Plastic Bamboo Connections

Transform plastic waste into a useful tool for remote and low-income areas

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Master of Science (MSc) thesis

Plastic bamboo connections - Transform plastic waste into a useful tool for remote and low-income areas.

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PREFACE

This report encompasses a graduation project submitted to fulfilment of the requirements for the title of Master of Science at the Delft University of Technology at the Faculty of Architecture and the Built Environment.

This research has the goal to empower people living in remote and low-income areas, with the ability to construct long lasting bamboo houses. When bamboo is constructed in a poor manner it only lasts for 3-5 years. After 3 years it is often covered in fungi and full of insects, resulting in an unhealthy living environment. To make the bamboo last for 30-50 years, alternative methods to cut, harvest, treat and construct are thoroughly described in this paper. Today bamboo is still seen as a poor man's timber. However, enlarging the durability of bamboo could change this view. This extended lifetime of the bamboo introduces a new challenge. Yet, the material's extended lifetime introduces a new challenge: no connection element or system is available nor affordable for people living in remote and low-income areas.

Another seemingly unrelated, but big problem the world is facing, is plastic waste. Plastic waste can be found everywhere in the world, on land and in the ocean. In a lot of countries proper waste treatment is lacking, and in remote areas it is often impossible to have any kind of waste treatment. Therefore, ways to locally solve this plastic waste problem should be found.

This work makes an attempt to solve these two problems at once. A standardised system for bamboo structures made from plastic waste is designed and developed. These bamboo connectors can be produced by relatively simple self built machines to be used as a self-help tool in low-income and remote areas.

ABSTRACT

This graduation project ''Plastic Bamboo Connections'' originates from a project called Bamboo Factory. A group of students, together with Bamboo Social and the Delft University of Technology, realized a Bamboo Factory in Esperanza, Nicaragua. In this factory bamboo can be treated and dried properly, making the bamboo last for 30-50 years, instead of the usual 3-5 years. The enlarged life expectancy unburdens the local people from reconstructing their houses every 5 years. To ensure this extended durability, the bamboo has to be lifted from the ground to keep it dry and the bamboo needs to be protected from direct sunlight by making a big overhanging roof. Next to the advantages of the treated bamboo, the extended durability of the bamboo also introduced a new challenge.

A technique to mount the bamboo, that lasts for 30-50 years is lacking in Esperanza. Traditional lashings are used to construct bamboo structures. However, these lashings tend to loosen in about 5 years. For the Bamboo Factory steel M10 screw thread, nuts and rings where used. A quick and strong system for constructing with bamboo. However, these materials aren't locally available in Esperanza and are too expensive. A new system needs to be found.

A proper waste treatment is lacking in Nicaragua. Waste can be found everywhere on the streets and in rivers, about 50% of the waste is plastic waste. In remote areas like Esperanza it is even more difficult to get rid of waste in a sustainable way. Resulting in incineration of the waste, which includes plastic. The goal of this project is to find a way to transform this plastic waste into a standardized system that enables local people in Esperanza to build with bamboo. When recycling contaminated plastic, drastic deterioration of the mechanical properties can be expected. Mechanical tests are performed on the recycled plastic to get an insight of the quality and the possible applications.

A relatively simple injection moulding machine is build in order to reprocess the plastic waste. The standardized set of connectors are designed to be produced with the injection moulding machine. In order to construct with this simple set of connectors, only a hammer and a saw are needed. Making it very affordable and feasible for people that live in low income and remote areas.

CONTENTS

1. RESEARCH DEFINITION

1.1.1 INTRODUCTION

Bamboo is a fast-growing grass that can be found naturally on every continent except for Europe. When locally available this renewable, strong, flexible and environmental friendly grass is a very sustainable building material. Nevertheless, bamboo is mostly seen as the ‘’poor man’s timber’’ due to its short endurance. Untreated bamboo lasts for a maximum of five years. However, bamboo is very affordable, when locally available and enables lower-income groups to build their own houses from this material. Traditional techniques with ropes and leather are used to connect the bamboo culms. These techniques are sufficient for constructions that last for a maximum of five years. Today, treatment techniques are available which prevent the bamboo from being attacked by fungi and insects. Well treated bamboo has a life expectancy of 50 years without losing its structural properties(“Bamboo Construction Source Book,” 2013). Extending the life of bamboo creates a few challenges; the traditional connections of rope or leather will not suffice anymore.

Multiple connections have been developed varying from traditional and simple techniques to high-tech, sophisticated connections produced by expensive machinery. Logically, these high-tech techniques aren’t accessible for people with a low income that live in remote areas. What kind of connection lasts 50 years and is feasible for everyone?

Plastics are available almost everywhere in the world, in the form of packaging, bottles etc. Waste treatment for plastic is often lacking or inefficient, especially in remote areas. In most remote areas the only waste treatment is burning or landfill. What if we can re-use or recycle this commonly burned plastic to create a connection for bamboo structures that last for a decent amount of years?

1.1.2 PROBLEM STATEMENT: Effects of Treatment

Treatment is intended to extend the durability of bamboo; protecting it from fungi, insects and improving aesthetics. The chemical and most effective treatments extend the life expectancy to 30-50 years. If bamboo degrades in 3 to 5 years, it is obvious that one doesn’t invest too much time, money and effort to create a proper bamboo house or construction. This contributes to the image of the ‘’poor man’s timber’’. However, when the life expectancy of bamboo can be enlarged by treating it right; better, more beautiful and bigger bamboo constructions can be made, and more effort can be put in. The next challenge would then lay in the joinery. In remote areas modern standardized elements like bolts are not available or simply too expensive. Also, traditional lashing and pin techniques won’t last the extended life expectancy of the treated bamboo.

A joinery system needs to be developed with low tech techniques whilst using a material readily available. This leads us to the problem statement.

Problem statements

- There is no **standardized system** for **bamboo connections** that is available and affordable for people living in **low-income and remote areas**, that can last for more than **5 years**.

Plastic is burned besides other waste, unavoidably due to the lack of better waste treatments. Burning plastic waste is a high health risk for people and the environment.

- A proper **waste treatment is lacking** in Esperanza, resulting in **incineration** and waste scattered around the village and in the rivers.

1.1.3 RESEARCH OBJECTIVE

The objective consists of three main points:

(1) Designing a set of connections that enables one to build a bamboo structure with recycled plastic connection elements.

(2) Degradation of the mechanical properties of the plastic can be expected, therefore the reprocessed plastic needs to be tested.

(3) The connections are produced with low tech techniques and extend the durability of the plastic waste and the bamboo houses.

Boundary conditions
The plastic waste needs to be collected in the region of Esperanza. It would be inconsequential to transport plastics into Esperanza in order to recycle it in a low tech manner.

Constraints
The only electricity available in Esperanza is generated by small gasoline powered generators and solar panels. As it is a poor region, low investment and running costs are a constriction. Resulting in simple and easy to operate machines.

Assumptions
Stating that the plastic waste will be sorted, shredded, washed, dried and reprocessed with simple methods. Degradation will deteriorate the material properties of the end product. It is important to take this into account during the design process.

1.1.4 RESEARCH QUESTION

Having described the subject and objectives the research question can be formulated.

‘‘Is it possible to design **a set of plastic connections** that enables **people in low-income and remote areas** to build a **bamboo construction** that lasts for **30-50 years**? ‘‘

Sub questions:

(1) What steps do you need to perform in order to make bamboo last for 30 years?

(2) How many different types of connections do you need in order to build a bamboo structure?

(3) What type of plastic is available and suitable to create connections and how can it be processed?

(4) How can plastic be reprocessed in a way that is feasible for everyone?

1.1.5 RELEVANCE

Extending the life expectancy of bamboo by treatments and well designed constructions, improves the living quality of the people. It will no longer be necessary to rebuild homes every 3-5 years, saving money and time. Additionally, using bamboo instead of hard woods attenuates deforestation. Bamboo can be harvested after 4 years in comparison to hard woods that take decades to grow. Lastly, burning plastic among other waste is a very harmful practice to ones health and the environment. Collecting plastic in return for money or goods can create a way to generate income. This can be beneficial for the collector, the plastic user and the environment.

2. LITERATURE REVIEW

Figure 2.1 Project location, Esperanza, Nicaragua.

2.1 BAMBOO

2.1.1 BACKGROUND

The idea of developing plastic connections for bamboo originates from a project called BAMBOO FACTORY. The BAMBOO FACTORY is a project from BAMBÚ SOCIAL, a non-profit organization which aims at sharing knowledge and expertise as an alternative to conventional building methods. The Bamboo Factory Team consisted of a mix of Dutch, Italian and Nicaraguan students, young professionals and a experienced carpenter. All phases of the Bamboo factory were executed by the team, from preparation to the execution. During this whole process we successfully worked together with the TU Delft, the community of Esperanza, and local partners in the R.A.A.N. region.

The BAMBOO FACTORY was a seven-month lasting project of BAMBÚ SOCIAL, the first three months consisted of designing, preparing and funding the project, and in the last four months the actual bamboo treatment facility has been built. The Bamboo Factory is built together with the local people of Esperanza to ensure involvement. The aim of the Bamboo Factory Team and BAMBÚ SOCIAL is to enable people in remote communities along the Rio Coco to create affordable, sustainable buildings with local materials.

R.A.A.N.
The R.A.A.N. region is the home of the indigenous Miskito Indians. With their own culture and language they form a separate ethnic group in Nicaragua. Moreover the R.A.A.N. region is the poorest region of Nicaragua. The R.A.A.N. economy is mainly based on agriculture. Approximately 95% of the people live off their crops and under the extreme poverty line (less than 1$/ day).

Esperanza
Esperanza (Figure 2.1) is one of the biggest villages along the Rio Coco. Therefore, it functions as a centre for small surrounding villages. It counts approximately 3000 inhabitants. Despite its size and the amount of inhabitants every household lives from their own crops. The crops; mostly of rice and beans, are grown on land outside the village to provide the families for food. Only a few people get their money and food from doing something else. Like the priest, carpenter, boat men and local disco owner do not live from their own crops.

Location
Esperanza is a 7 to 10 hour boat ride upriver from the second biggest city in the R.A.A.N. called Waspam. Wooden boats with a gasoline motor are used for public transport. Most locals with a boat have a hollowed out tree, what makes a very narrow and unstable boat. Waspam is the only place in the region accessible by plane; every other community in the region is only accessible by boat from there.

