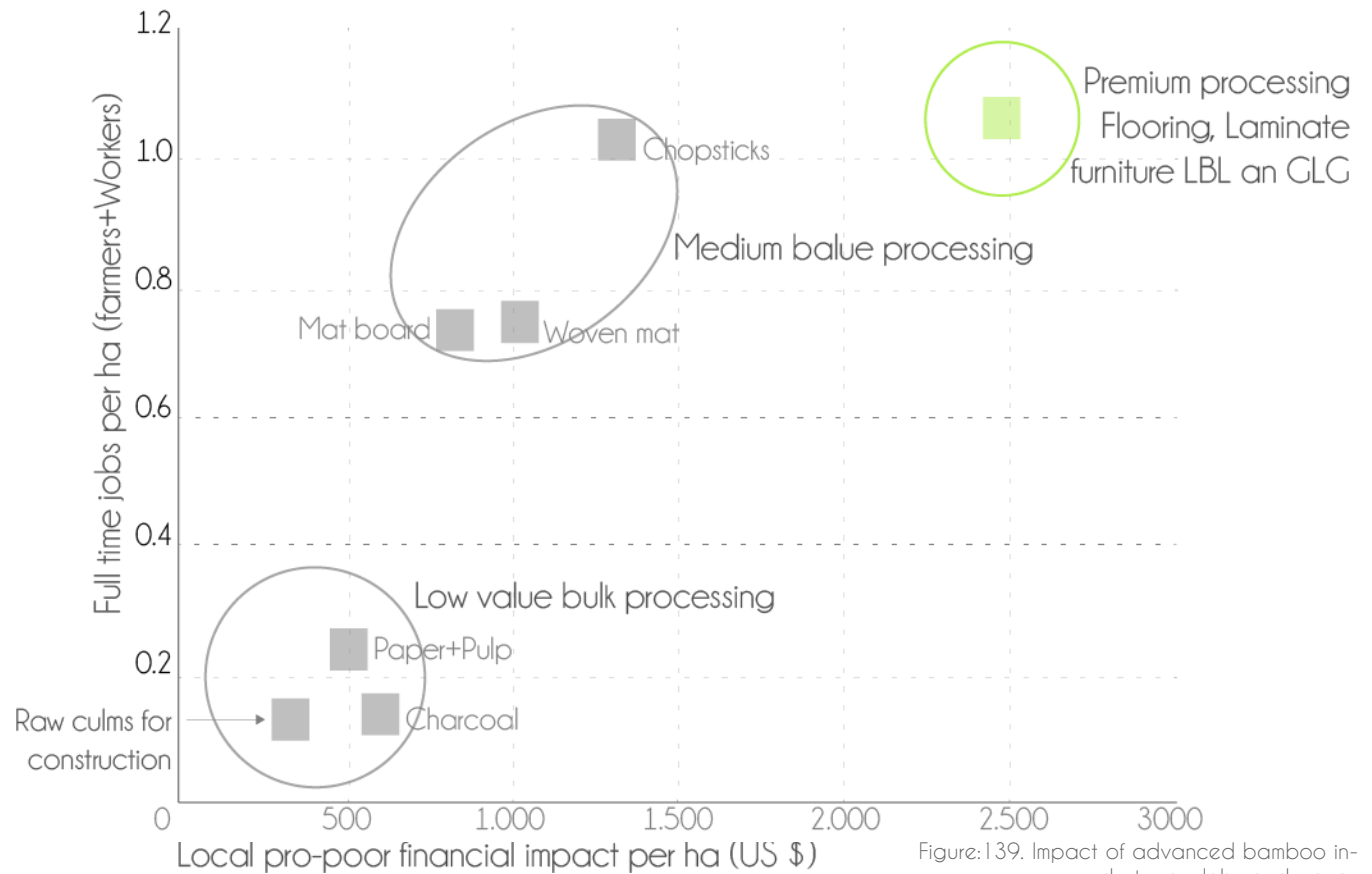

Figure:139. Impact of advanced bamboo industry on Jobs and money

Overall the building is social sustainable. The strongest direct influence is on education and interactions, but it's most important influence is to catalyze the start of a high-tech bamboo industry in Guayaquil. If this will happen depends on the success of the building, but if it will, it will severely improve the life of the poor in Ecuador and will improve the position of Ecuador overall.

High end bamboo products can improve the position of woman

Industry segment	Woman in Supply chain
Handicrafts	60%
Bamboo Shoots	31%
Flooring and other premium processing	49%
Chopsticks	49%
Woven mat	42%
Mat board (panels)	46%
Charcoal	37%
Paper + pulp	38%
Raw culms	31%

Adapted from (Marsh and Smith 2007)

Table:12. Equalization of woman in developing countries

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

9.2. Economic sustainability

Price comparison (2008)

Material

LVB   Glulam/LVL   Timber

Size

2x4   2x4   2x4

Cost

4x   2.5x   1x
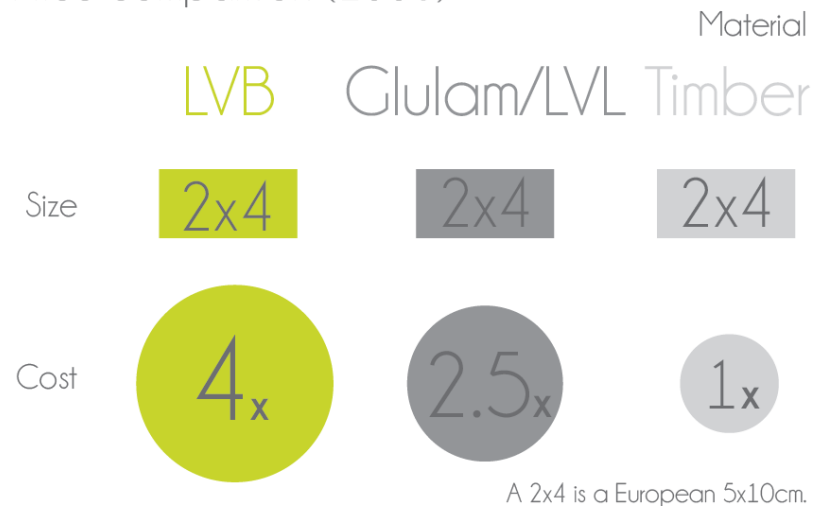
A 2x4 is a European 5x10cm.
One of the most common sizes in construction

Figure:140. Material cost comparison in the USA (2008) excluding shipping

Machining

Soft wood

LVB

Speed

Durability tools

Soft wood

LVB

Life time

Figure:141. Decrease tooling speed and lifetime of tools because of hardness of LVB

Wood drill bit   Steel drill bit
Figure:142. Difference wood drill and a steel drill

Sustainability can be divided in three pillars and one of them is Economic sustainability. Economic sustainability can be described as the sum of three elements: profit, economic growth and cost savings. That highly advanced industries can bring economic growth has been proven in the past and also holds for the bamboo industry (Marsh and Smith 2007, INBAR 2008). Advanced bamboo industries provide more money and jobs per ha, than low tech industries (Marsh and Smith 2007). And with the fast development and increased competition the costs of laminated bamboo will go down. However can a building of Laminated bamboo of 12 stories compete with comparable buildings using concrete, steel or wood?

Laminated bamboo is as material more expansive than wood. If a piece is obtained with identical detentions softwood is about 4 times cheaper and glue laminated timber is about 1.6 times cheaper (Rittironk and Elnieiri 2008). However this was the case in 2008, As the bamboo industry is catching up and more companies are developing similar products, it seems logical that the price will comedown. However it seems unlikely that the price in the future will be comparable to pine, but it could be that the price for LVB will become closer to that of glue laminated timbers and veneer lumber making it an affordable alternative, because it is also significantly stronger, harder and durable than regular pine. For a structural solution it can be assumed that the reduce in size almost compensates the difference in price.

In handling there will be a small difference compared to softwood and CLT (made of softwood). It can be machined with the same tools but, because of It's higher density and hardness (Making LVB comparable to hard wood) blades and other tools will decay faster and machining/processing takes more time. Fine saw blades and wood drills should be avoided, better to use steel drills and rough saw blades with both edges sharp (Tuoh 2008).

There are currently no studies carried out regarding the economic feasibility of a mid/high rise building with laminated bamboo as a structure (as far as the author is aware of). However several studies have been conducted to determine the cost effectiveness of mid-high rise timber structures using either CLT or LVL (Wong 2010,

Green and Karsh 2012, Zeitler FLetcher and de Jager 2014). And there are several buildings that have been realized already (in CLT and LVL) providing some insight regarding the cost comparativeness of LVB structures in mid/high rise. Financing and ensuring of tall timber buildings can be done in similar ways with very little deviation when compared to concrete/steel and low rise wood buildings. According to E3 the value of a tall timber building is in current models in Europe 20% lower, because in their opinion it's more-likely to catch fire and because its 'less durable' then conventional materials (Zeitler FLetcher and de Jager 2014).

A study done by Wong (2010) provide insight in the composition of the cost of a 6 story prestressed highly engineered hybrid timber buildings is build up in New Zealand. The design uses a post tensioned LVL system, with a hybrid floor system (although a different system than proposed in this thesis) and has been realized in 2010. The TCC LVL floor system, costing around $245- /m², was the least economical part of the building. A comparable concrete slab would cost +/- $90,- m². Keeping the cost for the floor under control is essential because it a bout 80% of the structure. The expenses for the system are for a great deal caused by the notch connections. Overall press lam structure is about 10% more expensive than concrete and 9% more expensive than steel. A building in steel has significant lower costs for ex- and interior wall finishes and upper floor systems, But higher cost for the structure itself and concrete is almost in all elements cheaper (Wong 2010). But as were steel and concrete on the mid/high -rise have been around and developed for many decades and high engineered timber products are just starting. There is a need to further develop systems which would lead to a price reduction.

If the same system is compared with a press laminated bamboo assuming a price increase of 1.6 for the Structural frame (the cost for the frame also include work hours, equipment, ect.). The 1.6 increase should make up for higher material and tooling cost, and with the novelty of LVB waring off should come down like the price for press-lam has already decreased by almost 2% in 2 years time (Wong 2010). As the building system becomes more regular and lessons are learned the price will further decrease.
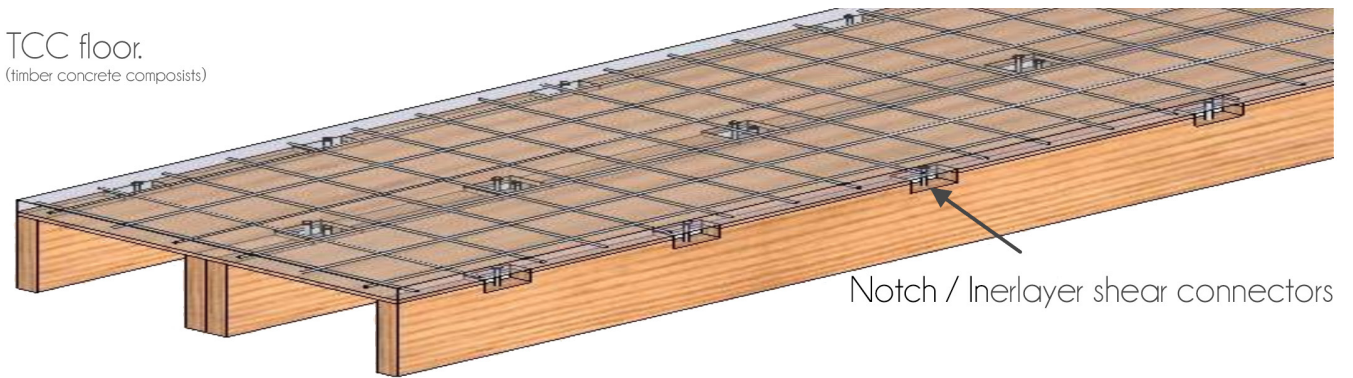
TCC floor.
(timber concrete composists)

Notch / Inerlayer shear connectors

Figure:143. TCC floor used in NZ

Earthquake proof building system NZ cost overview 2010 +Press-LBV

Costs of building in €

	Press-lam	Concrete	Steel	Press-LBV
Total	€2.41 M	€2.17 M	€2.20 M	€2.80 M
Roof	120,507	120,507	120,507	120,507
Upperfloors	678,896	513,156	457,872	678,896
External walls and finishes	789,809	747,170	303,968	789,809
Structural frames	657,172	630,091	1,155,260	1,051,476
Substructure	162,355	163,752	164,220	162,355

Building system

Currency rate:
1.41 NZ$ - 1 €
Date: 10-05-2015

Figure:144. Earthquake proof building system in New Zealand cost over view (2010)

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Economic sustainability
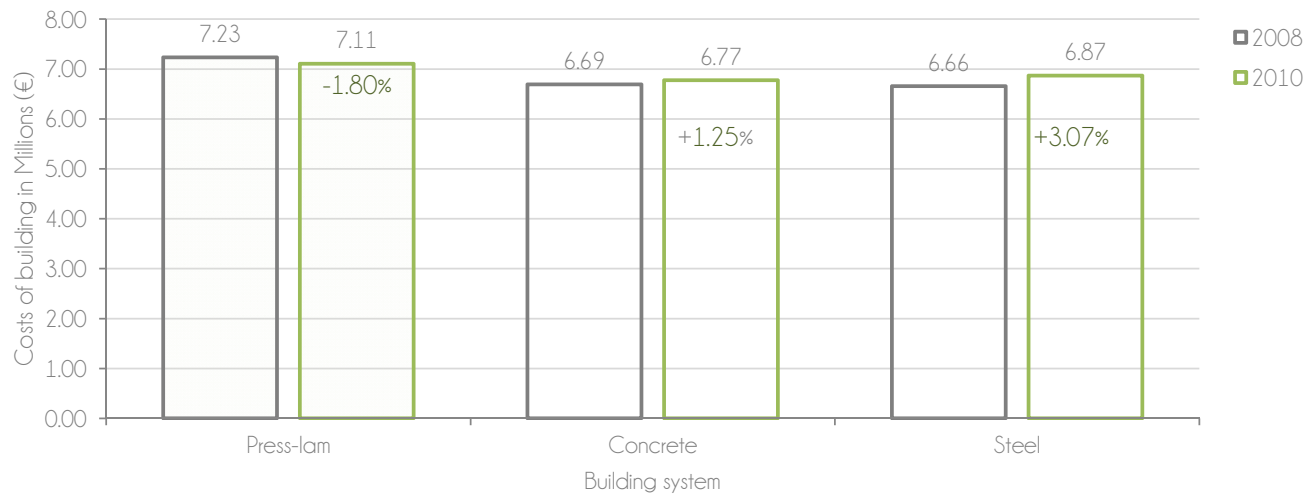
Building system cost overview NZ 2008-2010

Figure:145. Price fluctuating in New Zealand

Overview of building cost in Vancouver (Canada) in 2012

Figure:146. Over view cost per system per m floor compared to number of stories in Canada.

Green and Karsh (2012) believe it is cost effective maybe even beneficial using Greens proposed hybrid system. Green and Karsh used local producer to conduct prices for a 12 and a 20 story building and from them deduct square feet prices in Canadian dollars which have been translated to square meter prices in euro (using a exchange rate of 1$=0.76€). Although the estimations are based on a preliminary design, it showed a competitiveness epically for the 12 story building. In the peer review, proposals from the industry were made to significantly reduce the price. This seems in accordance with findings from Collins (2013) and Zumbrunnen (2012, November 7) who both state that with a good design it definitely can be cost competitive.

These comparisons do not take the life of the building in earthquake zones in regard and neglect repair costs after an earthquake. The proposed system is based on the system proposed by Buchanan, Deam et al. (2008) reducing the repair costs after an earthquake and allowing occupation after the earthquake instead of knocking the building down (which is very common with concrete and steel buildings designed for earthquakes). Therefore it is likely to save cost in the long run if engineered properly.

The materials, are more expensive, but there are considerable time savings making CLT/LVL comparative to concrete and steel. Structural laminated bamboo is at the moment more expensive than CLT/LVL at the moment and presumably take slightly more time to process, although it still will take less time than concrete. On the other hand structural bamboo gives more freedom in design and has significantly better performances than regular CLT or LVL. Structural LVB (with the right building system) can be cost competitive in earthquake zones (if the entire life span of the building is taken in to account) making it economical sustainable. Besides it can be assumed as LVB moves from niche market to the common market the price will come down, making it more competitive. To move this way, first a couple of prestige/ showcases have to be realized.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Page 100

9.3.   Environmental sustainability

As mentioned before sustainability can be divided in three pillars and the last of them is environmental sustainability. Environmental sustainability is about reducing the human footprint: less use of resources, using resources that regenerate, creating a safe environment to live in, reducing the amount of energy used and preventing toxic waste. This is captured in the total image: Eco-cost overview. In this sub chapter and in the sub chapters: C2G+End of Life, Land-use and Adhesives the impact on the environment will be discussed. Not all chapters of Eco-cost are covered but most are. The least covered in the other three chapters is the Eco-cost of Eco-systems. The influence on the Eco-system needs more research, especially towards the toxicity at the end of life face of burning the glue and the toxicity for nature in making the glue.

Effects not discuses in other 3 chapters

Proposal
The proposal uses green roofs and gardens to create a more inviting appearance to draw in people. It is also a sustainability beneficial. Green roofs and vegetation in the city are important for the human health and increase the biodiversity (Miller 2005, Schrader and Böning 2006). Greenery also improves the micro climate and reduces the urban heat island effect above cities.

Freshwater is a scares resource. Throughout the building process CLT uses about 30 times less water per m³ compared to concrete (Collins, G. 2013). No data is available regarding laminated bamboo, but it's assumable that it is similar to CLT. The pollution on site (noise, dust and contamination of water can also be reduced by 75%) (Collins, G. 2013).

Industry
Changing the land use can have a positive impact. Ecuador has been deforested for many decades, forest being replaced by pasture lands or palm oil plantations or have been abandoned after the soil degraded (result of poor farming). Replacing those fields with Guadals (bamboo forests) would increase the CO2 storage/fixation (Tian, Justicia et al. 2007), restore the soil and improve the water management (INBAR 2008).
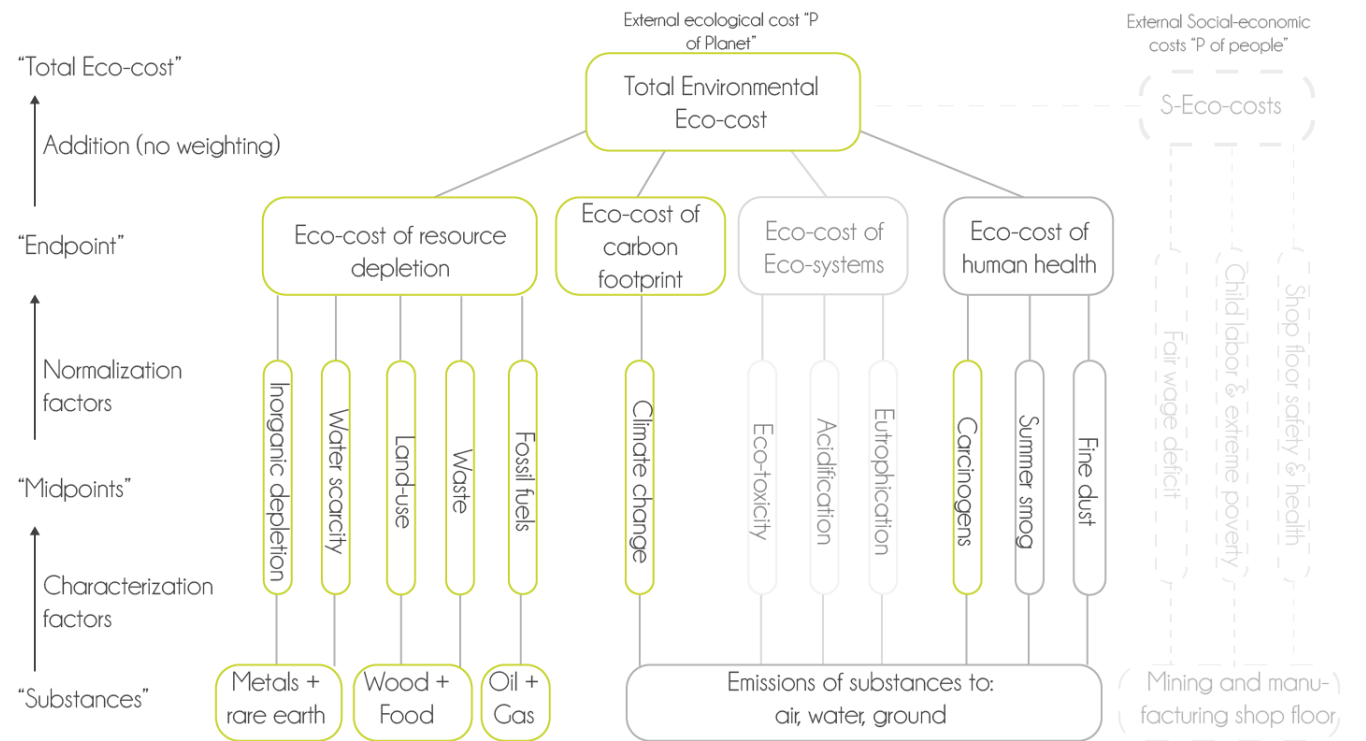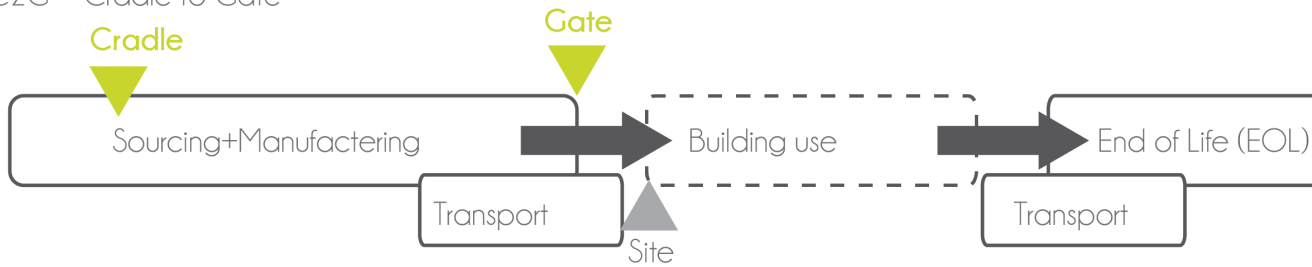

Figure:147.   Eco-cost overview

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

9.4. C2G + End-of-life
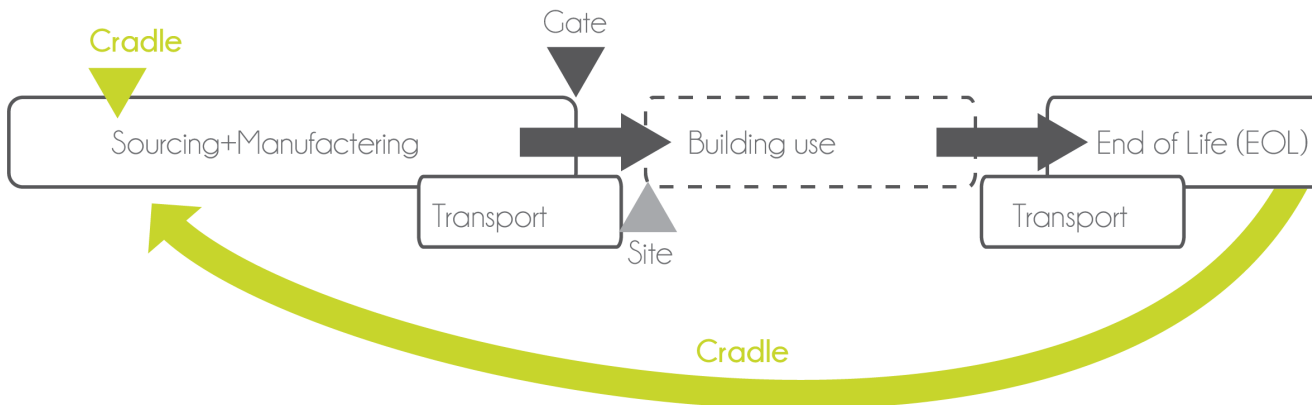
C2G = Cradle to Gate

C2C = Cradle to cradle

Figure:148. Difference between C2G and C2C

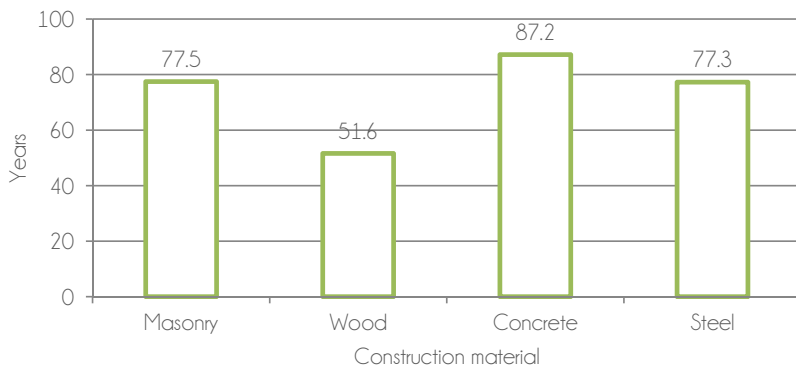## Average life span of a non residential building in Canada

Figure:149. Average life span of a non residential building in Canada

A well-known strategy to determine the environmental impact of a material is to look at the life cycle of a material by using a life cycle analysis (LCA). This chapter is primarily based on Kulik (2014) and Van der Lugt, Vogtlander et al. (2012) although Moso is used in examples as base material of the LVB not Guadua. To the best of the writers knowledge there is no educate information available regarding high end laminated Guadua bamboo. The only LCA study using Guadua used in this report is from Ramirez, Torres et al. (2014). A proper LCA of the proposal or laminated Guadua needs more research than conducted in this chapter, but because of the scope of the research, the thesis will be limited to modifying the data from Kulik (2014) and Van der Lugt, Vogtlander et al. (2012).

Introduction

There are different life cycle analyzes possible (Cradle to gate (C2G), cradle to site(C2S) and cradle to cradle(C2C)). Kulik (2014) compares the C2G and C2C to show the difference in projected sustainability and the influence of the end of life face. More accurate for the proposal would be to compare C2S to C2C, however due to the scope of the research and the time available this has not been done, it would be too time consuming and the comparison between C2G and C2C gives an good image of the impact of including the EOL.

Time frame

The LCA of Kulik and others is normally taken over a time period of 100 years. The service time of a building depends on controllable (proper design, adaptability, good detailing, etc.) and non-controllable factors (earthquakes, war, fashion, fire, market changes, etc.). For Ecuador no information has been found, however O'Connor (2004) gives an overview of the situation in Canada regarding nonresidential buildings. It shows that there is a difference between construction materials and average lifetime of buildings. Wood scores bad in the comparison, wooden building however are normally designed for a different life span than the other buildings explaining also the shorter life span. But take the inner city of Amsterdam it stand for centuries being a combination of a brick facade and a wooden structure. Canada has a different

context than Ecuador, but it shows that the LCA comparisons are not completely to be trusted, not because the information is wrong, but because there are many variables that cannot be captured in a general LCA. The lifespan of the building is hard to predict and untrustworthy a 100 years however is a common assumption and therefore will be used. To increase the life time of the proposal the structure has been oversized, the design is flexible, put on a concrete base and allows for easy dismantling and reuse. If wanted it could be torn down and buildup in a different location with ease. If it will be reused after dismantling is not completely in the hands of the designer. It can be however be added to the contract forcing to take it in to account like owner organizations like Rendemint (is trying to achieve a circular environment) (Rendemint).

Compared materials

For the LCA comparison in this chapter four materials are used: Concrete (reinforced), steel (secondary), Plywood (LVL) and Ply bamboo (LVB). Secondary steel is recycled steel reducing the negative impact of in the LCA's. For the LCA 5 structures are used: concrete (reinforced), steel (secondary), Plywood (LVL), Ply bamboo (LVB) in NL and Ply bamboo (LVB) in Ecuador. To show the impact of a local 'sustainable' and a product that is considered to be sustainable but shipped across the world. Normal soft wood is not included, because it is not possible to build 12 floors whit normal softwood. It needs to be laminated.

Modification to 12 stories

For the comparison a 12 floor building is used like proposed. Kulik (2014) offers simple calculations from NIBE to translate numbers from 4-5 floors to numbers for a 12 story building. More stories doesn't impact the finish only the foundation and structure therefore the extra weight will be divided between the structure and the foundation using the ratio given for the 4-5 story building. See the tables to the side for the results. Above 8 stories it is presumed that the LVL structure is a hybrid structure with a weight distribution of 20% steel and 80% wood. For the laminated bamboo building (LVB) results from proposal are used. The impact of the steel cables can be negated in the calculation see appendix Sustainability. The density of Lamboo is 690kg/m³. The volume of structural

Lamboo per floor is 105,3m³. The floor area is 300m². These values are further described in sub chapter Land-use. The weight per square meter for a 12 floor building is: (105,3/300)x690=242kg/m².

The actual amount of Lamboo needed for the structure is less than projected, because the walls and columns are extra thick to provide the required fire safety without needing to cover them in gypsum boards. The wood protecting the floor is not included, nor is the low amount of steel for the tensioning bars and the energy dispensers. The other values are more general values, based on the Dutch rule of thumb for residential buildings (original source is NIBE a Dutch company). The real values depend on many factors, like building system, material combinations, shape of the building, functional related loads (the proposal uses office loads not residential loads to be more flexible), wind loads and very important earthquake loads. Especially the last one is not included. Earthquakes are likely to be the determining factor for buildings in Guayaquil. Although the proposed Lamboo system is not completely passed on, it takes the effects more in to account than the rule of thumb buildings and therefore it is safe to say that the buildings calculated with the rule of thumb are using the more optimistic values, because less of the same material is less pollution.

4-5 fl. building

	Concrete	Steel	LVL	Material
Total	1400	700	440	kg/m²
Foundation	400	150	40	kg/m²
Structure	**600**	**250**	**200**	**kg/m²**
Finish	400	300	200	kg/m²

Influence of building hight on of total system (kg/m²)

	4-5 fl.	7-8	12-15	
Concrete	1400	-200*	+100*	* Prefab
Steel	700	+30	+90	
LVL	440	+20	+80**	** Hybrid

Influence of building hight on the Structure (kg/m²)

	4-5 fl.	7-8 fl.	12-15 fl.	
Concrete	600	514*	643*	* Prefab
Steel	250	261	282	
LVL	200	209	236**	** Hybrid

Table:13. Weight per structural system/height/part

Structural weight for a 12 story building per material (kg/m²)

Figure:150. Difference in mass per m² of a 12 story building

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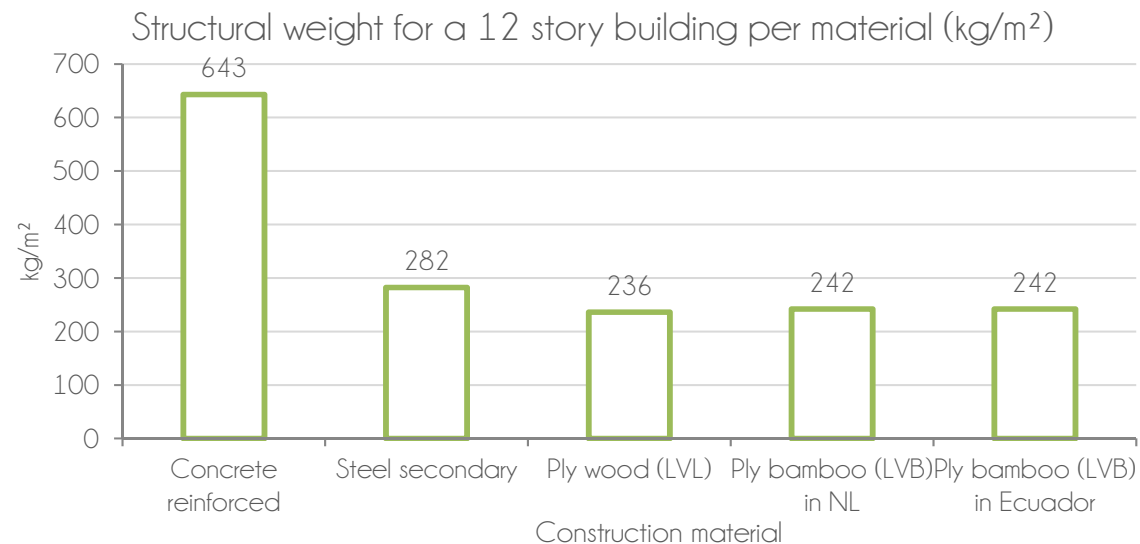
C2G+End-of-life

Table 1: Input data and results in CO₂e (carbon footprint) for the environmental impact assessment (cradle to gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed at the outsides, and one layer of 10 mm side pressed in the core). The Functional Unit used as the base element for this assessment is one board of 2440 x 1220 x 20 mm (2.98 m², with a weight of 41.7 kilograms (based on a density of 700 kg/m³).

Process step	amount	unit	Carbon fp kgCO₂e/unit	Carbon fp kgCO₂e/FU	Carbon fp kgCO₂ekg	Carbon fp %	
1. Cultivation and harvesting from plantation							
Gasoline consumption	0.224	litre / FU	3.895/ litre	0.873	0.0209	1.5%	
2. Transport from plantation to strip manufacturing facility; a 5 ton truck (transport of 23.1 FUs)	30	km / truck	0.63/ km	0.818	0.0196	1.4%	
3. Strip making	1.38	kWh/ FU	0.805/kWh	1.111	0.0266	1.9%	
4. Transport from strip manufacturing facility to factory; a 10 ton truck (transport of 77.6 FUs).	6̶0̶0̶ 300	km / truck	0.825/km	6.379	0.1530	10.8% 5.4%	
5. Rough planing	8.62	kWh/ FU	0.805/kWh	6.939	0.1664	11.8%	
6. Strip selection							
7. Carbonization	4.73	kWh/FU	0.805/kWh	3.808	0.0913	6.5%	
8. Drying carbonized strips	9.66	kWh/FU	0.805/kWh	7.776	0.1865	13.2%	
9. Fine planing	5.8	kWh/FU	0.805/kWh	4.669	0.1120	7.9%	
10. Strip selection							
11. Glue application (1-layer boards)	0.894	kg / FU	2.24 /kg	2.003	0.0480	3.4%	
12. Pressing strips to 1-layer board	1.89	kWh/FU	0.805/kWh	1.521	0.0365	2.6%	
13. Sanding 1-layer board	1.62	kWh/FU	0.805/kWh	1.304	0.0313	2.2%	
14. Glue application (3-layer board)	0.983	kg / FU	2.24 /kg	2.202	0.0528	3.7%	
15. Pressing three layers to one board	1.65	kWh/FU	0.805/kWh	1.328	0.0319	2.3% 4.6%	
16. Sawing	0.29	kWh/FU	0.805/kWh	0.233	0.0056	0.4%	
17. Sanding 3-layer board	0.86	kWh/FU	0.805/kWh	0.692	0.0166	1.2%	
18. Dust absorption (during all steps)	8.67	kWh/FU	0.805/kWh	6.979	0.1674	11.8%	
19. Transport from factory to harbour	12.51	ton.km/FU	0.086/ton.km	1.076	0.0258	1.8% 0%	
20. Transport from harbour to harbour	800.9736	ton.km/FU	0.011/ton.km	8.811	0.2113	14.9% 0%	
21. Transport from harbour to warehouse	4.7955	ton.km/FU	0.086/ton.km	0.412	0.0099	0.7% 0%	
TOTAL carbon footprint				58.93	1.413	100.0% 79.5%	

Table:14. Carbon Footprint modifications compared to Van der Lugt, Vogtlander et al. (2012)

Plywood*

A pure wood structure of 12 stories is possible (ReThinkWood. 2014, June 23). Regarding the kg/m2 of these structures is no data available. For the hybrid structure (which is more economically feasible) there are some values available regarding its kg/m2. Including the information that the weight balance is approximately steel (20%) wood(80%) (Kulik 2014). A wooden 12 story building is likely build with CLT. CLT is slightly more favorable then Plywood. Wood therefore is slightly more negatively represented in this regard, but data there was no time to modify data.

Ply bamboo in Ecuador

Kulik (2014) data is obtained from Van der Lugt, Vogtlander et al. (2012).It's about the LCA calculation of Moso bamboo. Being cut and processed in China, and transported to a warehouse in the Netherlands. The conducted LCA is an analysis from cradle to gate (C2G). The plate used in the C2G analyze is a cross laminated 3 layer carbonized laminated bamboo board of 2cm (outside layers are 5mm inside layer 10mm). Carbonizing is a heat treatment to increase durability, making the bamboo suitable for outside applications. Depending on the kind of heat treatment it can impart other properties of the material. Rule of thumb the darker the color (the longer the heat treatment or higher the temperature) the more brittle the bamboo (Koenen, C. 2010) although normally it increases the MOE. The production steps of a beam instead of a plate are similar, however making a beam will require more pressure to be able to glue all the layers together which will lead to an increase in pressure. The pressure/kg needed to press the plates together is depended on the thickness and surface area of the final beam/plate. The ticker and bigger the surface area the higher the energy needed to press them together the plates. No accurate data is available to what extend the pressure increases, for the global calculations therefore the number has been doubled to be safe.
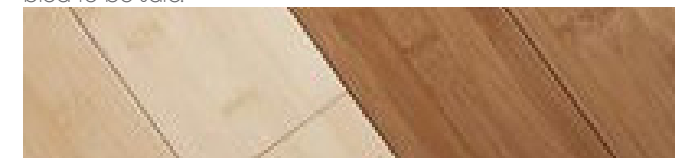
Figure:151. Plain bamboo (left) vs. Carbonized bamboo (right)

Besides a couple of reduction factors are applied. There are bamboo forests/plantations all over Ecuador and also near Guayaquil (Klop, Cardenas et al. 2003). Most of current bamboo processing factories are in Guayaquil. Therefore it is assumed that the transportation line is less than 300 km from plantation to factory. The product will be used inside of Guayaquil not in the Netherlands; therefore the shipping distance is eliminated in the comparison. Also the transport towards the harbor and transport from the harbor to the storehouse are eliminated. The proposal is a local project and assumed will be that products are stored in the factory before being transported directly to the site. The steps described before are applied on the Carbon and the Eco-cost. For the energy comparison of Kulik, the values of Kulik have been used, since it's unclear how constructed and if the same ratios apply. The energy impact is therefore the least trust worthy of the three (Carbon, Energy and Eco-cost).

One more side note has to be made. It is unknown which glues are used for the ply bamboo. Structural adhesives have in general a greater negative impact on the environment, see sub-chapter: Adhesives. Therefore the projected outcomes have to be altered when better data is obtained.

Ply bamboo in NL

Only two factors of the data provided by Van der Lugt, Vogtlander et al. (2012) will be modified. The impact of shipping will be reduced pressing using the same modifications as the Ply bamboo in Ecuador. The other factor that will be modified is the impact of shipping because the shipping difference is significant.

Shipping distance from Ecuador =10456.02 km.
Shipping distance from China = 19382.91 km
10456.02 km /19382.91 km ≈ 54%
Impact of shipping will be reduced with 54% compared to the values of Kulik (2014).

Steel secondary

For steel secondary steel has been used. This is 100% recycled steel. This way steel is shown as favorable as possible. Other options are typical steel (21~42% recycled) or virgin steel (0% recycled) Kulik (2014).

Table 2: Input data and results in eco-costs for the environmental impact assessment (cradle to gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed at the outsides, and one layer of 10 mm side pressed in the core). The Functional Unit used as the base element for this assessment is one board of 2440 x 1220 x 20 mm (2.98 m^2), with a weight of 41.7 kilograms (based on a density of 700 kg/m^3).

Process step	amount	unit	ecocosts €/unit	ecocosts €/FU	ecocosts €/kg	ecocosts %
1. Cultivation and harvesting from plantation						
Gasoline consumption	0.224	litre / FU	1.04/ litre	0.233	0.0056	1.7%
2. Transport from plantation to strip manufacturing facility; eco-costs of a 5 ton truck (transport of 23.1 FUs)	30	km / truck	0.243/ km	0.316	0.0076	2.3%
3. Strip making	1.38	kWh/ FU	0.109/kWh	0.150	0.0036	1.1%
4. Transport from strip manufacturing facility to factory; eco-costs of a 10 ton truck (transport of 77.6 FUs).	600 *300*	km / truck	0.32/km	2.474	0.0593	18.0% *9%*
5. Rough planing	8.62	kWh/ FU	0.109/kWh	0.940	0.0225	6.8%
6. Strip selection						
7. Carbonization	4.73	kWh/FU	0.109/kWh	0.516	0.0124	3.7%
8. Drying carbonized strips	9.66	kWh/FU	0.109/kWh	1.053	0.0253	7.7%
9. Fine planing	5.8	kWh/FU	0.109/kWh	0.632	0.0152	4.6%
10. Strip selection						
11. Glue application (1-layer boards)	0.894	kg / FU	0.57/kg	0.510	0.0122	3.7%
12. Pressing strips to 1-layer board	1.89	kWh/FU	0.109/kWh	0.206	0.0049	1.5%
13. Sanding 1-layer board	1.62	kWh/FU	0.109/kWh	0.177	0.0042	1.3%
14. Glue application (3-layer board)	0.983	kg / FU	0.57/kg	0.560	0.0134	4.1%
15. Pressing three layers to one board	1.65	kWh/FU	0.109/kWh	0.180	0.0043	1.3% *2.6%*
16. Sawing	0.29	kWh/FU	0.109/kWh	0.032	0.0008	0.2%
17. Sanding 3-layer board	0.86	kWh/FU	0.109/kWh	0.094	0.0022	0.7%
18. Dust absorption (during all steps)	8.67	kWh/FU	0.109/kWh	0.945	0.0227	6.9%
19. Transport from factory to harbour	12.51	ton.km/ FU	0.033/ton.km	0.413	0.0099	3.0% *0%*
20. Transport from harbour to harbour	800.9736	ton.km/ FU	0.0052/ton.km	4.165	0.0999	30.3% *0%*
21. Transport from harbour to warehouse	4.7955	ton.km/ FU	0.033/ton.km	0.158	0.0038	1.2% *0%*
TOTAL eco-costs (€)				13.75	0.330	100.0% *57.8%*

Table:15. Carbon Footprint modifications compared to Van der Lugt, Vogtlander et al. (2012)

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

C2G+End-of-life

	Concrete reinforced	Steel secondary	Plywood (LVL)*	Ply bamboo (LVB) in NL	Ply bamboo (LVB) in Ecuador
kg/m2	643	282	236	242	242
Eco-cost/kg (C2G)	0.05	0.12	0.19	0.35	0.20**
End of life	0	0	-0.18	-0.21	-0.21
Eco-cost (C2G)	32.1	33.9	45.3	71.9	49
Eco-cost (C2C)	32.1	33.9	3.8	21.1	-1.9

* Plywood (LVL)   Is a hybrid structure 80% wood, 20% steel.

** Ply bamboo (LVB) in Ecuador No shipping, no transport to harbor, no transport to warehouse, only 300km from plantation to factory not 600km

Table:16. Eco-cost for each structure

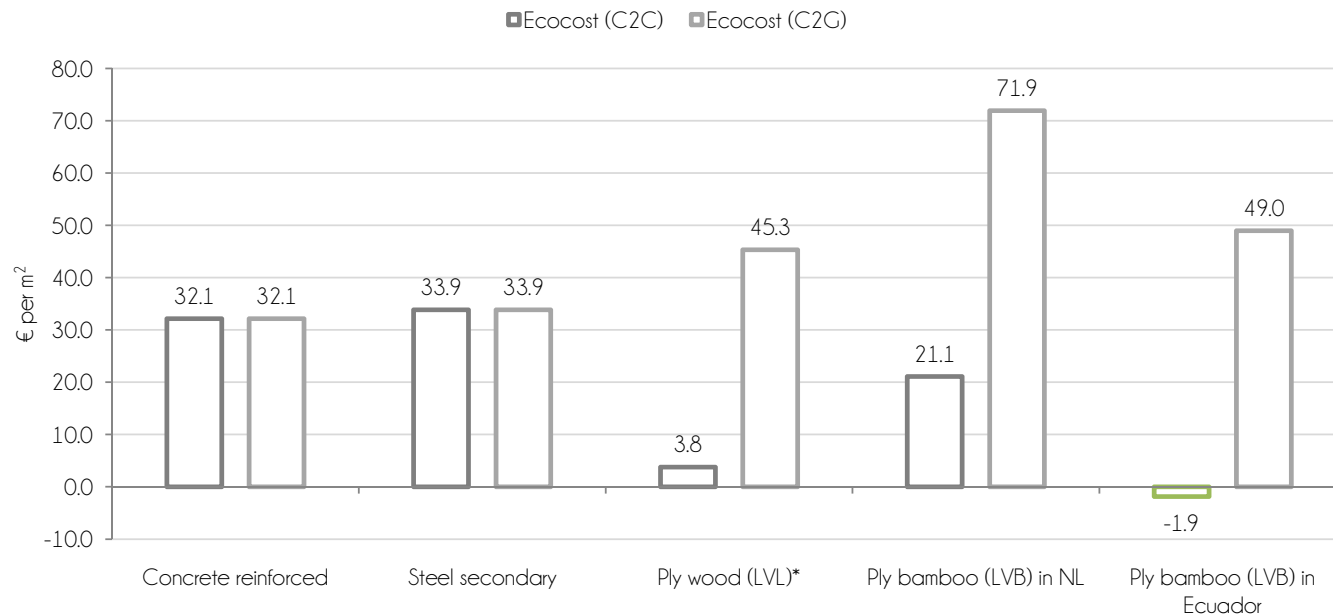## Ecocost C2G + end of life (€ per m^2) of a 12 story building

■Ecocost (C2C)   ■Ecocost (C2G)

Figure:152. Eco-cost C2G and C2C/m^2

	20%Steel secondary	+	80% Plywood (LVL)*	=	100% Plywood (LVL)*
kg/m2	282 (x20%)	+	236 (x80%)		236
Eco-cost/kg (C2G)	0.12 (x20%)	+	0.21 (x80%)		0.19
End of life	0 (x20%)	+	-0.22 (x80%)		-0.18
Eco-cost (C2G)	33.9 (x20%)	+	49.6 (x80%)		45.3
Eco-cost (C2C)	33.9 (x20%)	+	-2.4 (x80%)		3.8

* Plywood (LVL)   Is a hybrid structure 80% wood, 20% steel.

Table:17. Ecocost build-up Plywood hybrid structure

Eco-cost per m^2

With the factors determined in paragraph: Ply bamboo in Ecuador and Ply bamboo in NL comparisons with the other materials can be made. It makes a significant difference if the end of life face is included for all regrow able materials. This negative value comes from burning the material in a high efficient furnace releasing the energy stored in it during its growing period. Is this release of CO2 in the atmosphere sustainable? It is at least more sustainable than burning fossil fuels, because the CO2 from burning biotic materials is part of the short term CO2 cycle. The best solution is to use the material as long as possible before burning it following the principal of exergy (Rosen, Dincer et al. 2008). The first material should be a high end application (like structural laminated bamboo plates/beams) than slowly downs cycled to it least valuable option (in exergy terms spoken) which is burning the material. That is why the design is modular and the EOL is included in the contract to maximize the exergy potential of the structure. In the comparison however this is not included, just a fast down cycle to burning the material at the end.

A negative value in Eco-cost means a positive effect on nature (according to the calculation). With EOL included all biotic materials based structures are more sustainable compared to concrete and steel (if protected well from decay). Ply bamboo being shipped to the Netherlands with end of life included still outperforms concrete and steel, but has still a negative impact on the environment (about 2/3 of a concrete structure). The hybrid wood structure (Plywood*) is slightly more sustainable than ply bamboo structures of 12 floors when the end of life is not included, however when the EOL is included play bamboo becomes more sustainable. Ply bamboo is significantly stronger than plywood and the design proposal is technically a hybrid structure the amount of steel is neglectable. Without the EOL included all biotic options are less sustainable. Based on this information it could be said that a 12 story building with a laminated structure (either being wood or bamboo) without a proper plan for the EOL are not per definition sustainable the choices made at the end of the life of the building determine if it is more sustainable that concrete and steel.

To get a better understanding of material and context a second graph has been created, comparing materials not per kg/m² but per m3. This alters a couple of things. Steel becomes by far the least sustainable material, Therefore it is important that steel elements are optimized regarding it structural demands (H beams for example, or tension cables). Also concrete becomes less sustainable.

Ply bamboo in Ecuador becomes the most environmental friendly material when the environmental impact per m3 is compared and Plywood would be second. Plywood weights around half of that of ply bamboo (LVB) (Metsä Wood 2012). The density of plywood can be increased by using a denser species or it can be compressed. In tall buildings this is a disadvantage. In a 12 fl. building a lot more wood is needed to keep the building from being lifted, also more wood is needed to withstand the forces resulting in a similar weight per/m2. In most designs this leads to less freedom and flexibility in the floor plan, as is the case in Bergen Project (Norway), Forté Building (Australia) and Stadthaus (England).

Therefore building in Ecuador with ply bamboo (LVB) is regarding Eco-cost a sustainable solution and most likely the most sustainable if compared to a wood design that also takes seismic activity in to account (is not the case in this comparison). However making a 12 floor bamboo building in the Netherlands is not the most sustainable solution. It would be better to build in wood although that might lead to less flexibility and freedom in the floor plan. In all biotic cases it is very important to consider the EOL face to be able to be truly sustainable, otherwise just a sustainable image is created.

	Concrete reinforced	Steel secondary	Plywood (LVL)*	Ply bamboo (LVB) in NL	Ply bamboo (LVB) in Ecuador
Density kg/m³	2400.0	7800.0	350.0***	690.0	690.0
Eco-cost/kg (C2G)	0.05	0.12	0.19	0.35	0.20**
End of life	0	0	-0.18	-0.21	-0.21
Eco-cost/m³ (C2C)	120.0	936.0	29.4	60.1	-5.3

* Plywood (LVL)   Is a hybrid structure 80% wood, 20% steel.

** Ply bamboo (LVB) in Ecuador No shipping, no transport to harbor, no transport to warehouse, only 300km from plantation to factory not 600km

*** from (Metsä Wood 2012)

Table:18. Eco-cost for each structure per m³

Ecocost C2G + end of life (€ per m³) of a 12 story building

Figure:153. Eco-cost C2C/m³

C2G+End-of-life

	Concrete reinforced	Steel secondary	Plywood (LVL)*	Ply bamboo (LVB) in NL	Ply bamboo (LVB) in Ecuador
kg/m2	643	282	236	242	242
Carbon (kgCO2e/kg)	0.19	0.42	0.77	1.18	0.99**
End of life (kgCO2e/kg)	0	0	-0.98	-1.18	-1.18
Footprint (kgC/m) (C2G)	33.3	32.3	49.84	78.1	65.1
Footprint (kgC/m) (C2C)	33.3	32.3	-13.7	0.2	-12.8

* Plywood (LVL)   Is a hybrid structure 80% wood, 20% steel.

** Ply bamboo (LVB) in Ecuador No shipping, no transport to harbor, no transport to warehouse, only 300km from plantation to factory not 600km

Table:19. Carbon footprint for each structure

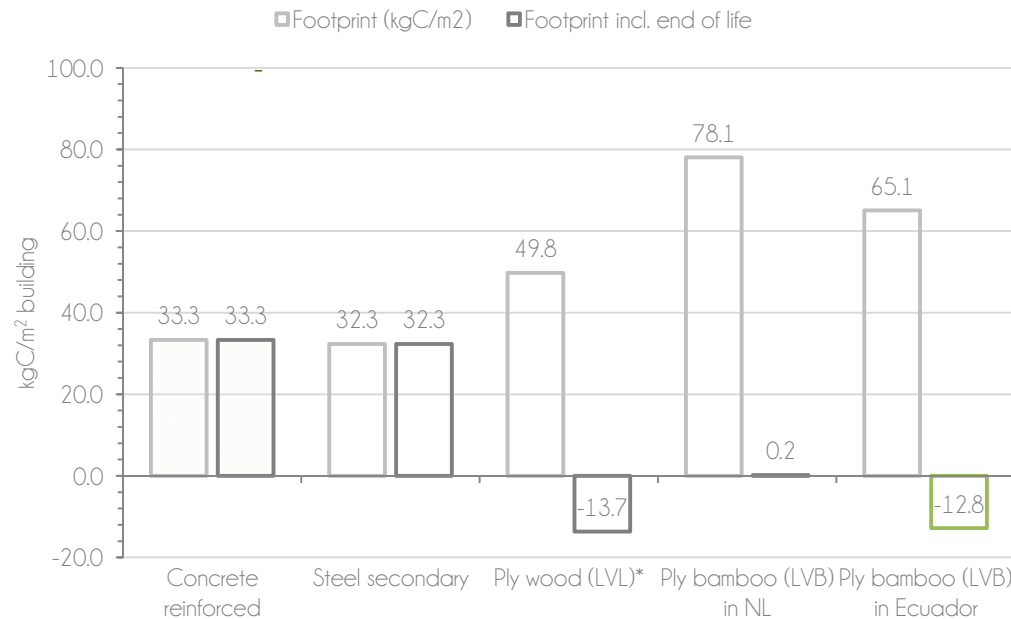## Carbon footprint structure 12 stories

Figure:154. Carbon footprint

		20%Steel secondary	+	80% Plywood (LVL)*	=	100% Plywood (LVL)*
kg/m2	282	(x20%)	+	236	(x80%)	236
Eco-cost/kg (C2G)	0.42	(x20%)	+	0.86	(x80%)	0.77
End of life	0	(x20%)	+	-1.23	(x80%)	-0.98
Eco-cost (C2G)	32.3	(x20%)	+	55.4	(x80%)	49.8
Eco-cost (C2C)	32.3	(x20%)	+	-23.8	(x80%)	-13.7

* Plywood (LVL)   Is a hybrid structure 80% wood, 20% steel.

Table:20. Carbon footprint build-up Plywood hybrid structure

Carbon Footprint

Another way of looking at sustainability besides Eco-cost is looking at the carbon footprint. The carbon footprint is all the greenhouse gas emissions combined regarding an event, product or person. In the LCA data base carbon values are often expressed as Carbon dioxide (kgCO2e/kg) (Kulik 2014). The small e in kg-CO2e means that all greenhouse gases have been translated in to carbon for the calculation. kgCO2e will be converted to kgC/m2. To be able to do this kgCO2e has to be translated to kgC. 1kgCO2 converts to 0.2727kgC (1x12/44=0.2727).

As to be expected from the Eco-cost the structural processed biotic materials emit more CO2 than steel and concrete per square meter building. Producing ply bamboo (LBV) emits more carbon in to the atmosphere then a plywood hybrid structure. Even after including the EOL face the hybrid plywood is more sustainable regarding carbon emissions. This is most likely because wood takes less processing; therefore the amount of work is lower resulting in a lower CO2 output. When ply bamboo is transported to the Netherlands the impact of transporting the material counts for almost 17% of the emissions. But when EOL is included the overall emission of CO2 is almost nullified.

Interesting is that apparently a plywood-steel hybrid structure and a Laminated bamboo structure in Ecuador' can have a positive impact on the Carbon emissions (by being negative in the graph). It's possible to have negative values (Lenzen and Treloar 2002, van der Lugt, Vogtlander et al. 2012). Wood and bamboo store CO2 in roots, trunks/stems, branches, twigs and leafs. Roots, leafs and twigs are normally not harvest and will decay in the forest release part of it energy in the ground (fixating it) and partly in the air. As the numbers of Kulik suggest (-1.23 wood and -1.18 bamboo) suggest the carbon sequestration of bamboo is comparable to wood, this is supported by (Parr, Sullivan et al. 2010, Yiping, L, et al. 2010). Kulik claims that bamboo roots are about 2,1 times the mass of the structure above ground, this may hold for some bamboo species, for mature Guadua however on average 20% of its mass is below ground and 8% consist out of leaves and 72% of its weight is from the culm (Riaño, Londoño et al. 2002)

(although in the 3th year of the plantation the roots take more than half its weight). Since Kulik (2014) based its information on van der Lugt, Vogtlander et al. (2012) the values assume that the bamboo plantations are increasing (5% annually). Very probable in China (van der Lugt, Vogtlander et al. 2012), with the annual growth of the market of 17-25% in Europe and China (van der Lugt and Lobovikov 2008) and plantations also growth in other part of the world (Hunter 2003, Takahashi 2006), therefore it is likely it increases in Ecuador aswell. If it's 5% is unknown, but is assumable and even conservative considering the high demands and limited availability of bamboo.

However van der Lugt, Vogtlander et al. (2012) presumes that the 5% increase will only replace pastures, no forest or more carbon absorbing land-uses (Palm oil plantations for example). Bamboo forest can store a larger amount of carbon compared to pastures. The difference is less or lost when other plantation are transformed to bamboo plantations, this would affect the Carbon sequestration. With the current policy in place in Ecuador to protect and increase forestry (Zambrano-Barragán 2010) it could be that only pastures or degraded soil is turned in forest, but to assume no forest or other plantations are turned in to a bamboo plantation is to optimistic. The values for carbon sequestration are therefore rather positive. The values will not be altered, because of the time frame and scope of the investigation.

For the carbon footprint one more important thing is not included and that are the energy recourses. In Ecuador 56% of total installed capacity comes from fossil fuels (2011 est.), 42% from hydroelectric plants and 1.2% comes from other renewable resources (2011 est.)(CIA 2014). Van der Lugt, Vogtlander et al. (2012) presumes a local power plant running on coals (a modern plant). Coals power plants are one of the most significant polluters, changing a part of the energy input to renewable resources would further downsize the impact. The impact on the outcome of the bamboo ply board could become more favourable if hydroelectric power is included.
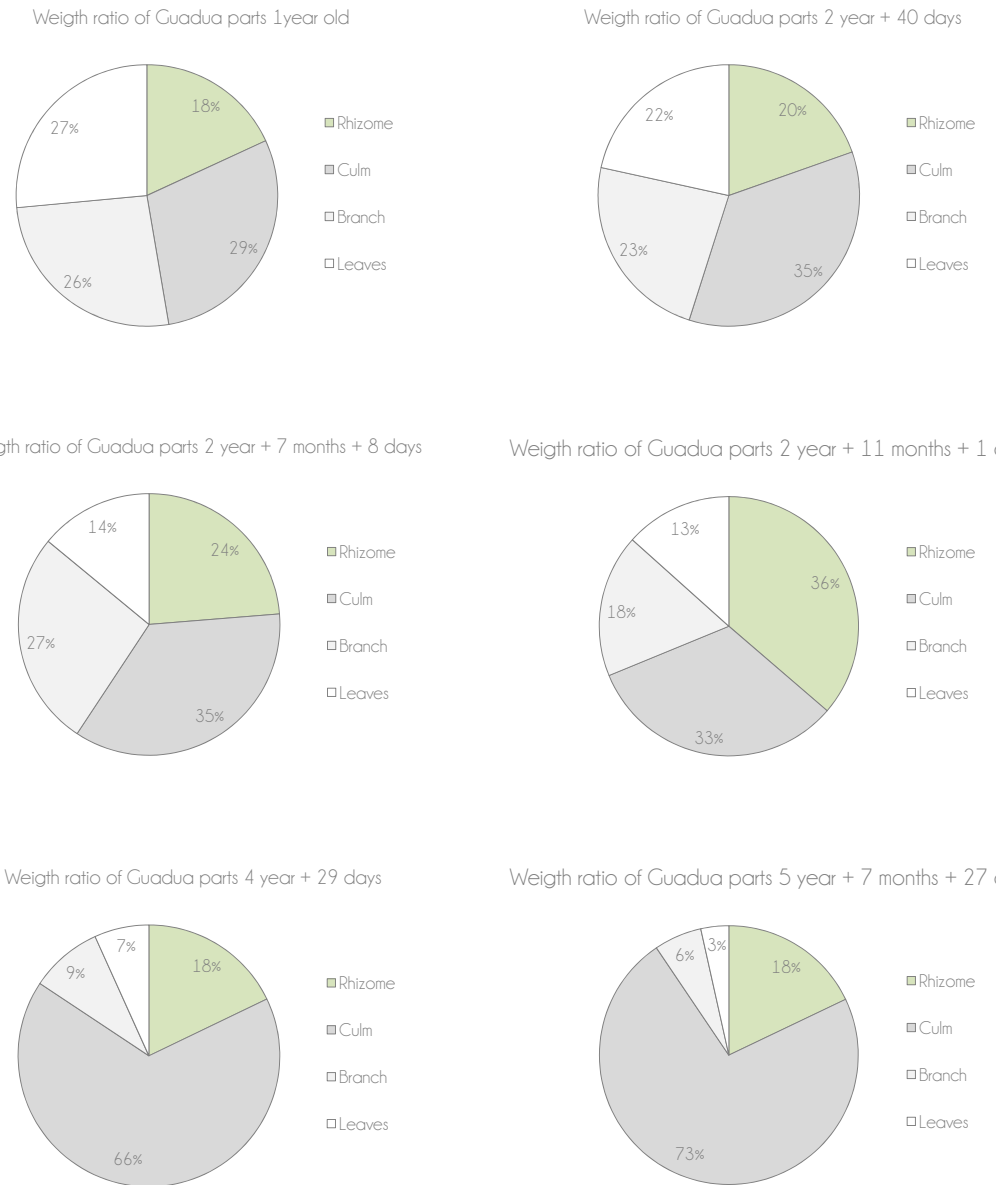
Weigth ratio of Guadua parts 1year old

Weigth ratio of Guadua parts 2 year + 40 days

Weigth ratio of Guadua parts 2 year + 7 months + 8 days

Weigth ratio of Guadua parts 2 year + 11 months + 1 days

Weigth ratio of Guadua parts 4 year + 29 days

Weigth ratio of Guadua parts 5 year + 7 months + 27 days

Figure:155. Weight of different Guadua parts related to time after planting

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

C2G+End-of-life

	Concrete reinforced	Steel secondary	Plywood (LVL)*	Ply bamboo (LVB) in NL	Ply bamboo (LVB) in Ecuador
kg/m2	643	282	236	242	242
Energy (MJ/kg)	2	9	12	22	15.4**
End of life	0	0	20.8	-25	-25
Footprint (kWh/m2)(C2G)	357	705	789	1478	1035
Footprint (kWh/m2)(C2C)	357	705	-574	-202	-645

* Plywood (LVL)　　　Is a hybrid structure 80% wood, 20% steel.

** Ply bamboo (LVB) in Ecuador No shipping, no transport to harbor, no transport to warehouse, only 300km from plantation to factory not 600km

Table:21. Energy footprint for each structure
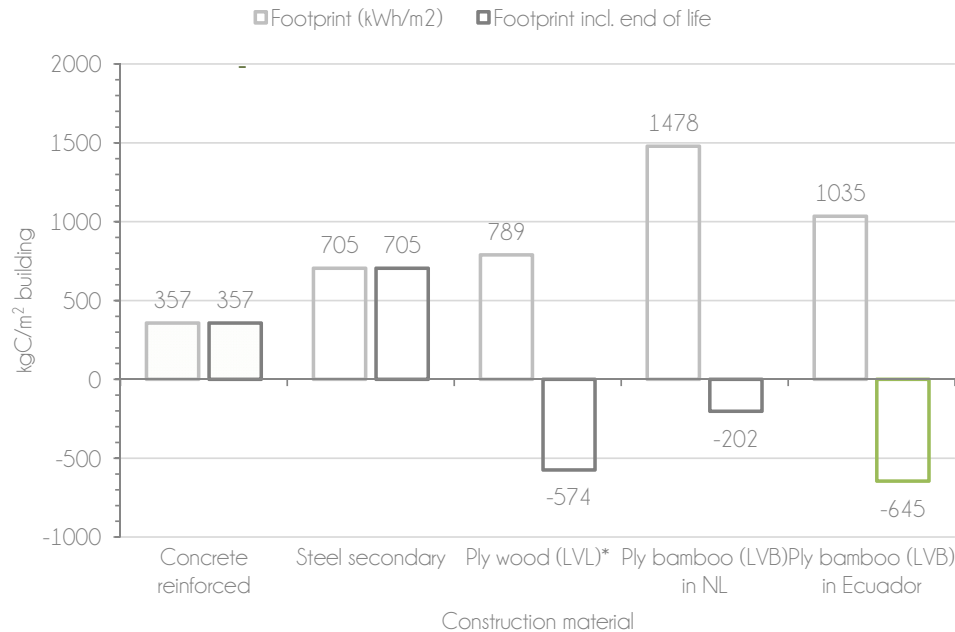
Energy footprint structure 12 stories

Figure:156. Energy footprint

Energy Footprint

One can also look at the materials impact on the environment to compare the embodied energy. How many MJ/kg has to be put in the material to produce and transport it? For the building comparison this has been translated to kWh/m2. The factor between MJ and kWh= 1MJ=0.2777kWh. When related to the building once more it makes significant difference in the calculation if the end of life is included or not. It is not completely clear how Kulik buildup all of EOL values. As it is not clear how the reduction regarding international transport is constructed.

The assumption of the embedded energy of wood and bamboo is rather positive. Kulik admits that the values for wood are between 16-26MJ/kg depending on the moisture content (MC). The lower the MC or the dryer the wood, the higher the value. The positive impact on the environment (a negative value for the energy footprint) can be explained. The material contains more energy than that the producing/ processing of the material costs. When burned at the EOL it produces more energy (and saves fossil fuels) then it costs to produce it.

	20%Steel secondary		+	80% Plywood (LVL)*		=	100% Plywood (LVL)*
kg/m2	282	(x20%)	+	236	(x80%)		236
Eco-cost/kg (C2G)	9	(x20%)	+	12.8	(x80%)		12
End of life	0	(x20%)	+	-26	(x80%)		-20.8
Eco-cost (C2G)	692	(x20%)	+	825	(x80%)		789
Eco-cost (C2C)	692	(x20%)	+	-851	(x80%)		-574

* Plywood (LVL)　　　Is a hybrid structure 80% wood, 20% steel.

Table:22. Carbon footprint build-up Plywood hybrid structure

Although the type of adhesive used is not mentioned, the carbon emissions related to gluing the board together is responsible for 7.1% (3.4%+3.7%) of the emissions of the board according to van der Lugt, Vogtlander et al. (2012). If this is translated to a local context (emissions of transport are reduced to local context) the impact increases to 8.9% (7,1/79,5 x100=8,9%). A study done by Ramirez, Torres et al. (2014) regarding the carbon emissions of laminated Guadua boards shows different results. Production of urea formaldehyde (27.6%) and vinyl acetate (20.1%) form almost half of the impact of the material regarding Greenhouse gases. The author doesn't explain why vinyl acetate is used, it could be used as a finish or as part of an adhesive. Urea formaldehyde is clearly the adhesive. Ramirez, Torres et al. (2014) admit that the choices for the adhesives have a significant impact, but also states that impact can be significantly reduces if other choices are made. It is also unclear how high the glue rate is in this particular product. Puettmann, Oneil et al. (2012) proves that for laminated timber (glulam in particular the impact of producing adhesives is also a major contributer to the carbon emissions

The kind of pressing technique has also influence on the sustainability. A cold press uses less energy than a high tech press. And a cold press also consumes less energy than a hot press (Aijazi 2013). The values of bamboo are based on Van der Lugt, Vogtlander et al. (2012) (bamboo high-tech cold-press) and Puettmann, Oneil et al. (2012) (Timber high-tech hot-press). Aijazi (2013) presumes that using the same pressing technique with different materials will have the same energy consumption.

Overall a biotic building of 12 stories is not necessarily more sustainable than a steel or concrete building, it strongly depends on the life time and the choices at the EOL.. If EOL is included and the LBV is used for more than 100 years it than can be a sustainable building especially if the material is local. Overall it preforms a little bit better than the hybrid wood solution (when EOL is incl.). But result are based on many assumptions and need to be verified. For example the kind of glue used has a significant impact on the material performance and is therefore important. And the toxicity of the chemicals used in the glues is not included.
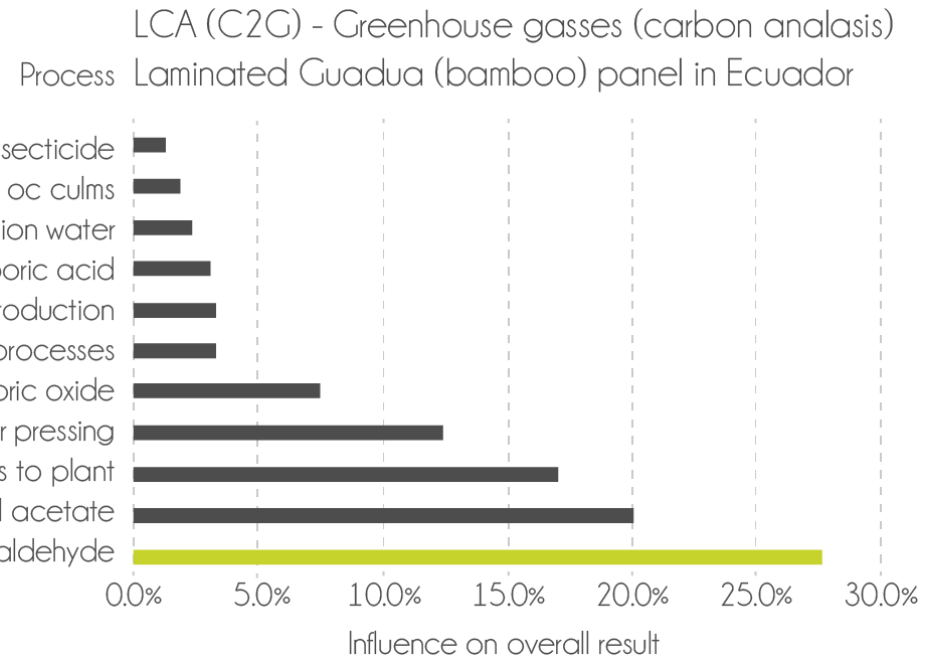
LCA (C2G) - Greenhouse gasses (carbon analasis) Laminated Guadua (bamboo) panel in Ecuador

Figure:157. LCA (C2G) Greenhouse gases for laminated Guadua panel in Ecuador

Energy comparison per pressing (with standard size ply panel 1.2mx2.4mx20mm)

Pressing process	Materials	Electricity consumption in manufacture (kWh/FU)	Carbon Footprint (kgCo₂e/FU)	Density (kg/m³)	Carbon Footprint (kgCO₂e/panel)
-Low-tech Cold-press	3-ply bamboo laminate (LVB)	39.15	31.51	700	0.76
-High-tech Cold-press	3-ply bamboo laminate (LVB)	45.17	36.36	700	0.87
-High-tech Hot-press	3-ply bamboo laminate (LVB)	52.44	42.21	700	1.01
-High-tech Hot-press	Glue laminated timber (Glulam/CLT)	52.44	42.21	560	1.26
-High-tech Hot-press	LVL	52.44	42.21	606	1.17

Table:23. Difference in energy consumed by different pressing techniques.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

9.5. Land use

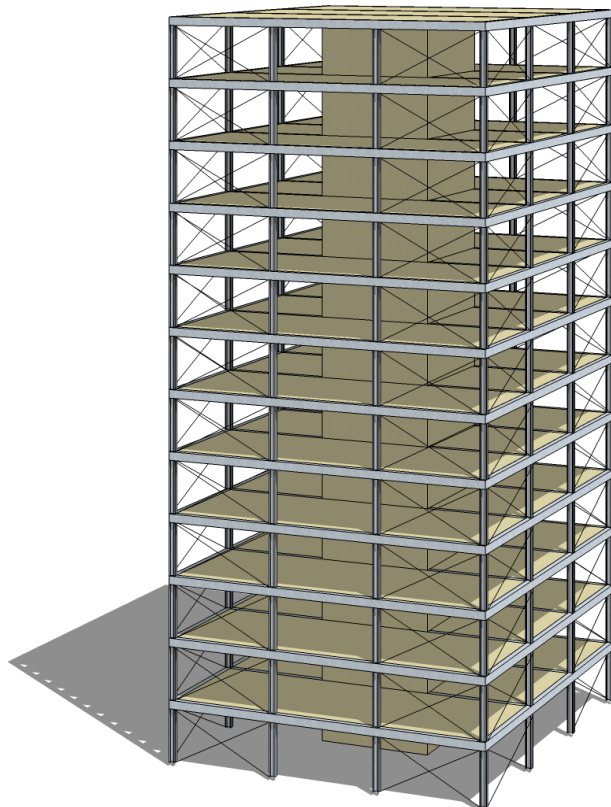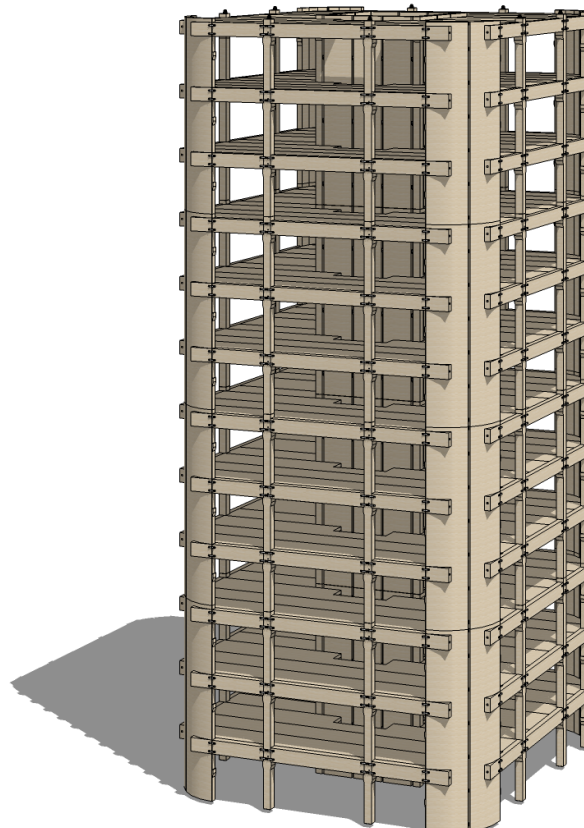

Figure:158. Hybrid structure

Figure:159. Lamboo structure

Another sustainability aspect that is becoming more important is land use. Buildings can be build "CO2 positive" with wood or bamboo, but it will require land use. What would be more profitable wood or bamboo? In this chapter the land use of the structure of the tallest building in the proposal is compared to that of a similar structure in wood.

M³ LVB in Una reunión educativa con el bambu

Per floor:
Curved walls
Number of walls: 4. Height: 3,0m Area: 1,2m²/wall. Total m³=14.4m³.
Core
Number of cores: 1. Height: 3,0m. Area: 7,2m² Total: 21.6m³
Columns:
Number of columns: 8. Height: 3,0m. Area: 0,16m² Total: 1.3m³
Floors:*
Number of floors: 1. Height: 0.18m. Area: 300m² Total: 54,0m³
Beams**
Length of beams: 88m. Height: 0.4m. Width: 0,4m Total: 14,0m³
Total per floor: 14,4+21,6+1,3+54,0+14,0=105,3 m³/floor
Total Building

Number of floors: 12
M³ per floor: 105,3

Total amount of LVB used:
12x105,3=1264m³

M³ of the wood alternative

For a comparable wood structure general numbers from the thesis of Kulik (2014) are used. How the values are adapted o fit a 12 story building can be found in sub chapter: "*C2G+End of Life*". According to the calculation there a hybrid wood building would weight 236kg/m² (this is a low estimation, because extra material for earthquake resistance is not included). The hybrid structure is estimated to be 80% wood and 20% steel. Therefore 236x80%= 189kg/m2 is wood. Presumed is that for the wood design CLT is used with a weight of 350kg/m³ (Metsä Wood 2012).

The total weight of the wood in the structure would be:
12 floors x 189 kg/m² x 300m²/floor=6,80x10⁵ kg.

The total amount of wood in the building would be:
6,80x10⁵ kg / 350 kg/m3 = 1.944 m3.

Presumed here is that for the fire safety the wood is encapsulated. This minimizes the amount of wood used reducing its land use.

*Floors are build up 2x9cm of Lamboo and a core of 8cm of recycled wood. (288m³)
**Beams are partly included in the floor

Recovery/ha/year: Guadua

Flanders and Rovers (2009) have constructed a research regarding the yield rate of laminated Guadua and compared it to Canadian pine. Vogtländer, Van der Lugt et al. (2010) also compares Land-use of premium products (MDF) including Guadua, but for the case study Flanders and Rovers (2009) is more applicable, It has a stronger focus on Guadua, the final product and gives a more detailed build-up of the calculation regarding Guadua and its plantations (Guadal).

An average natural Guadal has between 5000 and 6000 culms. Guadua can be harvest every 4-5 years depending on the circumstances (Kigomo 2007). Flanders and Rovers (2009) use a harvesting rate of 25% annually, therefore a growing circle of four years. Four years is slightly optimistic, on the other hand regarding the number, thickness and height of Guadua culms slightly conservative estimations are used and therefore overall it should be acceptable. The parts that can be used for structural LVB are Basa and Cepo (~40% of the total mass of the plant) see image: "Bamboo parts and utilization".
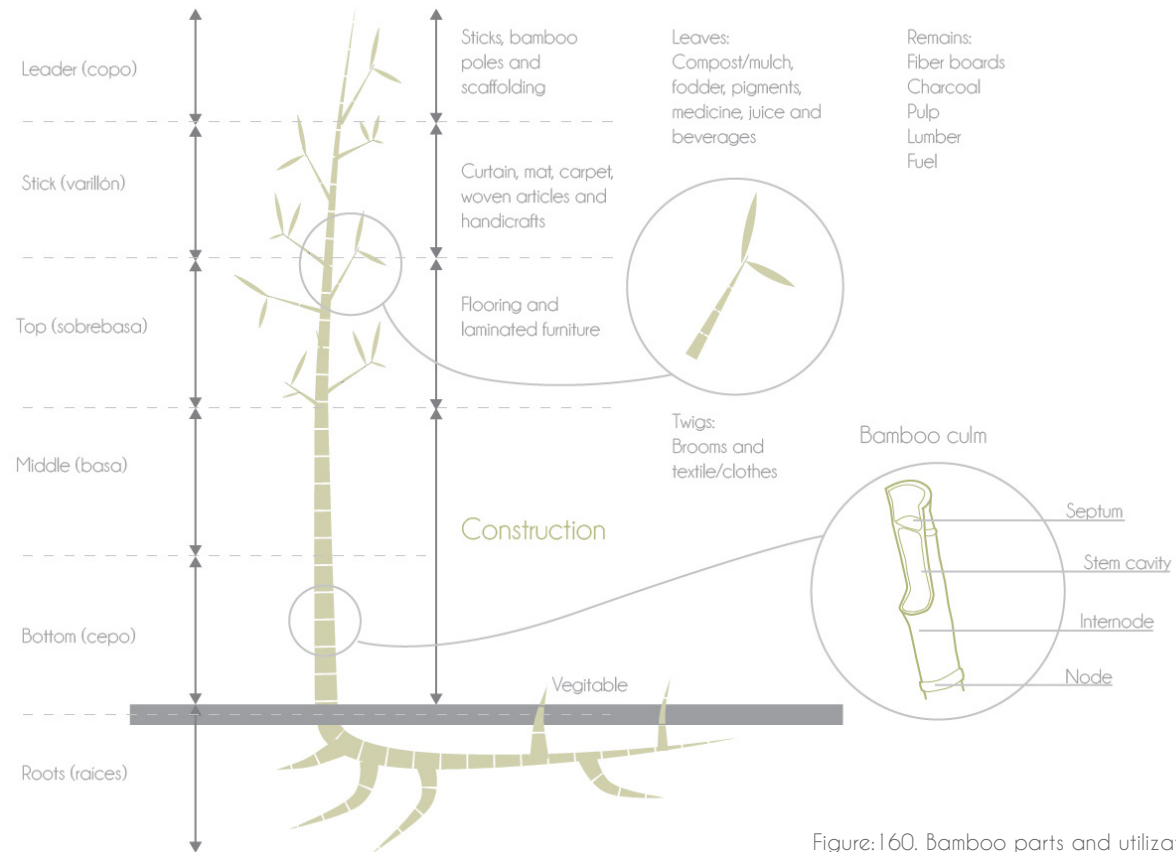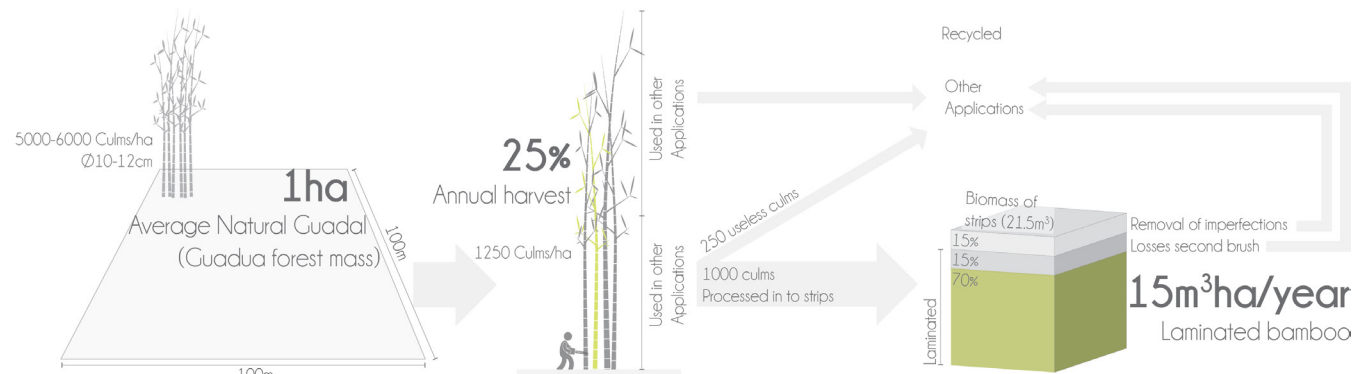

Figure:160. Bamboo parts and utilization

Figure:161. The yield of 1 ha Guadal

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Land use

The other parts are not 'lost'. If the process is optimized a 100% of the bamboo plant can be used (except the roots. Roots are needed to regenerate the bamboo culm) increasing the economic sustainability and the environmental sustainability at the same time. China is market leader in utilizing all parts of the plant according to A. van der Vegte , project manager & senior manager quality control, research and development (personal communication November 17, 2014), however because it is economically interesting the other bamboo countries will follow and therefore a 100% utilization of the bamboo plant can be achieved. In this comparison it will be assumed that a 100% is used without waste.