2.1.2 BAMBOO GENERAL

Bamboo has 7-10 subfamilies of genres and there are 1575 different species currently known, ranging from wood like material to bamboo herb (Suhaily, Khalil, Nadirah, & Jawaid, 2013). Bamboo is one of the oldest and most versatile building materials with many applications, from buildings to food. For Europeans, bamboo is an exotic plant, but on all the other continents it has already been used for thousands of years (Figure 2.2). Reducing the amount of available hard wood due to deforestation requires a replacement that is sustainable and renewable as a building material. An oak and equal species take 30 to 50 years to mature. Bamboo can be harvested 3 to 5 years after being planted and during this process it generates 35% more oxygen than an equivalent stand of trees. Unfortunately, bamboo is often restricted to temporary structures and lower grade buildings due to its short life expectancy and difficulties in jointing. Improvements in jointing, preserving, engineering and coding have to be made in order to transform this ‘’poor man’s timber’’ into a principal engineering and construction material (Kumar, Shukla, Dev, & Dobriyal, 1994).

2.1.3 DURABILITY

Bamboo can be damaged by fungi and insects during the drying process and its final use. Insects deteriorate bamboo, molds colonize it, staining fungi discolour it and rot fungi degrade it (Schmidt, Wei, Tang, & Liese, 2013). Untreated bamboo has a life expectancy of 3 to 5 years. The vulnerability of bamboo is an annoyance to its applicability. Compared to wood, bamboo can be treated to improve the durability and prevent fungi and insects from damaging the bamboo. As it has been used for thousands of years, a strong variety of techniques is available, each with their pros and cons. There are no radial pathways in the culms tissues, in addition the conductivity of the tissue is relatively low, making treatment of bamboo a difficult and time-consuming process. As soon as the bamboo is harvested a wound reaction blocks the conduction vessels, the culms thus should be treated immediately after harvesting (Bhawan & Marg, 2007). Causes of degradation are shown in Figure 2.3.

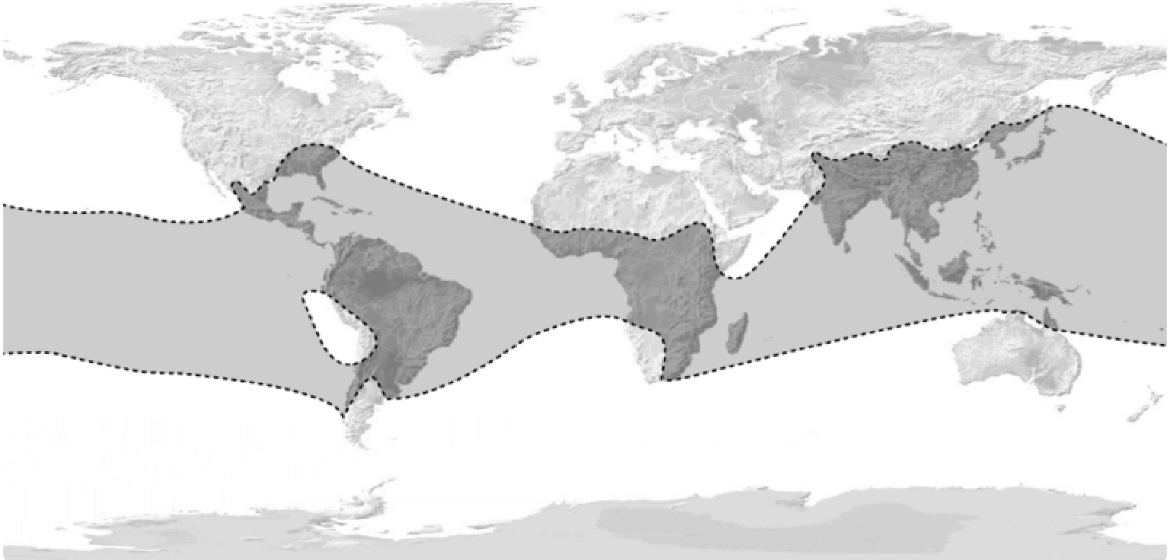


Figure 2.2 Bamboo growth areas (Bamboo growing areas, 2014).

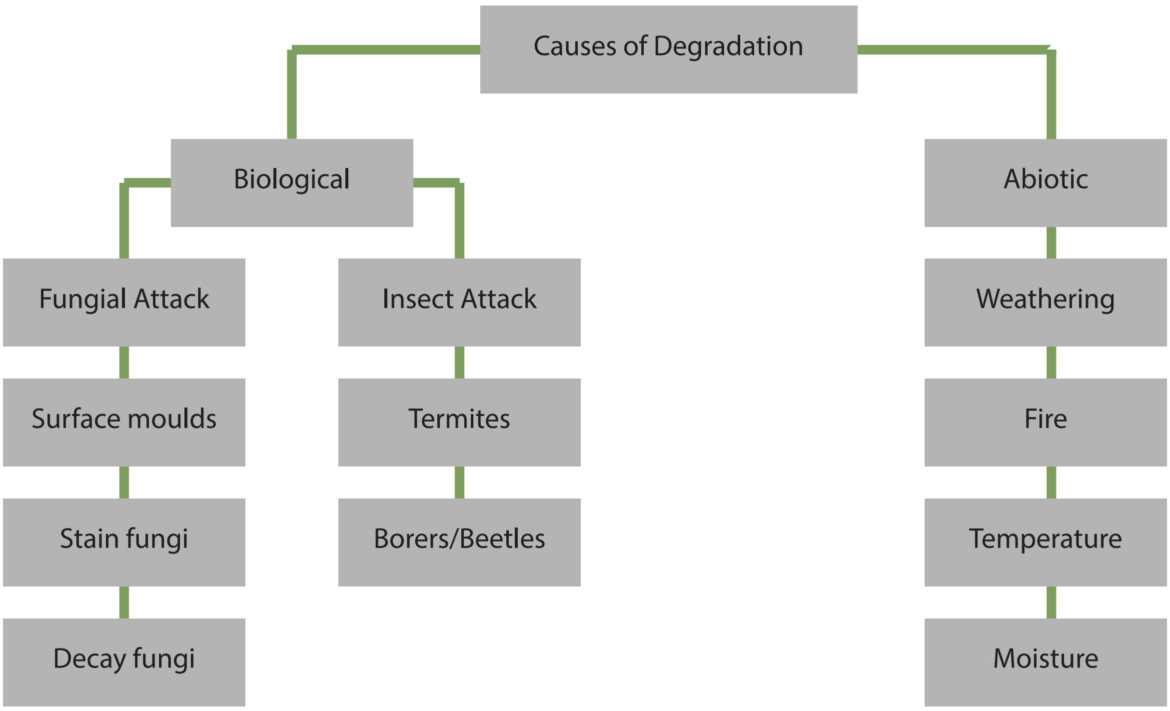


Figure 2.3 Causes of Degradation.

2.1.5 BAMBOO IN ESPERANZA

The main species of bamboo available in Esperanza are Gadua Amplexifolia , Gadua Aculeata and Gadua Macclurei. For the Bamboo Factory we used the most common specie: the Gadua Aculeata. The Gadua Aculeata can grow up to 15 meters high and matured culms have an average diameter of 100-150 mm.

2.1.6 HARVESTING METHODS

The methods used to harvest bamboo can have a great impact on the plant system and the culms. When the harvesting is executed correctly degrading factors will lower and the culms will retain their natural strength and form.

Time
Bamboo needs to be harvested during the dry season. In this season the starch content is significantly lower, which lowers the chance of degradation caused by fungi and insects. In addition, the culms are drier making it less likely to split or crack.

Selection
It is important to harvest the right bamboo. Only mature bamboo (> 3 years) is fit for constructions. White tarnish is a sign of maturity. Leaving 40% of the culms of a bamboo system will enhance the growing speed of the new culms, harvesting more will damage the bamboo plant and its roots.

Technique
The bamboo needs to be cut at the right position. Cut the bamboo 10-15 centimetres above the ground and just above the node. Cut it in such a way that the water can run out. Standing water can serve as a great habitat for mosquitoes and can stimulate the growth of fungi which can eventually harm the root structure and kill the plant.

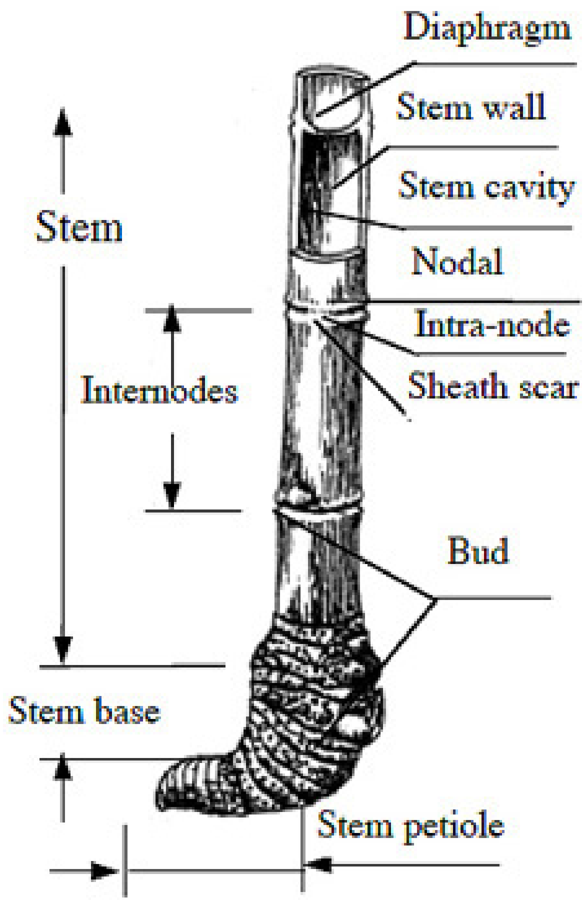


Figure 2.4 Stem anatomy (GuaduaBamboo, 2011).