The Basa and Cepo are split and planed to make the strips out of which beams and plates can be made. Of the 1250 culms about 250 are not suited, because of imperfections, curvature or damages. The weight after splitting and planing is ~21.5m³/ha. Around 15% of the strips are removed before laminating, because of defaults which could reduce the strength of the final product. After laminating another 15% is lost for planing and cutting to the requested sizes (Flanders and Rovers 2009). Resulting in a recovery rate of 15m³/ha/year of laminated bamboo.

Recovery/ha/year: Pine (Can)

Flanders and Rovers (2009) have also investigated the harvest rate of pine from British Colombia in Canada and serves as an example for other softwoods on which this paragraph is based.

Unlike bamboo wood grows in two directions. It gets thicker over time and has a solid core. This makes a difference in the harvesting process. It matters if a plot is cleared every 40, 125 our 400 years. The older the trunk the thicker the diameter. However the highest recovery rate is achieved by harvesting every 40 years in terms of dry cut lumber per hectare. A 40 year rotation results in limited sizes of lumber available, but laminating solves that problem.

From a log to surface dry lumber about 50% remains, depending on various factors. The bigger a tree (and therefore older) the higher the percentage of green lumber versus logs will be, this is because of the reduced saw losses caused by the round non homogeneous nature of the trunk and the fact that the trunk is tapered. Small tree trunks (diameter below 185mm) have a typical yield below 45% and as low as 36% depending on the way of cutting (Fredriksson, Bomark et al. 2015). Flanders and Rovers (2009) presume a rate of 45% for dry sawn lumber/timber.

With a 40 year rotation an average recovery rate is around 5m³. ha/year. After processing 3,55m³/ha/year is left of the 5m³. 3.35m³ includes MDF, Chip boards and beams. Of the 5m³ /ha/year only 45% of the mass are beams (2.25m³)(Flanders and Rovers 2009). When producing CLT panels a small additional loss has to be included for the second planing (estimated 5% but needs validation, the number is less than for bamboo, because of the increased size of the 'strips/beams'), resulting in 2.14m³ of CLT panels per hectare per year.

A down side of wood is that a timber plantation has to be replanted every time it is harvest. Leaving a denude area behind which has to be planted again. Bamboo when harvest properly doesn't result in a denude area and doesn't need to be replanted, it will regenerate itself, preventing erosion, maintaining its ecosystem. On top of that it also provides a steadier workflow (at least on the smaller plantations) (Garland 2003).

5m3/year
Annual harvest

1ha
Average Canadian pine plantation

100m
100m

40 year Rotation

Lost

29%

26% sawdust, ships

100% (5m/year)

45% dry sawn timber

Other aplications

Biomass of dry sawn Lumber (2.25m³)

5%
95%
Laminated

Losses from planing

2.14 m³/ha/year Lumber

Figure:162. The yield of 1 ha Canadian pine

Comparison on Building scale

Una reunión educativa con el bambu:
Bamboo: 1264m³/15= 84,3 ha.
(Recycled wood: 288m³/2.14=135ha.)
Total=219ha.

Regular multistory CLT building:
1944m³/2,14= 908ha.

The proposal would use 6.7 times less land, significantly less steel and instead of encapsulating the wood as in the hybrid proposal it uses its thickness for fire protection. The difference could even be larger if the wood used as fire safety is not counted as newly cut wood but as recycled wood (which it is, it is made from wood pallets no longer needed). or the wood would be replaced for bamboo having a higher yield rat. This however would make the project less feasible because of the increased cost.

Una reunión educativa con el bambu
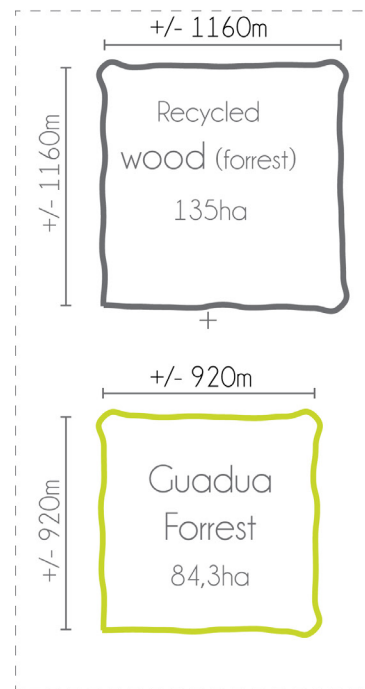
Regular multistory
CLT building

+/- 1160m

Recycled
wood (forrest)
135ha

+/- 1160m

+

+/- 920m

Guadua
Forrest
84,3ha

+/- 920m

6.7x

+/- 3010m

Wood
Forest

908ha

+/- 3010m

Figure:163. Difference in land-use between proposal and wood hybrid

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

9.6. Adhesives

Figure: 164. Lamboo used outdoor in solar roof

Figure: 165. Formaldehyde

Figure: 166. Generic phenolic formaldehyde structure
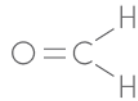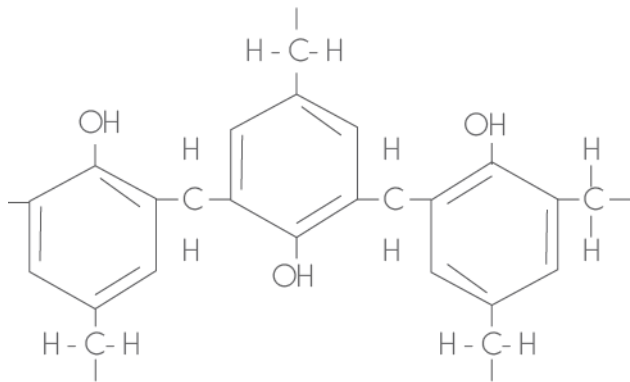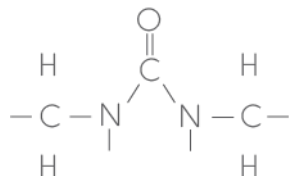

Figure: 167. Generic Urea formaldehyde structure

Laminated products use adhesives and the adhesives have a significant negative impact on the laminated products when it comes to sustainability and play a vital role in the strength of the product (Luna, Takeuchi et al. 2014, Correal and Ramirez 2010). In order to understand the impact better it is important to understand what kinds of glues are used and why, in what amount and what is the influence on the life cycle of the product. There is a large variety of glues on the market. Some are environmental friendly and some are highly polluting. Adhesives can be animal (fish hide, bones, hide), plant, and synthetic based. Normally it consist of small polymers. Many adhesives use formaldehyde, because it binds the other compounds in the adhesive (Green and Karsh 2012).

Formaldehyde

Formaldehyde is a gas which is used in panels and laminated products in the wood/bamboo industry. To a certain extent formaldehyde is always present in the outdoor air. It is produced by many 'natural' processes: photochemical reactions, biological activity and combustion of: cigarettes, gasoline and organic compounds (wood and the like). Formaldehyde is even a natural chemical building block in the human body (3ppm in blood) (Emery 2002). Formaldehyde can cause cancer, in particular throat and nose cancer. It also can result in nauseousness with symptoms such as headaches, coughing, scratchy eyes and nose bleeds. People with breading conditions, elderly and children are more vulnerable to exposure to Formaldehyde.

In the wood/bamboo industry there are basically two types of adhesives using formaldehyde (Urea formaldehyde adhesives and Phenol formaldehyde adhesives). Urea formaldehyde adhesives are normally used in indoor applications. Urea formaldehyde (UF) adhesives are water resistant, but not waterproof. When put in contact with water it will react and release formaldehydes. Most of the problems regarding adhesives using formaldehyde come from urea formaldehyde based adhesives (Emery 2002). Phenol formaldehyde (PF) is more stable and considered a 100% water proof. Once the interlinking bounds between phenol and formaldehyde have formed the bond becomes very stable and there is a very low risk of formaldehydes to escape. It can be used in structural applications and is UV resistant.

Lamboo uses formaldehydes and can be used for outdoor applications, see image: ' lamboo used outdoor in solar roof', therefore it seems assumable that the adhesive used is phenol-formaldehyde based however not accurate data is available at this moment.

Tests with the test method 'Large-Scale Test Chamber' show that when formaldehydes levels were measured of new adhesive based engineered wood products for several months the formaldehyde levels were so low that measuring them was difficult, because the measured levels were very close to the back ground, all were well below 0,1 ppm and disappear over time (Emery 2002). In 2010 in USA a bill was passed in the congress limiting the emission of formaldehyde in hardwoods with a veneer core at 0.05ppm (Congress U.S.A. 2010). LVL products in Canada have formaldehyde emissions ranging between 0,02 and 0,04ppm. Lamboo is a laminated veneer lumber (LVL) product according to the USA ASTM and therefore we can assume that its formaldehyde levels are below 0.05ppm. For as far as the author knows there is no evidence that these levels can cause health risks.

Life cycle impact

Phenol is a highly toxic liquid (Britannica 2015) and formaldehyde is also considered to be a toxic gas (Emery 2002). This results in a challenge in the end of life face. It is not biodegradable and it cannot be melted and then reforged. It is however possible to be reuse it and can be sawn and glued in new applications. The second option however costs always more energy and results in higher environmental loads compared to the first option. Therefore, it is important to design elements that can be reused as many times as possible. The main challenge will be designing the connections. At this moment there are no tested laminated bamboo alternatives that are biodegradable and can be used for structural applications within construction. Demands of the market urge the industry to look for alternatives for formaldehyde. At the moment this still seems difficult to do to without raising the costs and reducing the performance, there are however several investigations using soybeans and other organic material. Also in bamboo product research is ongoing to improve the adhesives used (Kun, Gulai et al. 2008, Kinoshita, Kaizu et al. 2009).

Advancements in Wood

The wood industry is as mentioned before more advanced and there is a lot of research going on in improving the adhesives from witch the bamboo industry also might benefit.

One of the tallest wooden buildings (Forte Tower, Melbourne Australia) used CLT panels without formaldehyde, by using high pressure and polyurethane (PUR/PU) adhesives (Collins 2013). There are no exposure limits regarding polyurethane, however it is flammable and when set to fire it creates a toxic black smoke, to prevent this often flame retardants are added. These however are all considered to be hazardous. However glue that works well on wood might not work on bamboo and in specific on Guadua. Gluing Guadua is more difficult than for example Moso and wood. PU adhesives in combination with wood have a tensile shear strength of at least 10 N/mm², PU in combination with Moso has a tensile shear strength between 4-7 N/mm² and Guadua with PU only a tensile shear strength between 1-4 N/mm² (Guadua Bamboo n.d. E). However other glues are able provide sufficient shear strength (UF, PF).

Quantity of adhesives

Different buildups of laminated/glued products require different amounts of adhesives. CLT uses about half of LVL, as where the particle board uses the largest amount of adhesives (Green and Karsh 2012). Because bamboo boards and beams are buildup with small strips LVB uses more adhesives than most wood products. Some experimental products have a resin ratio between 8-15% (Zaia, Cortez Barbosa et al. 2015). Moso has a glue rate between 3 and 5% (van der Vegte 2015) For Lamboo no exact data is available.

Compared to laminated wood products Laminated bamboo products are less sustainable when the amount of glue is considered. The common fear for Formaldehydes however seems unfounded, it is very unlikely that Lamboo will impact the health of the inhabitants in a negative way. At the moment there is no alternative on the market for formaldehyde which could structurally be applied in this project, however with current developments going on its likely to be a matter of time before a suitable alternative will be found.

Figure:168. Forte Building

PU adhesive performance

Figure:169. PU glue performance

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?
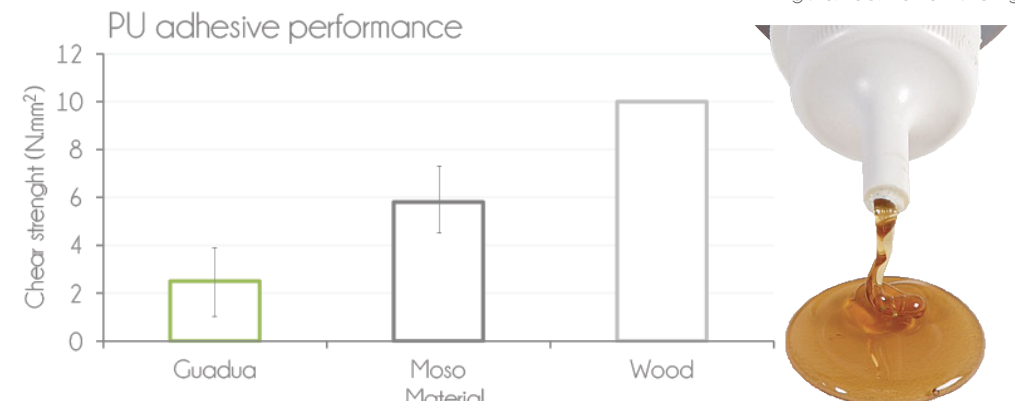
10.Physical tests

Figure:170. Four point bending test in TU delft

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

10.1. Boundary conditions

Figure:171. Obtained materials from Lamboo

Figure:172. Close up

Figure:173. Obtained materials from Moso

Figure:174. Obtained materials Moso 2

To validated claims of producers and the proposed design a four point bending test has been conducted with two different materials obtained from two different laminated bamboo producers. The manufacturers of the product are Moso and Lamboo. Because of logistical problems with obtaining the material the tests have been conducted between P4 and P5 and therefore the results are not processed in the design or the rest of the thesis (except for the conclusion and the recommendations). The boundary conditions of the tests conducted will be described in this chapter.

Materials

For the test two materials have been tested and compared. A beam from Lamboo (for shipping reasons cut in 4 pieces of 2 foot (+/- 60cm) and a plank of Moso (cut in three pieces for transport). The aim was to test a structural beam made of Guadua from Lamboo and compare it to the Moso samples. However in the ordering process a mistake was made and not a structural beam but a beam from there design line was obtained. This was not noted till after the material was obtained. The material obtained was a Lamboo® Design™ Series Products. Requested was Guadua bamboo but obtained was Moso bamboo, the test results also show this, because Guadua is stronger than Moso with higher E modules. A sample has been send to specialists from Moso to confirm it was Moso bamboo, and it is (personal communication with Arjan van der Vegte from Moso June 8, 2015). Moso looked at the way the shape and orientation of the vascular bundles which show the growth conditions and the origin. There is one more piece of evidence. The connection used to lengthen strips is a patented method from China.

Because of the test stet-up Moso offered a plank which has been cut in to parts for transportation. The plank is not specifically for construction it is comparable to the obtained samples of Lamboo as a design line product, (for furniture and such). But could be regarded as the least to expect value and between the structure line and the design line of Moso is little difference except the adhesive, which is not really tested in the conducted test. Both products use Urea-formaldehyde as adhesive and not phenolic formaldehyde which would be used in structural applications.
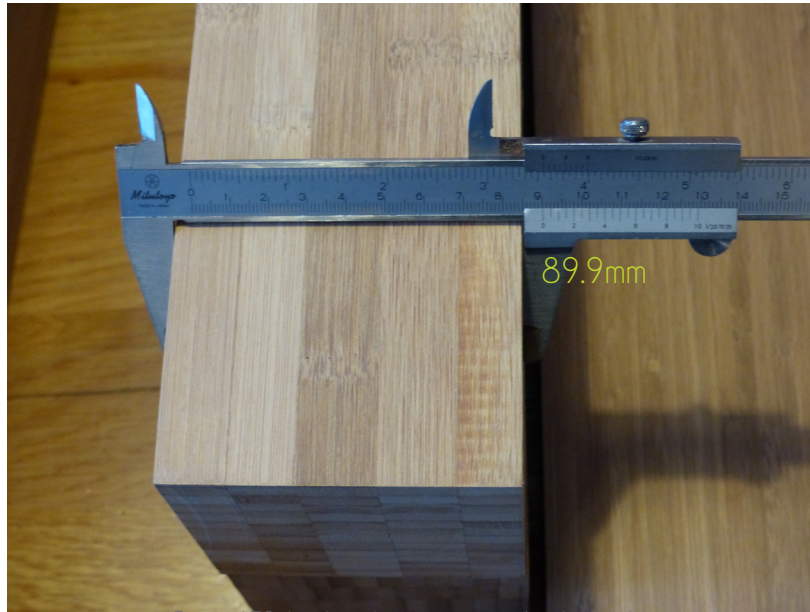
Figure:175. Lamboo beam measured with a caliper strips sideways
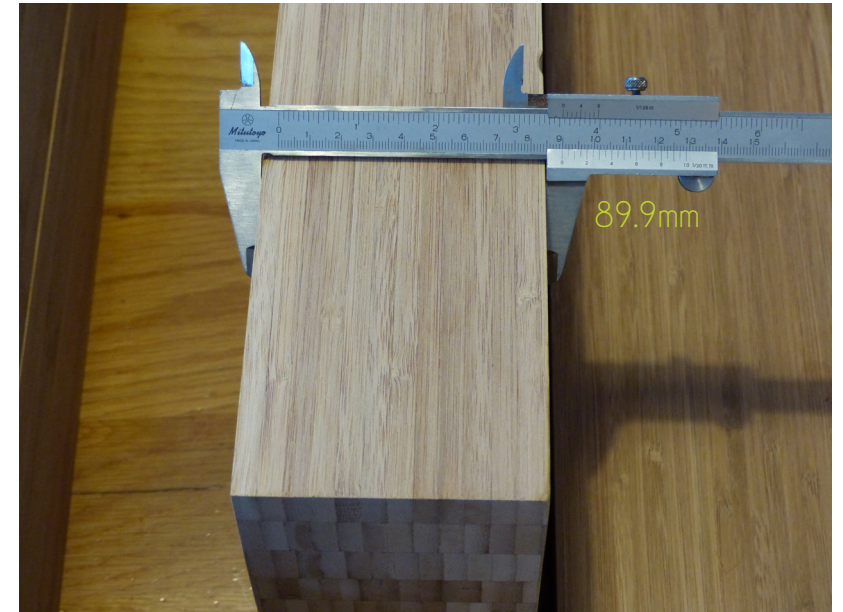
89.9mm

Figure:176. Lamboo beam measured with a caliper strips vertically

89.9mm

Figure:177. Short side Moso plank

19.3mm

Figure:178. Long side Moso plank

115.8mm

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Boundary conditions
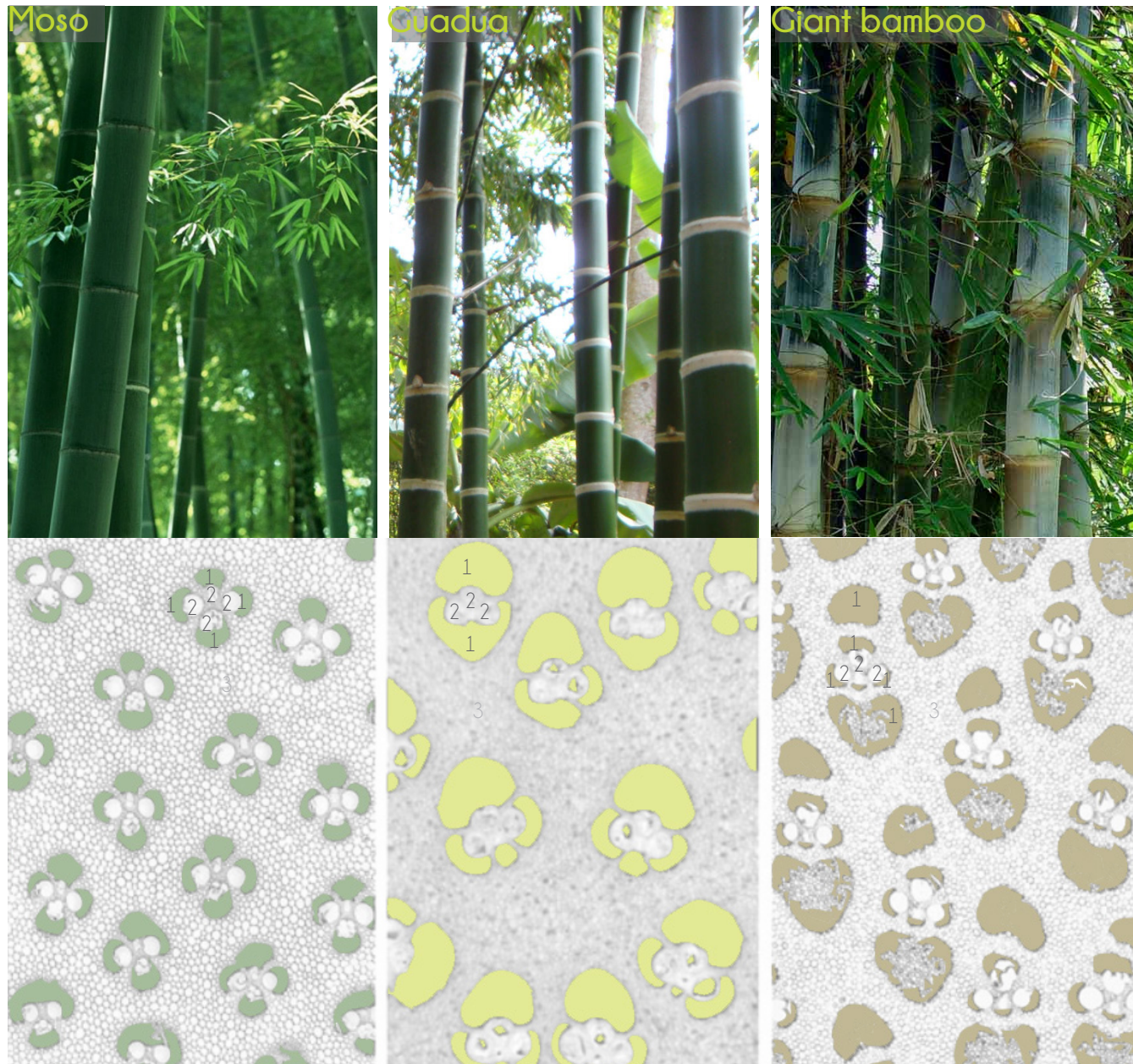
Recognizing Bamboo

When growing in a forest telling the difference between bamboo species is more easily, but telling the difference between bamboo species once dried, processed and treated can be more difficult.

To tell the difference between two pieces of laminated bamboo can be done by looking at the build-up of the strips themselves and with special care for the fibers/ vascular bundles. The way the bundles are grouped and the shape of bundles can help to identify the pieces. Guadua has one big bundle and some smaller ones. The big bundle is normally orientated towards the outside of the culm improving the strength of the culm. Moso on the other hand have more even sized groups of bundles with less difference between the vascular bundles (Liese and Köhl 2015).
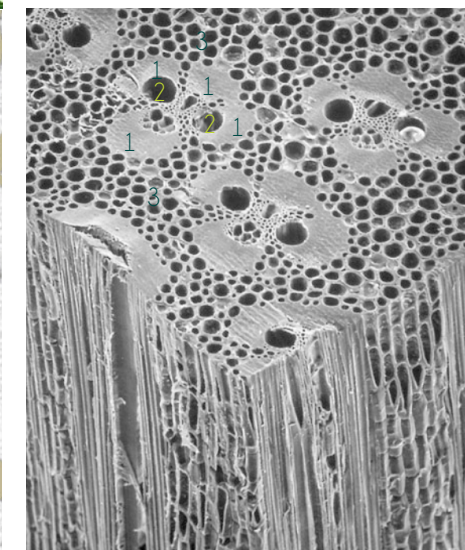
Figure:180. Three dimensional view of the culm tissue with vascular bundles and fiber sheaths embedded in ground paren-chyma

1: vascular bundles
2: fiber sheaths (hollow tubes)
3 parenchyma

Figure:179. Different cellular structures of different types of bamboo

Size samples

For the test samples were made with the following dimensions: 400mm long 40mm wide and 20mm high. The samples of Moso are 19mm thick not 20mm because Moso didn't have beams or planks of more than 20mm on stock at that moment and waiting wasn't an option. It has a small influence on the test results; however this will be taken care of in the calculations by altering the moment of inertia per sample according to the measured dimensions. Every sample was measured with an accurate of 0.5mm lengthwise and an accuracy of 0.05mm in the width and height using a caliper.

Defects

Once the Lamboo beam was cut it became clear that the material was not perfectly constructed. Trips were not perfectly aligned. In the entire beam the effect would most likely be less influential, but brought down to strip size it was on forehand assumed that it would influence the results in a negative way. Therefore the strips have been divided and numbered according to the amount of visible defects. Further in the report the results shall be compared to see if there is a significant decrease in strength of the samples when the amount of visible defects increases.

Numbering

All materials have been numbered and are categorized. Lamboo pieces are named L after Lamboo then numbered with a number counting the amount of defects and finally followed by a letter counting the number of samples with the same amount of defects. Moso samples are named M after Moso and otherwise numbered in the same manner as Lamboo

Number of vissible defects (0-3)

Producer of test sample
L=Lamboo
M=Moso

L.1.a.

Counting letter (a-z) of samples with a certain amount of visible defects of a producer
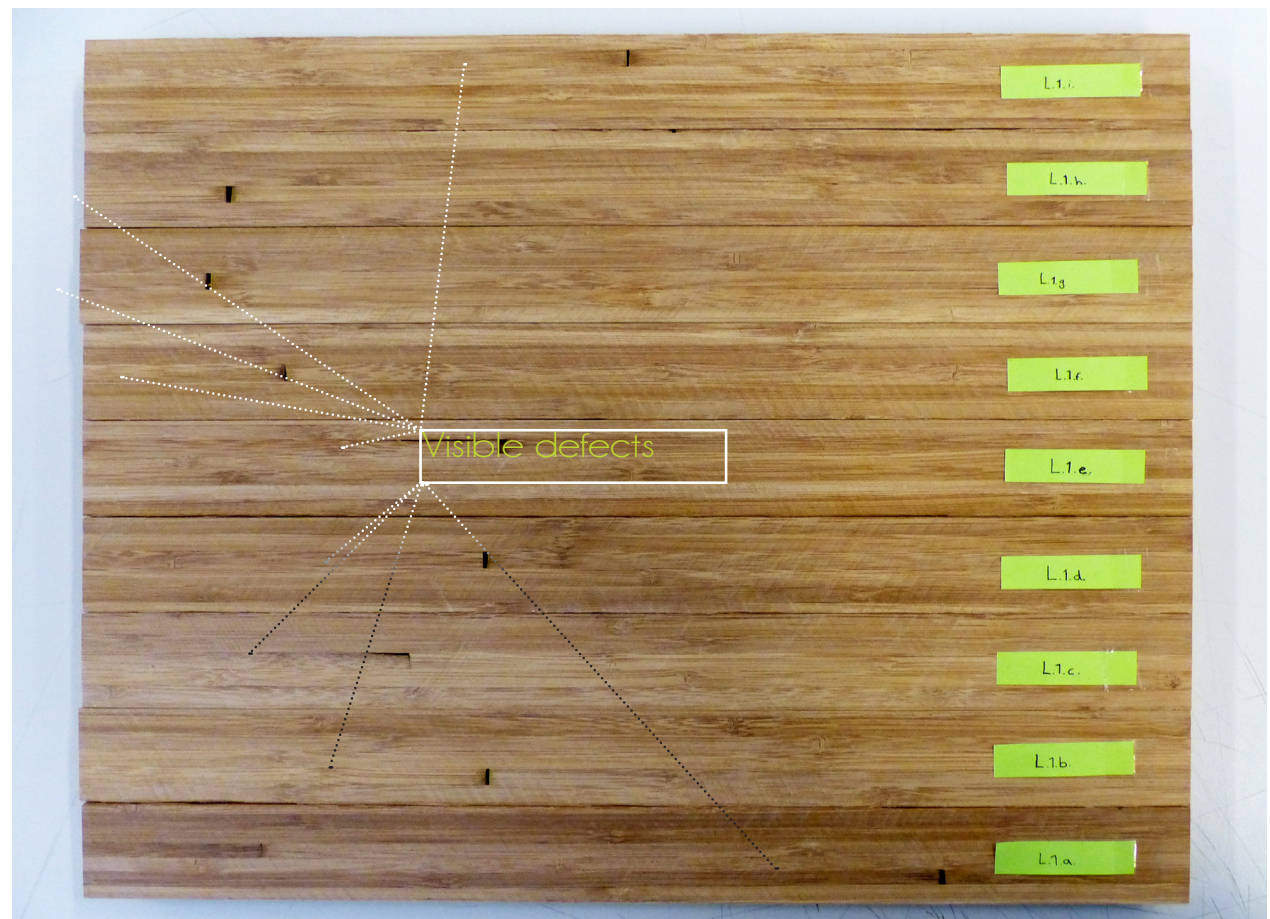
Figure:181. Numbering system according to the manufacturer, amount of visual deformations and the amount of samples

Boundary conditions

Pressure   Weakest option

Midpoint

Tension

Pressure   Strongest option

Midpoint

Tension

Pressure   Neutral option

Midpoint

Tension

Outside culm

Periphery

Middle

Inner wall

Inside culm

Shematic Culm wall

Culm

Figure:182. Influence of the vascular bundle distribution in the wall of the culm on translated to orientation of strips regarding its strength performance in bending.

Strip orientation

There is a significant difference between orientations regarding bending strength and MOE In a bending test when using strip size samples. This is caused by the different fiber densities within the strip itself. The strip is made by splitting the culm in pieces and plain it square. The properties from the wall buildup from the culm are also to be found in the strip. The wall of a bamboo culm is buildup out of three parts: the periphery, middle and inner wall and has two main components, vascular bundles (acts as fibers) and the parenchyma (acts as a resin) (Janssen 1981, Ghavami 2005, de Vos 2010, Chaowana 2013, Liese and Köhl 2015). The concentration of vascular bundles is highest near the outer wall in the periphery. A higher amount of vascular bundles means a higher strength. The periphery is stronger than the inner wall.

The single strips are about 1cm to 2cm wide for the Moso plank and similar for the Lamboo samples (although those are not purely single strips, which are the result of the cutting processes making samples from the obtained beams). On the scale of this test the influence of the orientation of the strips is important. In a bending test the strips have a weak, neutral and a strong side see image *"Influence of the vascular bundle distribution in the wall of the culm on translated to orientation of strips regarding its strength performance in bending"*. The aim of the research is to determine the MOE for large high beams such as proposed in the proposal, not for a strip. In bigger beams the effect of the orientation of the strip becomes less influential because the ratio between the distance to the center of the inner wall and the periphery becomes smaller. Most representatives therefore would be the neural orientation of the strips.

Expected breaking points

The most likely place for the samples to brake is either near a node or at the connection point of several strips together. The node is the weak point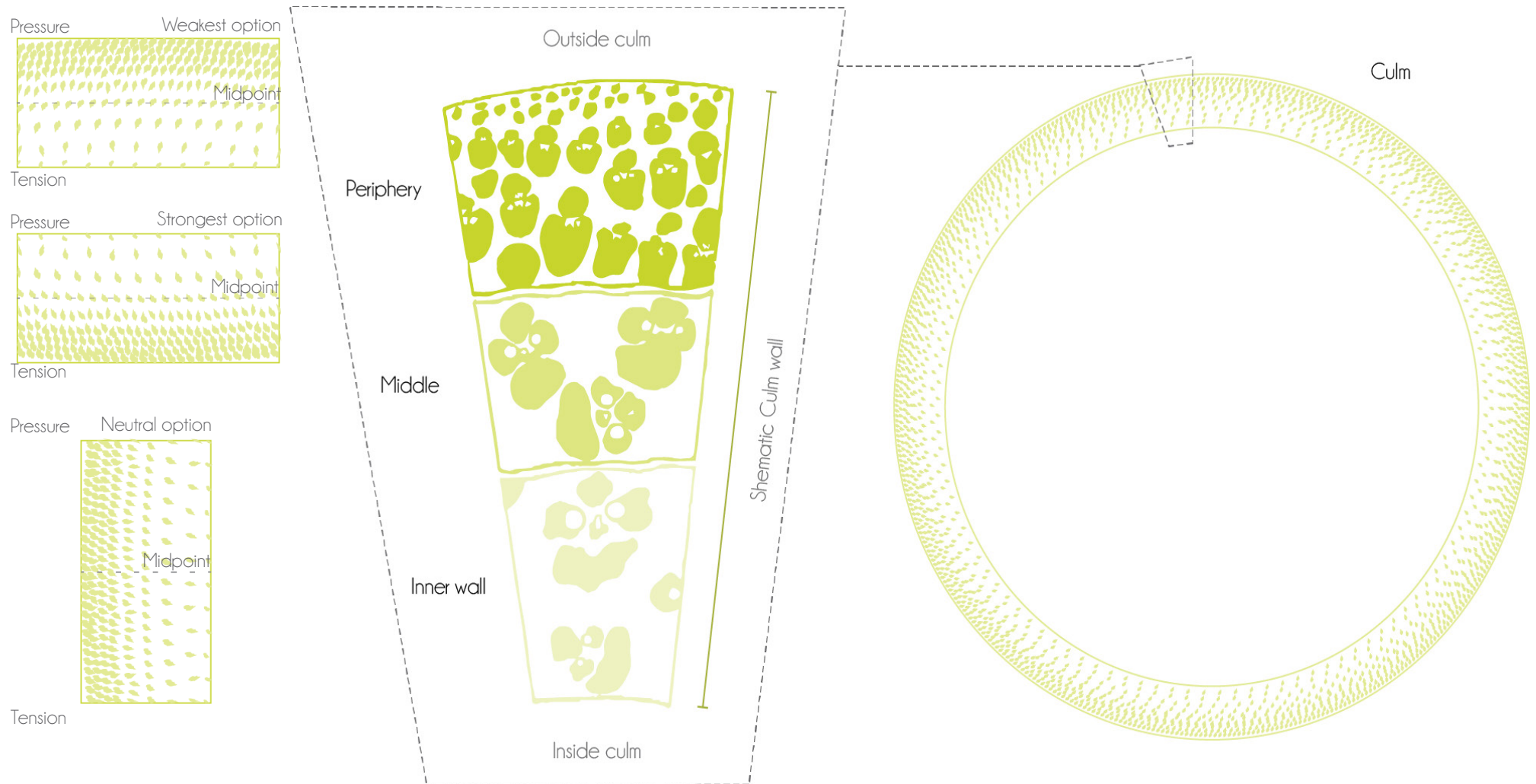 of the material (as are notches in wood). In the internode the fibers run parallel, but in the node it becomes sort of a spaghetti soup, see image "Bamboo Node". It decreases its bending strength (on the other hand it is positive to stop splitting from occurring). Because of the test setup the material is expected to split between the load points were the moment is largest.
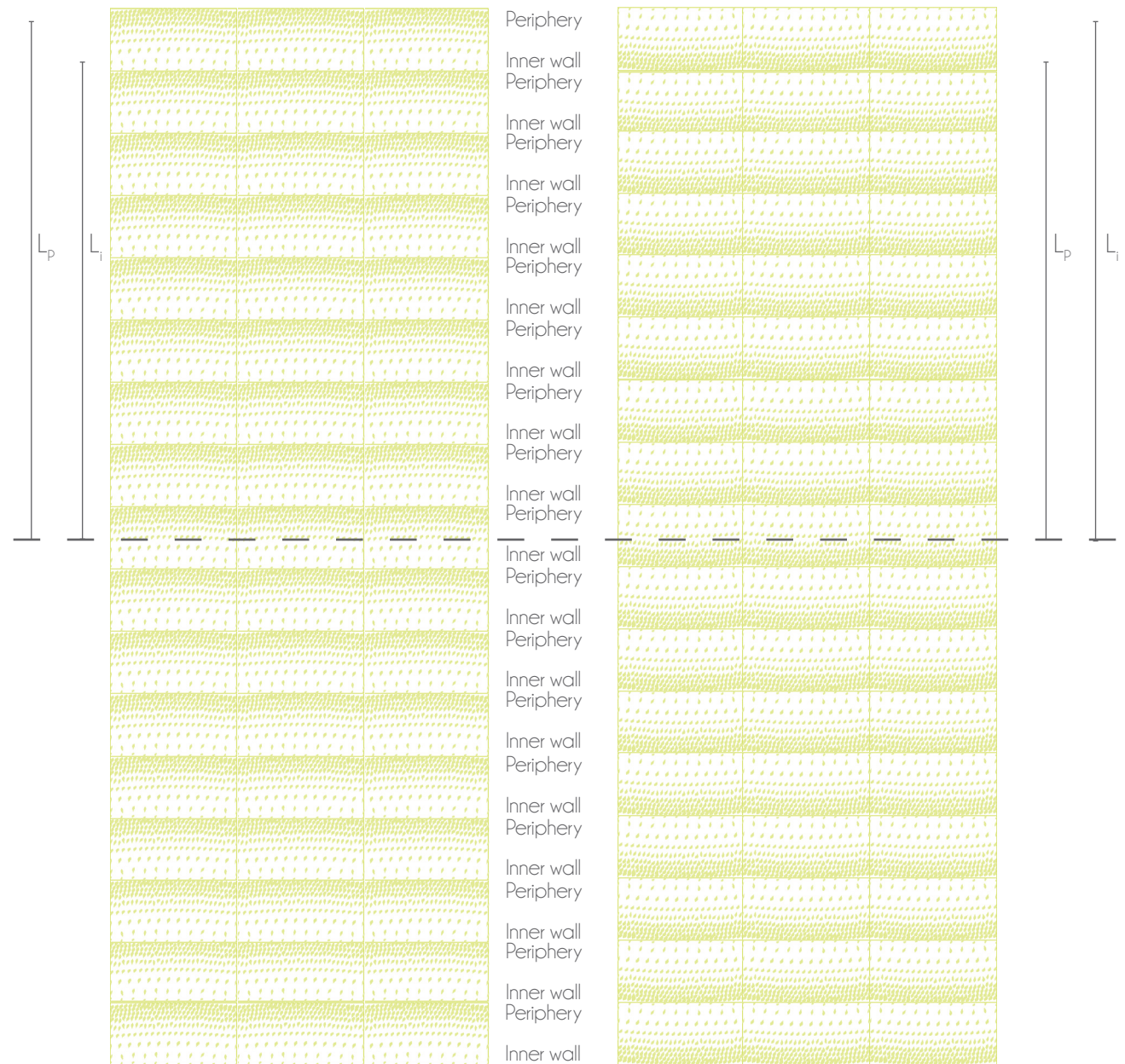
Figure:183. Difference of strip orientation becomes less important as beam gets higher

Boundary conditions

Figure:184. Strip orientation in testing showing a Lamboo sample

Why a 4 point bending test not a 3 point bending test

To determine the bending strength and the MOE there are basically two tests compelling to the European regulations. The three point bending test and the four point bending test. Manufactures tend to use a three point bending test. It is a very simple test, cheaper and the displacement of the head going down is directly the maximum displacement. The problem of this testing method is that the MOE that is obtained from it tends to be too high. This is because the test has a peak moment in the middle witch and also a maximum defection exactly in the middle, which makes it hard to measure accurately and on top of that deformations in the beam will normally not cause failure unless it is close to the center point. It also assumes that shear forces are so small that there influence is neglect able; this doesn't have to be the case.

The four point bending test has a consistent moment between the load-points and any deformations in the beam are more likely to play a key role in the breaking point. between the points were the material is expected to break the shear stress is also zero, eliminating the effect of shear stress and failure is likely completely because of the bending moment
(NPTE, Junior, Ferracane et al. 2008).