2.1.7 TREATMENT METHODS

Non-chemical
Non-chemical treatments are cheaper compared to chemical treatments. Thus, it is often used in remote areas where special equipment and money is absent. Not using chemicals is better for the environment, however it is certainly not as effective (Arya, 2010)

Leaching
Leaching (Figure 2.5) helps to remove the starch from the culms. The culms should be placed in the water for around 2 weeks. When a closed tank is used, the water needs to be refreshed to prevent growth of bacteria. Leaching is recommended when more flexibility is needed. After leaching the bamboo needs to be dried for a week in the shade to prevent the bamboo from cracking.

Smoking
The bamboos are placed above a fireplace (Figure 2.6). Smoking the bamboo removes the moisture in the culms, this eliminates the biological degradation. Smoke drying also reduces splitting.

Clump curing
Bamboo is stored vertically for a few weeks with the leaves and branches intact. The still living bamboo consumes its reserves and by doing this it reduces the starch content. This will keep insects from eating it (Arya, 2010).

Chalk
Chalk (Figure 2.7) is used in an experiment for Bambú Social as the borax and boric acid where hard to transport to Esperanza and hard to dispose after use. For this experiment 2 gram / litre is used to submerge the bamboo for a week. Until now the bamboo culms show no signs of fungi or other deterioration.

Chemical
Boucherie
Preservative is forced in the bamboo culms by either gravity or air pressure. The treatment is finished when the preservative drips out of the end of the bamboo in a certain concentration. Special equipment is needed (Figure 2.8), however the equipment that is needed for this technique is inexpensive.

Dip Diffusion method
Culms, strips or mats of bamboo are dipped in a chemical solution. The bamboo should be pressed down so it is completely immersed in the solution. A Hole should be drilled in each inter-node to speed up the process. Treatment of the culms takes 1 week, and strips or mats take about 3 days. The treated bamboo should dry for a week, protected from the sun and rain (Arya, 2010). For the Bamboo Factory we used Borax and boric acid (Figure 2.9 and Figure 2.10), with great result. However, it was hard to deposit this in a sustainable way.

Figure 2.5 Bamboo Leaching and washing.

Figure 2.6 Smoke treatment.

Figure 2.7 Chalk treatment.

Figure 2.8 Bamboo immunization (Bambu Tico, 2018).

Figure 2.9 Borax and Boric acid treatment.

Figure 2.10 Treatment bath.

2.2 PLASTIC

2.2.1 WASTE IN NICARAGUA

Waste is a huge problem in Nicaragua. In most places across the country, any form of waste treatment is lacking. In most big cities waste is only collected on the main streets. People that don't live close to a main road, need to walk large distances and this results in the waste being burned or put in a landfill. The small portion of waste that is collected still ends up in a fire or a landfill most of the time. Plastic is not seen as valuable or harmful by the locals. People will toss their wrappers out of the window of a local bus or burn it in front of their houses. This waste problem is enlarged by the increase of tourists visiting the country (Figure 2.11).

Only 8 % of the materials used in Nicaragua is made out of recycled material ("Nicaragua ready to Export its Recycled Material/Waste," 2013). A bulk of Nicaragua's waste is exported and generates millions of dollars. This sounds interesting, however waste that is recycled and traded locally has more positive effects on the economy, environment and it also has social benefits. When the waste is brought to a local recycle plant and transformed into valuable pallets or products, it can improve the local economy and it cleans the streets in a healthy way. In addition, it eliminates the cost and CO_2 emissions of shipping the waste large distances all over the world to recycle plants elsewhere.

It is clear that recycling waste can be improved on many aspects all across the country, but areas like islands or very remote areas like Esperanza are even worse. Shipping products to these areas is not a big problem, but collecting all the waste and shipping it to a recycling plant seems to be complicated and expensive (Chamorro, 2017). In these areas basically all the waste is burned or thrown on the streets or in rivers. In a region where they live under the poverty line (1$/day), it is unbelievable that a material with such potential value is burned.

The plastic is wasted because there is no use for the plastic yet to be recycled. A way to add value to this badly appreciated material, is introducing recyclables into building applications. When the demand for recycled plastics increases, the way it is treated will change. Besides this unemployed people could collect plastic in return for money, food or goods. Resulting in cleaner streets, rivers, beaches and less poverty.

2.2.2 PLASTIC WASTE

Waste in Nicaragua is composed 50% of plastic, 25% cans and 25% of other materials like paper, cardboard and glass (Ohimacher, 2011). The biggest part of the plastic waste is plastic bottles. Plastic bottles are often made from PET and HDPE and the caps are mostly made from HDPE. In areas like Esperanza all these bottles will eventually be burned. Recycling or reusing these materials would have a great positive impact on the environment, economy and socially. But how can these plastics be processed from waste into a product in these remote areas, where equipment, knowledge and money are scarce? Based on the availability and the possibilities the focus of this thesis will be on PET and HDPE.

Figure 2.11 *Trash in the Seagrass beds around Big Corn Island (McDonald et al., 2014).*

2.2.3 POLYETHYLENE TEREPHTHALATE (PET)

Polyethylene Terephthalate, labelled as #1, is a thermoplastic polyester, known by its strength, transparency and safety (Figure 2.12 and Figure 2.13). In order to get a high molecular weight, impurities need to be removed. The high molecular weight (MW) is essential for giving the PET strength, stiffness, toughness and creep resistance (Figure 2.14). Simultaneously PET provides flexibility, preventing it from cracking. PET has an excellent melt flow and a very good surface finish. 55 million tons of polyesters that was produced in 2012, largely consisting of PET, was mostly used for packaging and plastic bottles. It is undesirable to put these large amounts of valuable materials in a landfill after only a single use. PET is not very biodegradable and the process of making it produces a lot of greenhouse gasses and this process depletes our recourses. (López-Fonseca, Duque-Ingunza, de Rivas, Flores-Giraldo, & Gutiérrez-Ortiz, 2011).

UV durability
Products exposed in the outdoor can potentially be affected by UV radiation in the 290-400 nm range from sunlight. UV degradation can be measured in terms of the loss of mechanical properties. PET has a poor durability for UV radiation, meaning that PET requires protection for long-term UV radiation. Without protection PET will last for days or a few weeks (“CES EduPack 2017,” 2017).

Limitations
PET is easily affected through heat degradation in amorphous form, is very flammable in its pure form, can produce harmful toxics while processing and has a high mold shrinkage (“CES EduPack 2017,” 2017).

Figure 2.12 Plastic recycle logo PET (Tomia, 2006).

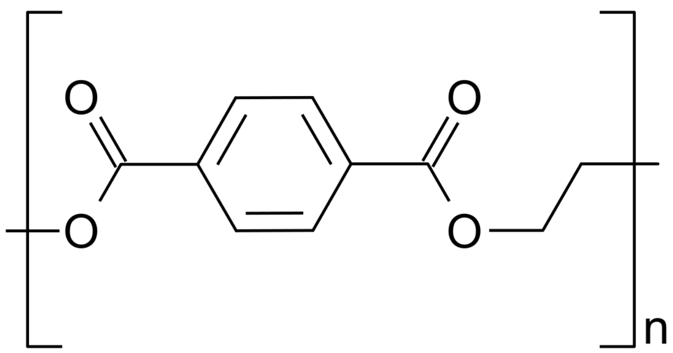


Figure 2.13 Structure of poly(ethylene terephthalate), PET (Wilc0NL, 2015).

Composition overview	
Compositional summary	(CO-(C6H4)-CO-O(CH2)2-O)n
Material family	Plastic (thermoplastic, amorphous)
Base material	PET (Polyethylene terephthalate)
Polymer code	PET
Physical properties	
Density	1.29e3 - 1.39e3 kg/m^3
Mechanical properties	
Young's modulus	2.8 - 3 Gpa
Tensile strength	55 - 60 Mpa
Elongation	280 - 320 % strain
Compressive strength	50 - 60 Mpa
Coefficient of thermal expansion	115 - 119 µstrain/˚C
Processing properties	
Melt temperature	260 - 280 ˚C
Durability	
Water (fresh/salt)	Excellent
UV radiation (sunlight)	Poor
Flammability	Highly flammable
Water absorption @ 24 hrs	0.14 - 0.18 %

Figure 2.14 Reference data for PET according to CES database.

2.2.4 HIGH DENSITY POLYETHYLENE (HDPE)

High-density polyethylene (HDPE or PEHD) is a plastic made from petroleum. Labelled as #2 plastic (figure 14), this type of plastic is used most in the form of bottles, bags and other packaging. HDPE can also be found in furniture, garden equipment, office products and the automotive industry ("What is HDPE?," n.d.). HDPE is opaque, has a relative high tensile strength and it doesn't transmit any chemicals into the product that is contained. HDPE is stronger than standard PE and acts as a barrier against moisture. HDPE is a relatively hard material, making it resistant to impact. HDPE is non-biodegradable thus putting it in landfills isn't a sustainable solution (Figure 2.17). In addition, HDPE is a very easy polymer to recycle and it is more cost-efficient to recycle than to use virgin HDPE (Thomas, 2012).

UV durability
Products exposed in the outdoor can potentially be affected by UV radiation in the 290-400 nm range from sunlight. UV degradation can be measured in terms of the loss of mechanical properties. HDPE has a fair durability for UV radiation, meaning that HDPE requires protection for long-term UV radiation. Without protection HDPE will last for months or maybe a year ("CES EduPack 2017," 2017).

Limitations
HDPE burns very easily, it can easily crack under environmental stress, the poor UV resistance and high mold resistance ("CES EduPack 2017," 2017).

Figure 2.15 Plastic recycle logo PE-HD, Polyethylene. (Tomia, 2006).

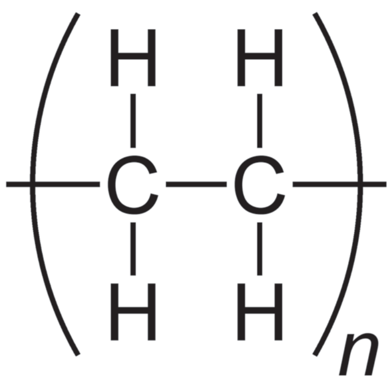


Figure 2.16 Skeletal formula of a polyethylene monomer. (Magmar, 2014).

Composition overview	
Compositional summary	$(CH_2\text{-}CH_2)_n$, typical n=10,000-20,000
Material family	Plastic (thermoplastic, semi-crystalline)
Base material	PE-HD (Polyetylene, high density
Polymer code	PE-HD
Physical properties	
Density	952 - 965 kg/m^3
Mechanical properties	
Young's modulus	1.07 - 1.09 Gpa
Tensile strength	22.1 - 31 Mpa
Elongation	1.12e3 - 1.29e3 % strain
Compressive strength	18.6 - 24.8 Mpa
Coefficient of thermal expansion	106 - 198 µstrain/˚C
Processing properties	
Melt temperature	177 - 274 ˚C
Durability	
Water (fresh/salt)	Excellent
UV radiation (sunlight)	Fair
Flammability	Highly flammable
Water absorption @ 24 hrs	0.005 - 0.01 %

Figure 2.17 *R*eference data for HDPE according to CES database

2.2.5 PLASTIC RECYCLING

Recycling plastic is the best option for economic and environmental reasons. Multiple grades of recycling are available (López-Fonseca et al., 2011).

1) Primary recycling. Includes the recycling of pre-consumer waste produced by the industry.

2) Secondary recycling. Covers the reprocessing of the waste, shredding, melting, extruding and injecting post-consumer waste.

3) Tertiary recycling. Chemicals are used to gain back the pure components in order to reprocess.

4) Quaternary recycling. Energy recovery by incineration.

Primary recycling: Pre-consumer waste is waste that doesn't reach a consumer. This waste is mostly manufacture waste coming from the industry. The advantages of pre-consumer plastic waste is that it doesn't contain as much contaminants as post-consumer waste. Pre-consumer plastic is not available in areas like Esperanza as there are no industries. The gross of the waste is post-consumer waste. Making primary recycling impossible, or very expensive and it would be fraudulent bringing pre-consumer waste to Esperanza.

Tertiary recycling: Chemical recycling of post-consumer
Chemical recycling is accomplished by depolymerization into monomers or oglimers. Chemicals like water, methanol and EG are used for the depolymerization. The requirement of needing chemicals is not convenient in remote areas. In addition chemical recycling is relatively expensive, making it unlikely to be done in isolated areas (Awaja & Pavel, 2005).

Quaternary recycling: Energy recovery by incineration
Incineration of waste is done when it is impossible or too expensive to recycle chemically or mechanically. Often plastic waste is of bad quality or it is mixed with other waste. Incineration is the last and most undesired choice, because it turns materials with potential into CO2, heat and other bad greenhouse gasses. However, these gasses can be neutralized. The heat produced by the incinerator can be used by distributing it through heat networks. Replacing heat that is produced by for example coal, making it a good alternative. Energy can also by produced by incinerating waste, however the efficiency is very low. Recovering heat from incineration is a complex process. Impossible to do in Esperanza.

In a remote area like, Esperanza Nicaragua, secondary recycling is the obvious option. Incinerating the waste is what they do now (Figure 2.18), but they don't have the equipment, knowledge and resources to generate energy from it. Burning waste like plastic produces toxic gasses, which are bad for health and environment.

Secondary recycling: Mechanical recycling of post-consumer
In the process of recycling post-consumer plastic by reprocessing, minimizing the amount of contamination is essential. Contamination drops the molecular weight resulting in a weaker and less durable end product. Secondary recycling is relatively simple, has a low impact on the environment and has low costs. The down side is that the editability degrades caused by thermal and hydrolytic degradation. It is necessary to minimize these degradation processes. Mechanical recycling is done in multiple steps. The plastics need to be sorted, shredded in flakes, washed and dried concerning the minimization of contaminants (Al-Sabagh, Yehia, Eshaq, Rabie, & ElMetwally, 2016).


Figure 2.18 *B*urning Plastic Waste is Dangerous to Health. (Ika Kumala Dewi, 2018).

2.2.6 CONTAMINANTS REMOVAL

Sorting
Different types of plastic need to be separated. A mix of plastics will affect the purity and properties, making the end result unreliable and even harder to recycle after its use. Most PET and HDPE available in Esperanza will be in the shape of packaging and bottles and are relatively easy to recognize. Paper, glue, rings and caps should be removed as much as possible. HDPE has a specific density of 0.93 to 0.97 g/cm3. This is much lower than that of PET which is 1.43-1.45 g/cm3, meaning that these plastic polymers can be separated by using the sink-float separation (Thomas, 2012).

Shredding
The sorted waste needs to be shredded in small flakes, making it easier to clean the plastic, removing possible remained contaminants. Shredding of plastic can be done by simple machinery with low investment involved. The small flakes can be processed more easily and consistently.

Washing
This step also includes the removal of contaminations. As mentioned above any kind of contamination can cause deterioration of the POSTC-PET. Washing with water can be done best in two steps. The first wash is a 2% NaOH solution at 80 °C followed by a cold wash with normal water. The PET flakes can also be washed with another solvent in water. TCE is applicable for washing PET flakes, however it is a chemical and toxic solvent (Al-Sabagh et al., 2016). Again, using toxic chemicals is discouraged in remote areas, it is most likely to be unavailable and disposing the chemicals in an environmental friendly manner is nearly impossible. Since this project focus is on remote areas, washing with only water is preferred.

Drying
A crucial part of re-processing plastic is drying the PET flakes, any moisture content can cause hydrolytic degradation. In the industry flakes are dried in temperatures between 140 and 170 °C during 3 to 7 hours. Admirably the moister content of the flakes is below 50 ppm. This can be achieved by applying a temperature of 170 °C for 6 hour (Awaja & Pavel, 2005).The scarcity of electricity and the remoteness of an area like Esperanza, makes it hard to create such a controlled environment for that amount of time. Another solution must be found. In the surroundings of Esperanza a lot of rice is produced. After the harvest the rice is dried on plastic sheets in the sun to preserve it. This technique might be a possible method for drying the plastic flakes. Although sun can affect the material properties. Tests have to ensure if this reduces the moisture content enough, without affecting the material properties too much.

2.2.7 MELT REPROCESSING

The cleaned and dried flakes can be reprocessed in an extrusion, injection or pressing machine (Figure 2.19). These machines exist in a range of low tech equipment to very sophisticated machines. The sophisticated machines are consistent, quicker and designed for large quantities. Logically these machines are very expensive and need to be operated by highly skilled people. Unfortunately, this won't be feasible in poor and remote areas like Esperanza. In these areas a simpler, easier and cheaper technique or techniques have to be found. Using low tech and simpler techniques, an assumption can be made that the quality and properties of the recycled material will differ from the normal values. The main disadvantage of mechanical re-processing is the reduction of the molecular weight (MW). Strategies must be found to minimize the reduction of the MW. In order to safely use the recycled plastic in buildings and structures, the 'new' properties have to be tested and analysed.

Re-processing plastic is an exact process. Factors like injection speed, melting temperature and the cooling time can affect the end result in a negative way. Commercial PET melts between 255 and 266 °C (Awaja & Pavel, 2005). The extrusion of PET to produce granules is done at 280 °C, these high temperatures make it hard to carry out in this situation. When processing PET a low screw speed is required. HDPE is very suitable for extrusion and injection moulding. The melting point of HDPE lays around 130 °C.

Disadvantages of melt reprocessing
Thermal and hydrolytic degradation causes reduction in viscosity and oligomers caused by depolymerization can alter the printability, dye ability and other material properties of the end product (Dulio, Po, Borrelli, Guarini, & Santini, 1995).

Figure 2.19 Machines overview. (Precious Plastics, 2018).

2.3 HOW TO BUILD WITH BAMBOO

2.3.1 EXISTING JOINTING TECHNIQUES

4.1 Bamboo jointing
Bamboo has a lot of advantages when used for housing, bridges, furniture etc. It is cheap, sustainable, strong and flexible. However, the difficulty lays in the joints of the culms. Bamboo culms are round, and the diameter varies, which creates difficult connections in the knots. Bamboo is hollow making it impossible to use screws, as they cause the bamboo to crack. Being a natural material, lengths, shape, curvature and quality vary. These problems are solved with techniques ranging from traditional, using low tech equipment to industrial and modern elements (RWTH Aachen, 2002).

Lashing

Traditional lashing (Figure 2.21) was the first connection used for bamboo. Natural fibres like sisal, palm or green bamboo strips are used. The fibres are watered before making the lashing. While the fibres dry the fibers become shorter, resulting in a stronger connection (RWTH Aachen, 2002). The variety of knots is great, but it is time consuming and requires some experience. When executed right a lashing knot is strong and flexible. Lashing is often used for scaffolding (Figure 2.22). Natural fibres don't last for many years, so they need to be replaced relatively often. Therefore, other materials like polypropylene ropes were introduced. Lashings can be used in combination with pinning to make an even stronger connection.

Pinning is often combined with positive fitting connections. Special cuts are made like the ''boca de pescado'' to empower a wooden connection with a pin and a wedge.

Advantages:
- Low tech machinery
- Cheap
- Available in remote areas
- Low tech machinery
- Quick

Disadvantages:
- Tend to loosen in few years
- Weak
- On the outside of the bamboo

Figure 2.20 Reference connections

Figure 2.21 Leather lashing BAMBU NATURAL

Figure 2.22 Scaffolding rope connection

Steel bolts or pinning

For steel bolt connections (Figure 2.25) threaded rods are used with washers and nuts on both ends. With steel bolts more complex connections can be made quicker and with more ease. Sometimes concrete is poured in the most critical bamboo to absorb shear stresses. However, concrete inside bamboo can increase the chance of cracks. Steel bolt connections are pin connections, therefore in order to make a stable construction, triangles need to be made (Vahanvati, 2015). Steel bolts are standard elements and available almost anywhere in the world, except in rural areas. However, these elements are more expensive than the traditional connections.