Figure:185. Bamboo node

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Page 126

Three point bending test (left):

$\frac{1}{2}L_{h.o.h.}$
190

$\frac{1}{2}L_{h.o.h.}$
190

F

Z → X

A C M D B

$\frac{1}{2}F$ $\frac{1}{2}F$

$\frac{1}{2}F$ $L_{h.o.h.}$ $\frac{1}{2}F$
380

400
L

Shear diagram V

$V(x)=\frac{1}{2}F$

A M B → X

$V(x)=-\frac{1}{2}F$

Peak moment
Shear forces add to failure

Moment diagram M

A M B → X

$M(max)=\frac{1}{2}FL_{h.o.h.}$

Four point bending test (right):

a
200

L_1
90

x
100

x
100

L_1
90

F

Z → X

$\frac{1}{2}F$ $\frac{1}{2}F$

A C M D B

$V_c=V_d$ $V_d=V_c$

$\frac{1}{2}F$ $L_{h.o.h.}$ $\frac{1}{2}F$
380

400
L

Moso

Y
Z →   h
40
b

Lamboo

Y
Z ← → Z h
40
b

Strip orientation

No shear force between load points

Shear diagram V

$V(x)=\frac{1}{2}F$

A M B → X

$V(x)=-\frac{1}{2}F$

Constant max moment
Imperfections sample are more likely to effect results

Moment diagram M

A M B → X

$M(max)=\frac{1}{2}Fa$

Figure:186. Difference between three point and a four point bending test

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
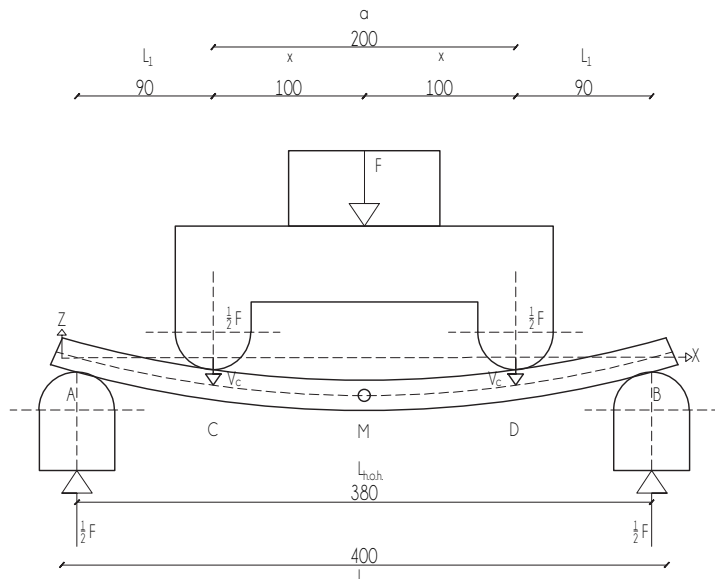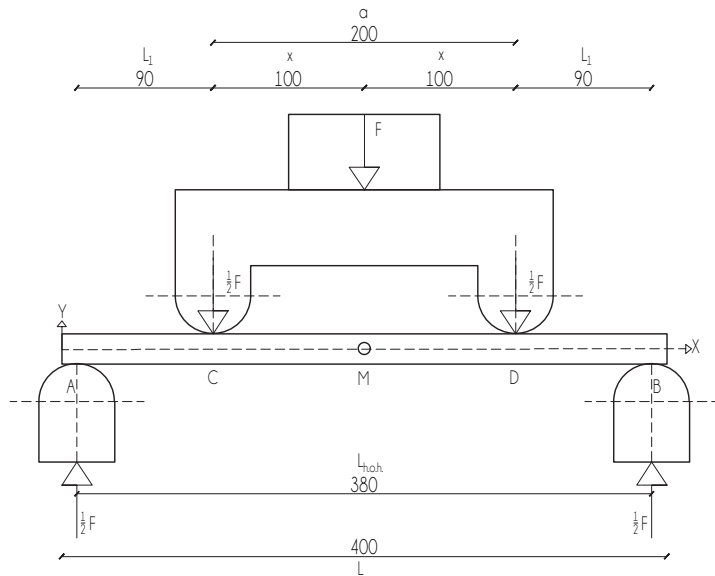
Test setup

Testing order:
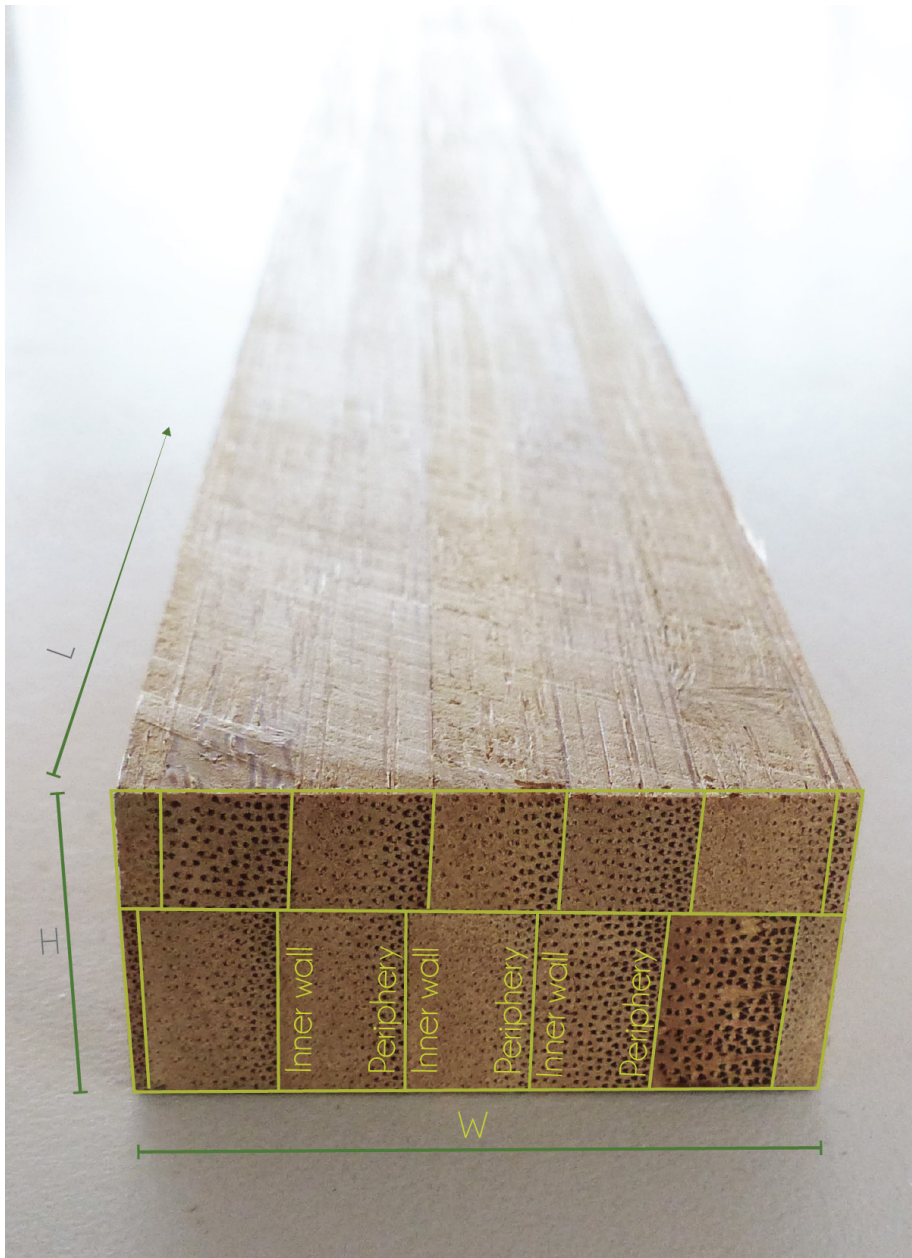
Test	Sample
Test 1-3:	M.0.i
Test 4:	M.0.a.
Test 5:	M.0.b.
Test 6:	M.0.c.
Test 7:	L.0.a
Test 8:	L.0.b
Test 9:	L.0.c
Test 10:	L.0.d
Test 11:	M.0.d.
Test 12:	M.0.d.
Test 13:	M.0.e.
Test 14:	M.0.f.
Test 15:	M.0.g.
Test 16:	M.0.h.
Test 17:	M.0.j.
Test 18:	M.0.k.
Test 19:	M.0.l.
Test 20:	M.0.m.
Test 21:	L.1.a
Test 22:	L.1.b
Test 23:	L.1.c
Test 24:	L.1.d
Test 25:	L.1.e
Test 26:	L.1.f
Test 27:	L.1.g
Test 28:	L.1.h
Test 29:	L.1.i
Test 30:	L.2.a
Test 31:	L.2.b
Test 32:	L.2.c
Test 33:	L.2.d
Test 34:	L.2.e
Test 35:	L.2.f
Test 36:	L.3.a
Test 37:	L.3.b
Test 38:	L.3.c
Test 39:	L.3.d

● Lamboo   ● Moso

Test 1 and 2 had the wrong settings and were stopped before the sample was damaged

Table:24. Testing order

Testing conditions

The test conducted was a four point bending test. To the side the setup of the test is shown. Strips were placed between the four rounded heads being supported by the two outer heads. The two center heads are used to apply the pressure. Pressure is applied till breaking point and slightly beyond to see the behavior of the material after breaking.

The test was conducted in the Laboratory of Material Science of the TU Delft and the samples were tested in a Zwick Z100, which is annually calibrated. Test where performed under supervision of dr. ir. Fred Veer. The samples were tested at room temperature. The MC (moisture content) was not measured. For Lamboo no data was available therefore it is assumed that it is similar to the samples provided from Moso which have according to Moso itself a moisture content between 7,7% - 9,8%. The relative humidity in which the test took place is unknown, the lab was well ventilated and had typical room temperature conditions.

Formula used to determine MOE

Because the test was conducted with measurements do not compel with the prescribed boundary conditions of the NEN-EN 408, or the conditions of the ASTM E855-08. The difference is in the distances a and l1. Formulas described in the NEN-EN 408 cannot be used either, because the deflection in the middle is used in the formula and/or use a gauge, which wasn't available for the constructed tests.

Formula according to EN-408:

$$E_{m,l} = \frac{a{l_1}^2(F_2 - F_1)}{16I(w_2 - w_1)}$$

$E_{m,l}$ = Local MOE in bending (N/mm²=MPa)
a= Distance between loading point and nearest support (mm)
l_1= Gauge length in (mm)
$(F_2 - F_1)$= Increment of load in (N)
I= Moment of inertia (mm⁴)
$(w_2 - w_1)$= Increment of displacement in the center of the beam (mm)

When translated to letters used and data available the formula becomes:

$$E = \frac{l_1(?)^2(\Delta F)}{16I(\Delta v)}$$

E= Modules of Elasticity (MPa)
l_1= Distance between loading point and nearest support (mm)
?= Gauge length in (mm) (unknown device not used)
ΔF= Average increment of load between 5 samples ranging between 0.1Fmax and 0.4Fmax always including the range 0.2Fmax to 0.3Fmax in (N)
I= Moment of inertia (mm⁴)
Δv= Is unknown (mm)

There are 3 unknowns, therefore the formula can not be used, also with the different set up used it is questionable if the formula would still hold.

There is however a formula that can calculate the E modules with the data known (Gere and Goodno 2012):

$$V(x) = -\frac{Px}{6EI}(3al - 3a^2 - x^2)$$

V(x)= Deflection in the Y direction at point x (mm)
P= Point load= 1/2 of the total amount of force applied (N).
x= A point on the length of the beam (mm)
E= Modules of Elasticity (MPa)
I= Moment of inertia (mm⁴)
a= distance of the load from nearest support (in scheme of setup of the test represented as l_1) (mm)
I= Distance from one support to the other support (in scheme of setup of the test represented as $l_{h.o.h.}$)

When transformed to calculated the E and changing it to the letters used in the scheme it becomes:

$$V(x) = -\frac{Fx}{12EI}(3l_1 l_{h.o.h.} - 3l_1^2 - x^2)$$

Which can be rewritten to:

$$E(x) = -\frac{Fx}{12VI}(3l_1 l_{h.o.h.} - 3l_1^2 - x^2)$$

The moment of inertia (I) can be calculated, the samples are rectangular and therefore I can be described as:

$$I = \frac{1}{12} \times b \times (h)^3$$

This results in:

$$E(x) = -\frac{\Delta Fx}{\Delta Vb(h)^3}(3l_1 l_{h.o.h.} - 3l_1^2 - x^2)$$

E= Modules of Elasticity (MPa)
F= Average increment of load between 5 samples ranging between 0.1Fmax and 0.4Fmax always including the range 0.2Fmax to 0.3Fmax in (N)
x= A point on the length of the beam (mm)
V= Average increment of deflection, of 5 samples ranging between 0.1Fmax and 0.4Fmax always including the range 0.2Fmax to 0.3Fmax, in the Y direction at point x (mm)
b= With of the sample tested (mm)
h= Height of the sample measured (mm)
l_1= Distance of the load from nearest support (mm)
$l_{h.o.h.}$= Distance from support to support

Maximum bending stress

The maximum stress caused by bending commonly known as the bending stress can be described as:

$$\sigma_M = \frac{M}{W}$$

σ_m= Stress caused by bending (N/mm²)
M= Moment (Nmm)
W= Section modulus (mm³)

The maximum bending stress occurs when the moment is maximum. The maximum moment can be described as:

$$M = \frac{P}{2} \times L_1 = \frac{F}{4} \times L_1$$

M=Moment (Nmm)
F= Force applied measured in Neuton (N)
l_1= Distance of the load from nearest support (mm)

The Section modules can be described as:

$$W = \frac{I}{z} = \frac{(1/12\ bh^3)}{0.5h} = \frac{bh^2}{6}$$

W= Section modulus (mm³)
I= Distance of the load from nearest support (mm)
Z= Distance from gravity point to outer fiber along the Y direction (mm)
b=Width (mm)
h=Height (mm)

Resulting in:

$$\sigma_M = \frac{3Fl_1}{bh^2}$$

σ_m= the maximum stress caused by bending (N/mm²)
F= Force applied measured in Neuton (N)
l_1= Distance of the load from nearest support (mm)
b=Width (mm)
h=Height (mm)

If the moment in the formula is the maximum obtained σ_m is equal to σ_m.max.
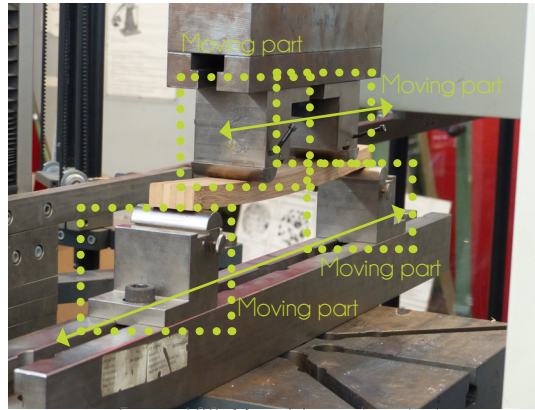
How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

10.3. Results

Figure:188. Movable parts in test equipment
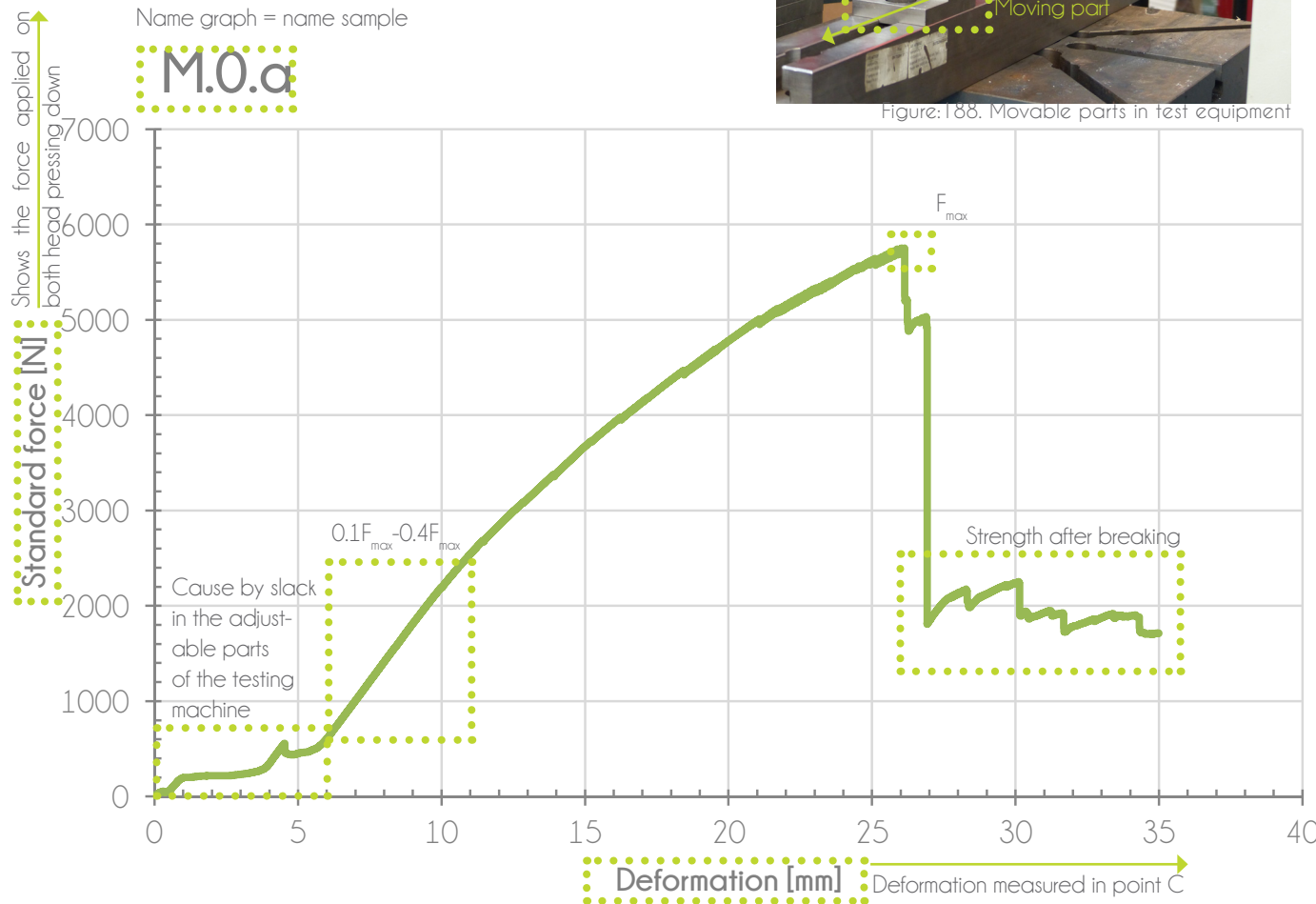
Graph interpretation

The results are automatically transferred to Excel and a graph is created for each sample using the data comparing the standard force with the deformation measured in the load points. A few notes have to be made regarding the results visualized in the graphs. The first part of the graph has to be excluded from the results and no data points have been taken in this part for further analysis. The irregularities in the first part of the graph are created by the moving parts. Because the parts can be adjusted there is always some movement when a force is applied and needs to settle first. After settling the graph becomes a typical stress vs deformation graph. In the first part (0.1Fmax to 0.4Fmax) the behavior is elastic, further towards F_{max} the material starts to permanently deform and an increase speed of deformation can be seen. To determine the E modules (MOE) only the area that shows elastic deformation can be used. Elastic deformation means that it deforms under a load, but when the load is removed the material goes back to its original form. In the EN-408 for woods and laminated woods the area that may be used has to be between 10% and 40% of the maximum load and has to cover the area between 20% and 30% of the maximum load (F_{max}). After the material breaks it doesn't lose all of it strength as can be seen in the graph. The material when it false doesn't break all the way but partly. The remaining part still has significant strength left in them. See image: "Typical graph obtained".

In the graph between $0.1F_{max}$ and $0.4F_{max}$ is not a straight line. It jigsaws a bit, although the effect is very small as can be seen in the image: "*Two different ranges showing the showing the measured points and the "trend-line"* ". It is taken in to account. Five samples of the deformation and the associated force for each graph between $0.1F_{max}$ and $0.4F_{max}$ covering at least the area between $0.2F_{max}$ and $0.3F_{max}$ have been taken, summed up and averaged creating more accurate values.

Figure:189. Typical graph obtained

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Page 130

M.0.b

| | 0.1 F_max | 0.2 F_max | 0.3 F_max | 0.4 F_max |
| | 611 N | 1223 N | 1835 N | 2447 N |

Range	P1 F (N)	P2 F (N)	ΔP F (N)
1	730	2019	1290
2	837	2123	1286
3	946	2220	1274
4	1053	2319	1266
5	1162	2340	1178
	P1 V (mm)	P2 V (mm)	ΔP V (mm)
1	8.131	11.167	3.036
2	8.384	11.419	3.036
3	8.636	11.672	3.036
4	8.889	11.924	3.036
5	9.141	11.977	2.836

L.0.a.

| | 0.1 F_max | 0.2 F_max | 0.3 F_max | 0.4 F_max |
| | 427 N | 854 N | 1281 N | 1708 N |

Range	P1 F (N)	P2 F (N)	ΔP F (N)
1	640	1304	664
2	735	1354	619
3	879	1415	536
4	1053	1475	423
5	1175	1596	421
	P1 V (mm)	P2 V (mm)	ΔP V (mm)
1	5.950	7.312	1.361
2	6.145	7.412	1.267
3	6.440	7.537	1.096
4	6.797	7.662	0.865
5	7.048	7.909	0.862

L.0.b.

| | 0.1 F_max | 0.2 F_max | 0.3 F_max | 0.4 F_max |
| | 583 N | 1167 N | 1751 N | 2335 N |

Range	P1 F (N)	P2 F (N)	ΔP F (N)
1	667	1792	1125
2	814	1912	1099
3	964	2012	1049
4	989	2113	1124
5	1015	2218	1202
	P1 V (mm)	P2 V (mm)	ΔP V (mm)
1	5.654	7.922	2.268
2	5.952	8.166	2.213
3	6.254	8.388	2.133
4	6.307	8.577	2.270
5	6.359	8.776	2.417

Figure:190. 3 examples of graph obtained and points selected for Δv and ΔF

M.0.a

M.0.a

Figure:191. Two different ranges showing the showing the measured points and the "trend-line"

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Results

Failed specimens

All 37 specimens failed between the two load points on the bottom side of the specimen where the fibers snapped. All Moso samples failed near or at the nodes. In the Lamboo samples the failure occurred also near the connection points. Labels are normally placed on top except in the case of M.0.i were the sample was place upside down, this was a mistake, but doesn't influence the result because of the chosen direction of the individual strips.

The way the material fails shows the strong difference in strength between the Vascular bundles (or fibers) and the parenchyma. When a group of fibers snaps in a bending test it is pealed back ripping a far greater surface area apart of parenchyma.

Figure:192. Bending test during test and after breaking point, always breaks at the bottom side

100mm

200mm breaking zone were the moment is the greatest

100mm

Figure:193. Sample always brakes in range a between the load point were the moment is constant and the largest, but without shear , showing that failure was caused by pure bending

Fibers ripped of (failure of the parenchyma)

Vascular bundles snap

Failure ad node

Failure at connection

Failure at connection

Chinese patented connection

Failure at connection

Failure at connection

Figure:194. Failure at connections and nodes

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
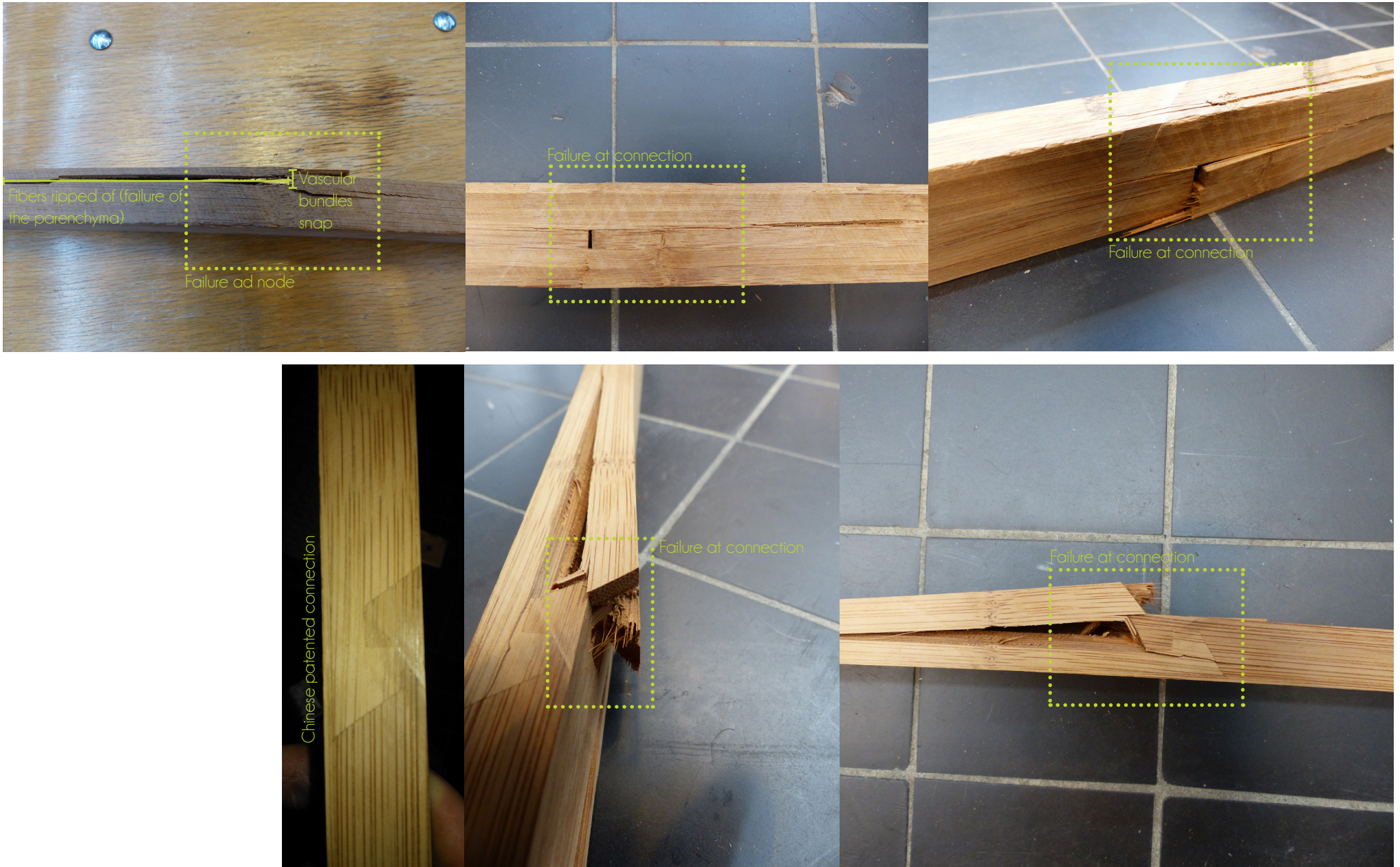
10.4. Analyze

Moso	MOE (MPa)	$\sigma_{m.max}$ (N/mm²)
M.O.a.	8,749	51.7
M.O.b.	9,050	54.3
M.O.c.	10,045	61.8
M.O.d.	9,173	51.1
M.O.e.	9,350	52.1
M.O.f.	9,996	58.6
M.O.g.	9,556	55.7
M.O.h.	11,037	66.2
M.O.i.	9,941	54.0
M.O.j.	8,853	54.1
M.O.k.	10,547	59.9
M.O.l.	9,503	61.6
M.O.m.	10,097	57.6
M.O.n.	9,795	56.1
M.O.o.	Not tested	Not tested

Moso	MOE (MPa)	$\sigma_{m.ma}$ (N/mm²)
Min	8,749	51.1
Max	11,038	66.2
Average/mean	9,688	56.8
SD (σ)	650	4.4
Standard error of the mean	174	1.18
CV (<5%)	8,620	49.5

SD=Standard deviation
CV=Characteristic value

Number of samples tested **14**
M.O.o. Not tested to show at presentation

Table:25. Summery of the MOE and $\sigma_{m.ma}$ Values obtained

Lamboo	MOE (MPa)	$\sigma_{m.max}$ (N/mm²)
L.0.a	9550	35.5
L.0.b	9806	49.2
L.0.c	9878	49.1
L.0.d	9583	42.3
L.1.a	9434	51.2
L.1.b	8876	45.2
L.1.c	8788	42.2
L.1.d	9522	52.0
L.1.e	9416	49.3
L.1.f	10288	51.6
L.1.g	9933	55.9
L.1.h	9368	51.6
L.1.i	9818	47.8
L.2.a	8862	43.0
L.2.b	9947	51.6
L.2.c	8573	41.7
L.2.d	10280	52.4
L.2.e	9691	56.2
L.2.f	8631	44.4
L.3.a	9791	39.5
L.3.b	8843	52.4
L.3.c	8817	48.9
L.3.d	9543	53.4
L.3.e	Not tested	

Lamboo	MOE (MPa)	$\sigma_{m.max}$ (N/mm²)
Min	8573	35.5
Max	10,288	56.2
Average/mean	9,446	48.1
SD (σ)	516	5.4
Standard error of the mean	108	1.13
CV (<5%)	8,596	39.2

Number of samples tested **23**
L.3.e. Not tested to show at presentation 35.5

Determining the MOE and sigma. m. max have been done by using the formula's described in the sub chapter: "*Test setup*". The data has been processed using Excel 2010. The average value has been determined using the formula:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

$\bar{X}$ = Average/mean
$\sum X_i$ = Summation of values, i is 1 means it counts every value
n = Population count

The standard deviation is normally marked with a sigma (σ) which is also used as the symbol of stress, to prevent confusion the standard deviation is marked in the thesis with the symbol (σ_{SD}). The standard deviation shows how likely it is that something occurs and is needed to create a bell curve. Assumed is that the bell curve is applicable and that the behavior of the material is according to the standard bell curve/ deviation. If it is applicable is tested and visualized in the images: "*Obtained maximum bending stress values in % with a projected bell curve added to it of Lamboo and Moso samples*" and "*Obtained MOE values in % with a projected bell curve added to it of Lamboo and Moso samples*". The MOE regarding Moso seams a reasonable fit regarding only 14 samples have been tested. Lamboo however fits less well, this has most likely to do with the large difference between strength in samples with and without connections. The standard divination can be determined by using the formula:

$$\sigma_{SD} = \sqrt{\frac{\sum_{1}^{n}(x_i - \mu)^2}{n}}$$

σ_{SD} = Standard divination
X_i = Observations
μ = Mean of population
n = Population count

Standard Bell graph

Characteristic value (CV)

Area left of the CV underneath the graph is 5%

Area both sides of the mean underneath the graph is 50%

Y axis shows how often a value occurs with a standard deviation the steeper the graph the more homogeneous the material is

Value of area under graph always 1

SD= Standard deviation

-3SD -2SD -1SD Mean +1SD +2SD +3SD

68.3%

95.4%

99.7%

Location on the x axis determines the strength of a material

Figure:195. Standard bell graph explained in relation to standard deviation and mean.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Analyze

With the σ_{SD} known not only the bell graph can be created also the Standard error of the main can be calculated also known as sampling error.

$$\sigma_{\bar{x}} = \frac{\sigma_{SD}}{\sqrt{n}}$$

σ_x = Standard error of the main
σ_{sd} = Standard divination
n = Population count

It statistically shows the how far of the "real" mean could be compared to the calculated mean. In short the more samples the lower the Standard error of the main the more accurate the calculated mean is and the closer it is to the "real mean".

MOE (MPa):
Calculated Moso : 9,693   Real MOE between: 9,520-9,866
Calculated Lamboo 9,553 Real Bending strength: 9,338-9,553

Bending strength (N/mm²):
Calculated Moso 56.8   Real Bending strength: 55.6-58.0
Calculated Lamboo 48.1   Real Bending strength: 47.0-49.3

As can be seen there is still too much difference between the predicted and the possible real values, more samples need to be tested to fiend the real values, but the values obtained show a clear indication of where results are heading.

MOE samples
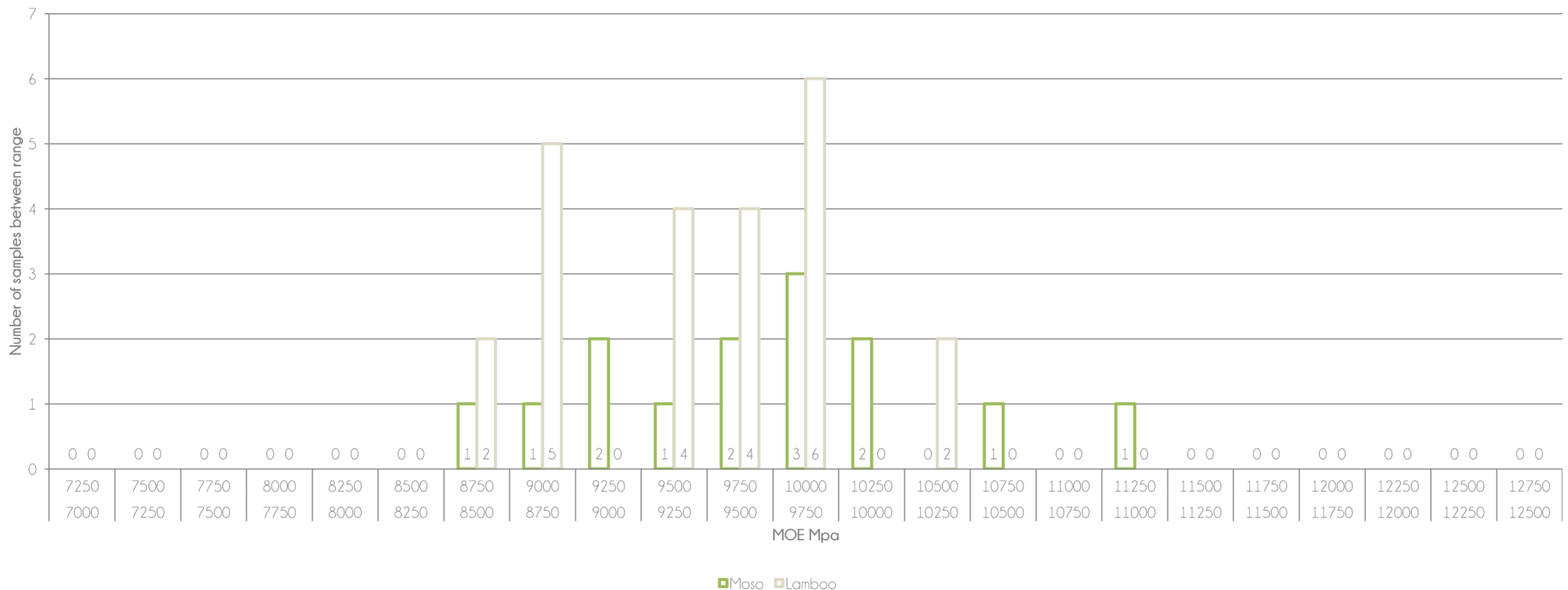
Figure:196. Graph showing how often a obtained MOE is between a certain value (absolute)
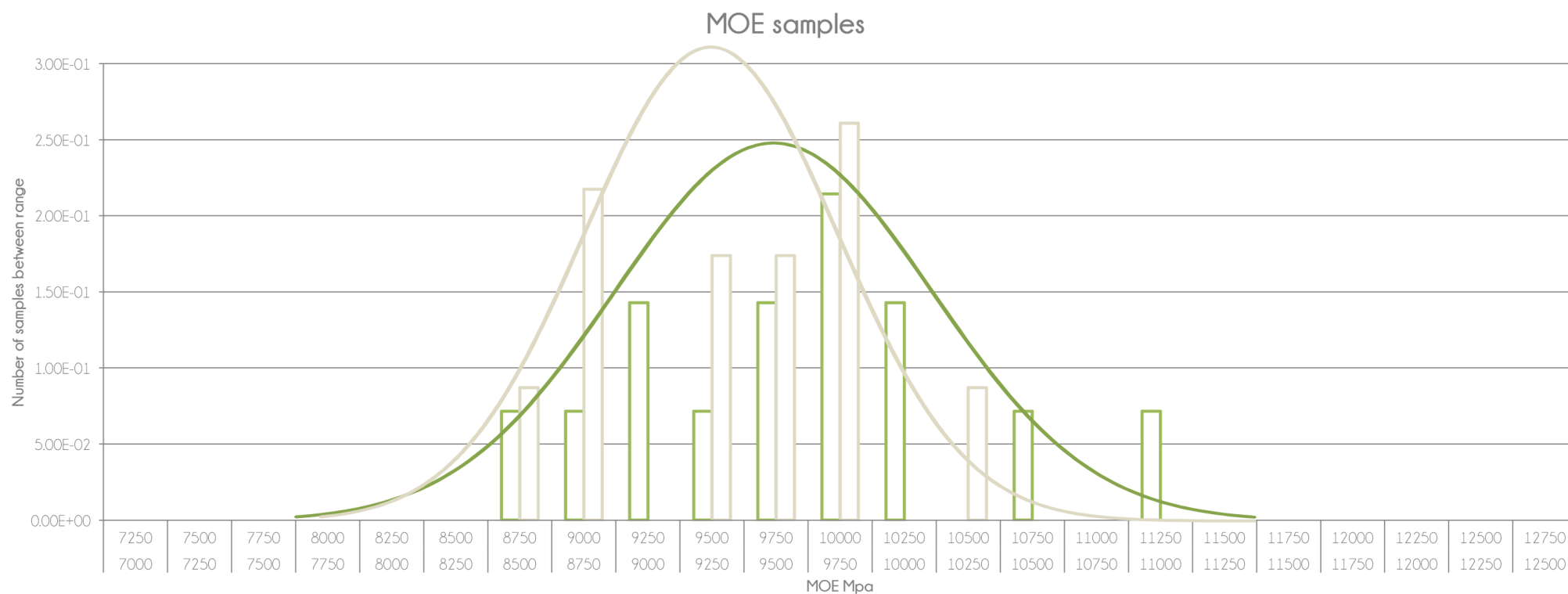
MOE samples

Figure:197. Obtained MOE values in % with a projected bell curve added to it of Lamboo and Moso samples

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Analyze

M$_{max}$ occurances in absolute numbers (n)
between ranges Lamboo, Moso and Lamboo+Moso

Figure:198. Graph showing how often a obtained maximum bending stress is between a certain value (absolute)

M$_{max}$ occurances (%) Lamboo, Moso and Lamboo+Moso

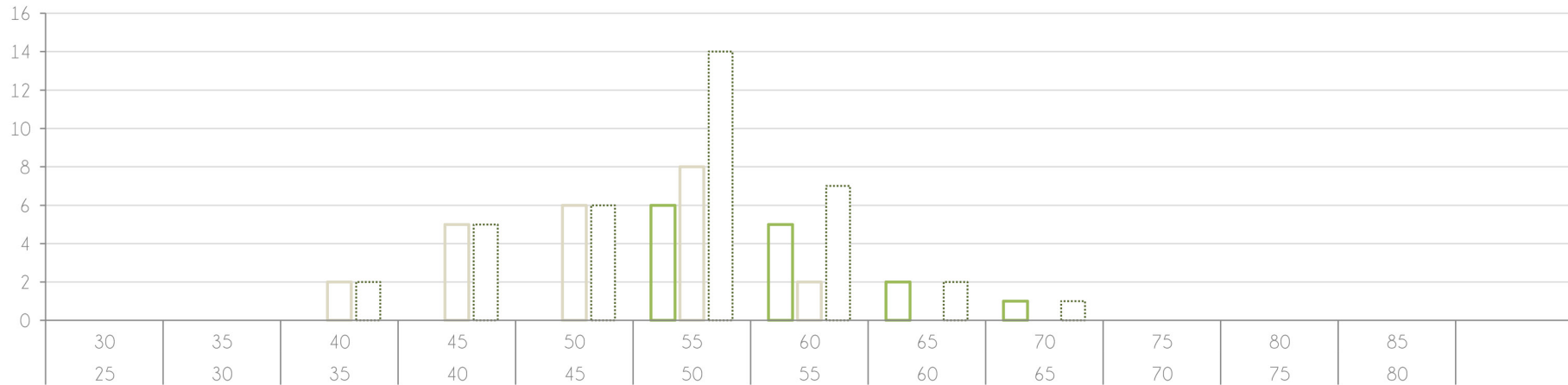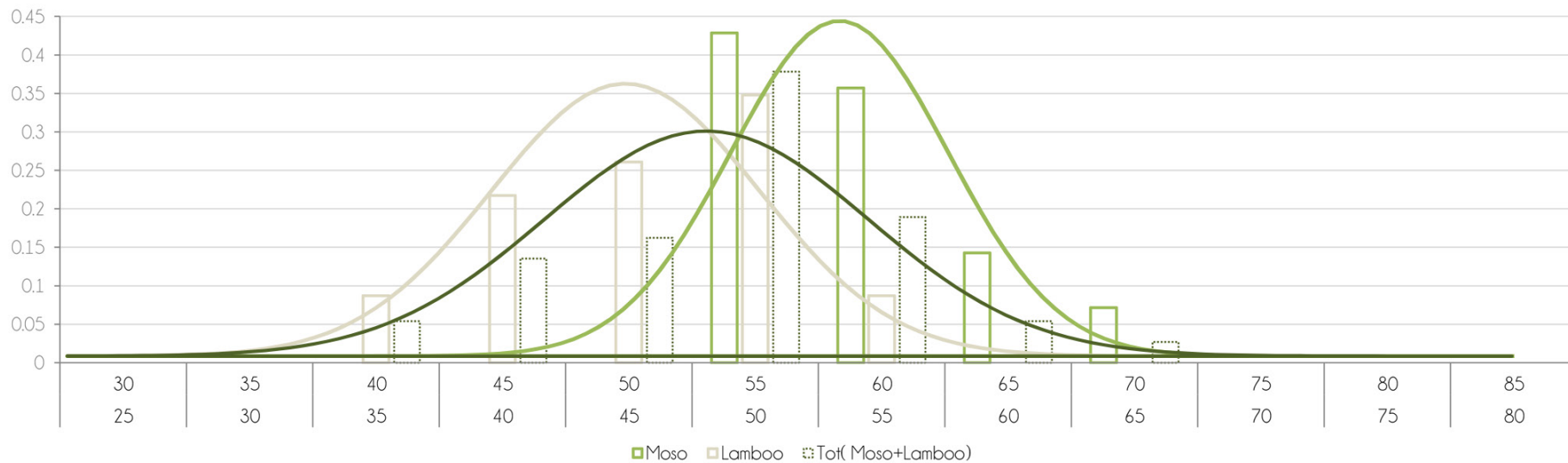□ Moso   □ Lamboo   □ Tot(Moso+Lamboo)

Figure:199. Obtained maximum bending stress values in % with a projected bell curve added to it of Lamboo and Moso samples

Visual control comparison

The samples of Lamboo have visible imperfections and are categorized by the amount of imperfections per sample. The aim is to see if an increase of visual imperfections leads to an decrease in structural performance. The results are plotted to the side as are the σ_{sd} , σ_x and n for the MOE and the $\sigma_{m.max}$. Hard conclusion from the comparison are hard to draw, there is no signification difference. Selecting samples or beams this way doesn't seem to guarantee improved results, the pieces with no visible imperfections seemed to preform worse regarding the maximum bending strength. Although one side node has to be made the selection was done by an untrained eye. In building applications however visual selection will be even less likely to work because most of the strips and imperfections are hidden inside the beam.