Advantages:
- Complex connections
- Quick
- Standard elements
- Strong triangular constructions
- Mostly inside of the bamboo

Disadvantages:
- Relative expensive
- Not available in remote areas
- Out of vision

Figure 2.23 Plastic bolts and rivet

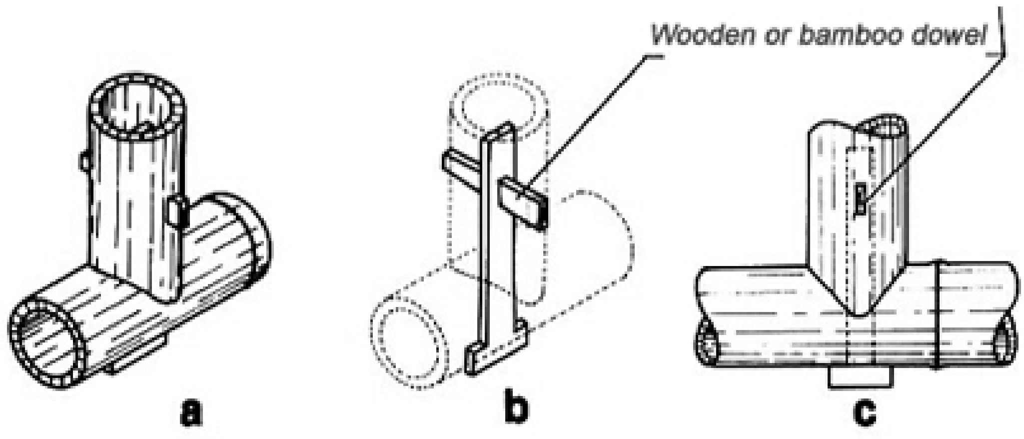


Figure 2.24 Wedge system for perpendicular bamboo connection

Figure 2.25 Bamboo joint. (Guaduabamboo, 2009).

Hubs and Clamps

A hub connector (Figure 2.27 and Figure 2.28) mostly consists of a ring or centre connector. Hubs are often combined with clamps to connect to the bamboo. Hub connectors facilitate a connection for many bamboos in one knot. These kinds of connections are frequently seen in geodesic domes or other geometric constructions. A disadvantage of hubs is that there are no standard systems for bamboo, due to its changing diameter and shape. This makes it relatively complex and expensive.

Advantages:
- Facilitates many bamboo connections in one point
-Ideal for geometric shapes.

Disadvantages:
- Custom
- Expensive

Brackets and plates

Brackets and plates (Figure 2.26) facilitate a connection of bamboos in one plane. This type of connection is often used for trusses. The plates are made of steel or plywood and are connected to the bamboo with bolts.

Advantages:
- Connections in one plane
- Quick
- Strong

Disadvantages:
- Custom made brackets/plates
- Also need bolts

Figure 2.26 *Brackets and plates. (*Munir Vahanvati, 2015).


Figure 2.27 *Hub connectors.* (Munir Vahanvati, 2015).


Figure 2.28 *Hub connectors.* (Munir Vahanvati, 2015).

2.3.2 BAMBOO CHARACTERISTICS

Making strong, durable and aesthetically pleasing connections is rather complicated, because bamboo is a natural material. It is hollow, tapered and varies from shape and diameter. Bamboo's strength is along its length on the longitudinal axis. Bamboo has to be selected, treated, dried and constructed in the right way in order to create a durable construction. When designing a bamboo joint, it is very important to keep these constraints in mind. Although building with bamboo has existed for a long time, traditional joints don't use the properties of bamboo to its fullest potential and modern connections need to be custom made and are therefore expensive and complicated. Proper information about bamboo connections is lacking. In order to lose bamboo's image of ''poor man's timer'' a standard joinery system has to be designed and tested. With a standard set of connections bamboo can become a popular construction material available and suitable for everyone(Schröder, 2009).

Use the right materials in the right way
The usage of bolts tend to crack bamboo, due to the forces on the transverse direction. Bamboo has nodes, it is important to use these strong spots, and make connections near the nodes. If it is impossible to achieve this on both sides, use wooden inserts or a fitting bamboo with a node (Figure 2.30). Make basic cuts, this doesn't require heavy equipment, a set of traditional tools will do (Figure 2.29). Bamboo doesn't last long when exposed to the elements (Figure 2.31). Keep the bamboo construction dry and out of the sun, using a big overhanging roof. Keep the bamboo from the ground to prevent moisture from the ground damaging the bamboo. This can be done by using a hard wood or concrete foundation. Keeping the bamboo dry and out of direct sunlight will simultaneously protect the plastic connectors.

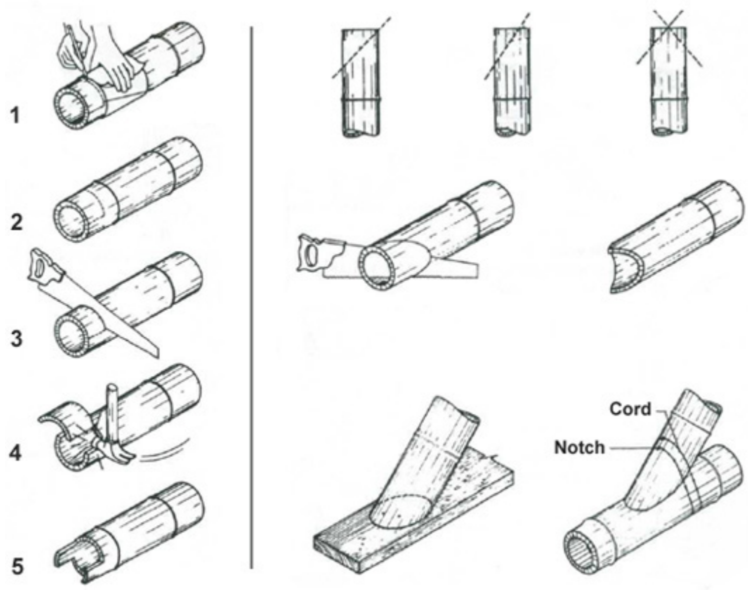


Figure 2.29 Bamboo cuts. (Guaduabamboo, 2009).

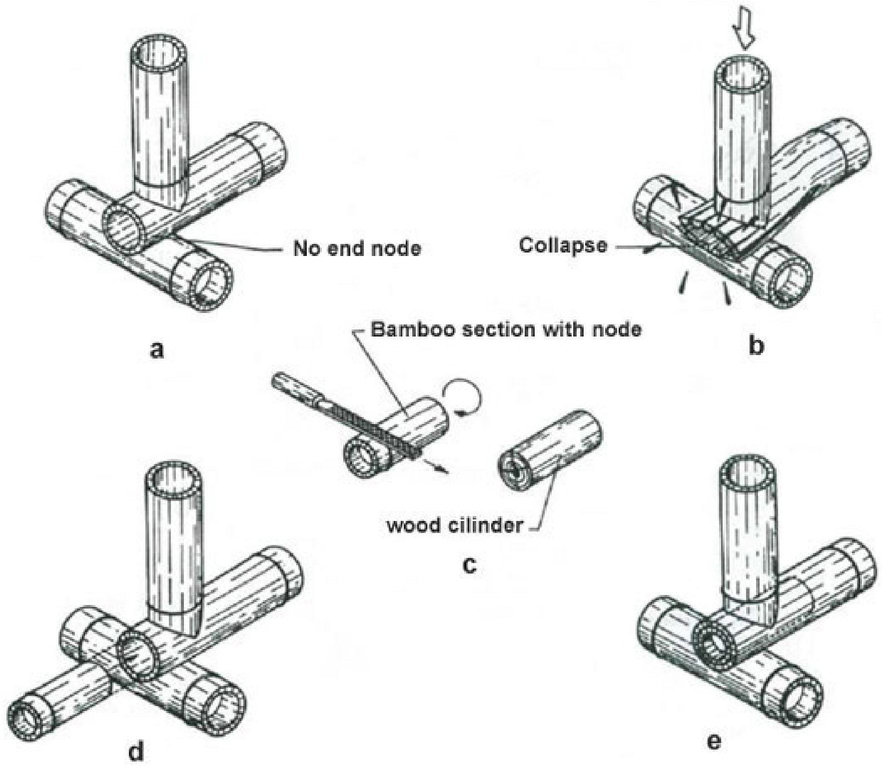


Figure 2.30 Bamboo nodes. (Guaduabamboo, 2009).

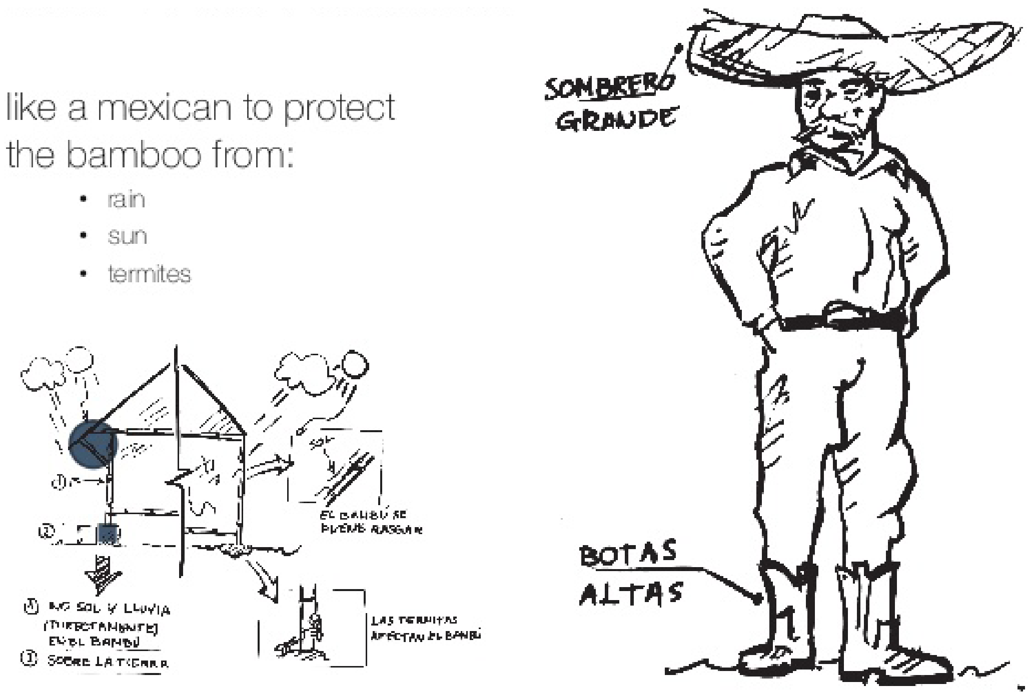


Figure 2.31 Design with Bamboo. (Machgeels, (2014).