Regarding the images: Imperfection by visual inspection MOE and Imperfection by visual inspection $\sigma_{m.max}$ a few interesting things occur although it has to be mentioned that the sample size was very small and the Standard error of the mean and the standard deviation are relatively high. It seems that less imperfections doesn't lead to more strength but the values seem to be more homogeneous than the other values, although this also could be caused by the fact that L1 for example had more than twice the amount of samples. It is also interesting to see that the mean MOE is higher of L0. than of the others, but the maximum bending stress is less. This could be caused by the small sample size, the effect of connections of strips to increase the length and the location of the imperfections.

MOE

	Standard Deviation (σ_{sd})	Standard error of the mean	Population (n)
L0.	163	81	4
L1.	479	160	9
L2.	734	300	6
L3.	494	247	4

Table:26. Standard deviation and Standard error of the mean according to population of Lamboo samples per visual imperfection regarding Modules of elasticity. Standard

$\sigma_{m.max.}$

	Standard Deviation (σ_{sd})	Standard error of the mean	Population (n)
L0.	6.5	3.3	4
L1.	4.1	1.4	9
L2.	6.0	2.4	6
L3.	6.5	3.8	4

deviation and Standard error of the mean according to population of Lamboo samples regarding maximum bending stress.
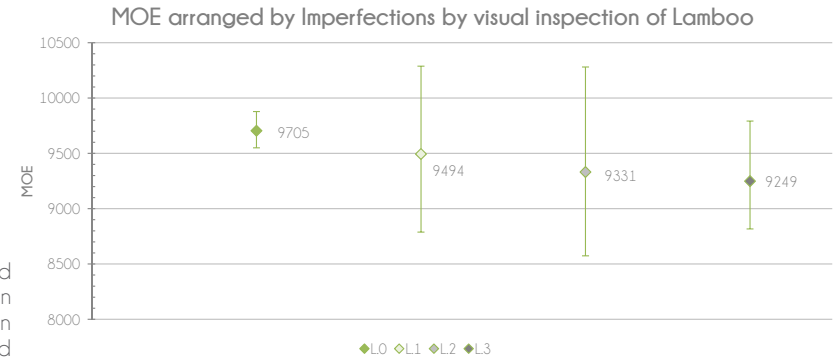

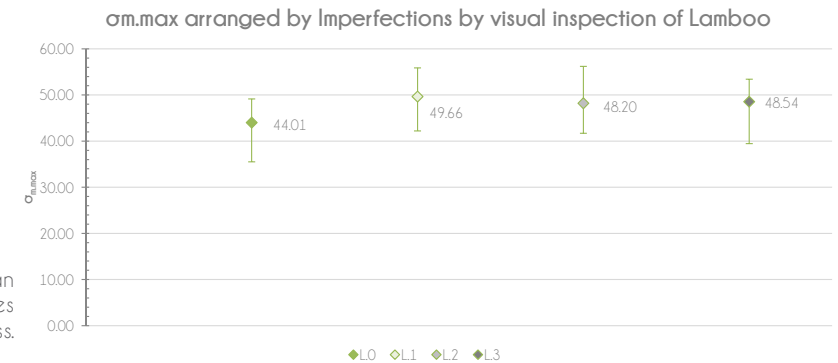Figure:200. MOE mean and max and minimum obtained values per visible imperfection

Figure:201. $\sigma_{m.max}$ mean and max and minimum obtained values per visible imperfection

10.5. Discussion

MOE claimed by Lamboo using a compresion test:
Mean: Unknown
Characteristic: 19305 MPa

Bending stress claimed by Lamboo:
Mean: Unknown
Characteristic: 24.1 N/mm²

MOE in a four point bending test claimed by Moso:
Mean: 8866-9721 (9721 is comparable to the orientation used in this thesis)
Characteristic: Still needs to be determined

Bending stress claimed by Moso:
Mean: Unknown
Characteristic: 50.8-56.7 (depending on the orientation of the strips)

MOE in compressive strength test claimed by Moso:
Mean between: 8166-1252 MPa (depending on the orientation of the strips)

Comparison with Moso and Lamboo

The values regarding Lamboo cannot be checked, because the wrong material was obtained. Lamboo claims regarding the MOE are based on the test described in the ASTM D 1037 (Lamboo 2014a). The test mentioned in the ASTM D 1037 regarding determine the MOE is a compressive strength test. This is a different test then conducted in this thesis and will lead to other results as well. From the data made available by Moso there is a significant deference in MOE (van der Vegte 2015), depending on the orientation it can differ between 8166 and 1252 MPa. With 1252 as most favorable obtained from a compressive strength test orientating the force perpendicular to the grain/fiber/vascular bundles and testing the bamboo strips flat-wise. The lowest mean MOE for compressive strength is parallel to the vascular bundles which results in a MOE of 8166MPa. So there is a difference of 4000 MPA. In the data provided by Lamboo it is not clear which value is used. When seriously interested and being a potential client Lamboo will provide more clarity regarding how results are conducted. In the case of the thesis Lamboo didn't want to fully cooperate and therefore the specifics regarding the tests are unknown.

According to the National Institute of Standards and Technology of the United States the test that should be conducted to determine the MOE for structural laminated wood like products is a AITC 200 (T116) test (Knab 2009). In this test a bending test with a ratio 1:100 (h:L) is described (Williamson and Yeh 2009) which hasn't been conducted by Moso nor by Lamboo as for as far as the author can ascertain. The author did consider conducting the test according to this ratio, however was advised not to by dr. ir. Fred Veer who supervised the test because of the extreme deformation occurring during such a test.

This does mean that the test numbers provided by Lamboo can be questioned and might not be correct/or can not be used, however this first has to be proven. The aim of the author is not to accuse Lamboo but dealing with Lamboo has proven to be a challenge and verification is needed before the claims by Lamboo regarding its structural material can be trusted.

Conclusion

Before the tests were conducted the aim was to verify the data provided by Lamboo. This was not possible, since the wrong material was obtained, there are however some conclusions to be drawn. It is very important look at what kind of tests are conducted to obtain the values, how the force is applied to the material and how many samples have been tested.

As expected the type of bamboo used determents the strength. When a obtaining a material it is important to check what kind of bamboo is used. The processing and treatment make more difficult to determine the bamboo spices used, but it is of vital importance and can be done looking at the vascular bundles, fiber sheaths and parenchyma buildup. Conducting strength test before usage also could help clarifying the bamboo spices.

The population of the test was relatively small and therefore the values obtained are without prejudice. The values of the Moso samples are close to the values obtained on the other hand the values from the Lamboo samples are far from the claims of Lamboo, but knowing that not a structural beam but a design beam was obtained the results proves nothing regarding Lamboo structural line.

The values obtained however could be used as a sort of minimum value for a structural design, but as mentioned before time was too short to alter the design to these values.

11.Conclusion

Main research question:

"How to design a residential building (complex) of multiple floors in Guayaquil, Ecuador, showcasing structural and sustainable possibilities and consequences of laminated Guadua bamboo?"

Answer:

By studying the material the structural and technical challenges and solutions, the context, the market and comparable markets. Then designing a building where the emphasize is on the structure and sustainability obeying the boundary conditions created from the analysis and then evaluate and finally to be able to show the possibilities and consequences.

Sub Questions

The main research question has been divided in 4 sub questions of which 3 of them are attempted to be answered in this master thesis. The forth is done by making a design running parallel to the research which is summarized in this thesis.

The three sub questions answered in this thesis:

· Is the world, and especially Ecuador capable of building a laminated Guadua multi floor buildings? In other words: is the world Ready?

Bamboo technology has improved dramatically and structural laminated Guadua is available. All the elements proposed can technically be made, but the market still needs to become more mainstream and no building has been constructed so far using laminated bamboo for more than a couple of stories, although this is a matter of time. The wood industry has already a couple of mid-rise buildings and more projects are planned. The bamboo industry of Ecuador is not as far as some other countries (China, Colombia and USA) but has potential and could be ready in a few years' time.

· What are the decisive structural and technical limitations of a residential building with multiple floors in Laminated Guadua bamboo and how high the building can be according to those limitations. In other words: Can it be done?

Because of lateral forces (wind/earthquakes) and the laws of physics the biggest limitation to the building height with a structure a 100% made out of laminated bamboo structure is the mass of the structure. The density of laminated bamboo is around 30% of concrete. This would result in tension at the foundation and the building would flip. Depending on the location and the building system the building could be between 12 and 18 meters high before tension occurs. By adding additional mass making a hybrid structure the height of the building can be increased to around 31m. To go beyond that the structure has to be anchored to the ground pre-stressed with for example steel tendons. The maximum height could this way be increased, to at least 12 floors and with modifications even further. The final design proposal is 12 floors on top of a concrete base and uses a combination of stiff frames and a stiff core. Solutions as multiple cores on the outside, a tube in a tube or an external super frame could increase the maximal height of the building even further. Because of the wish to be flexible a stiff frame with a core has been chosen leaving the facade mainly free for adaptation. The overall structural proposal has been checked with hand calculations. Further simulations are needed as are physical testing to test the behavior in the details.

Because bamboo is an anisotropic material LVB also has a strong and a weak direction. Therefore shear elements would benefit from cross lamination. Because of its anisotropic behavior it is important to prevent moments in the connections, because it creates tension parallel to the fiber direction and causes the material to split. A solution is to pre-stress the connections. Fire is often mentioned as an objection, but when designed well a LVB structure can guarantee sufficient fire safety and when engineered properly it can meet the sound standards. However it results in covering up the structure partly. Leaving a 100% of the structure exposed and meet all the demands is not feasible and concessions have to be made.

Extra compression caused by prestressed tendon

Tension caused by moment

Compression caused by moment

No tension in construction no splitting caused by tension parallel to the fiber direction
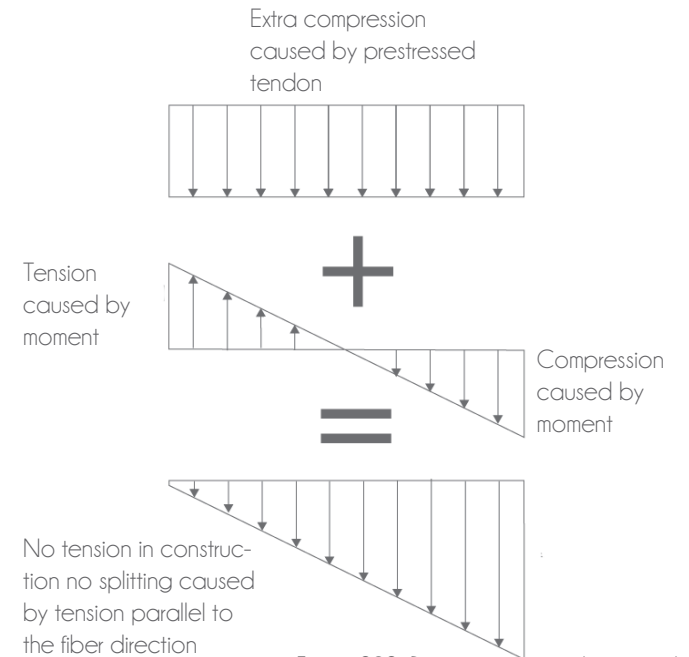
Figure:202. Diagram structural principal.
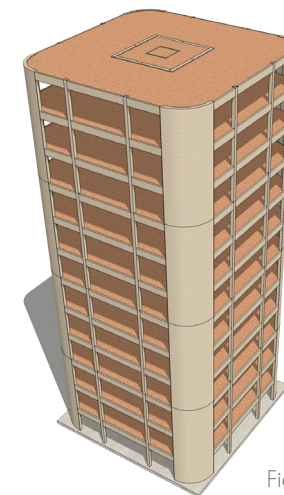
12 Floors
Are possible

Figure:203. 12 story structural proposal

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Conclusion

Figure:204. Master bed room artist impression

Figure:205. Living/dining room + kitchen artist impression

- In what way does it contribute to the three spheres of sustainability and how does the building preform compared to similar sized buildings regarding environment. In other words: is it sustainable?

Depending on the context and the exact composition of the laminated bamboo, structures made out of it can be sustainable regarding all three spheres. For social sustainability it can add to the standard of living of the poor people, it can help equalizing rights and prospects and help to give expression to culture. The proposal does even more it increases interaction and improves education. Wood can be cost competitive compared to steel and concrete, laminated bamboo would be slightly more expensive, but would offer advantages in durability and with the proposed system the real gain is the resistance against earthquakes allowing the building to be repaired instead of demolished. Developing the industry would also bring an increase in economic growth to Ecuador

If used and produced locally with an end of life scenario guaranteed and a life time of a 100 years laminated bamboo structures can have a significant impact on the environmental sustainability of multiple floor buildings. The Eco-cost would be reduced and calculations made show it even would have a positive impact on Eco-cost, carbon footprint and energy footprint. Land-use could be reduced more than 6 times when compared to wooden (hybrid) alternatives and could even be more when the structure is encapsulate instead of exposed. To further enhance the sustainability of the proposal the structure is completely demountable, facades and internal lay out are kept flexible, the structure has been calculated with office loads and in combination with extra floor height allowing alterations of usage over time

The only big negative impact is the effect of adhesives. It seems unfounded to presume the formaldehyde in the adhesives influence the human health of occupants of the building, but adhesives are considered to be toxic waste and take a large amount of energy to produce and are needed in larger quantities then when compared to CLT. However development is ongoing and there are alternatives on the horizon.

- How to create a building that shows the possibilities of laminated bamboo, but at the same time complies with the current expectations of a building. In other words: How could it look like (and be excepted)?

The answer to that is the design made for the thesis. The design consists out of a building complex of 5 different towers of various heights (4,6,8,10 and 12 floors) placed on a concrete base. The towers are squares with rounded edges this to reduce the wind loads but at the same time maintain a practical floor plan and with the cantilevers forms a symbolic reference to the base material it is made of (Bamboo). The structure is partly visible on the inside (columns, walls and beams). It is not exposed to the outside, because of the impact of the hot humid climate on the durability and structural performance of the laminated bamboo. To enhance its sustainable character the Facade cladding is made of strand woven bamboo with is thermally treated with a guarantee of 30 years durability being directly exposed to the weather. The roof is provided with a green roof to cool the building, increase biodiversity and allows resident to use it to recreate.

The concrete base is needed to protect the structure from weather conditions and occasional floods of the river. Most of the concrete walls are provided with a green wall system to enhance biodiversity and protect the concrete from over heating. To further prevent over heating cantilevers are used of 1 meter providing full cover of the facade during midday and orientation of the towers and the apartments is based on the wind and allows night cooling of the building to reduce the heat load and the need of air conditioning.

Figure:206. Artist impression of facades

Page 143

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

12.Recommendations

Figure:207. Future steps

How to make a 10+ residential building out of laminated bamboo in a seismic active zone in a sustainable way?

Recommendations

The goal of the thesis was to explore the possibilities, limitations of laminated Guadua bamboo structures. Focusing on structure, sustainability, technical aspects and the development of the market. The idea is very new and promising conclusions are drawn in this report about the feasibility, but most are based on assumptions and combining scattered information and as mentioned in the report many fields need more research to make a 12 floor building a reality. This chapter will list the most vital areas that need further research. Focusing on structure, other technical issues and sustainability issues.

Structural research suggestions

· Testing the claims made by Lamboo regarding the performance of the structural line. A good way to do this is to test the MOE in different tests to collect more data. The tests that should be included should be: ASTM D 1037, ASTM E855-08, AITC 200 (T116) and NEN-EN 408. Also important factors to confirm are the shear strength and compressive strength. To be able to do this it is important is to contact Lamboo early on, by calling to them directly (mail is ineffective). For the Thesis several attempts have been made to obtain the material, but obtaining the material has proven difficult.
· Fem models need to be made to verify the hand calculations and to test the individual elements on internal stresses.
· Computer modeling and physical testing is needed to check the assumed behavior during earthquakes and if it stays within the norms and to optimize the design.
· Physical tests are needed to determine the creep values (otherwise wood values have to be used)

Technical research suggestions

· Physical tests regarding delamination have to be designed/constructed with special care for the adhesives used.
· More research needs to be done regarding the fire behavior of the material and the entire structure. For starters a cone calorimeter tests has to be constructed to be able to determine char rates according to the norms and to test the formula used in the master thesis(although if delamination occurs the cone calorimeter test values are not usable).
· Sound values for CLT have been used, a bamboo plate has a higher density, therefore further research should be constructed to give the acoustic isolation performance of various standard building solutions (CLT handbook: cross-laminated timber by (Gagnon and Pirvu 2011) could provide the base for standard solutions).
· Physical test should be constructed to determine it's natural frequency and if harmonics of footsteps cause problems.
· Assembly and construction should be discuses with local contractors, international specialists and manufacturers to optimize design and reduce cost.
· Detailing should be further investigated and tested to see if assumptions made in the general structural calculation are correct.

Sustainable research suggestions

· A market analyze should be made of the current state of the bamboo industry in Ecuador (only data available is outdated)
· A study specifically for Ecuador should be constructed regarded the claimed improvement of social sustainability regarding the standard of living and equalization of rights.
· A complete cost analyze and exploitation estimations should be made for the proposed system so see if it's cost effective.
· To stimulate cooperation towards a high tech bamboo industry in Ecuador a study should be constructed to see what the effects have been in other countries and were the potentials for Ecuador are.
· A study has be constructed to investigate how much Guadua forest (Guadal) is available, were it is located and were it strategically could be planted near Guayaquil with the most positive environmental impact.
· LCA regarding structural laminated Guadua have been based on Moso being produced in China. The same kind of studies should be constructed for Ecuador, using all local parameters to give a more accurate image than provided in the thesis.
· Analyzes of the Eco-cost of the Eco-system still have to be constructed.
· The most important research regarding sustainability would be the impact of the adhesives and how to reduce the impact of the adhesives with finding a balance regarding the structural capacities, economics and sustainability.

13.References

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

13.1. References

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Figure:18. *Two global players: Lamboo (US) Moso (Europe) in Laminated bamboo.* Retrieved at November 16, 2014. From: http://www.deve-parketservice.nl/Bamboe.html and Retrieved at December 2, 2014 From: https://lambooincorporated.wordpress.com/tag/sustainability/

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How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

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Figure:37. Basic design essentials in hot humid climates 2. Based on Climate consultant data 5,5. Bangkok EPW data file.

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Figure:63. Guadua growing in a adjustable metal frame. Retrieved: January 14, 2015. From: http://www.agenciadenoticias.unal.edu.co/ndetalle/article/cultivaran-guadua-triangular.html (Spanish)

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Figure:65. Cross laminated panels become thicker and larger. Retrieved: February 24, 2015. From: http://www.lamboo.us/#linterior-design-solutions/zoom/c1hto/image_1xo9

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Figure:68. Size vs. stiffness. Self made image

Figure:69. Density of common wood like species. Based on: Hardwood Species Index and Softwood Species Index. Retrieved at January 04, 2015. From: http://www.sykestimber.co.uk/timber/european-oak.html and based on: Comparing Mechanical Properties of Bamboo: Guadua vs Moso. Retrieved November 11, 2014. From: http://www.guaduabamboo.com/blog/comparing-mechanical-properties-of-bamboo-guadua-vs-moso

Figure:70. Material's max height considered its stress to weight ratio. Based on: Brinksma, h., et al. (2011). Bouwmethoden Utiliteitsbouw. Amersfoort, ThiemeMeulenhoff (Dutch)

Figure:71. Calculation example Hybrid structure. Self made

Figure:72. Shear principal. Self made

Figure:73. Difference plane and edge glued. Self made

Figure:74. Principal rolling shear. Self made

Figure:75. The advantage of combining a stiff frame with a stiff core. Adapted from: Brinksma, h., et al. (2011). Bouwmethoden Utiliteitsbouw. Amersfoort, ThiemeMeulenhoff.

Figure:76. Dimensions core. Self made

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Figure:78. Different kind of stiff core configurations. Based on: REVEKAR, A. PIPPAL,D. (2013, May 04). 'High rise structural systems'. from: http://www.slideshare.net/aks254447/highrise-structural-systems

Figure:79. Overview different Tall timber buildings/proposals. Based on: SOM (2013), Green and Karsh (2012), Timmer (2011), Buchanan, Deam et al. (2008), Shigeruban (2013), Vest Cran (2014) Babrauskas, (2004

Figure:80. Proposal, North/south elevation. Self made

Figure:81. Proposal, West elevation. Self made

Figure:82. Proposal Span direction floors. Self made

Figure:83. Orientation of tension cables. Self made

Figure:84. Principle diagram system. Self made

Figure:85. 3D structure of proposal. Self made

Figure:86. 3D Structure of proposal 2. Self made

Figure:87. Close up of one 3 ply bamboo element. Self made

Figure:88. Exploded view floor element. Self made

Figure:89. Close op of connection exploded view. Self made

Figure:90. Connecting two panels using a internal spline. Self made

Figure:91. Look of finished connection. Self made

Figure:92. Different floor connection option. Based on Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Figure:93. Build-up of one wall element located in the core. Self made

Figure:94. Apartment side and staircase side. Self made

Figure:95. Wall elements horizontal connection finished. Self made

Figure:96. Horizontal connection wall elements. Self made

Figure:97. Top and bottom view wall elements core. Self made

Figure:98. Top bottom connection wall elements core. Self made

Figure:99. Top bottom connection wall elements core connected. Self made

Figure:100. Top floor buildup of tension cabbing

Figure:101. Exploded wall connection core element. Self made

Figure:102. Wall connection core element. Self made

Figure:103. Upper floor with Tension cabin and green roof build up. Self made

Figure:104. Visualization of ornamented hallway showing structural dissensions. Self made

Figure:105. 3DStructure of proposal 2 Problems like Fire, Sound, Vibration and connections needs to be solved in a building. Retrieved 02-04-2015 from: http://www.dailymail.co.uk/news/article-2234694/Flames-engulf-luxury-34-story-high-rise-Dubai.html

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Figure:111. Consequences of structural resistance regarding fire. Self made

Figure:112. Casualties in 4 story motels in case of fire comparing (non)/combustible materials and (no)/sprinkler buildings. Reprint of FIGURE 1. Injury rates (per 1,000 fires, plus 95% confidence intervals) by sprinkler protection status and building material combusibility from: Maxim, P., et al. (2013) Taller Wood Buildings and Fire Safety: Existing Evidence about Large Wood Construction. 8

Figure:113. USA/Canadian building standard demands. Self made. Based on: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

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Figure:115. Acoustic build up wall. Self made. Based on: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Figure:116. Different solid wood floor buildups and acoustical performance. from: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Figure:117. Flanking sound. self made

Figure:118. Proposed Formula's from the mass timber industry. From:-Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Figure:119. Possible assembly for a 6 story building. Self made

Figure:120. Strong and weak points of Anisotropic materials. Self made.

Figure:121. Problem with end connections. Self made

Figure:122. Example of moment stiff connection, by adding steel plates. Retrieved at January 28, 2015. From: http://www.trendsfloor.com/types-of-flooring/photos-of-floor-truss-projects/attachment/wood-floor-trusses-itnuupx/

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Figure:130. Structural challenge regarding edge grain face grain. Self made

Figure:131. Splitting or springing of fibers. Reprint from: http://www.instructables.com/id/Making-an-end-grain-cutting-board-I-made-it-at-T/step2/Why-end-grain/

Figure:132. Face, edge and end grain. Self made

Figure:133. A 3D Design suggestion in Lamboo for a 3 point node with anchor. Selfmade

Figure:134. Bamboo forest. Retrieved at January 12, 2015. From: http://bateydelcemi.com/wp-content/uploads/2014/01/guadua.jpg

Figure:135. A traditional organization vs the proposed organization. Self made

Figure:136. Nearby functions and its interaction with them. Self made

Figure:137. The preferred architectural strategy: I like my neighbors. Self made

Figure:138. Possible look of the proposed building. Self made

Figure:139. Impact of advanced bamboo industry on Jobs and money. Based on: New bamboo industries and pro-poor impacts: lessons from China and potential for Mekong Countries. International Conference on managing forests for poverty reduction: capturing opportunities in forest harvesting and wood processing for the benefit of the poor.

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Figure:141. Decrease tooling speed and lifetime of tools because of hardness of LVB. Self made

Figure:142. Difference wood drill and a steel drill. Retrieved at April 15. From: http://www.faithfulltools.com/p/Wood_Drill_Bits and http://www.ffx.co.uk/tools/category/Drill%20Bits%20%20Metal,%20Cobalt%20Metal%20Drill%20Bits/1

Figure:143. TCC floor used in NZ. Adapted from: Wong, R. C. W. (2010). "Construction time and cost of multi-storey post-tensioned timber structures."

Figure:144. Earthquake proof building system in New Zealand cost over view (2010). Adapted from: Wong, R. C. W. (2010). "Construction time and cost of multi-storey post-tensioned timber structures."

Figure:145. Price fluctuating in New Zealand. Adapted from: Wong, R. C. W. (2010). "Construction time and cost of multi-storey post-tensioned timber structures."

Figure:146. Overview cost per system per m floor compared to number of stories in Canada. Based on: Green, M. and J. Karsh (2012). "TALL WOOD-The case for tall wood buildings." Vancouver: Wood Enterprise Coalition: 240.

Figure:147. Eco-cost overview. Reprint from: http://en.wikipedia.org/wiki/Eco-costs#/media/File:Ecocosts_system_(new).png

Figure:148. Difference between C2G and C2C. Reprint from: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Figure:149. Average life span of a non residential building in Canada. Reprint from: O'Connor, J. (2004). Survey on actual service lives for North American buildings. Woodframe housing durability and disaster issues conference, Las Vegas.

Figure:150. Difference in mass per m² of a 12 story building. Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis.

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Figure:151. Plain bamboo (left) vs. Carbonized bamboo (right). From: http://www.ehow.com/about_5090940_carbonized-bamboo.html

Figure:152. Eco-cost C2G and C2C/m². Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Figure:153. Eco-cost C2C/m³. Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Figure:154. Carbon footprint. Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

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Figure:156. Energy footprint. Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Figure:157. LCA (C2G) Greenhouse gases for laminated Guadua panel in Ecuador. Reprint from: Ramirez, A., et al. (2014). "Life cycle assessment of greenhouse gas emissions arising from the production of glued and pressed wall panels derived from Guadua Angustifolia Kunth (bamboo) in Ecuador." Eco-Architecture V: Harmonisation between Architecture and Nature 142: 447.

Figure:158. Hybrid structure. Self made

Figure:159. Lamboo structure. Self made

Figure:160. Bamboo parts and utilization. Based on: Flander, K. D. and R. Rovers (2009). "One laminated bamboo-frame house per hectare per year." Construction and Building Materials 23(1): 210-218.

Figure:161. The yield of 1 ha Guadal. Based on: Flander, K. D. and R. Rovers (2009). "One laminated bamboo-frame house per hectare per year." Construction and Building Materials 23(1): 210-218.

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Figure:162. The yield of 1 ha Canadian pine. Based on: Flander, K. D. and R. Rovers (2009). "One laminated bamboo-frame house per hectare per year." Construction and Building Materials 23(1): 210-218.

Figure:163. Difference in land-use between proposal and wood hybrid. Self made

Figure:164. Lamboo used outdoor in solar roof. Retrieved at February 25 From: http://www.lamboo-solar.com/#!sunshade-array/c1gxi

Figure:165. Formaldehyde. Retrieved at February 24 From: http://nl.wikipedia.org/wiki/Formaldehyde

Figure:166. Generic phenolic formaldehyde structure. Retrieved at February 24 From: http://dwb4.unl.edu/Chem/CHEM869E/CHEM869ELinks/qlink.queensu.ca/~6jrt/chem210/Page5.html

Figure:167. Generic Urea formaldehyde structure. Retrieved at February 24 From: http://www.britannica.com/EBchecked/topic/13548/aldehyde-condensation-polymer

Figure:168. Forté Building. Retrieved at December 15, 2014. From http://www.victoriaharbour.com.au/live-here/forte-living

Figure:169. PU glue performanc Reprint of: PU-glue. Retrieved: February 25, 2015. From: http://www.guaduabamboo.com/guadua/comparing-mechanical-properties-of-bamboo-guadua-vs-moso And from: http://www.finehomebuilding.com/tools/departments/what-is-the-difference/pva-polyurethane-cyanoacrylate-glue.aspx

Figure:170. Four point bending test in TU delft. Self made

Figure:171. Obtained materials from Lamboo. Self made

Figure:172. Close up. Self made

Figure:173. Obtained materials from Moso. Self made

Figure:174. Obtained materials Moso 2. Self made

Figure:175. Lamboo beam measured with a caliper strips sideways. Self made

Figure:176. Lamboo beam measured with a caliper strips vertically. Self made

Figure:177. Short side Moso plank. Self made

Figure:178. Long side Moso plank. Self made

Figure:179. Different cellular structures of different types of bamboo. Based on: Fig. 8.11 Different growth habitats reflect as different vascular bundle types From: Liese, W. and M. Köhl (2015). Bamboo: The Plant and its Uses, Springer. Images bamboo from: http://www.bambooinvitro.com/wp-content/uploads/2011/05/Guadua-angustifolia-produced-in-costa-rica-and-exported.jpg (Guadua), http://www.bambooinvasions.com/images/Invasive%20Bamboo%20Phyllostachys%203.jpg (Moso) and http://www.bambooweb.info/images/bamboo/D.brand.972.jpg (Giant bamboo)

Figure:180. Three dimensional view of the culm tissue with vascular bundles and fiber sheaths embedded in ground parenchyma. Based on: Fig. 8.10 Threedimensional view of the culm tissue with vascular bundles and fiber sheaths embedded in ground parenchyma, Oxytenanthera abyssinica From: Liese, W. and M. Köhl (2015). Bamboo: The Plant and its Uses, Springer.

Figure:181. Numbering system according to the manufacturer, amount of visual deformations and the amount of samples. Self made

Figure:182. Influence of the vascular bundle distribution in the wall of the culm on translated to orientation of strips regarding its strength performance in bending. Based on: Liese, W. and M. Köhl (2015). Bamboo: The Plant and its Uses, Springer.

Figure:183. Difference of strip orientation becomes less important as beam gets higher. Self made

Figure:184. Strip orientation in testing showing a Lamboo sample. Self made

Figure:185. Bamboo node. Self made

Figure:186. Difference between three point and a four point. Self madebending test

Figure:187. Four point bending test setup. Self made

Figure:188. Movable parts in test equipment. Self made

Figure:189. Typical graph obtained. Self made

Figure:190. 3 examples of graph obtained and points selected for Δv and ΔF

Figure:191. Two different ranges showing the showing the measured points and the "trend-line"

Figure:192. Bending test during test and after breaking point, always breaks at the bottom side

Figure:193. Sample always brakes in range a between the load point were the moment is constant and the largest, but without shear , showing that failure was caused by pure bending

Figure:194. Failure at connections and nodes. Self made

Figure:195. Standard bell graph explained in relation to standard deviation and mean. Self made

Figure:196. Graph showing how often a obtained MOE is between a certain value (absolute). Self made

Figure:197. Obtained MOE values in % with a projected bell curve added to it of Lamboo and Moso samples. Self made

Figure:198. Graph showing how often a obtained maximum bending stress is between a certain value (absolute). Self made

Figure:199. Obtained maximum bending stress values in % with a projected bell curve added to it of Lamboo and Moso samples. Self made

Figure:200. MOE mean and max and minimum obtained values per visible imperfection. Self made

Figure:201. $\sigma_{m,max}$ mean and max and minimum obtained values per visible imperfection. Self made

Figure:202. Diagram structural principal. Self made

Figure:203. Master bed room artist impression. Self made

Figure:204. Living/dining room + kitchen artist impression. Self made

Figure:205. Artist impression of facades. Self made

Figure:206. !2 story structural proposal. Self made

Figure:207. Future steps. Self made

Figure:208. Artist impression of the west facade. Self made

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

13.3. References Tables

Table:1.   *Housing need Ecuador.* From: Klaufus, C. and L. Cedrés Pérez (2014). From Shortage reduction to a wellbeing approach- Changing paradigms in Ecuadorian housing policies. Affordable Housing in the Urban Global South: Seeking Sustainable Solutions. J. Bredenoord, P. Van Lindert and P. Smets. New York, Routledge.

Table:2.   *Top 15 highest buildings in Ecuador.* Adapted From: http://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Ecuador. Retrieved at: January 7, 2015

Table:3.   *Mechanical properties Glubam according to the Chinese timber structure design standard.* Reprint from: Y. Xiao, et al. (2014). main mechanical properties of Glubam. Materials and Joints in Timber Structures. S. Aicher, H.-W. Reinhardt, H. Garrecht and e. al., Springer: 591.

Table:4.   *Legislation world wide (2014).* Reprint from: Gatóo, A., et al. (2014). "Sustainable structures: bamboo standards and building codes." Proceedings of the ICE-Engineering Sustainability 167(5): 189-196.

Table:5.   *Relevant European norms and ISO timber standards and their application to bamboo.* Reprint from: Gatóo, A., et al. (2014). "Sustainable structures: bamboo standards and building codes." Proceedings of the ICE-Engineering Sustainability 167(5): 189-196.

Table:6.   *Charing speed of CLT lumber.* Reprint from: Gagnon, S. and C. Pirvu (2011). CLT handbook: cross-laminated timber, FPInnovations.

Table:7.   *Deformation modification factor, $_{kdef}$ (table 3.2. EN 1995-1-1).* From: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Table:8.   *Strength modification factor, K_{mod} (table 3.1. EN 1995-1-1).* From: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Table:9.   *Service classes (clause 2.3.1.3. EN 1995-1-1).* From:- Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Table:10. *Load duration classes (table 2.1. EN 1995-1-1).* From: Gagnon, S. and C. Pirvu (2011). "CLT Handbook Cross-Laminated Timber–Canadian Edition." FP Innovations, Québec.

Table:11. *Equalization of woman in developing countries.* Based on: .Marsh, J. and N. Smith (2007). New bamboo industries and pro-poor impacts: lessons from China and potential for Mekong Countries. International Conference on managing forests for poverty reduction: capturing opportunities in forest harvesting and wood processing for the benefit of the poor.

Table:12. *Equalization of woman in developing countries.* Reprint from: Marsh, J. and N. Smith (2007). New bamboo industries and pro-poor impacts: lessons from China and potential for Mekong Countries. International Conference on managing forests for poverty reduction: capturing opportunities in forest harvesting and wood processing for the benefit of the poor

Table:13. *Weight per structural system/height/part.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Table:14. *Carbon Footprint modifications compared to Van der Lugt, Vogtlander et al. (2012)*

Table:15. *Carbon Footprint modifications compared to Van der Lugt, Vogtlander et al. (2012)*

Table:16. *Eco-cost for each structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Table:17. *Eco-cost build-up Plywood hybrid structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Table:18. *Eco-cost for each structure per m^3.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Table:19. *Carbon footprint for each structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87.

Table:20. *Carbon footprint build-up Plywood hybrid structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87

Table:21. *Energy footprint for each structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87

Table:22. *Carbon footprint build-up Plywood hybrid structure.* Self made. Based on: Kulik, M. (2014). A Visual Life Cycle Analysis. Architectural Engineering. Delft, TU Delft. Master student: 87

Table:23. *Difference in energy consumed by different pressing techniques.* Reprint from: Aijazi, A. N. (2013). Material characterization of Guadua bamboo and the environmental feasibility of structural bamboo products, Massachusetts Institute of Technology.

14.Appendix

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?
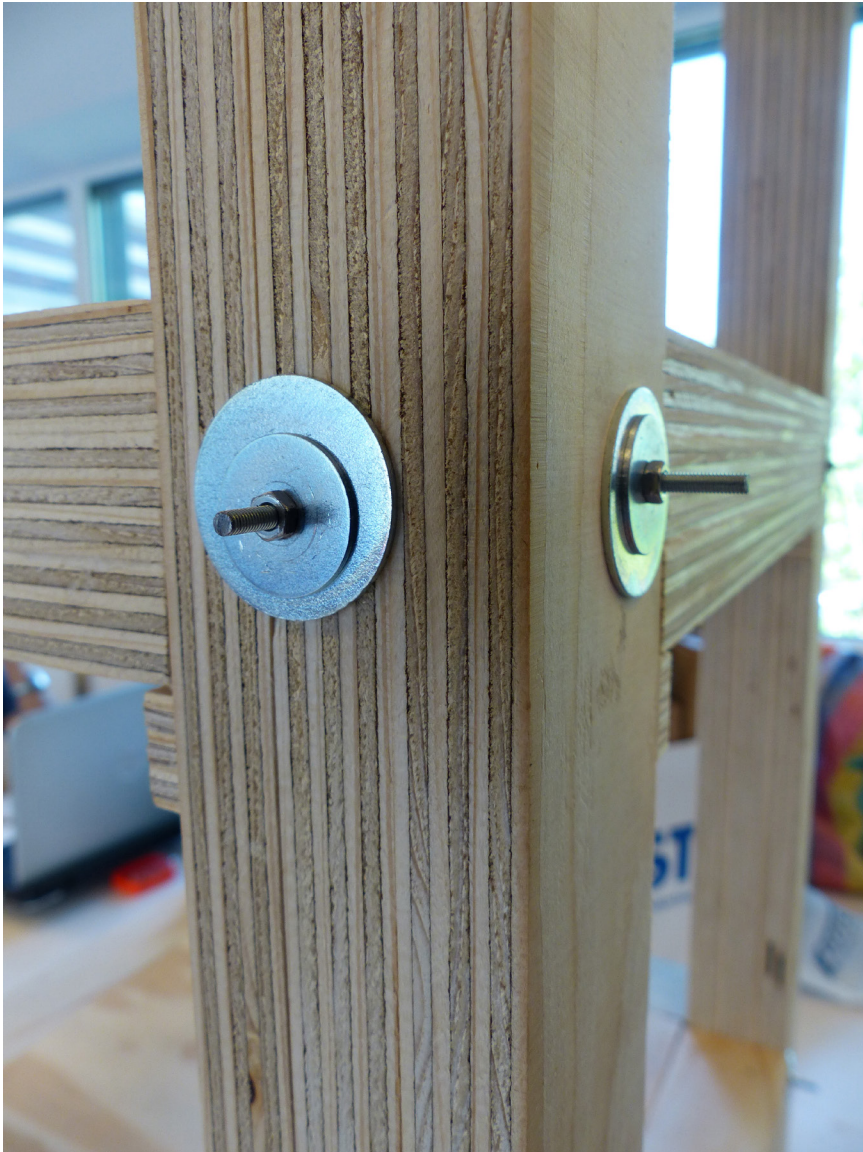
14.1.   Structure

	Laminated bamboo				Wood			Laminated Veneer			Steel	
	Guadua Lamboo	Guadua Colombia	Moso High density	Moso laminated	American Red Oak	Douglas Normal	Douglas structural selected	LVL Pine	LVL Dougla	Concrete C25/30		
Compression parallel	93.0	60.0	-	34.4	46.6	9.2	11.7	20.1	18.8	16.7		Mpa
Compression ⊢	21.0	21.6		9.2	6.1	4.3	4.3	3.6	3.3	16.7		Mpa
Tensile Strength	148.0	61.4	-	31,8	5.1	4.0	6.9	12.4	12.1			Mpa
Flexural Strength	24.1	85.0	65.4	50.8	25.5	6.2	10.3	19.3	20.1			Mpa
Shear Strength	20.0	4.7	-	2.3	7.7	1.2	1.2	2.0	2.0	11.0		Mpa
Modulus of Elasticity	19,305.3	14,000.0	12,505.0	9721-8866	12,548.0	11,031.6	13,100.0	13,789.5	13,789.5	31,000.0		Mpa
Density	690.0	730.0	1050-1100	650-700	700.0	480.0	480.0		-	2,400.0		kg/m³
Thermal Conductivity	0.14	-	-	-	0.14	0.12	0.12		-			W/m·K (Btu·in/h·ft2·°F)
Thermal Resistivity	7.9	-	-	-	6.9	8.5	8.5		-			W/m·K (h·ft2 ·°F/Btu·in)
Dimensional Stability Coefficient												
Volumetric stability factor	0.00144	-										
Parallel	-0.04%	-										
Perpendicular	0.10%	-										
Thickness swell	-0.13%	-										
Moisture Content (MC)	4.9	6 to 8		7.7 to 9.8	12.0	12.0	12.0					%
Hardness	12,455.0			5,687.0	4,200.0	1,868.0	2,669.0					lbf (Janka Ball test)
Friction Static coëfficent	0.56?											
Friction Dynamic coëfficen	0.49?											
Flammability ASTM E 84	Class B											
Flammability ASTM E 648	Class A											
Smoke Density												
Pest Resistance												

(Luna and Takeuchi 2014)

Guadua Colombia

LGL laminated guadua lumber

Red oak info from: http://www.matweb.com/search/DataSheet.aspx?MatGUID=f1530de2e5124fe997a436260d11a260
Douglas Normal From: http://www.matweb.com/search/DataSheet.aspx?MatGUID=f5d34eede73042609c739f1fc5533011

LVL Douglas   LVL Pine

NOG TE VERWERKEN!!