2.3.3 ESSENTIAL CONNECTIONS

When designing a set of connectors for bamboo constructions, it is desired to minimize the amount of elements. Therefore, the essential connections need to be outlined. Basically, there are three types of connections. When one is able to build these connection, it is possible to build a whole bamboo structure.

1) Two bamboos perpendicular
2) Two bamboos parallel or crossing
3) Three bamboos parallel or crossing

The essential bamboo connections are shown in Figure 2.32. Possible knots are shown in Figure 2.33.

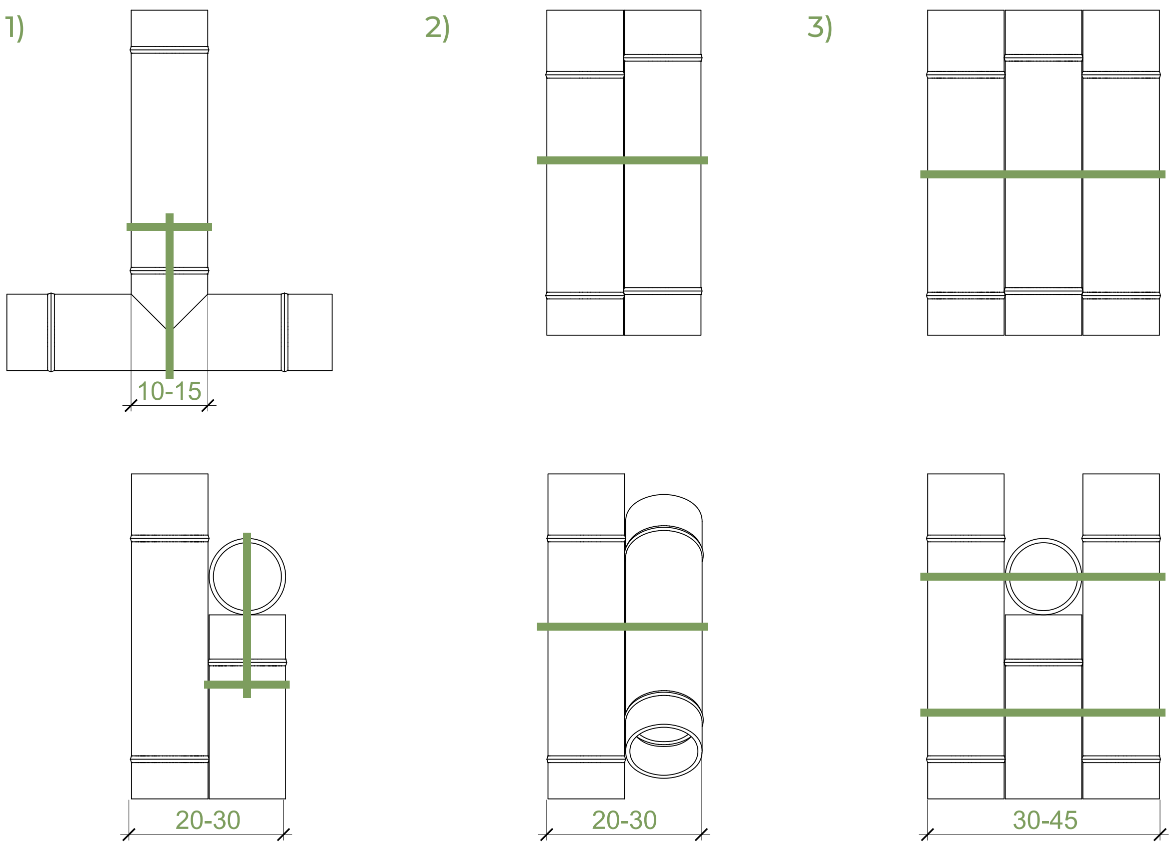


Figure 2.32 Essential bamboo connections

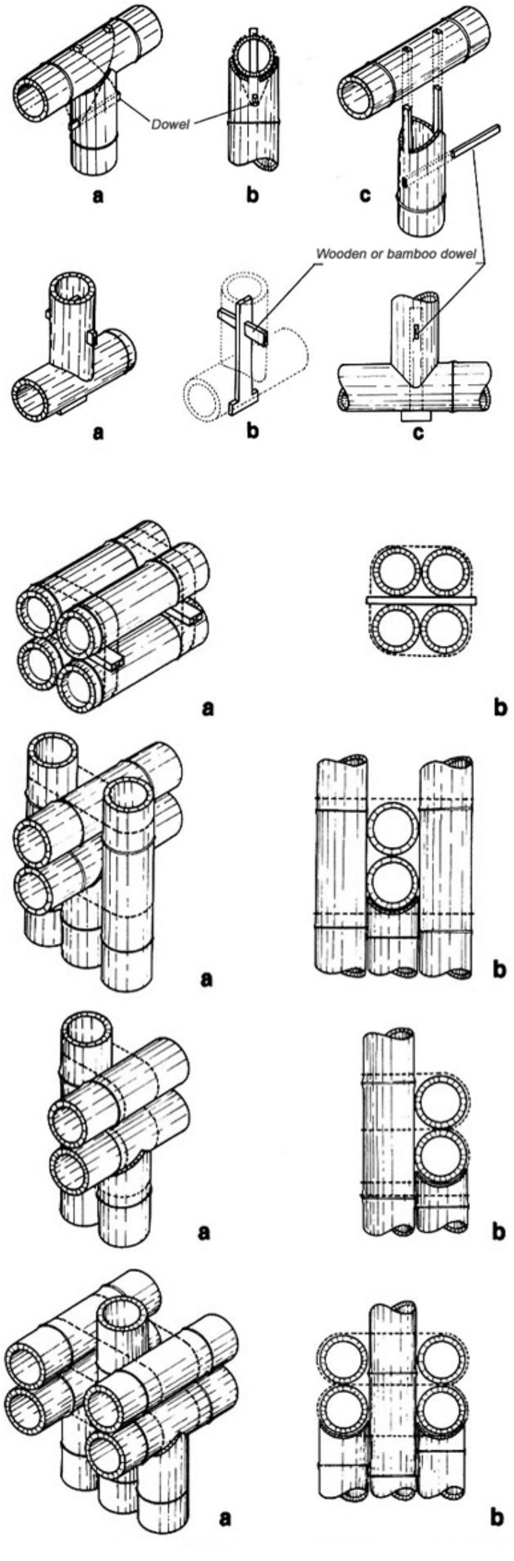


Figure 2.33 Bamboo joinery. (Guaduabamboo, 2009).

3. TESTING PROPERTIES

3.1 EXPERIMENTAL APPROACH

3.1.1 INTRODUCTION

This study evaluates recycled HDPE and PET in the form of reprocessing in a low tech manner, performing the tensile strength test to determine its material properties and feasibility as a connection material for bamboo structures. The circumstances in remote and poor areas are far from ideal for melt reprocessing plastic waste. As explained above, many factors can have a bad influence on the properties of the end product. Therefore, it is extremely important to understand how contaminants can be removed as best as possible. Preparation methods and results for low tech recycled PET and HDPE will be given. The ambition is to give insight of difficulties and possibilities for plastic recycling in poor and remote areas.

3.1.2 COLLECTING PLASTIC

First the plastic needs to be collected. The main plastic waste in Esperanza consists out of PET bottles with HDPE caps and rings and HDPE jugs. Therefore PET bottles and HDPE jugs are collected. After collecting the different types of plastic, the bottles need to be sorted.

Figure 3.1 PET bottles with HDPE caps and rings, HDPE milk jugs with caps and rings.

3.1.3 FEEDSTOCK SORTING

HDPE in Esperanza can be found as caps and rings of plastic bottles, drinking bottles and milk or water jugs. Jugs and caps will be tested separately and mixed. PET can be found as transparent plastic bottles, avoid transparent PVC bottles. It is important to sort the types of plastic and recycle them separately. Labels, paper, glue and other contaminants that can be removed by hand, are removed. Four different flows will be the result after the sorting

1) HDPE (M) mix of caps, rings, jugs
2) HDPE (C) caps and rings
3) HDPE (J) milk and water jugs
4) PET plastic bottles

Figure 3.2 PET and HDPE.

3.1.4 SHREDDING

The sorted PET en HDPE pieces will be shredded by a relatively simple machine with a electric motor and some steel blades (Figure 3.3). The pieces will be cut in flakes around 5 by 5 mm. Small flakes will ease the process later on. To feed the shredder, the bottles need to be cut in smaller pieced.

Figure 3.3 Shredder. (Precious Plastics, 2017).

Figure 3.4 PET and HDPE flakes.

3.1.5 WASHING

Washing will be done with only water. Chemicals are avoided due to earlier mentioned reasons. The water needs to be as clean as possible to avoid contamination through the cleaning water. Based on the possibilities in Esperanza three methods of washing the flakes will be executed, in order to find the most efficient washing method. During this test, the sorting, drying and reprocessing methods need to be the same to ensure the end results will be comparable.

1) Wash with cold water (room temperature)
2) Wash with hot water (80 °C)
3) Cut out label and glue areas and wash with 'cold' water

In order to find the most efficient washing method, the test will be done only on PET. As labels and glue are often stuck on PET bottles. A minimum of 5 test specimen for each method is required to validate the results.

Assuming the possibility of not being able to wash off all the glue, cutting out the glued and labelled areas will also be executed. Cutting out glued areas will give some extra work. However when the bottles are cut to feed the shredder, it isn't a big extra effort to cut out the glue areas. A disadvantage is that the parts with glue will be unused.

Figure 3.5 Washing PET flakes.

3.1.6 DRYING

PET is more susceptible for moisture contamination than HDPE. Therefore, three drying methods will be tested on PET flakes.

1) Drying on a black plastic sheet in the shadow for 8 hours
2) Drying in oven at 140 °C for 7 hours
3) Drying in oven at 170 °C for 6 hours

When performing the first method (using a plastic sheet) it is important to avoid contaminants like sand and dust (Figure 3.6). Also the plastic needs to be kept out of the sun. The avoid UV degradation.

When using an oven, the flakes shouldn't melt. Flakes melted into one mass, would be hard to reprocess. In Esperanza an oven can be powered by a solar panel. The extra effort put into the drying process has to be considered. Again, during this test, the sorting, washing and reprocessing methods need to be the same to ensure the end results will be comparable. A minimum of 5 test specimen for each method is required to validate the results.

Figure 3.6 Drying rice. (Shutterstock, 2018).

Figure 3.7 Drying PET in oven

3.1.7 TEST SPECIMEN

Test specimen

The different types of treated plastics (Figure 3.8) will be injection moulded into testing specimens. A self made injection moulding machine (Figure 3.11) will be producing these specimen (Figure 3.9). The moulds will be 3D printed out of Liqcreate Strong-X. Its flexural strength of 135MPa makes it excellent for heavy duty applications such as injection moulding and engineering tools. Replacing aluminium milled moulds, reducing the costs of prototype moulds.

The different mixtures and methods will be tested through test specimens using a Zwick z10 universal testing machine (Figure 3.10) with Test Expert 4.12 software. From these tests the most suitable washing and drying methods will be derived. Next, the four mixes of plastic can be tested using the chosen washing and drying methods. To be able to get an insight of the deterioration during the recycling process, virgin HDPE and PET will be processed with the same melt processing techniques. The virgin test specimen will be tested and compared. All the test specimens will be tested on the Young's modulus and yield strength.

Feedstock 1	PET Cold Wash (oven 140 °C) (5x)
	PET Hot Wash (oven 140 °C) (5x)
	PET Cut Labels and Glue (oven 140 °C) (5x)
	PET In Shadow (cut out labels and glue) (5x)
	PET Oven 170 °C 6h (cut out labels and glue) (5x)
	PET Glue, Lables and no wash (5x)
	PET virgin granules (5x)
Feedstock 2	HDPE (M) (chosen wash and dry methods) (5x)
	HDPE (C) (chosen wash and dry methods) (5x)
	HDPE (J) (chosen wash and dry methods) (5x)
	HDPE virign granules (5x)
UV	PET (chosen wash and dry methods) (5x)
	HDPE (chosen mixture, wash and dry methods) (5x)

Figure 3.8 Mixtures investigated

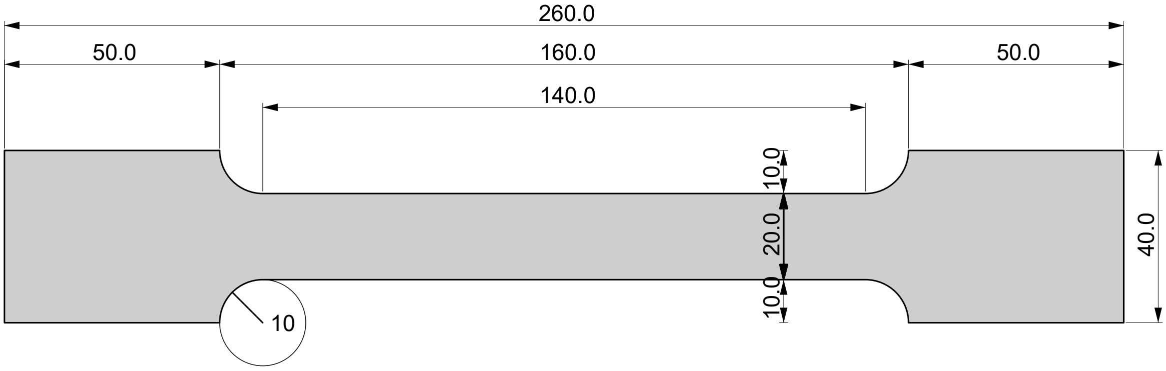


Figure 3.9 Dimensions test specimen

Figure 3.10 Zwick z10 universal testing machine. (Zwick Roell, 2018).

Figure 3.11 Self made Injection Machine

3.2 MELT REPROCESSING

3.2.1 MELT REPROCESSING

As the self made injection moulding machine comes without instructions, the right temperature, waiting time and so on need to be figured out by doing. PET has a melting temperature range of 260-280 °C and a decomposition range of 283-306 °C. Herefore the margins for a successful test specimen are very small. This makes the reprocessing of PET difficult. In addition crystallised PET is strong but also brittle, making the elements to crack easily. In order to produce a usable test specimen, the mould need to be improved and changed.

HDPE has a melting temperature range of 177-275 °C and a decomposition range of 335-450 °C. Giving HDPE a large temperature range wherein it actually can be injected. This large range makes HDPE easier for injection moulding than PET.

3.2.2 MOULD DESIGN

Mould 1.0

In the first attempts of producing a PET dog bone test specimen, the dog bone broke by twisting the mould from the steel plate where the mould is mounted to the barrel or by parting the two parts of the mould. The seam in the middle of the mould weakens the dog bone even more (Figure 3.13).

The HDPE dog bones came out in one part. However the dog bones have some air bubbles in the area of the seam in the middle. In addition the steel plate that closes the mould bends under the pressure that is needed to inject the HDPE into the mould (Figure 3.14). This causes a deviation in the dimensions of the dog bones.

A plumbing system with screw thread (Figure 3.15) is used on the barrel of the injection machine and on the mould to easily mount the mould. However the molten plastic gets into the screw threads, making it harder to mount the mould. In addition, a part of the plastic stays behind in the barrel after pushing the rod all the way down (Figure 3.12). To get more control over the amount of plastic that is injected, the nozzle is adjusted.

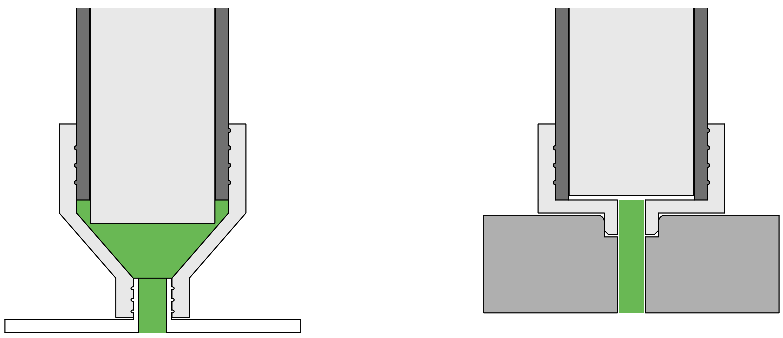


Figure 3.12 Improved nozzle injection machine

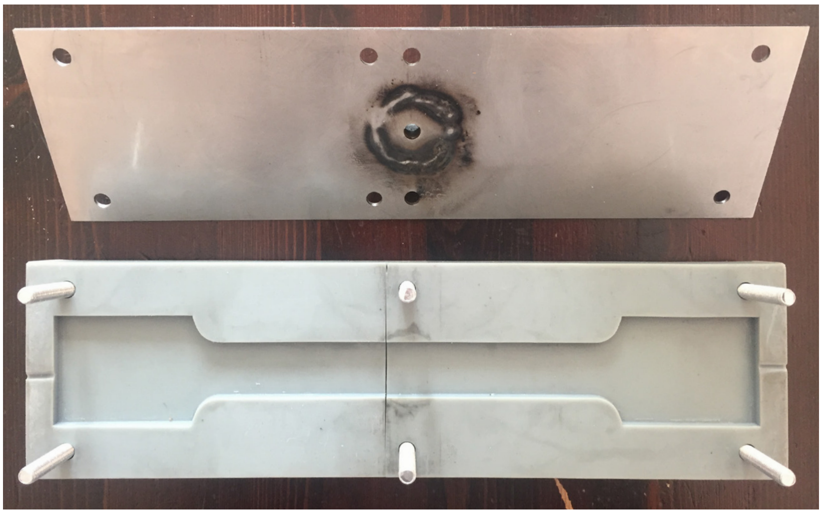


Figure 3.13 Mould open (thick)

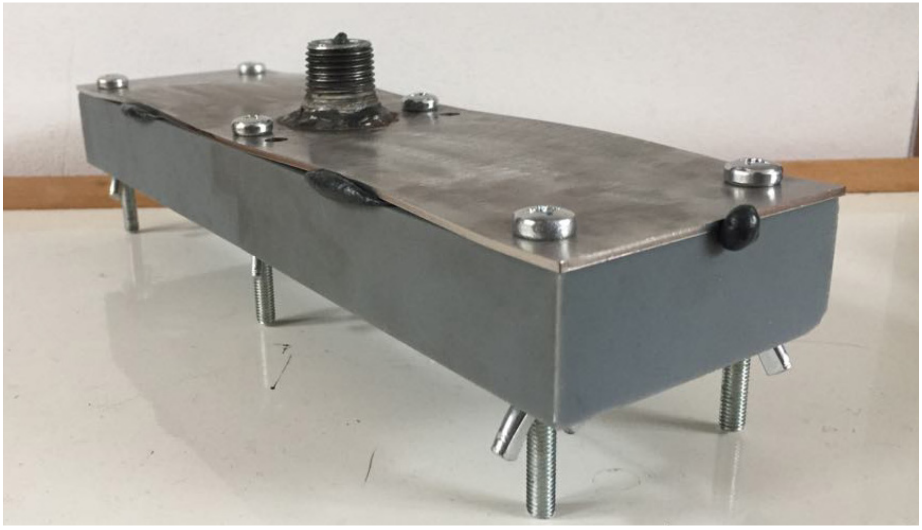


Figure 3.14 Mould assembled (thick)

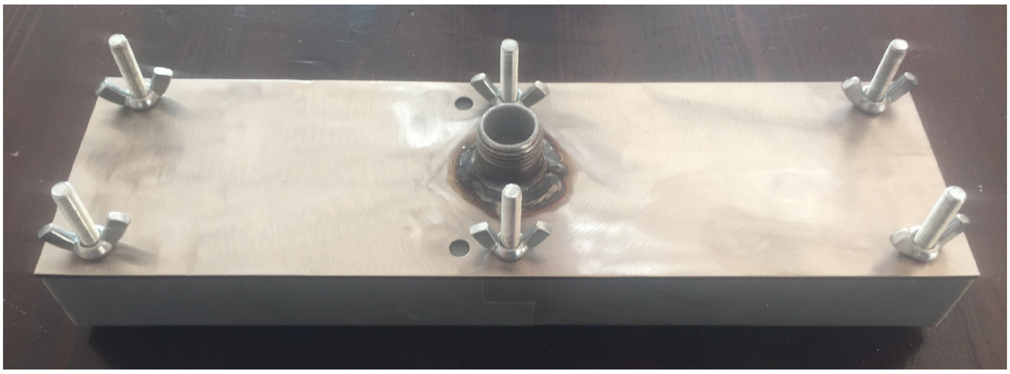


Figure 3.15 Mould assembled (thick)

Mould 2.0

In order to ease the release of the dog bone from the mould, a thin mould is made, which is clamped between two steel plates. By removing the steel plates, the dog bone can be pushed out of the mould. However the 5 millimetre thick mould was not strong enough and it broke into multiple pieces (Figure 3.16). In addition the PET tends to stick to the mould material. To avoid the dog bone from sticking to the mould a kind of mould release need to be used. It could also help to bevel the sides of the mould to ease the removal from the mould.