(Moso. Mechanical properties of Moso Bamboo Products 2015) (weak direction has been used

(Caltrans. 2010)

(Ramage, Mulligan et al. 2014)

(Luna and Takeuchi 2014)

(Simpson and TenWolde 1999)

Lamboo product overview

LAMBOO® *STRUCTURE™* DIMENSIONAL COMPONENTS

DIMENSIONAL COMPONENT SIZES

SIZE CODE	NOMINAL SIZE	ACTUAL SIZE		AVAILABLE LENGTHS		IN STOCK ITEMS		
	(in x in)	(in x in)	(mm x mm)	(in feet)	(in meters)	HSP	VSP	SSP
104	1 X 4	3/4 X 3-1/2	19 X 89	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
106	1 X 6	3/4 X 5-1/2	19 X 140	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
108	1 X 8	3/4 X 7-1/4	19 X 184	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
110	1 X 10	3/4 X 9-1/4	19 X 235	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
112	1 X 12	3/4 X 11-1/4	19 X 286	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
						N/A	in stock	N/A
202	2 X 2	1-1/2 X 1-1/2	38 X 38	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
204	2 X 4	1-1/2 X 3-1/2	38 X 89	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
206	2 X 6	1-1/2 X 5-1/2	38 X 140	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
208	2 X 8	1-1/2 X 7-1/4	38 X 184	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
210	2 X 10	1-1/2 X 9-1/4	38 X 235	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
212	2 X 12	1-1/2 X 11-1/4	38 X 286	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
						N/A	in stock	N/A
404	4 X 4	3-1/2 X 3-1/2	89 X 89	8ft.. 16ft.	2.4m & 4.9m	N/A	in stock	N/A
406	4 X 6	3-1/2 X 5-1/2	89 X 140	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
406	4 X 8	3-1/2 X 7-1/4	89 X 184	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A
408	4 X 12	3-1/2 X 11-1/4	89 X 286	8ft., 16ft.	2.4m & 4.9m	N/A	in stock	N/A

Lengths up to 20 feet (6 meters) is available upon request with a 6-8 week lead time. Custom sizes also available per request.

Strand Components Available In Custom Sizes Upon Request

(HSP = Horizontal) (VSP = Vertical) (SSP = Strand)	STRUCTURE™ Product Weight - 42lbs/ft3 - 673kg/m3

Phone: +1.866.966.2999   **E-Mail:** info@lamboo.us

Lamboo, Inc. - 510 East Adams Street - Springfield IL, 62701 - www.Lamboo.us

Above chart of structural products of Lamboo.
One beam of the structural line of Lamboo (404) has been ordered, but not obtained, Obtained was a design line beam with the same dimensions.
The beam has been cut in strips of 40mm by 20mm with a length of 400mm.

Lamboo® Structure™
3 Part Specification

GENERAL NOTES TO SPECIFIER:

PLEASE GO TO www.lamboo.us TO VERIFY THIS IS THE MOST CURRENT VERSION OF THIS SPECIFICATION.

THE FOLLOWING PRODUCT SPECIFICATION LANGUAGE IS INTENDED TO ASSIST DESIGN PROFESSIONALS IN SPECIFYING STRUCTURAL COMPONENTS FOR BUILDINGS. COMPONENTS INCLUDE BEAMS, COLUMNS, SECOND FRAMING AND TRUSS COMPONENTS.

SAMPLE LANGUAGE IS PROVIDED FOR APPLICABLE ARTICLES IN PART 1—GENERAL AND PART 2—PRODUCTS FOLLOWING THE CONSTRUCTION SPECIFICATION INSTITUTE'S *SECTIONFORMAT*. BECAUSE OF THE VARIATION IN SPECIFICATION SYSTEMS CURRENTLY IN USE, ARTICLE AND PARAGRAPH NUMBERS AND TITLES MAY DIFFER SOMEWHAT THAN PRESENTED HEREIN. THE SAMPLE LANGUAGE SHOULD BE EDITED ACCORDINGLY TO FIT EACH FIRM'S SPECIFICATIONS.

ARTICLES AND PARAGRAPHS OF THIS PRODUCT SPECIFICATION ASSUME THE PROJECT MANUAL WILL CONTAIN COMPLETE DIVISION 1 DOCUMENTS INCLUDING:
    SECTION 01 25 13-PRODUCT SUBSTITUTION PROCEDURES
    SECTION 01 33 00-SUBMITTAL PROCEDURES
    SECTION 01 62 00-PRODUCT OPTIONS
    SECTION 01 66 00-PRODUCT STORAGE AND HANDLING REQUIREMENTS
    SECTION 01 74 00-CLEANING AND WASTE MANAGEMENT
    SECTION 01 77 00-CLOSEOUT PROCEDURES
    SECTION 01 78 00-CLOSEOUT SUBMITTALS

CLOSE COORDINATION WITH DIVISION 1 SECTIONS IS REQUIRED. IF THE PROJECT MANUAL DOES NOT CONTAIN THESE SECTIONS, ADDITIONAL INFORMATION MAY BE INCLUDED UNDER THE APPROPRIATE ARTICLES.

NOTES TO THE SPECIFIER ARE IN ALL UPPER CASE TEXT AND ARE CONTAINED WITHIN ROWS OF ASTERISKS.

GREY HIGHLIGHTED GREEN TEXT AND NOTES RELATE TO LEED® PROJECTS AND CAN BE DELETED IF THE PROJECT IS NOT INTENDED TO ATTAIN LEED CERTIFICATION.

OPTIONAL ITEMS REQUIRING SELECTION BY THE SPECIFIER ARE ENCLOSED WITHIN BRACKETS, E.G. [35] [40] [45]. MAKE APPROPRIATE SELECTIONS AND DELETE OTHERS.

To the right the product properties claimed by lamboo.
It is a product overview and therefore the characteristic values.

LAMBOO®
T E C H N O L O G I E S

PHONE: 866.966.2999
EMAIL: tech@lamboo.us

Part 1-General:

1.01   Summary

A. Section Includes
1. Columns for support of primary framing members in floor, wall and roof systems.
2. Beams for support of secondary framing member for floors, walls and roof systems.
3. Secondary Framing members for support floor deck, wall panels and roof deck. [Joist, girts and purlins].
4. Truss components including compression and tension members. (Steel connections of truss components must be engineered for individual applications.)
5. Manufacturing partners:
   a.   Western structures inc. [usa]
   b.   Walsh industries [international]
   c. G.R. PLUMBE (USA)
   d. MM KAUFMANN (AUSTRIA)
B.   RELATED SECTIONS
1.   Bearing plates, shoes, saddles and hangers for connecting lamboo® structure™ to other building components. [all connections to be engineered for applicable loads including: dead, live, snow, wind & seismic load]
2.   building components supported by lamboo® structure™. Components include: floor systems, roof systems and wall systems.
3.   curtain wall systems [lamboo® renewall™]

Vertical and/or horizontal members can be proportioned for spans and loading conditions beyond the capabilities of typical aluminum curtain wall systems.

Curtain wall manufacturers:

Dover
Solar innovations
Ic2 technologies
Raico
Pacific architectural millwork
Ct windows

lamboo® renewall™ can be designed to withstand category [5] five hurricane typhoon wind loading.

510 East Adams – Springfield, IL 62701
www.lamboo.us

LAMBOO®
T E C H N O L O G I E S

PHONE: 866.966.2999
EMAIL: tech@lamboo.us

1.02   Submittals – SEE SECTION – 133000 SUBMITTALS

A. Product Data
   1. certified test data of strength of materials.
B. Samples
C. detail shop drawing for all components fabricate specifically for this project.
   1. [Illinois] shop drawings must bear the seal of an illinois structural engineer.
   2. [other states] shop drawings must bear the seal of a professional engineer licensed in [state where building is to be constructed].

INCLUDE THE FOLLOWING IN THE "PRODUCT DATA" PARAGRAPH:

1. Lamboo® OR STRUCTURE™ manufacturer's product data.

B. LEED Submittals

INCLUDE THE FOLLOWING FOR LEED PROJECTS, AS APPLICABLE:

1. Credit MR 6, Rapidly Renewable Materials: Bamboo manufacturer's product data for each product used, indicating that product(s) are manufactured from a rapidly renewable resource.

2. Credit EQ 4.1, Low Emitting Materials: Adhesive and/or sealant manufacturer's product data for each product used, indicating adhesive agent contains low voc adhesive.
3. Credit EQ 4.2, Low Emitting Materials: Paints and/or coatings manufacturer's product data for finishes used.

1.03 DELIVEERY AND STORAGE
   A. JUST IN TIME DELIVERY
      1. deliver lamboo® structure™ components to the construction site so that they can be taken directly from truck and incorporated into the building.
   B. PACKAGING
      1. all lamboo® structure™ components to be individually wrapped in kraft paper.

510 East Adams – Springfield, IL 62701
www.lamboo.us

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Lamboo product overview

a. KRAFT PAPER TO BE TIGHTLY WRAPPED AND SECURED WITH WATER RESISTANT TAPE.
2. ALL LAMBOO® STRUCTURE™ COMPONENTS FABRICATED SPECIFICALLY FOR THIS PROJECT TO BE TAGGED WITH DESIGNATIONS THAT CORRESPOND TO FINAL APPROVED SHOP DRAWING DESIGNATIONS.

C. [IF JOB SITE STORAGE IS REQUIRED] MATERIAL TO BE STORED AT JOB SITE ELEVATED ON 6" HIGH BLOCKING WITH 'X' AXIS HORIZONTAL. MEMBERS TO BE COVERED WITH TARP WITH ENDS THAT CAN BE OPENED TO ALLOW AIR MOVEMEMENT.
1. TARP IS NOT REQUIREDIF MEMBERS ARE STORED UNDER A ROOF OR IN PROTECTED PORTION OF UNFINISHED BUILDING.
2. MULTIPLE LAYERS OF LAMBOO® STRUCTURE™ COMPONENTS TO BE SEPARATED BY 1X 2 SLATS TO ALLOW AIR FLOW.
A. MEMBERS OF SAME DIMENSION TO BE STORED ON CORRESPONDING LAYER.

1.05 SEE PRODUCT WARRANTY www.lamboo.us

INCLUDE THE FOLLOWING SPECIAL WARRANTY:

A. A Special Warranty for Lamboo Inc. Products referenced at www.lamboo.us

PART 2—PRODUCTS

2.01 MATERIALS

INCLUDE THE FOLLOWING PARAGRAPHS AND SUBPARAGRAPHS FOR LAMBOO® STRUCTURAL™ AS APPROPRIATE.

A. LAMBOO® STRUCTURAL™ COMPONENTS ARE MANU-FACTURED FROM SHAPED VERTICAL GRAIN STRAND /SLATS OF BAMBOO LAMINATED TOGETHER WITH EXTERIOR GRADE ADHESIVES.
1. RAW MATERIALS
A. LAMBOO® STRUCTURE™ HAS ISOLATED 4 OUT OF THE 1600 SPECIES OF BAMBOO TO SELECT THE HIGHEST PERFORMING & MOST

UNIFORM SPECIES FOR ALL OF ITS STRUCTURAL APPLICATIONS.

2. ADHESIVES USED IN LAMBOO® STRUCTURE™ ARE EXTERIOR GRADE TYPE1 AND MAINTAIN INTEGRITY OVER NORMAL SERVICE LIFE OF FINISH PRODUCT.

A. THE HIGH STRENGTH ADHESIVES USED BECOME AN INTEGRAL PART OF THE STRUCTURE™COMPONENT.

2.02 MECHANICAL PROPERTIES
A. COMPRESSION
1. ASTM 3501-86 A – PARALLEL TO GRAIN: 13,488 PSI
2. ASTM 3501-86 – PERPENDICULAR TO GRAIN: 3043 PSI
B. TENSILE STRENGTH
1. ASTM 3500-90 – PARALLEL TO GRAIN: 21,465 – 55694 PSI
3. PERPENDICULAR TO GRAIN: 543 PSI
C. FLEXURAL STRENGTH
1. ASTM D3043 – 3,500 PSI
D. SHEAR STRENGTH
1. ASTM 3048 – 2901 PSI
E. MODULUS OF ELASTICITY
1. ASTM D 1037 – 2,800,000 PSI
F. THERMAL PROPERTIES
1. THERMAL CONDUCTIVITY: $K=(W/M\cdot K(BTU\cdot IN/H\cdot FT^2 \cdot °F)) = 0.14(0.94)$
2. THERMAL RESISTIVITY (R) VALUE = $(K\cdot M /W(H\cdot FT^2\cdot°F/BTU\cdot IN)) = 7.9(1.1)$
3. SPECIFIC GRAVITY: 0.60
4. DENSITY: 38#'s/FT³.
G. DIMENSIONAL STABILITY COEFFICIENT
1. VOLUMETRIC STABILITY FACTOR: 0.00144
2. Solid Lamboo dimensional stability at 20% rh – linear expansion: (astm d 1037) parallel -0.04 percent average (astm D1037) perpendicular 0.10 percent average
3. (astm d 1037) thickness swell: -0.13 percent average
H. MOISTURE CONTENT
1. (ASTM D 4442) – SOLID LAMBOO: 4.9 PERCENT AVERAGE

LAMBOO
TECHNOLOGIES

I. **HARDNESS**
1. (JANKA BALL TEST): 2,800 LBF (AVG)
J. **FRICTION**
1. (ASTM D2394) – STATIC COEFFICIENT – 0.562
DYNAMIC COEFFICIENT – 0.497
K. **FLAMMABILITY**
1. CLASS 1 (ASTM E 648 –
CRITICAL RADIANT PANEL TEST)
CLASS B (ASTM E 84 SURFACE BURNING)
L. **SMOKE DENSITY:**
1. (ASTM E622) – 270 FLAMING MODE
2. (ASTM E622) – 300 – NON-FLAMING MODE
* PASSING IS ANY NUMBER BELOW 450

PART 3: EXECUTION
3.01 PREPARATION
A. LAMBOO® STRUCTURE™ STANDARD COMPONENTS AND COMPONENTS THAT ARE CUSTOM MADE FOR THIS PROJECT.
1. GENERAL CONTRACTOR (G.C.) TO COORDINATE SUBCONTRACTORS TO INSURE THAT ALL SHOES, SADDLES, HANGERS, BEARING PLATES AND EMBEDS ARE SET CORRECTLY BASED ON FINAL SHOP DRAWINGS.
2. ALL LAMBOO® STRUCTURE™ COMPONENTS (I.E.) TRUSSES) TO BE PRE-ASSEMBLED IN THE MANUFACTURING FACILITY AND THEN DISASSEMBLED FOR SHIPPING.
   a. COMPLETE ASSEMBLY INSTRUCTIONS TO BE DISSIMINATED TO ALL RESPONSIBLE PARTIES:
      1) GENERAL CONTRACTOR
      2) DISTRIBUTOR
      3) ERECTOR
   (PACKAGED WITH COMPONENTS SENT TO JOB SITE)
      4) OTHER AS REQUIRED

3. BASED ON APPROVED SHOP DRAWING, ALL STEEL COMPONENTS SET IN CONCRETE OR MASONRY TO BE PROPER ELEVATION ALIGNMENT AND POSITION.

3.02 EXAMINATION
A. ERECTOR TO VISIT JOB SITE AND VERIFY THAT SUPPORT ELEMENTS TO RECEIVE LAMBOO® STRUCTURE™ ARE PLACED WITHIN ACCEPTABLE TOLERANCES.

LAMBOO
TECHNOLOGIES

1. VERIFY ELEVATION, ALIGNMENT AND CRITICAL DIMENSIONS TO ENSURE THAT ALL COMPONENTS WILL ALIGN AND ASSEMBLE PERFECTLY.
2. NOTIFY A/E (ARCHITECT/ENGINEER) OF ANY JOB SITE MODIFICATIONS REQUIRED FOR PROPER FIT.
B. ALL LAMBOO® STRUCTURE™ COMPONENTS TO BE EXPOSED TO ELEMENTS, UNTIL BUILDING IS ENCLOSED, TO BE WRAPPED WITH KRAFT PAPER.
1. EACH MEMBER TO BE PROPERLY LABELED FOR IDENTIFICATION IN THE FIELD.

3.03 INSTALLATION
A. SAFETY OF WORKERS
1. OSHA (OCCUPATIONAL SAFETY AND HEALTH ACT)
2. SCAFFOLDING ACT
B. LIFTING OF LAMBOO® STRUCTURE™ COMPONENTS
1. CRANES, HOISTS AND MATERIAL LIFTS TO BE OF ADEQUATE CAPACITY TO SAFELY HANDLE COMPONENTS.
C. OPERATORS TO BE PROPERLY TRAINED AND CERTIFIED FOR OPERATING NECESSARY EQUIPMENT.
D. ALL COMPONENTS TO BE PROPERLY SECURED WITH TEMPORARY BRACING UNTIL ALL COMPONENTS OF THE FINISHED STRUCTURE ARE IN PLACE.
1. GENERAL CONTRACTOR/ERECTOR IS RESPONSIBLE FOR ALL TEMPORARY BRACING.
2. ENSURE THAT CONSTRUCTION LOADS FROM BUILDING MATERIALS AND EQUIPMENT ARE PROPERLY PLACED.
   a. CONSULT DESIGN PROFESSIONAL (A/E) FOR PLACEMENT OF CONSTRUCTION LOADS.

3.04 PROTECTION
A. KRAFT PAPER/PROTECTIVE PACKAGING TO STAY IN PLACE UNTIL BUILDING IS ENCLOSED.
1. MOISTURE AND SUNLIGHT CAN CAUSE DISCOLORATION OF EXPOSED PORTIONS OF STRUCTURAL COMPONENTS.
2. IF MOISTURE COLLECTS INSIDE OF KRAFT PAPER/PROTECTIVE PACKAGING, PLACE TWO INCH SLITS AT SIXTEEN INCHES ON CENTER ON BOTTOM SIDE OF HORIZONTAL COMPONENTS TO ALLOW MOISTURE TO ESCAPE.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Lamboo product overview

LAMBOO®
TECHNOLOGIES

3.05 INSPECT AND CLEAN

A.   AFTER BUILDING IS COMPLETELY ENCLOSED AND
WEATHERTIGHT, REMOVE ALL KRAFT PAPER AND
PROTECTIVE PACKAGING.

1. INSPECT LAMBOO® STRUCTURE™ FOR
DAMAGE DURING SHIPPING, ERECTION
AND JOB SITE EXPOSURE TO ELEMENTS.

2. SAND AND CLEAN AS REQUIRED.   APPLY
MATCHING STAIN AND FINISH

END OF SPECIFICATION

LAMBOO®
TECHNOLOGIES

1. Lamboo Inc. Architectural and Structural Bamboo
   A) Tel: 866-966-2999.
   B) www.lamboo.us

2. Species: Moso (Phyllostachys Pubescens).

INCLUDE THE FOLLOWING SUBPARAGRAPH IF PRODUCTS ARE USED
FOR WALL OR CEILING FINISHES PURSUANT TO IBC SECTION 803.

3. Fire Resistance Classification: [Class A] [Class C].

A) Test surface burning characteristics in accordance
with ASTM E 84.

4. Type:

SELECT APPROPRIATE TYPE(S) BELOW TO SUIT PROJECT
REQUIREMENTS. DELETE THOSE NOT USED. FABRICATION ARTICLE OR
DRAWINGS MUST CLEARLY IDENTIFY SPECIFIC USES.

GO TO www.lamboo.us FOR AVAILABLE FACE SIZES.

5. Physical/Mechanical Properties:

END OF SPECIFICATION

12 story round edge

Column façade centre

Floor area to support: 13.5 m² (3x4.5)/floor

Life loads: 2 kN/m² =27 kN/floor

Dead loads: 4.6 kN/m² → (4.6x13.5)+12.4+19.8+3.3= 97 kN/floor

    Floor (CLB): 6.9 kN/m³x0.25m = 1.7 kN/m²

    Separation walls: 1.2 kN/m²

    Installations: 0.5 kN/m²

    Concrete floor: 24 kN/m³ x 0.05m = 1.2kN/m²

    Beams: 9x0.5x0.4x6.9=12.4 kN/column/floor

    Length: 9m | height: 0.5m | With:0.4m | Weight:6.9 kN/m³

    Façade: 6x3.3x1=19.8 kN/column/floor

    Length façade: 6m1

    Height façade: 3.3

    Façade: 1 kN/m Assumption

    Columns weight: 3m x 0.4m x 04m x 6.9 kN/m³= 3.3kN
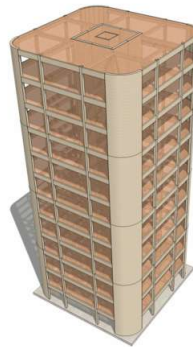
What is a common value? Without calculating it all the way through?

Number of floors: 12

Ψ=0.4   G=1.35   Q=1.5

Life loads: 1.5x0.4x27x12=194 kN

Dead loads: 1.35x97x12=1571 kN

Total (Life loads + Dead loads)=**1765 kN**

    CLB = Cross laminated Bamboo

    Ψ= Occupation reduction factor (unlikely all floors are fully occupied)

Compression strength

F_{cr} (Force applied): 1765 kN = 1.77 x10⁶N

Compression strength Lamboo= 92,966 kN/m² ≈ 93 N/mm²

Surface area= A ∨   In case of a square column L=B=X

A= 1.77 x10⁶N / 93 N/mm² = 1.90x10⁴ mm²   (L x B = A → X²=A → X=√A)

X= √1. 90x10⁴=**138mm**

Buckling

(Only considering life loads and permanent loads, NO WIND)

$$F_{cr.} = \frac{\pi^2 \times E_i \times I}{L_{cr.}^2}$$

E_i= 19305 Mpa (from Lamboo data)

$$I = \frac{1}{12} \times l \times b^3$$

$$L_{cr.}^2 = 2700^2 = 7.29 \times 10^6 mm^2$$

$$F_{cr.} = 1.77 \times 10^6 N$$

$$I = \frac{F_{cr.} \times L_{cr.}^2}{\pi^2 \times E_i}$$

$$I = \frac{1.77 \times 10^6 \times 7.29 \times 10^6}{\pi^2 \times 19305} = \frac{1.29 \times 10^{13}}{1.91 \times 10^5} = 6.79 \times 10^7 mm^4$$

If a square column is used I=b

$$l^4 = I \times 12 = 6.79 \times 10^7 \times 12 = 8.15 \times 10^8$$

$$l = \sqrt[4]{8.15 \times 10^8} = 168mm \approx \textbf{169mm}$$

Buckling incl. pre-stressing 100kN

$$I = \frac{1.97 \times 10^6 \times 7.29 \times 10^6}{\pi^2 \times 19305} = \frac{1.44 \times 10^{13}}{1.91 \times 10^5} = 7.54 \times 10^7 mm^4$$

If a square column is used I=b

$$l^4 = I \times 12 = 7.54 \times 10^7 \times 12 = 9.05 \times 10^8$$

$$l = \sqrt[4]{9.05 \times 10^8} = 173mm \approx \textbf{175mm}$$

Building height=3.3. Floor height 300mm. Bottom part beams= 400mm below floor. L_{cr}=2.6

12 story structural calculations

Wind combination

Permanent load on one facade

$$Y_g/floor = beams + floors + column + walls + facade$$

Beams: L=12+3+3=18m1

   Weight=6.9 kN/m³

   $A_{section}$=0.4 x 0.4 = 0.16 m²

$$Y_{g\,(beams)} = 18 \times 6.9 \times 0.16 = 19.9\ kN/floor$$

Floor: Q=4.6 kN/m²/floor

   A=49m²/floor

$$Y_{g\,(floor)} = 4.6 \times 49 = 225\ kN/floor$$

Columns:	Amount: 2	Walls:	Amount: 2
	L=3.3m1/floor		L=3.3m1/floor
	Weight=6.9 kN/m³		Weight=6.9 kN/m³
	A=0.4 x 0.4 = 0.16m²		A=0.3 x 2.15 = 0.65m²

$$Y_{g\,(colums)} = 2 \times 3.3 \times 6.9 \times 0.16 = 7.3\ kN/floor \qquad Y_{g\,(Walls)} = 2 \times 3.3 \times 6.9 \times 0.65 = 29.4\ kN/floor$$

Facade: h=3.3m1   L=18+3+3=24m1   G=1kN/m²

$$Y_{g\,(Facade)} = 1 \times 3.3 \times (18 + 3 + 3) = 79.2\ kN/floor$$

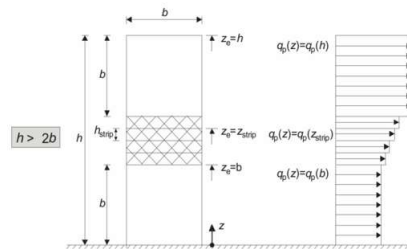$$Y_g/floor = 19.9 + 225 + 7.3 + 29.4 + 79.2 = 361\ kN/floor$$

$$Y_g = Y_g/floor \times numbr\ of\ floors = 361 \times 9 = 4.33 \times 10^3\ kN$$

Wind load

$$q_{rep} = C_s C_d \times C_f \times q_p$$

Zone: II Urban area

Height building (4.5m concrete base + 12x3.3=44.1 Lamboo build-up = 39.6m) (lxb=18x18)

$q_{p(Top)} = 1.16\ kN/m²$ for the top 18m of the building

$q_{p(Rest)} = ((1.16-0.86)/2) = 0.15\ kN/m$ (L =8.1m)

$q_{p(Bottom)} = 0.86\ kN/m$

$C_{ep} = 0.8+0.4$ (Pressure front side, suction backside) = 1.2

$C_f = C_{fo} \times \Psi_r$ 2.1x0.583=1.23

d/b=18/18→ C_{fo} =2.1

r/b=3m/18=1.67→ Ψ_r=0.583

CsCd = 1 (NEN-EN 1991-1-4+A1+C2:2011 chapter:6 paragraph:2) *"Voor gebouwen met een raamwerkconstructie en stabiliteitswanden lager dan 100 m en waarvan de hoogte minder is dan 4 maal de gebouwdiepte in de richting van de wind, mag de waarde van cscd gelijk zijn genomen aan 1."*

Windloads per m² per section of the building

$$q_{rep(Top)2} = 1 \times 1,23 \times 1.16 = 1.43\ kN/m²$$

$$q_{rep(Rest)m2} = 1 \times 1,23 \times 0.15 = 0.18\ kN/m²$$

$$q_{rep(Bottom)m2} = 1 \times 1,23 \times 0.86 = 1.05\ kN/m²$$

NEN-EN 1991-1-4+A1+C2:2011
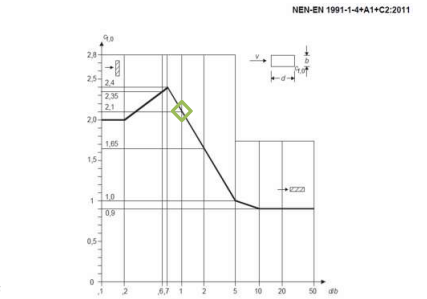
Figuur 7.23 — Krachtcoëfficiënt $c_{f,0}$ voor rechthoekige doorsneden met scherpe hoeken en zonder
OPMERKING 2 Figuur 7.24 mag ook zijn gebruikt voor gebouwen met h/d > 5,0
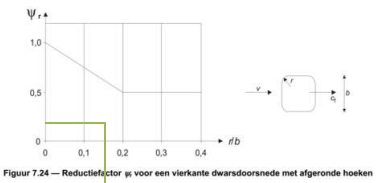
Figuur 7.24 — Reductiefactor ψ_r voor een vierkante dwarsdoorsnede met afgeronde hoeken

OPMERKING   De extreme stuwdruk behoort uniform te zijn aangenomen over elke beschouwde horizontale strook.

Figuur 7.4 — Referentiehoogte z_e, afhankelijk van h en b, en de bijbehorende profielen van de stuwdruk

q_{load} at the width of the building

W=18m.

$q_{rep(Top)} = 1.43 \times 18 = 25.7 \ kN/m1$

$q_{rep(Rest)} = 0.18 \times 18 = 3.24 \ kN/m1$

$q_{rep(Bottom)} = 1.05 \times 18 = 18.9 \ kN/m1$

The line load of the wind can be altered to a point load in order to calculate the moment in the base.

$F_{wind\ (Top)} = l_1 \times q_{rep(Top)} = 18 \times 25.7 = 463 \ kN$

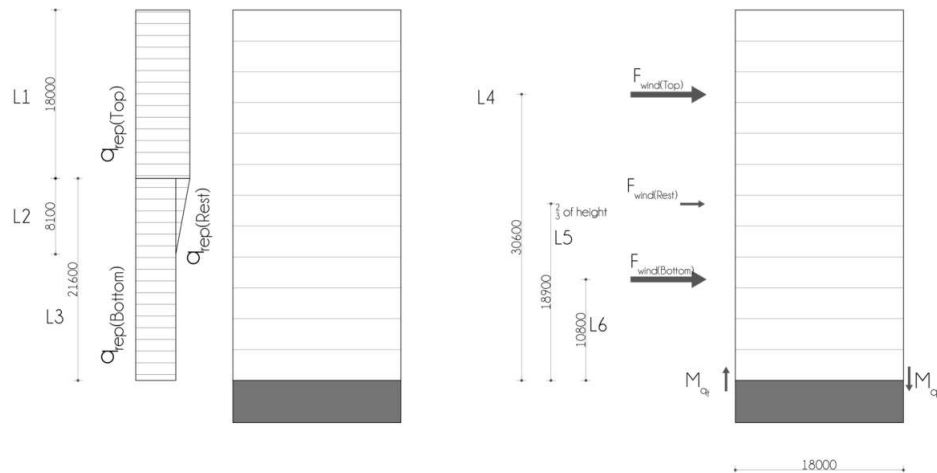$F_{wind\ (Rest)} = l_2 \times q_{rep(Rest)} = 8.1 \times 3.24 = 26.2 \ kN$

$F_{wind\ (Bottom)} = l_3 \times q_{rep(Bottom)} = 21.6 \times 18.9 = \ 402 \ kN$

Moment at bottom crated by the wind

$M_{fwind\ max} = F_{wind\ (Top)} \times l_4 + F_{wind\ (Rest)} \times l_5 + F_{wind\ (Bottom)} \times l_6$

$M_{fwind\ max} = 463 \times 30.6 + \ 402 \times 10.8 + 26.2 \times 18.9 = 1.90 \times 10^4 \ \text{kNm}$
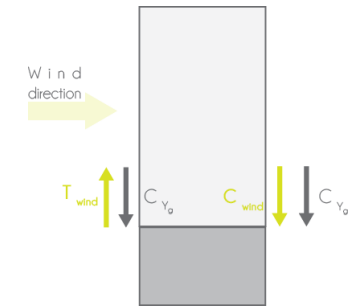
$T_{wind} = C_{wind} = \frac{M_{fwind\ max}}{b}$

The depth of the building is 18m

$T_{wind} = C_{wind} = \frac{1.90 \times 10^4}{18} = 1.06 \times 10^3 \ kN$

Not used

$F_{sw1} = T_{wind} + C_{Y_g} = -1.06 \times 10^3 + 1.57 \times 10^3 = 510 kN$

$F_{sw1} = C_{wind} + C_{Y_g} = 1.03 \times 10^3 + 1.57 \times 10^3$

$= 2.63 \times 10^3 kN$

With Load combination

$Wind\ load\ combination\ 0.9G \times 1.5Q$

$F_{sw1} = T_{wind} + C_{Y_g} = 1.5 \times -1.03 \times 10^3 + 0.9 \times 1.32 \times 10^3 = -132 \ kN$

$F_{sw2} = C_{wind} + C_{Y_g} = 1.5 \times -1.03 \times 10^3 + 1.35 \times 2.23 \times 10^3 = \mathbf{3.66 \times 10^3 kN}$

The tension in the columns has to be compensated. For the structural principal tentsion is needed in the first place but I don't Know how much.

Effect of tensioning Tendons

Let's presume I ad 4 cables adding 200 kN each to the structure (I think I will needed in Earthquake scenario)

$F_{sw1} = T_{wind} + C_{Y_g} = 1.5 \times -1.03 \times 10^3 + 0.9 \times 1.32 \times 10^3 + 4 \times 200 = 732 \ kN$

$F_{sw2} = C_{wind} + C_{Y_g} = 1.5 \times -1.03 \times 10^3 + 1.35 \times 2.23 \times 10^3 + 4 \times 200 = \mathbf{4.46 \times 10^3 kN}$

12 story structural calculations

Dimensioning the columns

Using the wind load combination values.

$$F_{sw2} = A \times \sigma_{max}$$

F_{sw2} = 4.46 x 10^3 kN = 4.46 x 10^6 N

σ_{max} = 92,966 kN/m² ≈ 93 N/mm²

$$A = \frac{F_{sw2}}{\sigma_{max}} = \frac{4.46 \times 10^6}{93} = 4.80 \times 10^4 mm^2$$

Number of columns: 4st

$$\sqrt{\frac{4.80 \times 10^4 mm^2}{4}} = \textbf{110mm}$$

Buckling with wind

$$I = \frac{F_{cr.} \times L_{cr.}^2}{\pi^2 \times E_i}$$

$$I = \frac{4.46 \times 10^6 \times 9.6 \times 10^6}{\pi^2 \times 19305} = \frac{4.37 \times 10^{13}}{1.95 \times 10^5} = 2.20 \times 10^8 mm^4$$

If column is square:

$$l^4 = I \times 12 = 2.20 \times 10^8 \times 12 = 2.64 \times 10^9$$

$$l = \sqrt[4]{2.69 \times 10^9} = 226mm \approx \textbf{230mm}$$

Earthquake

$$F_{eq} = ? \times C_{Y_g} = 0.9 \times \dots \dots \dots = \dots \dots \dots kN$$

$$M_{eq} = \frac{1}{2} H \times F_{eq} = \frac{1}{2} \times 39.6 \times \dots \dots \dots =$$

Deformation

Formulas deformation Framework:

This method is abandoned and a stiff core has been chosen. .

Standard deformation formula:

$$U_{top} < \frac{n \times h}{300}$$

The deformation per floor is equal to the deformation per floor:

$$U_{top} < \frac{h}{300} \times \frac{1}{n} \times (n + n - 1 + \dots + 2 + 1)$$

$$(n + n - 1 + \dots + 2 + 1) = n \times \frac{n+1}{2}$$

U_{top} can therefore be rewritten as:

$$U_{top} < \frac{h}{300} \times \frac{1}{n} \times n \times \frac{n+1}{2}$$

This can be simplified as:

$$U_{top} < \frac{h}{300} \times \frac{(n+1)}{2}$$

h=

The maximum allowed deformation:

$$U_{Max\ allowed} < \frac{h \times n}{500}$$

The norm is:

$$U_{top} < U_{Max\ allowed}$$

From which the following formula can be used:
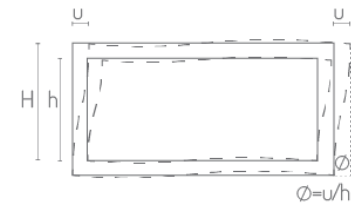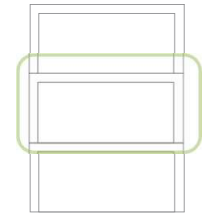
$$\frac{h \times n}{500} < \frac{h}{300} \times \frac{(n+1)}{2}$$

In case of a 12story building with a framework only

$$\frac{h \times n}{500} < \frac{h}{300} \times \frac{(n+1)}{2} \rightarrow \frac{2700 \times 12}{500} = 64.8$$

$$\frac{2700}{300} \times \frac{(12+1)}{2} = 9 \times 6.5 = 58.5$$

64.8 > 58.5   Doesn't compel too much deformation, but structure is not a mere framework.

Formulas deformation with stiff core:

Deformation of an element clamped on one side under an equal distributed load:

$$u = \frac{Q_{rep} \times l^4}{8 \times E \times I}$$

q_{rep} increases with the building height, therefore the largest amount of deformation can be expected in the top. And the deformation increases exponentially with the height of the building.

The maximum allowed deformation:

$$u < \frac{l}{500}$$

The stiffness needed is then:

$$E \times I = \frac{500 \times Q_{rep} \times l^3}{8} \quad \rightarrow \quad E \times I > 62.5 \times Q_{rep} \times l^3$$

Deformation of a 12story building with a core only

E = 19305 MPa

Q$_{rep}$ = 22.32 kN/m (((1.43-1.05)/2+1.05)x18m=1.24kNm²)

Is this correct?

L= 39.6m=3.96x10⁴mm

I= 3.86mm⁴

The Moment of resistance can be calculated using:

$$I_{rectangle} = \frac{1}{12} \times b \times h^3$$

The core is hollow not solid this can be calculated using:

$$I = I_{core} = I_1 - I_2$$

$$I_1 = \frac{1}{12} \times 6000 \times 6000^3 = 1.08 \times 10^{14} mm^4$$

$$I_2 = \frac{1}{12} \times 5400 \times 5400^3 = 7.09 \times 10^{13} mm^4$$

$$I_{core} = 1.08 \times 10^{14} - 7.09 \times 10^{13}$$
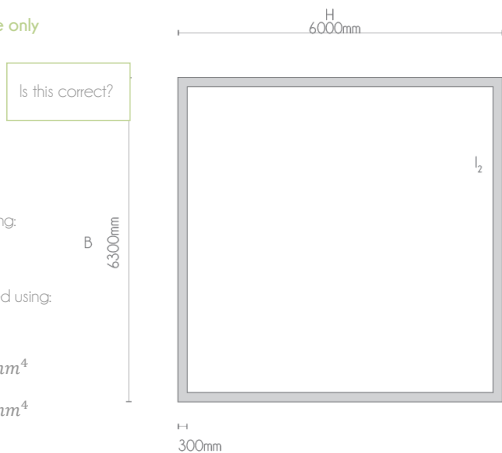$$= 3.71 \times 10^{13} mm^4$$

In I$_{core}$ the door openings are not included nor are the outer walls included.

$$E \times I > 62.5 \times Q_{rep} \times l^3$$

$$19305 \times 3.71 \times 10^{13} > 62.5 \times 22.32 \times (3.96 \times 10^4)^3$$

$$7.16 \times 10^{17} > 8.28 \times 10^{16}$$

So with a wall thickness of 300mm and a core of 6000x6000mm the building would be stiff enough if the base connection is sufficiently stiff.

H
6000mm

I_1

I_2

B

6300mm

300mm

The largest angular displacement can be calculated with

$$\emptyset = \frac{q_{rep} \times l^3}{6EI}$$

$\emptyset$ has to be less than 1/300 this leads to:

$$\emptyset = \frac{q_{rep} \times l^3}{6EI} < \frac{1}{300} = 3.33 \times 10^{-3}$$

$$EI > 50 \times q_{rep} \times l^3$$

$$19305 \times 3.86 \times 10^{13} > 50 \times 22.32 \times (3.96 \times 10^4)^3$$

$$7.45 \times 10^{17} > 6.62 \times 10^{16}$$

Double check:

$$\emptyset = \frac{q_{rep} \times l^3}{6EI} = \frac{22.32 \times (3.96 \times 10^4)^3}{6 \times 7.45 \times 10^{17}} = 3.1 \times 10^{-4}$$

$$3.1 \times 10^{-4} < 3.33 \times 10^{-3}$$

There is sufficient stiffness to ensure that the deformation by wind stays within limits.

The joint height of separation walls:

$$\emptyset_{max} = \frac{1}{300} \times h_{storeyheight}$$

$\emptyset_{max}$ = maximum allowed angular displacement

h$_{storey\ height}$=from ceiling to ceiling?? =3300mm

$$\emptyset_{max} = \frac{1}{300} \times 3300 = 11mm$$

The height of the joints has to be at least 11mm

Shear on the core by wind
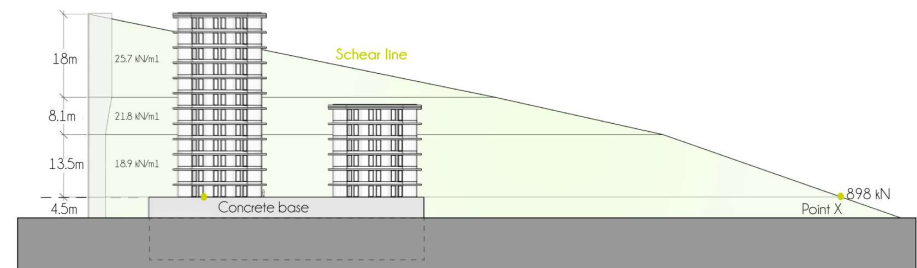### Wind loads per m1

W=18m.

$$q_{rep(Top)} = 1.43 \times 18 = 25.7 \ kN/m1$$

$$q_{rep(Rest)} = 1.21 \times 18 = 21.8 \ kN/m1$$

$$q_{rep(Bottom)} = 1.05 \times 18 = 18.9 \ kN/m1$$

18m · 25.7 kN/m1 · Schear line

8.1m · 21.8 kN/m1

13.5m · 18.9 kN/m1

4.5m · Concrete base · 898 kN · Point X

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

12 story structural calculations

Shear force in connection concrete base to bamboo

$$F_{Shear\,(point\,X)} = q_{rep(Top)} \times 18 + q_{rep(Rest)} \times 8.1 + q_{rep(Bottom)} \times 13.5$$

$$F_{Shear\,(point\,X)} = 25.7 \times 18 + 21.8 \times 8.1 + 18.9 \times 13.5 = 894\ kN$$

To see if the material can withstand the shear stress the following formula is used:

$$F_{Shear} = \tau \times A$$

F Shear = Shear force in point X= 894 kN.

T lamboo = Shear resistance (material property) = 20 MPa = 0.02 kN/mm².

A= Area of core= (6000x6000)-(5400x5400) = 6.84 x 10⁶mm².

$$F_{Shear\,(point\,x)} < \tau_{l\,amboo} \times A_{core}$$

$$894\ kN < 0.02 \times 6.84 \times 10^6 = 1.37 \times 10^5$$

Core will easily withstand shear forces

One sited clamped beam with a constant q load

Creep

Floor

Connection type
Both sides supported beam with hinged connections. Multiple span are beneficial and used when possible, but the calculation for the floor thickness is checked with a single span.
It is the least advantageous connection and presumed in the design stage.
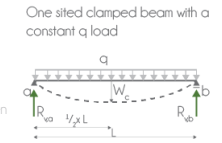
Dead loads
Solid cross laminated bamboo floor with a span of 5.4 m and a thickness of 25 cm (17cm Lamboo and 8cm recycled wood) with a density of 6,9 kN/m³.
　Own weight of 6,9x0,25=1,7 kN/m².
　Separation walls= 1.2 kN/m²
　Installations: 0.5 kN/m²
　Concrete floor (50mm) = 1.2 kN/m²
　Total 1.7+1.2+0.5+ 1,2 =4.6 kN/m²

For the creep only the Lamboo is considered as structural, although the recycled wood also will work to reduce creep. And the density of the recycled wood is unknown therefore the same weight as Lamboo is used. It could be pine but also oak.

Life loads
Floor load of: 2.5 kN/m².
Office load are used to increase possibilities of redevelopment. Dwelling has a load 1.75kN/m² for normal floors and 2.5kN/m² for balconies. The choice also allows that balconies can be places everywhere))

Creep calculation
Creep factor
$$U_{fin} = U_{fin,p} + U_{fin,Q_1} + U_{fin,Q_i}$$

U_{fin}　　= Total deformation including creep
$U_{fin,P}$　= The final deformation by permanent loads including creep　= $U_{fin,P}$ =4,6x(1+0,8)=8.3 kN/m²
U_{fin,Q_1}　= The final deformation by main live loads including creep　= U_{fin,Q_1} =2,5x(1+0,3x0,8)=3,1 kN/m²
U_{fin,Q_i}　= The final deformation by accompanying live loads (snow)　= U_{fin,Q_i} =Not applicable
The values are further explained in main report. Wood norms have been used since there is no norm for laminated Guadua bamboo from Lamboo.
$$U_{fin} = 8.3 + 3.1 + 0 = 11.4\ kN/m^2$$

Deformation of floor:
$$W_c = \frac{5 \times U_{fin} \times L^4}{384 \times E \times I}$$

W_c　　= W_{tot} = Total deformation over time in mm
U_{fin}　= Total creep factor　　　= 11.4kN/m² →11,4 N/mm
L　　= Free span　　　　= 5200 mm
E　　= MOE　　　　　= 19305 GPa
I　　= Moment of inertia　　= (1/12)xbxh³= (1/12)x1000x(170)³=4.09x10⁸mm⁴
$$W_c = \frac{5 \times 11.4 \times 5200^4}{384 \times 19305 \times 4.09 \times 10^8} = 13.7 mm$$
U_{fin} =directly transmittable because of solid floor 1m wide is investigated

Max allowed deformation
W_{max}=0,004xL
W_{max}=0,004x5400=21,6mm
19,8mm <21.6mm
W_{tot} < W_{max} Maximum deformation floor is adaptable

Centre beam (old situation)

Connection type

Both sides supported beam with hinged connections
It is the least advantageous connection and presumed in the design stage.
The pre-stress is not included in the calculations.

Dead loads

Solid cross laminated bamboo floor with a span of 5.4 m and a thickness of 25 cm (17cm
Lamboo and 8cm recycled wood) with a density of 6,9 kN/m³.
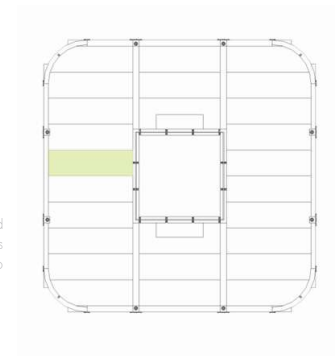 Own weight of 6,9x0,25=1,7 kN/m².
  Separation walls= 1.2 kN/m²
  Installations: 0.5 kN/m²
  Concrete floor (50mm) = 1.2 kN/m²
  Total 1.7+1.2+0.5+ 1,2 =4.6 kN/m²

Life loads

Floor load of: 2.5 kN/m².
Office load are used to increase possibilities of redevelopment. Dwelling has a load 1.75kN/m² for normal floors and 2.5kN/m²
for balconies. The choice also allows that balconies can be places everywhere))

Creep calculation

Creep factor

$U_{fin} = U_{fin,p} + U_{fin,Q_1} + U_{fin,Q_i}$

U_{fin} =Total deformation including creep
$U_{fin,p}$ = The final deformation by permanent loads including creep = $U_{fin,p}$ =4.6x(1+0.8)=8.3 kN/m²
U_{fin,Q_1} = The final deformation by main live loads including creep   = U_{fin,Q_1} =2.5x(1+0.3x0.8)= 3.1 kN/m²
U_{fin,Q_i} = The final deformation by accompanying live loads (snow) = U_{fin,Q_i} =Not applicable
The values are further explained in main report. Wood norms have been used since there is no norm for laminated Guadua
bamboo from Lamboo.
$U_{fin} = 8.3 + 3.1 + 0 = 11.4$ kN/m²

Deformation beam

$W_c = \frac{5 \times U_{fin} \times L^4}{384 \times E \times I}$

W_c = W_{tot} = Total deformation over time in mm
U_{fin} = Total creep factor   =11.4kN/m² area 5.4m wide
→6.1.56kN/m²= 61.6N/mm
L   = Free span   = 5300 mm
E   = 1½OE   = 19305 GPa
I   = Moment of inertia
Moment of inertia according to theorem of Steiner:

$I = I_1 + A_1 \times (Z_1 - Z)^2 + I_2 + A_2 \times (Z_2 - Z)^2$

$I_1 = {}^1/_{12} \times b \times h^3 = {}^1/_{12} \times 400 \times 260^3 = 5.86 \times 10^9 mm^4$

$I_2 = {}^1/_{12} \times b \times h^3 = {}^1/_{12} \times 600 \times 390^3 = 2.97 \times 10^9 mm^4$

$I = 5.86 \times 10^9 + 10.4 \times 10^5 \times (238)^2 + 2.97 \times 10^9 + 2.34 \times 10^5 \times (87)^2 = 6.42 \times 10^{10}$

$$W_c = \frac{5 \times 61.6 \times 5300^4}{384 \times 19305 \times 6.42 \times 10^{10}} = 0.51 mm$$

Max allowed deformation

W_{max}=0,004xL
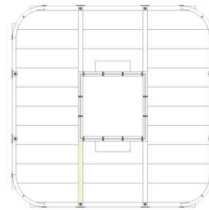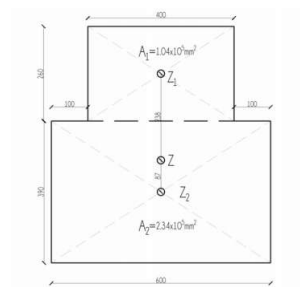W_{max}=0,004x5200=20,8mm
0.51mm <20.8mm
$W_{tot} < W_{max}$
Maximum deformation beam is adaptable

12 story structural calculations

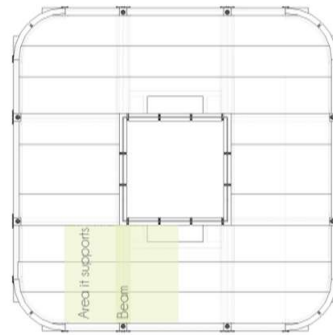## Centre beam (New situation)

Connection type

Both sides supported beam with hinged connections
It is the least advantageous connection and presumed in the design stage.
The pre-stress is not included in the calculations.

Dead loads

Solid cross laminated bamboo floor with a span of 5.4 m and a thickness of
25 cm (17cm Lamboo and 8cm recycled wood) with a density of 6,9 kN/m³.
   Own weight of 6,9x0,25=1,7 kN/m².
   Separation walls= 1.2 kN/m²
   Installations: 0.5 kN/m²
   Concrete floor (50mm) = 1.2 kN/m²
   Total 1.7+1.2+0.5+ 1,2 =4.6 kN/m²

Life loads

Floor load of: 2.5 kN/m².
Office load are used to increase possibilities of redevelopment. Dwelling has a load 1.75kN/m² for normal floors and 2.5kN/m²
for balconies. The choice also allows that balconies can be places everywhere))

Creep calculation

Creep factor

$U_{fin} = U_{fin,p} + U_{fin,Q_1} + U_{fin,Qi}$

U_{fin} = Total deformation including creep
$U_{fin,P}$ = The final deformation by permanent loads including creep = $U_{fin,P}$ =4,6x(1+0,8)=8.3 kN/m²
$U_{fin,Q1}$ = The final deformation by main live loads including creep   = $U_{fin,Q1}$ =2,5x(1+0,3x0,8)=3,1 kN/m²
$U_{fin,Qi}$ = The final deformation by accompanying live loads (snow) = $U_{fin,Qi}$ =Not applicable
The values are further explained in main report. Wood norms have been used since there is no norm for laminated Guadua
bamboo from Lamboo.
$U_{fin} = 8.3 + 3.1 + 0 = 11.4$ kN/m²

Deformation beam

$$W_c = \frac{5 \times U_{fin} \times L^4}{384 \times E \times I}$$

W_c = W_{tot} = Total deformation over time in mm
U_{fin} = Total creep factor   = 11.4kN/m² area: 5.4m wide →61.56kN/m= 61.6N/mm
L   = Free span   = 5300 mm
E   = MOE   = 19305 GPa
I   = Moment of inertia   = 1/12 x b x h³ =1/12 x600 x390³=2.97 x10⁹ mm⁴
Moment of inertia according to theorem of Steiner.

$$W_c = \frac{5 \times 61.6 \times 5300^4}{384 \times 19305 \times 2.97 \times 10^9} = 11mm$$

Max allowed deformation

W_{max}=0,004xL
W_{max}=0,004x5200=20,8mm
11mm <20,8mm
W_{tot} < W_{max}
Maximum deformation beam is adaptable

Earthquake

X=seismic hazard factor. Assumed is X=0.4 (Toughest USA load case)

$F_{eq} = X \times C_{Y_g} = 0.4 \times 1.32 \times 10^3 = 528\ kN$

Assumed is that the centre point of the weight in the building is located at ½ H

$M_{eq} = \frac{1}{2} H \times F_{eq} = \frac{1}{2} \times 39.6 \times 528 = 1.05 \times 10^4\ kNm$

Load combinations (without pre tensioning)

$F_{eq1} = 1.35G + 1.5 \times C_{M_{eq}} = 1.35 \times 1.32 \times 10^3 + 1.5 \times 1.05 \times 10^4 = 1.75 \times 10^4\ kN$

$F_{eq2} = 0.9G - 1.5 \times T_{M_{eq}} = 0.9 \times 1.32 \times 10^3 - 1.5 \times 1.05 \times 10^4 = -1.46 \times 10^4 kN$

To eliminated tension pre-stress structure with 1.46x10⁴ kN.

$F_{eq1,tensioned} = 1.35G + 1.5 \times C_{M_{eq}} = 1.35 \times 1.32 \times 10^3 + 1.5 \times 1.05 \times 10^4 + 1.46 \times 10^4 = $ **$3.21 \times 10^4\ kN$**

10 cables available for pre tensioning per cable 1.46x10³ kN

Dimensioning the columns in Earthquake

Aria ratio between shear walls : columns is +/- 85% : 15%

Using the wind load combination values.

$F_{eq1,tensioned\ column} = 15\% \times A \times \sigma_{max}$

$F_{eq1, tensioned}$ = 3.21x10⁴ kN = 3.21 x 10⁷ N

σ_{rep} = 92,966 kN/m² ≈ 93 N/mm²

$$A = \frac{0.15 \times F_{sw2}}{\sigma_{rep}} = \frac{0.15 \times 3.21 \times 10^7}{93} = 5.18 \times 10^4 mm^2$$

Number of columns: 2st

$$\sqrt{\frac{5.18 \times 10^4 mm^2}{2}} = \textbf{160mm}$$

Buckling with in Earthquake

$$I = \frac{F_{eq1_{tensioned}} \times L_{cr.}^2}{\pi^2 \times E_i}$$

$$I = \frac{3.21 \times 10^7 \times 9.6 \times 10^6}{\pi^2 \times 19305} = \frac{3.08 \times 10^{14}}{1.95 \times 10^5} = 1.61 \times 10^9 mm^4$$

If column is square:

$l^4 = I \times 12 = 1.61 \times 10^9 \times 12 = 1.93 \times 10^{10}$

$l = \sqrt[4]{1.93 \times 10^{10}} = 226mm \approx \textbf{373mm}$

Vibrations

All based on **CLT Handbook Cross-Laminated Timber–Canadian Edition** from **Gagnon, S. and C. Pirvu (2011)**

Design Criterion

$$\frac{f}{d^{0.7}} \geq 13 \; or \; d \leq \frac{f^{1.43}}{39}$$

f = fundamental natural frequency calculated using equation [2] in Hz

d = 1 kN static deflection calculated using equation [3] in mm

Equations for Calculating the Criterion Parameters

$$f = \frac{3.142}{2l^2} \times \sqrt{\frac{EI_{eff}^{1m}}{\rho A}}$$

f = fundamental natural frequency of 1 m CLT panel simply supported in Hz

l = CLT floor maximum span in meter

EI_{eff}^{1m} = effective apparent stiffness in the span direction for 1 m wide panel in N-m²

ρ = density of CLT in kg/m3

A = area of cross-section of 1 m wide CLT panel, i.e. thickness x 1 m wide in m²

$$d = \frac{1000Pl^3}{48EI_{eff}^{1m}}$$

d = static deflection at mid-span of the 1 m wide simply supported CLT panel under 1 kN load in mm

P = 1000 N

Values

L= 5.7 m

ρ = 690 kg/m3

A = 0.250x1=0.25m²

P = 1000 N

EI_{eff}^{1m} =?????

E= 19305 MPA = 19.305 GPA

$$I_{eff}^{1m} = \frac{-1489 \times 5.7^2 \times 21781 \times 8980.7}{10^8} = \frac{8.48 \times 10^4}{10^8} = 8.5 \times 10^{-4} cm^4$$
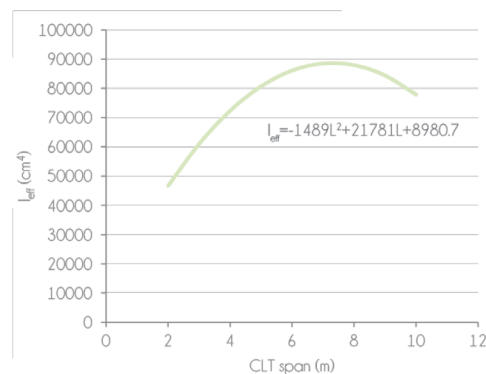
I_{eff}^{1m} is not correct, but without testing this specific material behaviour this cannot be determined.

$$f = \frac{3.142}{2l^2} \times \sqrt{\frac{EI_{eff}^{1m}}{\rho A}} = \frac{3.142}{2 \times (5.7)^2} \times \sqrt{\frac{19305 \times 8.5 \times 10^{-4}}{690 \times 0.25}} = 4.8 \times 10^{-2} \times 0.31 = 1.5 \times 10^{-2}$$

$$d = \frac{1000Pl^3}{48EI_{eff}^{1m}} = \frac{1000 \times 1000 \times 5.7^3}{48 \times 19305 \times 8.5 \times 10^{-4}} = \frac{1.85 \times 10^8}{788} = 2.35 \times 10^5$$

The control

$$\frac{f}{d^{0.7}} \geq 13 \; or \; d \leq \frac{f^{1.43}}{39}$$

$$\frac{1.5 \times 10^{-2}}{(2.35 \times 10^5)^{0.7}} = 2.6 \times 10^{-8} \geq 13$$

$$2.35 \times 10^5 \leq \frac{1.5 \times 10^{-2^{1.43}}}{39} = 6.32 \times 10^{-5}$$

For design method

$$5.7 = l \leq \frac{1}{9.15} \times \frac{\left(EI_{eff}^{1m}\right)^{0.293}}{(\rho A)^{0.123}} = \frac{1}{9.15} \times \frac{(19305 \times 8.5 \times 10^{-4})^{0.293}}{(690 \times 0.25)^{0.123}} = \frac{1}{9.15} \times \frac{16.4^{0.293}}{(172.5)^{0.123}} = \frac{1.2}{9.15}$$
$$= 0.13$$

This would mean the example calculation passes with ease.

However results are very surrealistic. This can partly be explained by the incorrect I_{eff}^{1m} factor. However I_{eff}^{1m} can only be determined by full scale field testing. Which is costly and elements first have to be developed before they can be tested. But it might also be that the formulas are not applicable to solid LVB floor plates.

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Details

D

F   F

Metal bars, fall prevention

Double glazed window in LVB frame turning to the inside

Air seals

Stone window board
LVB strip
Double L profile connection
to allow movement of
settling in facade
Aluminum corner profile

Aluminum window sill

6600+P
6550+P

6595+P

Steel rod to 7cantiliever 10mm h.o.h. 1000mm

Edge beam LVB
Sound isolation
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High density bamboo to improve weather resistance

6300+P

LVB strip

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish

Horizontal tendon

Aluminum cap

6050+P
6000+P

5900+P

LVB strip

Energy dissipator

Water hole incase of condensation

drip edge

Corbel

Stuc stop

5700+P

Double glazed window in LVB frame turning to the inside

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High density bamboo to improve weather resistance

D

0mm   500mm

D

F

F

Plaster 10mm
Double layer of gypsum board 2x12.5mm
Lamboo Strand cross ply 19mmmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High density bamboo to improve weather resistance

Aluminum corner profile

6600+P

6550+P

LVB strip

LVB strip

6595+P

Edge beam LVB
Sound isolation
Waterproof membrane color black
Lamboo Strand cross ply 19mmmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High density bamboo to improve weather resistance

6300+P

LVB strip

Horizontal tendon

Aluminum cap

Steel rod to 7cantilever 10mm h.o.h. 1000mm

6050+P

6000+P

5900+P

LVB strip

Water hole incase of condensation

drip edge

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish
Structural LVB beam Lamboo
Energy dissipator

Corbel

D

5700+P

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High density bamboo to improve weather resistance

Una reunión educativa con el bambu

Detail: B. (Facade build-up)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

Void 40x40mm
Steel tendon Ø 20mm
Column 400x400mm LVB
Isolation
Double layer of gypsum board 2x12.5mm
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High density bamboo to improve weather resistance

LvB 12mm cover
Wooden frame filed with sound isolation
Energy dissipator
Waterproof membrane
Structural LVB from Lamboo
Aluminum corner profile
Energy dissipator

LVB strip

Weatherstrip around removable panel

Removable 'door' panel for maintenance

Energy dissipators

Steel Anchor plate with reinforce trips

Steel anchor plug
end tendon
Removable isolation

Aluminum cap

Steel rod to 7cantilever 10mm h.o.h. 1000mm

Water hole incase of condensation

drip edge

Corbell 100mm

6600+P
6550+P
6300+P
5900+P

6595+P
6050+P
6000+P
5700+P

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High density bamboo to improve weather resistance

Una reunión educativa con el bambu
Detail: C. (Cut through column)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

A   B   C

F   F

LvB 12mm cover
Wooden frame filled with sound isolation
Energy dissipators
LBV beam

6600+P

6595+P

6550+P

6300+P

LVB strip

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish

Steel tendon 20mm

Steel tendon 20mm in LVB beam in the facade

Structural LVB from Lamboo 600mm x 390mm

6050+P

6000+P

5900+P

Energy dissipators

A   B   C

5700+P

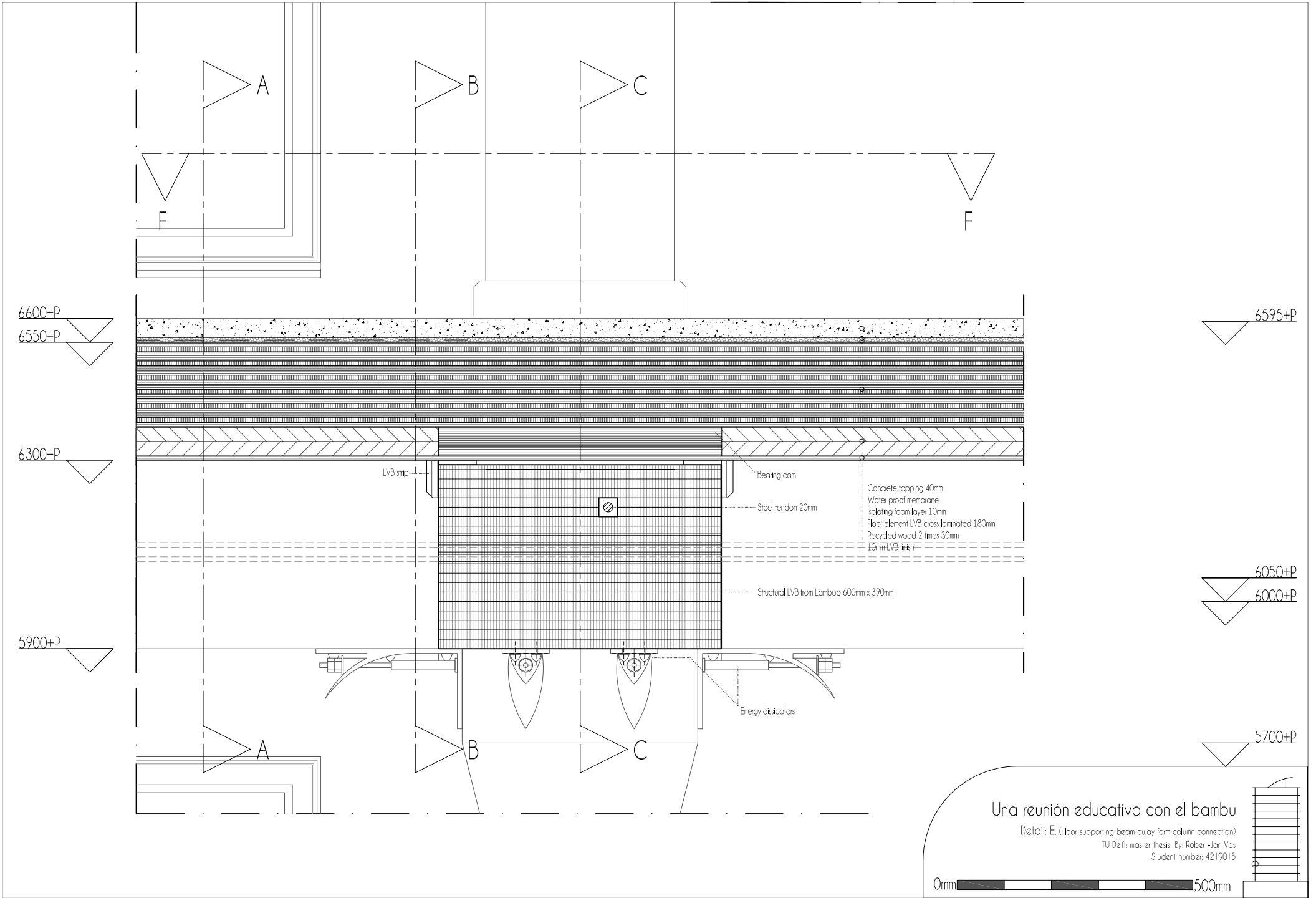Una reunión educativa con el bambu

Detail: D. (Floor supporting beam)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

A

B

C

F

F

6600+P

6595+P

6550+P

6300+P

LVB strip

Bearing cam

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish

Steel tendon 20mm

6050+P

6000+P

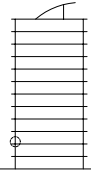Structural LVB from Lamboo 600mm x 390mm
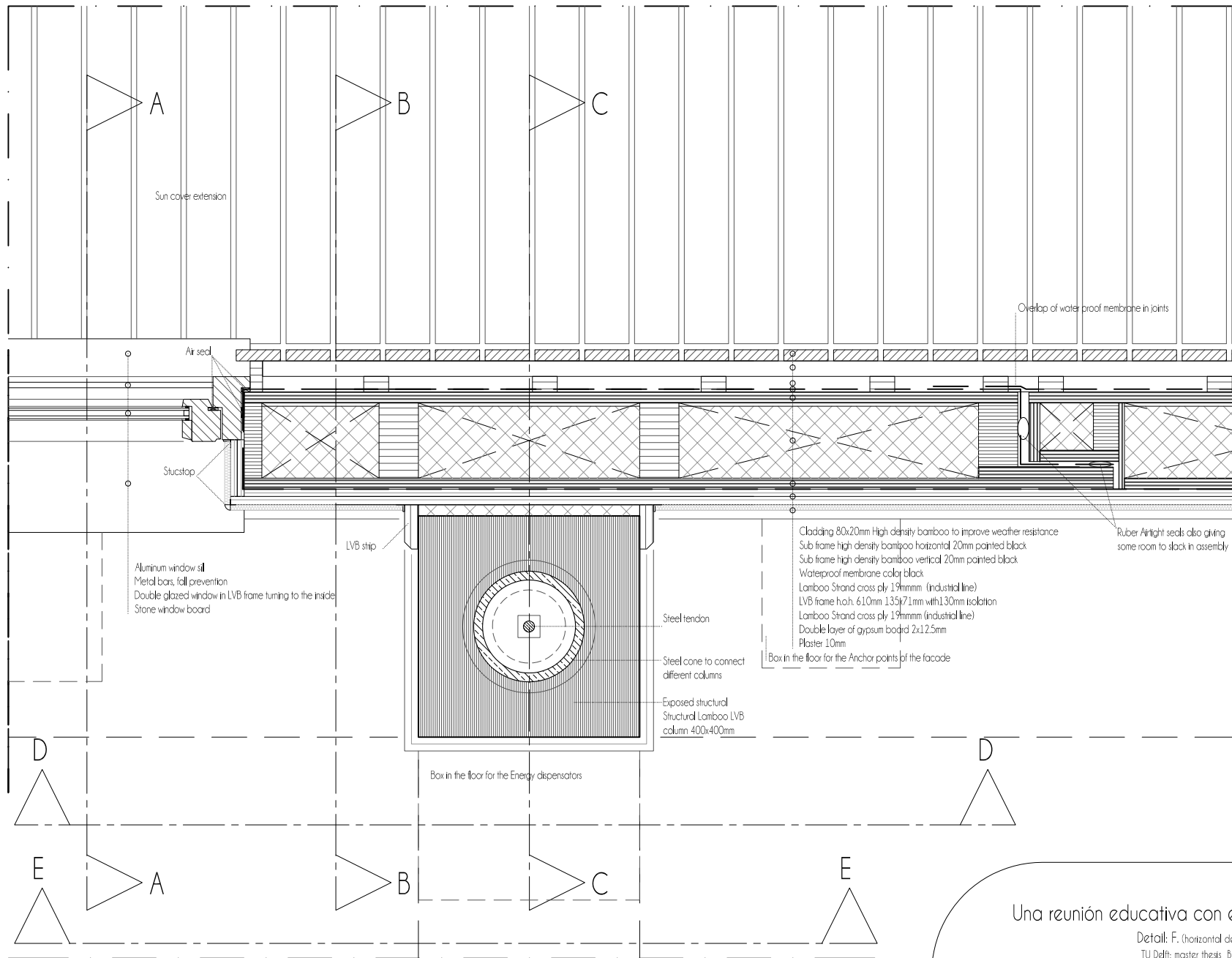
5900+P
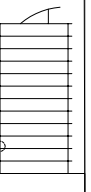
Energy dissipators

A

B

C

5700+P

Una reunión educativa con el bambu

Detail: E. (Floor supporting beam away form column connection)

TU Delft: master thesis By: Robert-Jan Vos

Student number: 4219015

0mm
500mm

A

B

C

Sun cover extension

Overlap of water proof membrane in joints

Air seal

Stucstop

LVB strip

Aluminum window sil
Metal bars, fall prevention
Double glazed window in LVB frame turning to the inside
Stone window board

Ruber Airtight seals also giving
some room to slack in assembly

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo horizontal 20mm painted black
Sub frame high density bamboo vertical 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmmm (industrial line)
Double layer of gypsum board 2x12.5mm
Plaster 10mm
Box in the floor for the Anchor points of the facade

Steel tendon

Steel cone to connect
different columns

Exposed structural
Structural Lamboo LVB
column 400x400mm

D

D

Box in the floor for the Energy dispensators

E

A

B

C

E

0mm

500mm

LVB strip

Facade connection to
frame fixed connection

9900+P

9850+P

9600+P

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish

LVB strip

Horizontal tendon

9200+P

Energy dissipator

Corbel

LVB strip
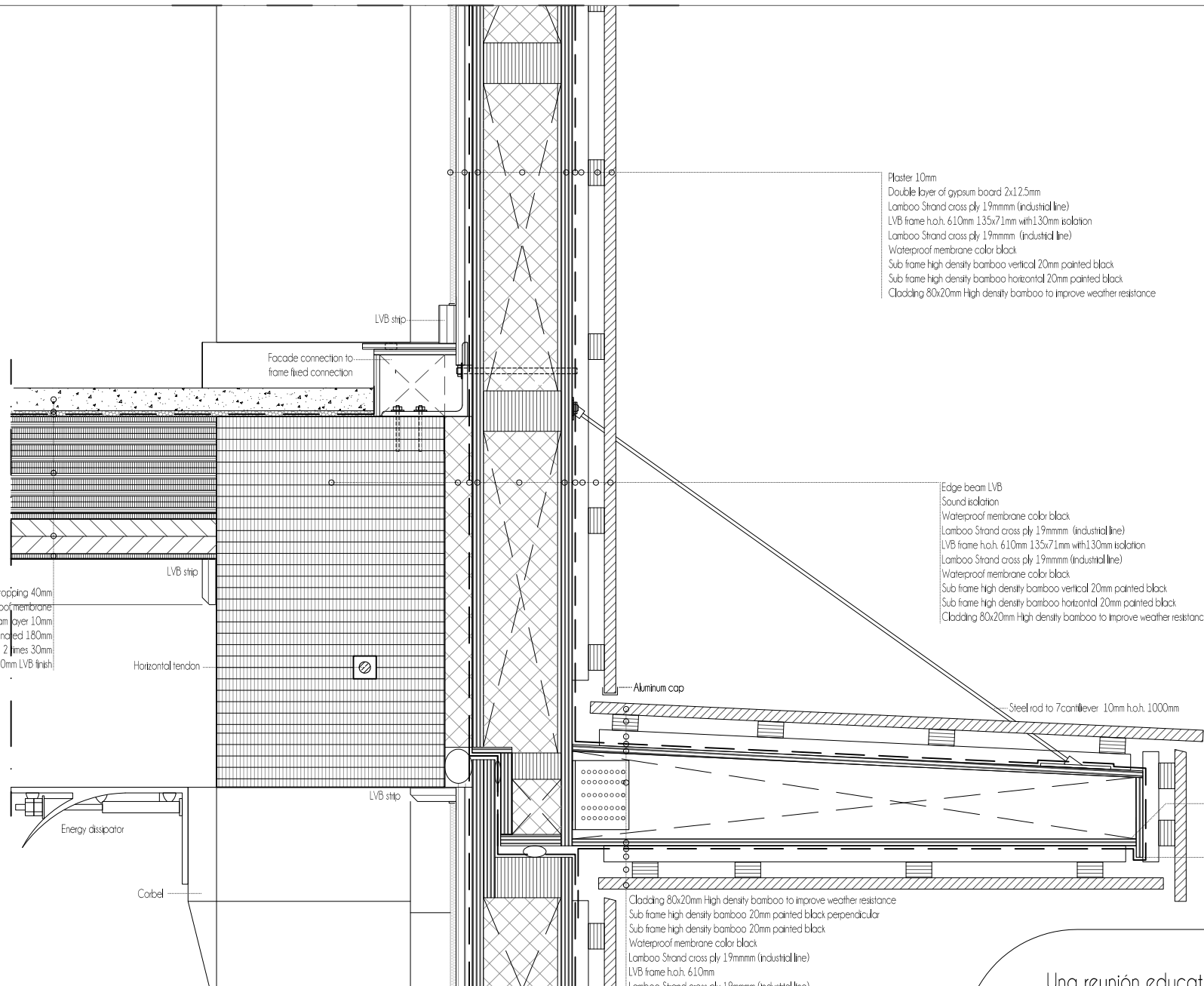
Plaster 10mm
Double layer of gypsum board 2x12.5mm
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
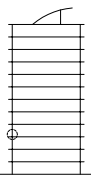Cladding 80x20mm High density bamboo to improve weather resistance

9785+P

Edge beam LVB
Sound isolation
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High density bamboo to improve weather resistance

Aluminum cap

Steel rod to 7cantilever 10mm h.o.h. 1000mm

9350+P
9300+P

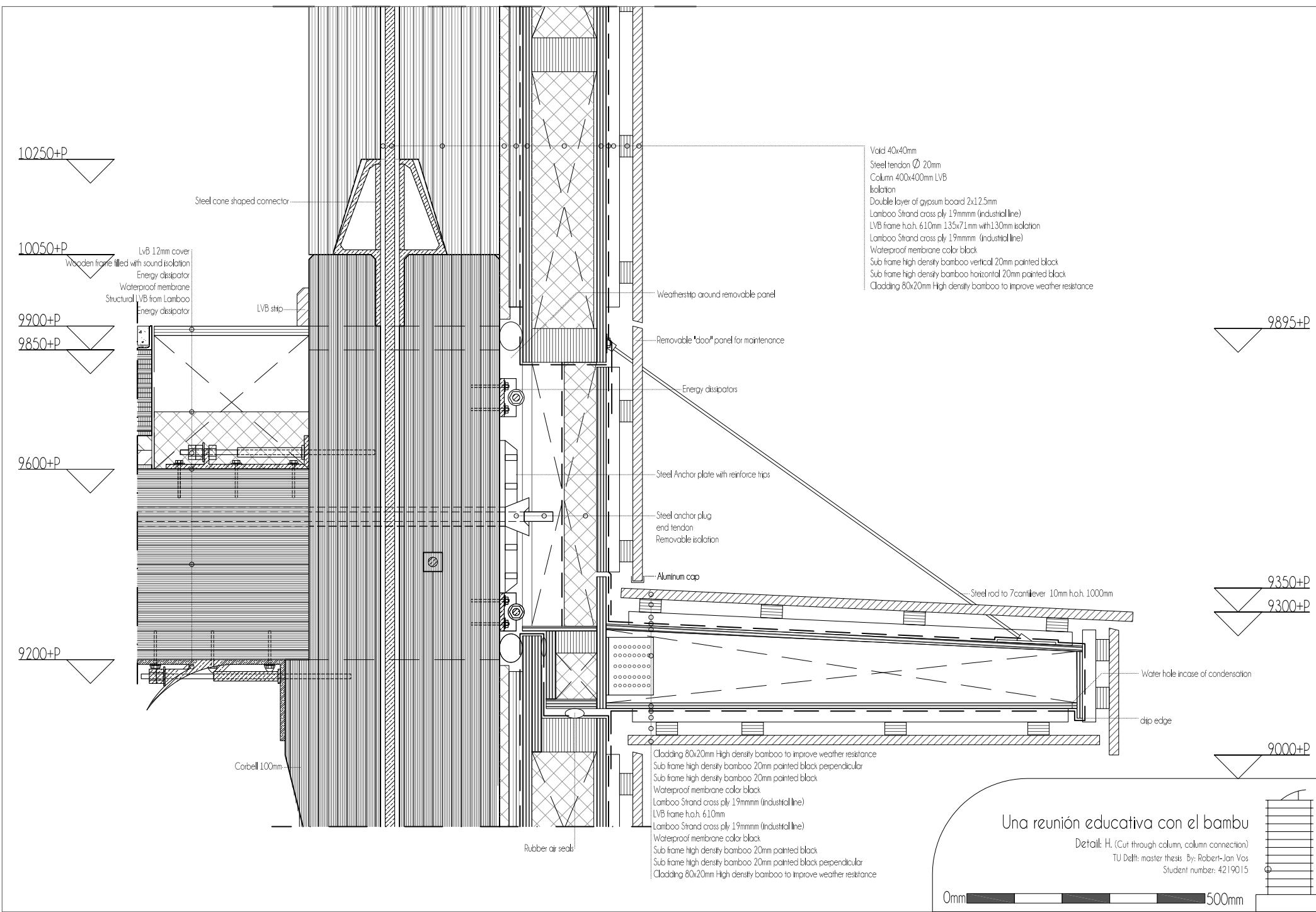Water hole incase of condensation

drip edge

9000+P

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High density bamboo to improve weather resistance

Una reunión educativa con el bambu
Detail: B. (Facade build-up)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

10250+P

10050+P

9900+P

9850+P

9600+P

9200+P

Steel cone shaped connector

LvB 12mm cover
Wooden frame filled with sound isolation
Energy dissipator
Waterproof membrane
Structural LVB from Lamboo
Energy dissipator

LVB strip

Corbell 100mm

Rubber air seals

Weatherstrip around removable panel

Removable "door" panel for maintenance

Energy dissipators

Steel Anchor plate with reinforce trips

Steel anchor plug
end tendon
Removable isolation

Aluminum cap

Void 40x40mm
Steel tendon ⌀ 20mm
Column 400x400mm LVB
Isolation
Double layer of gypsum board 2x12.5mm
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
Cladding 80x20mm High densty bamboo to improve weather resistance

9895+P

9350+P
9300+P

Steel rod to 7cantilever 10mm h.o.h. 1000mm
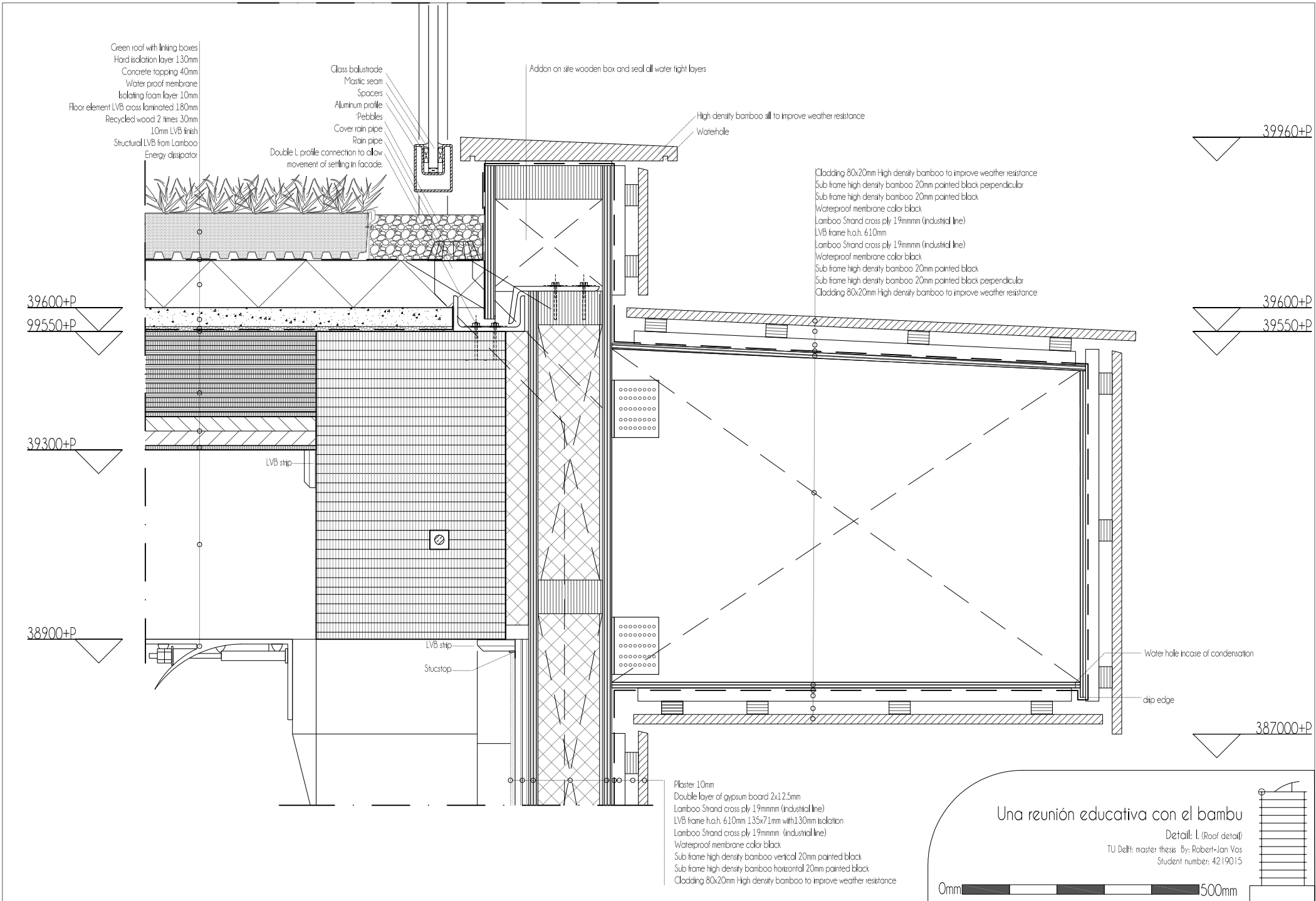
Water hole incase of condensation

drip edge

9000+P

Cladding 80x20mm High densty bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High densty bamboo to improve weather resistance

Una reunión educativa con el bambu

Detail: H. (Cut through column, column connection)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm
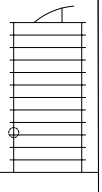
Green roof with linking boxes
Hard isolation layer 130mm
Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish
Structural LVB from Lamboo
Energy dissipator

Glass balustrade
Mastic seam
Spacers
Aluminum profile
Pebbles
Cover rain pipe
Rain pipe
Double L profile connection to allow
movement of settling in facade.

Addon on site wooden box and seal all water tight layers

High density bamboo sill to improve weather resistance
Waterhole

39960+P

Cladding 80x20mm High density bamboo to improve weather resistance
Sub frame high density bamboo 20mm painted black perpendicular
Sub frame high density bamboo 20mm painted black
Waterproof membrane color black
Lamboo Strand cross ply 19mmmm (industrial line)
LVB frame h.o.h. 610mm
Lamboo Strand cross ply 19mmmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo 20mm painted black
Sub frame high density bamboo 20mm painted black perpendicular
Cladding 80x20mm High density bamboo to improve weather resistance

39600+P

39600+P

99550+P

39550+P

39300+P

LVB strip

38900+P

LVB strip

Stucstop

Water hole incase of condensation

drip edge

387000+P

Plaster 10mm
Double layer of gypsum board 2x12.5mm
Lamboo Strand cross ply 19mm (industrial line)
LVB frame h.o.h. 610mm 135x71mm with130mm isolation
Lamboo Strand cross ply 19mmmm (industrial line)
Waterproof membrane color black
Sub frame high density bamboo vertical 20mm painted black
Sub frame high density bamboo horizontal 20mm painted black
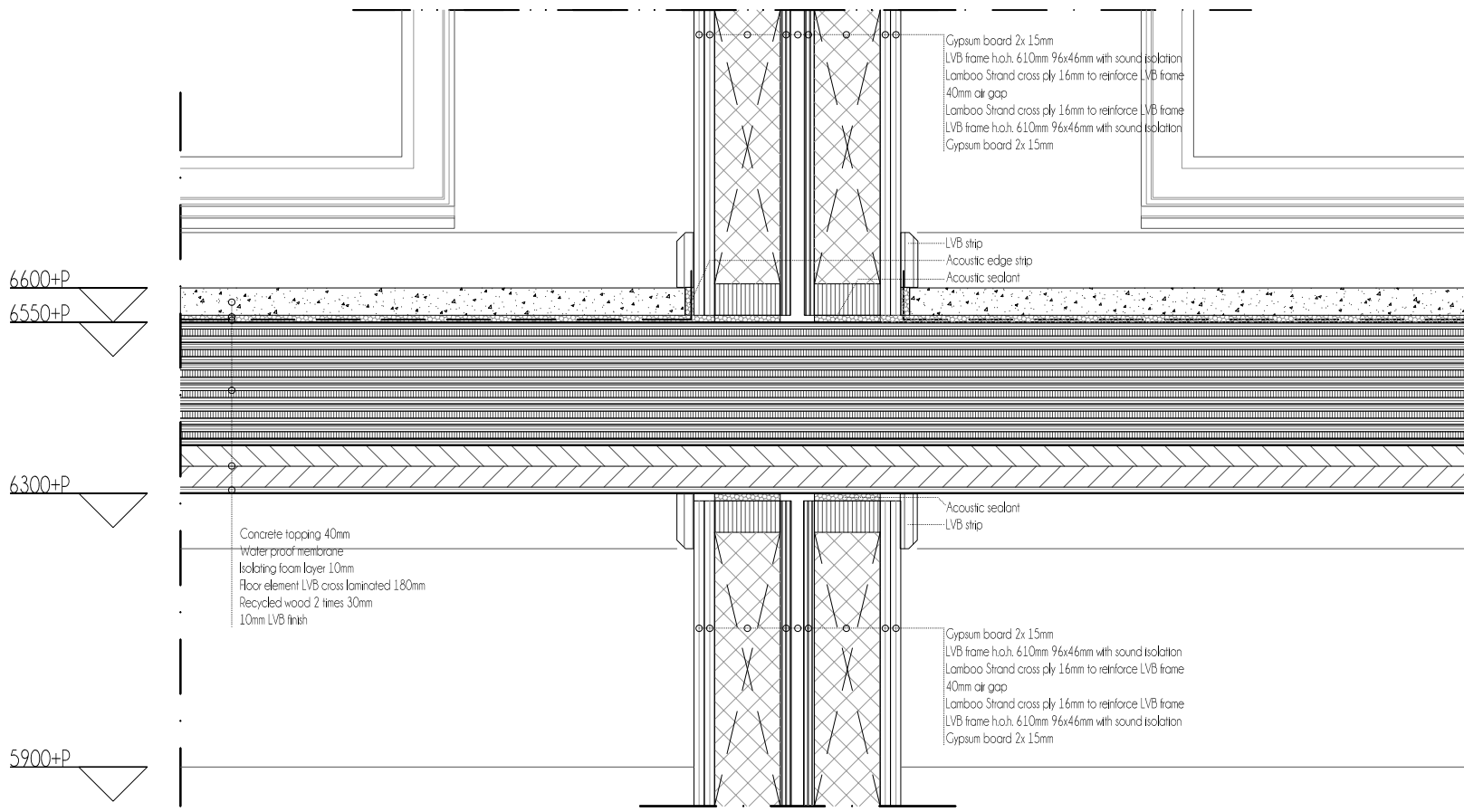Cladding 80x20mm High density bamboo to improve weather resistance

Una reunión educativa con el bambu
Detail: I. (Roof detail)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

6600+P

6550+P

6300+P

5900+P

Gypsum board 2x 15mm
LVB frame h.o.h. 610mm 96x46mm with sound isolation
Lamboo Strand cross ply 16mm to reinforce LVB frame
40mm air gap
Lamboo Strand cross ply 16mm to reinforce LVB frame
LVB frame h.o.h. 610mm 96x46mm with sound isolation
Gypsum board 2x 15mm

LVB strip
Acoustic edge strip
Acoustic sealant

Acoustic sealant
LVB strip

Concrete topping 40mm
Water proof membrane
Isolating foam layer 10mm
Floor element LVB cross laminated 180mm
Recycled wood 2 times 30mm
10mm LVB finish

Gypsum board 2x 15mm
LVB frame h.o.h. 610mm 96x46mm with sound isolation
Lamboo Strand cross ply 16mm to reinforce LVB frame
40mm air gap
Lamboo Strand cross ply 16mm to reinforce LVB frame
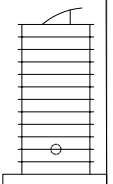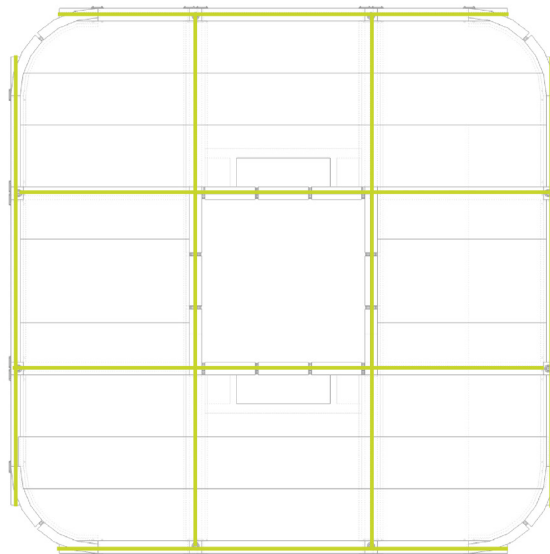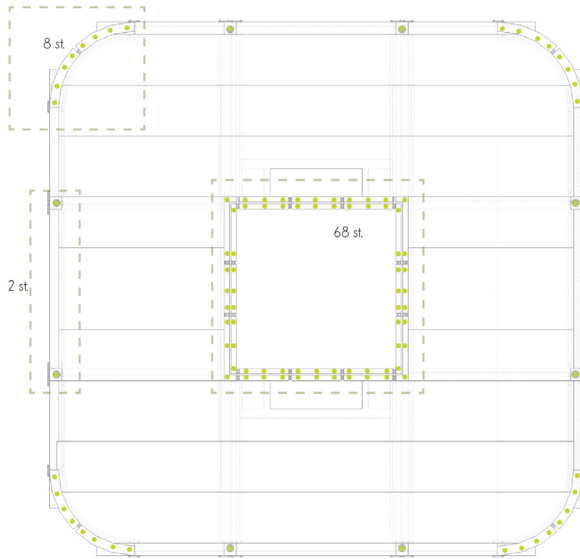LVB frame h.o.h. 610mm 96x46mm with sound isolation
Gypsum board 2x 15mm

Una reunión educativa con el bambu

Detail: J. (Separation wall detail)
TU Delft: master thesis By: Robert-Jan Vos
Student number: 4219015

0mm   500mm

Influence of steel cables on weight structure of the proposal

Vertical cables
Number of cables=
4 Corners + 8 Columns + 1 Core= 4x8+1x8+36=76st

Length of 1 cable =	35m1 (the height of the lamboo building)
Diameter 1cables =	2cm
Area 1 cables =	$\pi r^2= \pi \times 1^2=3,14cm^2=3,14 \times 10^{-4}m^2$

Volume=76stx35mx3,14x10^{-4}m^2=0,84m^3

Horizontal cables
Number of cables=
(1 circular + 4 crosswise) x 12 floors

Length of circular cables =	18x4=72m^2
Length of crosswise cables=	18m
Diameter 1cables =	2cm
Area 1 cables =	$\pi r^2= \pi \times 1^2=3,14cm^2=3,14 \times 10^{-4}m^2$

Running length of cables combined
12 x 72+ 4 x 12 x 18=1728m1

Volume=1728m1x3,14x10^{-4}m^2=0,54m^3

Vertical cables+ Horizontal cables
0.84+0.54=1.38m^3

Density steel =	7200kg/m^3
Weight steel cables =	1,38x7200kg/m^3=9.94 x 10^3kg

Total area building
Floor area =	300m²
Number of floors =	12st
Tot area =	300x12=3.600m^2

Weight cables per m² floor area
9.94 x10^3/3600=2,76kg/m²

This is a rough calculation of the weight of the steel cables on the overall building. The lamboo weights around 242kg/m² the steel cables just 2,76 kg/m². In other full timber multiple story buildings the amount of steel from brackets and fasteners is normally under 5% of the buildings weight and therefore excluded in the LCA. The 1% added for the steel cables will not drastically change this and are therefore excluded as well from the LCA study.

It is assumed in the rough calculation that all cables have the same diameter this will not be true, some will be thinner only running through the element not all the way to the top.

8 st.

68 st.

2 st.

14.4. Physical testing
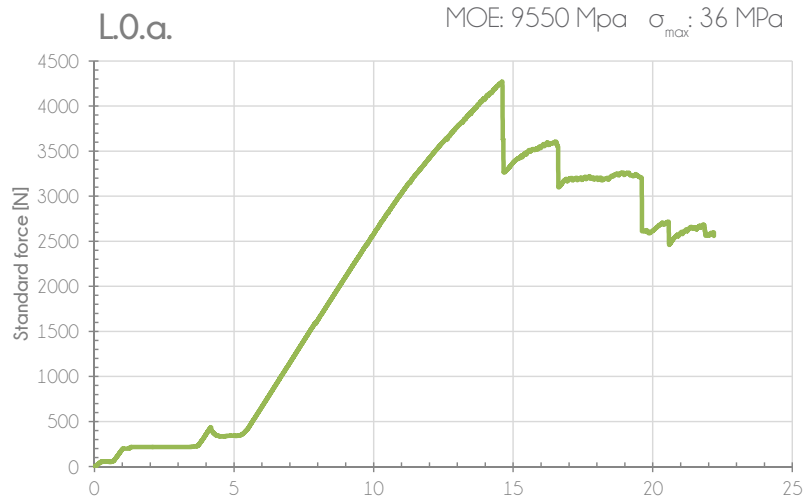
L.0.a.

MOE: 9550 Mpa σ_{max}: 36 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
427	854	1281	1708	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
5.950	640	7.312	1304	1.361	664
6.145	735	7.412	1354	1.267	619
6.440	879	7.537	1415	1.096	536
6.797	1053	7.662	1475	0.865	423
7.048	1175	7.909	1596	0.862	421
				1.090	532
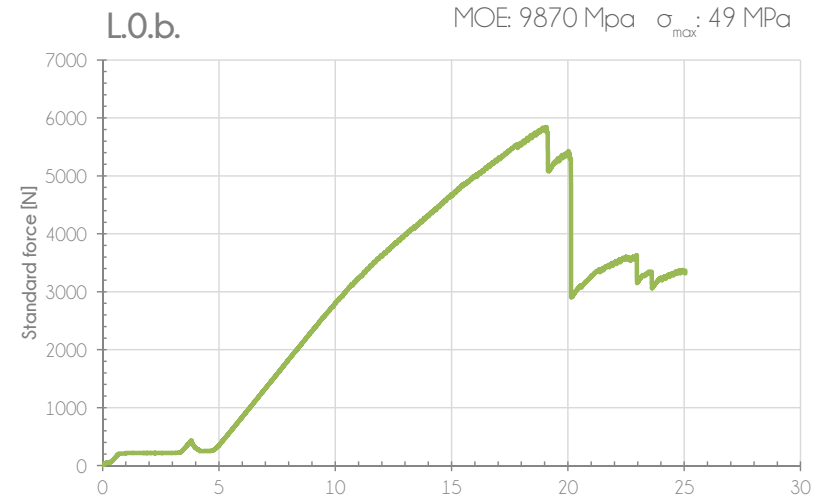
L.0.b.

MOE: 9870 Mpa σ_{max}: 49 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
584	1168	1752	2336	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
5.654	667	7.922	1792	2.268	1125
5.952	814	8.166	1912	2.213	1099
6.254	964	8.388	2012	2.133	1049
6.307	989	8.577	2113	2.270	1124
6.359	1015	8.776	2218	2.417	1202
				2.260	1120
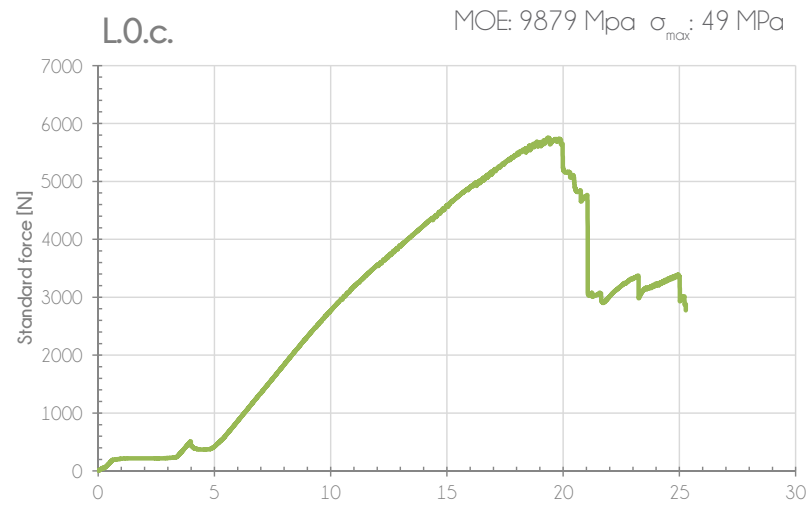
L0.c.

MOE: 9879 Mpa σ_{max}: 49 MPa

L0.d.

MOE: 9584 Mpa σ_{max}: 42 MPa

L0.c.

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
575	1151	1727	2303		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.714	720	7.964	1819		2.251	1098
6.016	869	8.208	1939		2.192	1070
6.315	1015	8.460	2063		2.145	1048
6.368	1040	8.679	2164		2.311	1124
6.420	1065	8.919	2284		2.499	1219
					2.279	1112

L0.d.

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
499	998	1496	1995		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.653	632	7.682	1597		2.029	965
5.955	772	7.929	1718		1.974	946
6.257	915	8.179	1841		1.922	926
6.309	939	8.347	1924		2.039	984
6.362	965	8.432	1966		2.071	1002
					2.007	964

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Physical testing

L.1.a.

MOE: 9435 Mpa σ_{max}: 51 MPa
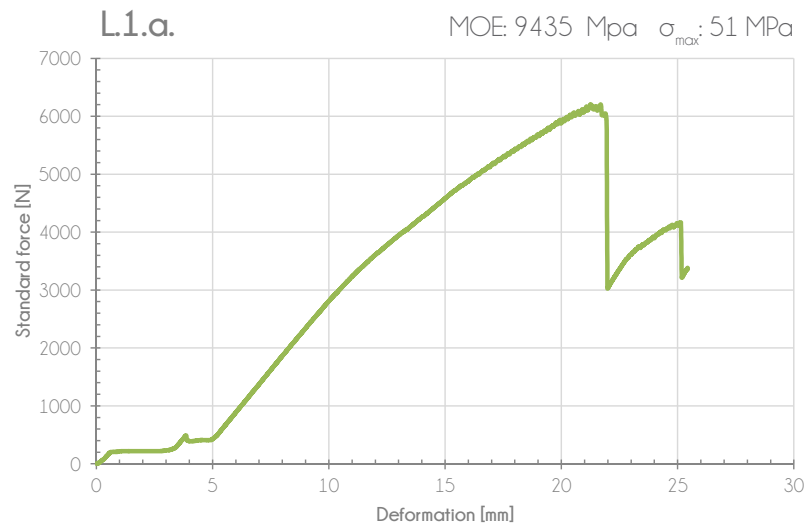
0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
621	1241	1862	2483		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.620	700	8.120	1920		2.500	1219
5.954	863	8.287	2001		2.333	1138
6.287	1025	8.620	2161		2.333	1135
6.454	1106	8.953	2319		2.500	1213
6.620	1188	9.287	2476		2.667	1288
					2.467	1199

L.1.b.

MOE: 8877 Mpa σ_{max}: 45 MPa
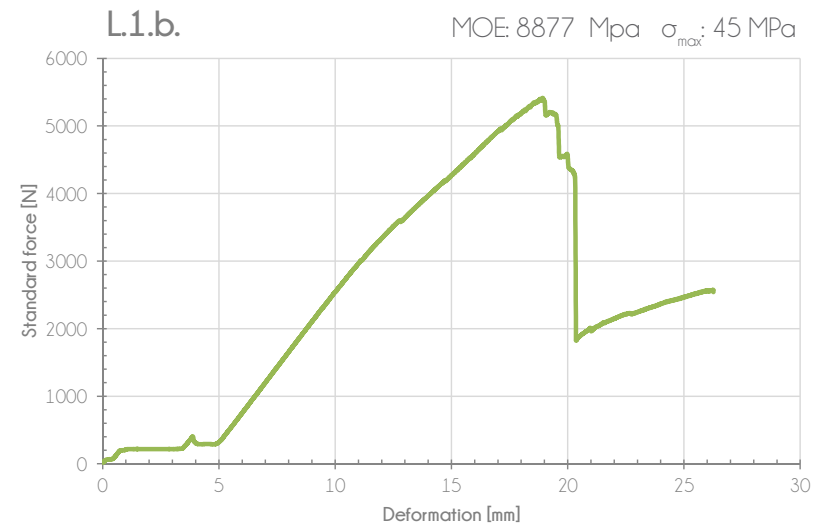
0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
541	1083	1624	2165		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.619	579	8.119	1709		2.500	1130
5.952	729	8.285	1784		2.333	1055
6.286	880	8.619	1935		2.333	1055
6.453	956	8.952	2084		2.500	1128
6.619	1029	9.119	2157		2.500	1129
					2.433	1099

L.1.c.

MOE: 8788 Mpa σ_{max}: 42 MPa
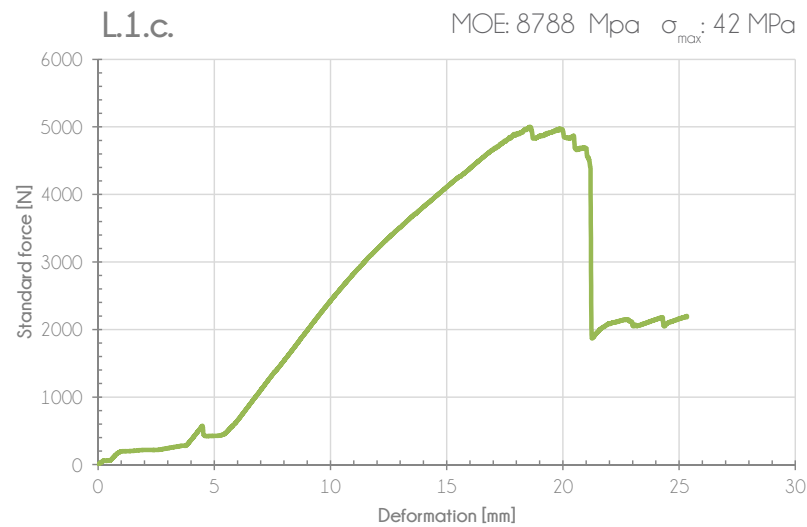
0.1 F$_{max}$	0.2 F$_{max}$	0.3 F$_{max}$	0.4 F$_{max}$		ΔDeformation	ΔForce (N)
500	1000	1500	2000		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.620	514	8.120	1591		2.500	1077
5.953	633	8.287	1664		2.333	1031
6.287	780	8.620	1815		2.333	1034
6.454	855	8.787	1892		2.333	1037
6.620	931	8.954	1965		2.333	1034
					2.367	1043

L.1.d.

MOE: 9523 Mpa σ_{max}: 52MPa
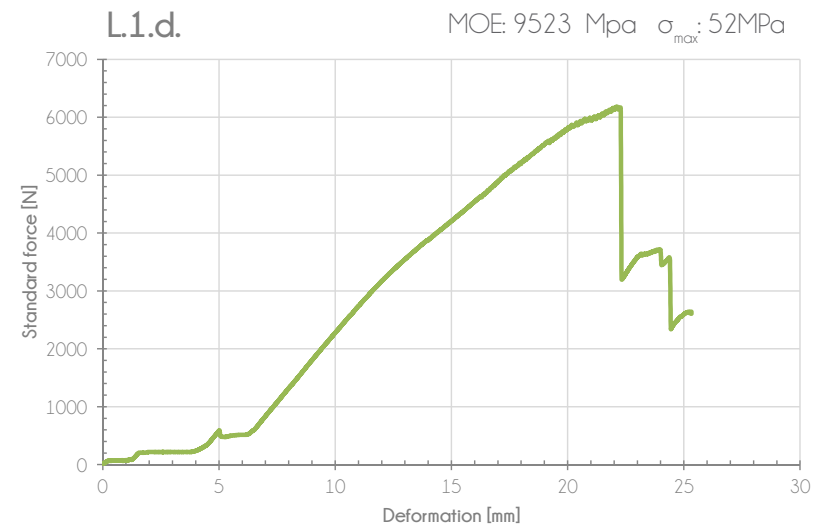
0.1 F$_{max}$	0.2 F$_{max}$	0.3 F$_{max}$	0.4 F$_{max}$		ΔDeformation	ΔForce (N)
618	1236	1855	2473		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
6.955	814	9.122	1862		2.166	1048
7.288	976	9.288	1942		2.000	965
7.455	1056	9.621	2100		2.167	1044
7.622	1137	9.955	2257		2.333	1120
7.788	1218	10.288	2412		2.500	1194
					2.233	1074

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Physical testing

L.1.e.
MOE: 9435 Mpa σ_{max}: 49 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
603	1205	1808	2410			
V1	F1	V2	F2		ΔP (mm)	ΔF (N)
5.616	670	7.949	1828		2.334	1159
5.949	836	8.282	1994		2.333	1157
6.282	1004	8.615	2157		2.333	1154
6.449	1086	8.949	2323		2.500	1236
6.616	1169	9.116	2389		2.500	1220
					2.400	1185

L.1.f.
MOE: 10288Mpa σ_{max}: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
622	1245	1867	2489			
V1	F1	V2	F2		ΔP (mm)	ΔF (N)
7.117	957	8.617	1748		1.500	790
7.184	990	8.950	1926		1.767	936
7.217	1008	9.284	2103		2.067	1095
7.450	1130	9.617	2281		2.167	1151
7.617	1217	9.950	2458		2.333	1241
					1.967	1043

L.1.g.

MOE: 9933Mpa σ_{max}: 56MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
692	1385	2077	2770		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.623	739	8.289	2172		2.666	1433
5.956	917	8.623	2336		2.667	1419
6.290	1094	8.956	2501		2.667	1408
6.623	1272	9.290	2689		2.666	1416
6.790	1360	9.456	2768		2.666	1408
					2.667	1417

L.1.h.

MOE: 9369 Mpa σ_{max}: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
614	1229	1843	2457		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.950	731	8.287	1844		2.337	1113
6.284	893	8.617	2001		2.333	1108
6.617	1047	8.950	2158		2.333	1110
6.784	1129	9.284	2312		2.500	1183
6.950	1208	9.450	2389		2.500	1181
					2.400	1139

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Physical testing

L.1.i.

MOE: 9818 Mpa σ_{max}: 48 MPa
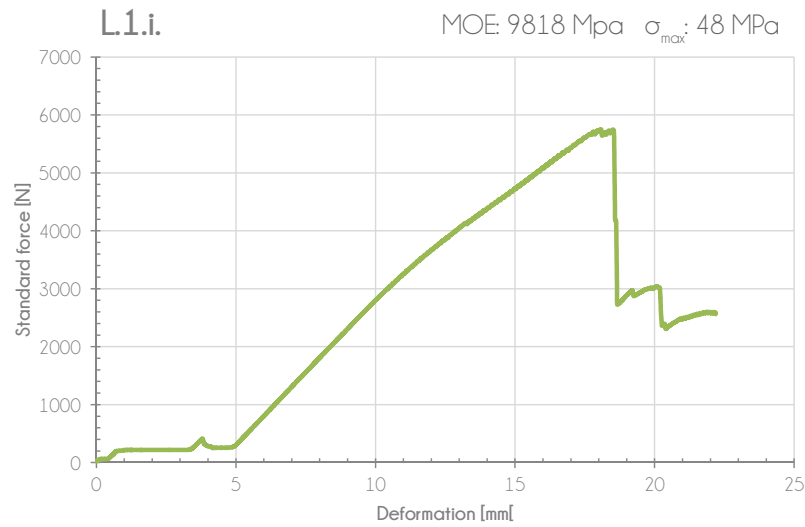
0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}	ΔDeformation	ΔForce (N)
575	1150	1726	2301	ΔP (mm)	ΔF (N)
V1	F1	V2	F2		
5.617	611	7.950	1786	2.333	1175
5.950	778	8.283	1952	2.333	1174
6.283	947	8.617	2118	2.333	1171
6.450	1031	8.783	2202	2.333	1171
6.617	1116	8.950	2283	2.333	1168
				2.333	1172

L.2.a.

MOE: 8862 Mpa σ_{max}: 43 MPa

Standard force [N] vs Deformation [mm]

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}	ΔDeformation	ΔForce (N)
524	1049	1573	2098	ΔP (mm)	ΔF (N)
V1	F1	V2	F2		
6.953	913	8.453	1608	1.500	695
6.986	928	8.286	1534	1.300	606
7.020	944	8.786	1757	1.767	813
7.053	961	8.953	1839	1.900	878
7.086	976	9.119	1914	2.033	938
				1.700	786

L.2.b.

MOE: 9947 Mpa σ_{max}: 52 MPa

Standard force [N] vs Deformation [mm]

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}	ΔDeformation	ΔForce (N)
620	1240	1860	2480	ΔP (mm)	ΔF (N)
V1	F1	V2	F2		
6.952	901	8.952	1920	2.000	1019
6.985	917	9.285	2090	2.300	1172
7.018	934	9.618	2259	2.600	1324
7.051	952	9.785	2340	2.733	1387
7.085	969	9.951	2424	2.866	1455
				2.500	1272

Physical testing

L.2.c.

MOE: 9369 Mpa σ_{max}: 42 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
494	988	1482	1976			
V1	F1	V2	F2		ΔP (mm)	ΔF (N)
6.288	750	8.021	1492		1.733	742
6.454	822	8.121	1541		1.667	719
6.521	847	8.254	1596		1.733	749
6.754	946	8.387	1647		1.633	701
6.787	964	8.621	1750		1.834	786
					1.720	739

L.2.d.

MOE: 10280 Mpa σ_{max}: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
620	1239	1859	2479			
V1	F1	V2	F2		ΔP (mm)	ΔF (N)
7.289	1060	8.855	1865		1.566	805
7.356	1096	8.889	1884		1.533	789
7.389	1114	8.922	1902		1.534	788
7.456	1146	9.189	2036		1.733	891
7.522	1180	9.289	2089		1.766	908
					1.627	836
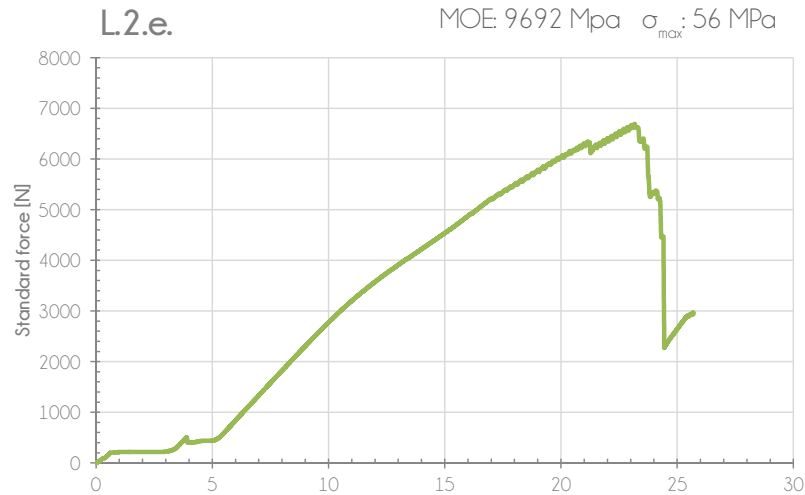
L.2.e.

MOE: 9692 Mpa σ_{max}: 56 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
669	1338	2008	2677		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
6.286	981	8.853	2236		2.567	1255
6.453	1063	8.886	2253		2.433	1191
6.620	1144	8.920	2269		2.300	1125
6.786	1225	9.186	2394		2.400	1169
6.953	1308	9.286	2443		2.333	1135
					2.407	1175

L.2.f.

MOE: 8831 Mpa σ_{max}: 44 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
534	1067	1601	2135		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
6.290	704	8.857	1838		2.566	1134
6.457	777	8.890	1854		2.433	1077
6.624	852	8.924	1870		2.300	1018
6.790	926	9.190	1980		2.400	1054
6.957	1000	9.290	2029		2.333	1029
					2.407	1062

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Physical testing

L.3.a.

MOE: 9792 Mpa σ_{max}: 39 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
478	956	1434	1912		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
6.684	778	8.184	1529		1.500	751
6.785	826	8.218	1548		1.433	723
6.884	875	8.251	1569		1.367	694
6.951	908	8.518	1705		1.567	798
7.051	955	8.617	1759		1.566	804
					1.487	754

L.3.b.

MOE: 8844 Mpa σ_{max}: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
633	1266	1899	2532		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
7.353	1050	9.520	2031		2.167	982
7.454	1094	9.553	2054		2.100	960
7.554	1141	9.620	2081		2.067	940
7.620	1169	9.854	2194		2.233	1025
7.720	1217	9.954	2238		2.233	1021
					2.160	986

L.3.c.

MOE: 9369 Mpa σ_{max}: 49 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
494	988	1482	1976	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.288	750	8.021	1492	1.733	742
6.454	822	8.121	1541	1.667	719
6.521	847	8.254	1596	1.733	749
6.754	946	8.387	1647	1.633	701
6.787	964	8.621	1750	1.834	786
				1.720	739

L.3.d.

MOE: 8817 Mpa σ_{max}: 53 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
620	1239	1859	2479	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.290	845	8.524	1856	2.234	1011
6.457	921	8.890	2016	2.433	1095
6.557	968	8.957	2052	2.400	1085
6.624	996	9.524	2303	2.900	1307
6.723	1042	9.623	2347	2.900	1305
				2.573	1160

How to make a multi story residential building out of laminated bamboo in a Guayaquil in a sustainable way?

Physical testing

M.0.a

MOE: 8749 Mpa σ_{max}: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
575	1150	1725	2300	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.429	775	8.929	1785	2.499	1011
6.679	876	9.178	1883	2.499	1007
6.929	977	9.429	1980	2.499	1003
7.179	1077	9.679	2077	2.499	1000
7.305	1129	9.929	2172	2.624	1043
				2.524	1013

M.0.b

MOE: 9050 Mpa σ_{max}: 54 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
612	1224	1835	2447	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
8.131	730	11.167	2019	3.036	1290
8.384	837	11.419	2123	3.036	1286
8.636	946	11.672	2220	3.036	1274
8.889	1053	11.924	2319	3.036	1266
9.141	1162	11.977	2340	2.836	1178
				2.996	1259

M.O.c.

MOE: 10056 Mpa σ_{max}: 62 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
574	1147	1721	2294	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.222	902	8.011	1733	1.788	831
6.274	926	8.262	1853	1.988	927
6.327	950	8.515	1969	2.188	1019
6.379	974	8.767	2086	2.387	1112
6.432	998	9.014	2197	2.583	1199
				2.187	1017

M.O.d.

MOE: 9174 Mpa σ_{max}: 51 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
585	1170	1754	2339	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
5.981	650	9.026	1940	3.045	1290
6.178	727	9.106	1975	2.928	1248
6.479	854	9.359	2081	2.880	1227
6.836	1006	9.611	2186	2.775	1180
7.088	1113	9.864	2287	2.775	1174
				2.881	1224

Physical testing

M.O.e.

MOE: 8749 Mpa $\quad \sigma_{max}$: 52 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}	ΔDeformation	ΔForce (N)
575	1150	1725	2300		
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.429	775	8.929	1785	2.499	1011
6.679	876	9.178	1883	2.499	1007
6.929	977	9.429	1980	2.499	1003
7.179	1077	9.679	2077	2.499	1000
7.305	1129	9.929	2172	2.624	1043
				2.524	1013

M.O.f.

MOE: 9998 Mpa $\quad \sigma_{max}$: 59 MPa

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}	ΔDeformation	ΔForce (N)
624	1249	1873	2497		
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.639	911	8.928	1980	2.288	1070
6.892	1029	9.180	2097	2.289	1068
6.959	1059	9.227	2119	2.268	1060
7.145	1147	9.353	2176	2.207	1029
7.198	1172	9.602	2289	2.405	1117
				2.291	1069

M.0.g.

MOE: 9557 Mpa σ_{max}: 56 MPa

Standard force [N] vs Deformation [mm]

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
745	1490	2235	2980	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.695	801	9.789	2257	3.094	1456
6.948	918	9.889	2304	2.942	1386
7.014	1035	10.116	2400	3.102	1365
7.202	1155	10.120	2403	2.918	1248
7.254	1275	10.340	2505	3.086	1229
				3.028	1337
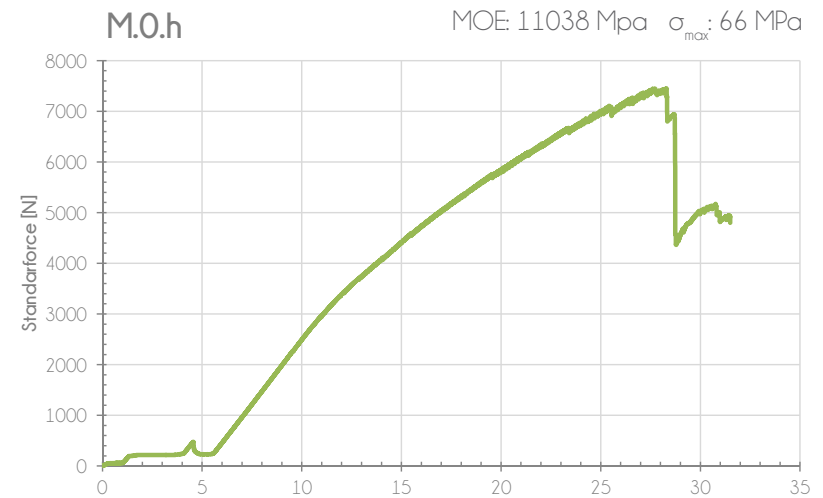
M.0.h

MOE: 11038 Mpa σ_{max}: 66 MPa

Standardforce [N] vs Deformation [mm]

0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		
608	1216	1825	2433	ΔDeformation	ΔForce (N)
V1	F1	V2	F2	ΔP (mm)	ΔF (N)
6.619	767	8.790	1878	2.171	1110
6.867	893	9.034	2003	2.167	1110
7.117	1018	9.277	2128	2.160	1109
7.204	1062	9.520	2254	2.316	1192
7.448	1189	9.727	2352	2.279	1163
				2.219	1137

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Physical testing

M.O.i. MOE: 9942 Mpa σ_{max}: 54 MPa
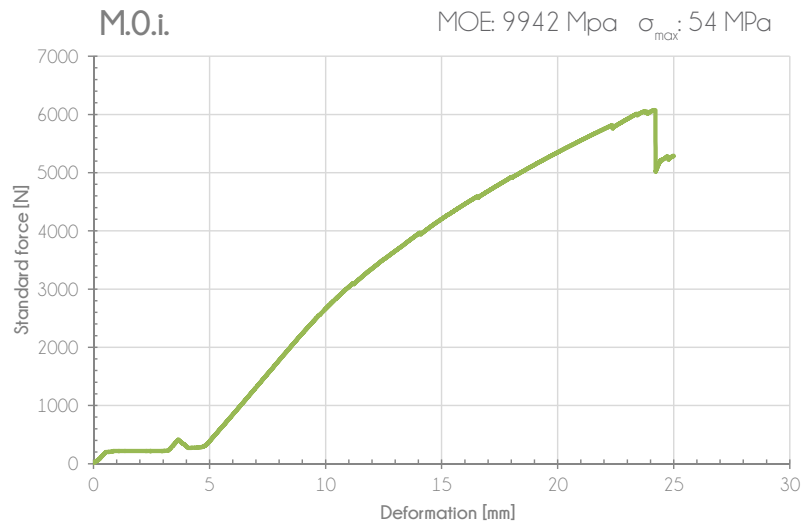
0.1 F_{max}	0.2 F_{max}	0.3 F_{max}	0.4 F_{max}		ΔDeformation	ΔForce (N)
694	1389	2083	2778		ΔP (mm)	ΔF (N)
V1	F1	V2	F2			
5.988	837	8.779	2139		2.791	1301
6.239	954	9.031	2252		2.791	1298
6.492	1070	9.283	2362		2.791	1292
6.744	1189	9.535	2473		2.791	1284
6.997	1307	9.788	2573		2.791	1266
					2.791	1288