Figure 3.16 Mould 2.0 first brittle PET specimen

Mould 3.0

The steel plates are left out of the third version of the mould for the dog bones, as the steel plates tend to bend during the injection moulding. The mould consists out of two pieces. Each part represent half of the thickness of the dog bone. The thickness of the two parts will ensure that the mould stays flat. After separating the mould parts, the dog bone will only be sitting in one part for half its thickness, this eases the release of the dog bones.

To fit the improvements of the injection machine nozzle, the mould also needed some adjustments. The plumbing elements are removed from the machine and the new nozzle is based on pressure. This pressure is provided with a jack. The jack makes it possible to place and remove the mould quickly and properly. As the mould is pushed onto the nozzle, no extra screws are needed to close the mould. The screw holes are replaced with pins and slots to ensure that the two parts are lined up properly. Therefore, the third mould (Figure 3.17) is even easier and quicker to open, in order to ease the removal of the dog bones.

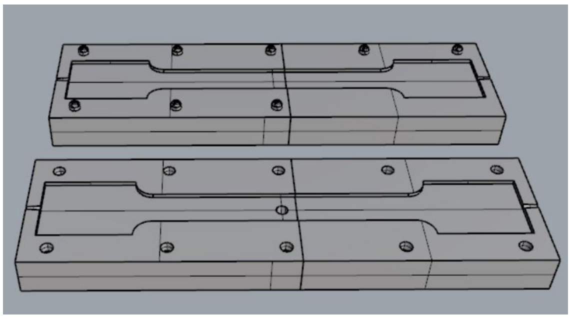


Figure 3.17 Mould 3.0

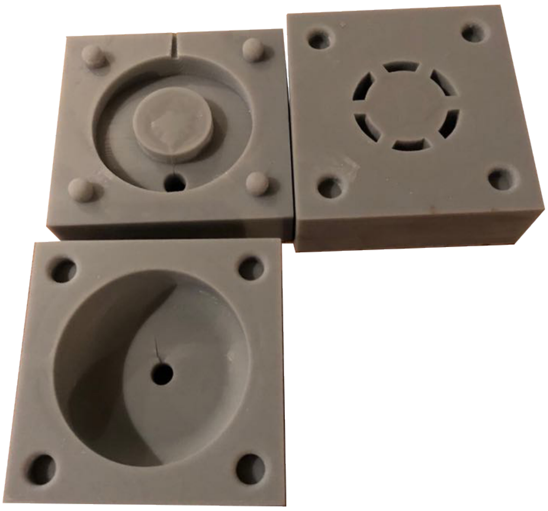


Figure 3.18 Pressure cap mould

Pressure cap moulds

The pressure cap mould is designed with the same rules as the mould 3.0. The mould for the element with the fingers releases the injected element perfectly. Only one sprue has to be cut. However not all fingers are completely filled with HDPE. This is caused by trapped air. To release the cap element from the mould takes more effort. The cap element grabs the mould as it shrinks when cooling down. Therefore, two small holes are drilled in the mould. Through these holes the air can escape, and after cooling down the cap can be pushed out the mould with nails, using these holes.

The pressure cap moulds need to be further developed in collaboration with a professional, in order to be able to CNC mill steel moulds.

3.2.3 PET INJECTION MOULDING

As expected, PET has its difficulties in de production process. Contaminations like moisture causes defects in the polymer chains, resulting in degradation of the physical properties ("Crystalline vs. Amorphous PET," 2018). Degraded PET can not be restored by further processing. The PET has to be dried prior injection to a moisture content of 0.02 % in weight. A higher moisture content will result in decreased mechanical properties (Figure 3.20). This also means that the inside of the barrel and the air inside the barrel should not contain to moisture. With a low tech self made machine it is hard or even nearly impossible to reach these requirements.

Bottle grade plastic is amorphous, however it can crystallize when heated above 110 °C (Figure 3.21). The PET becomes cloudy when it crystallizes, it becomes brittle (Figure 3.19) and the impact resistance is reduced. In order to recycle PET properly it is important to keep between its glass transition temperature, and its crystallization temperature (~70 °C - ~110 °C). Melting the PET is necessary to be able to injection mould the PET. As the melting temperature range lays around 260 - 280 °C. It is impossible to prevent the PET from crystallizing.

Injection moulded PET is semi-crystalline, however the grade of crystallinity can be controlled by many factors. The crystallization of PET can be controlled by adding chemicals and/or fillers and reinforcements (Sepe, 2012). The use of chemicals or other kind of additives is not desired in remote areas like Esperanza. It is hard to dispose the chemicals in a proper way and it will bring extra costs to the process. The crystallization can also be controlled by factors like, the air quality, the injection speed, the injection pressure, melting temperature, the cooling time and residence time. In brief it is very difficult and complex to control the crystallization process. With the self made injection machine it is nearly impossible to produce a high quality end result. The tests with PET resulted in very brittle dog bones, burned plastic and multiple times a jammed rod. The contaminated PET also sticks to the mould, resulting in damages in the mould. Therefore it has been decided that PET is not suitable for this project.

Figure 3.19 First brittle PET specimen

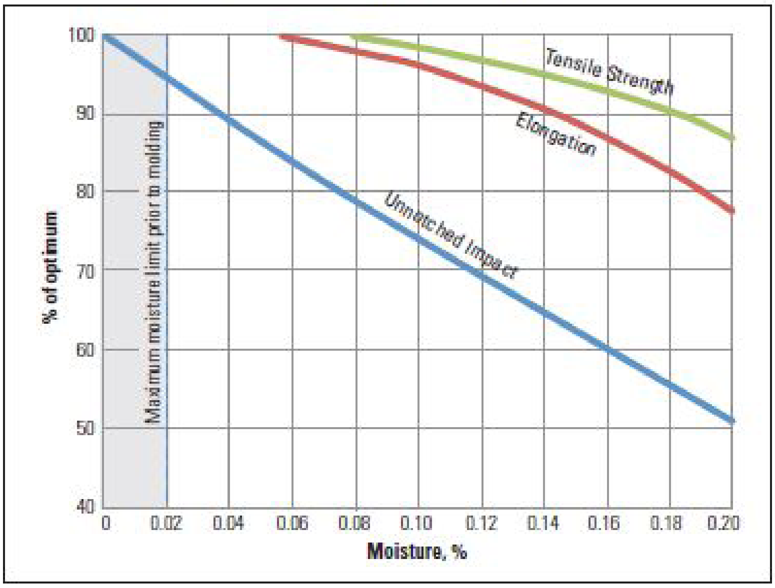


Figure 3.20 Moisture contamination PET degradation

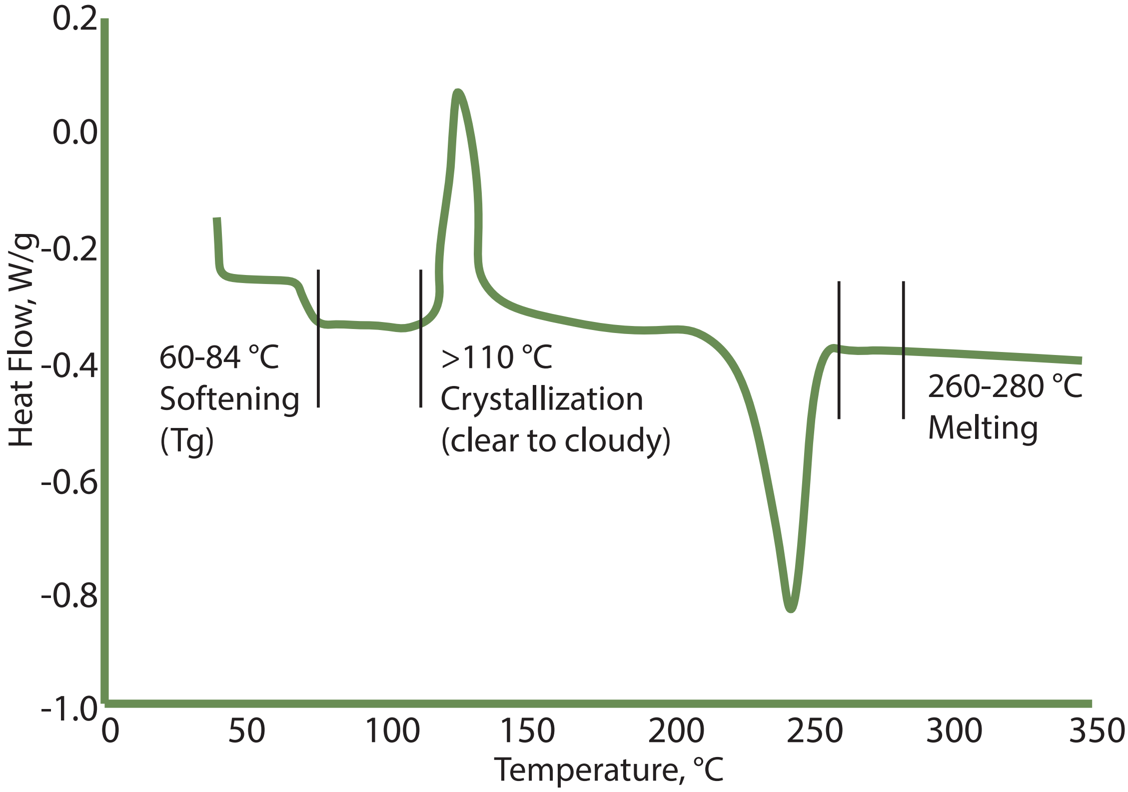


Figure 3.21 Narrow temperature window PET

3.2.4 HDPE INJECTION MOULDING

The decision on omitting PET in the further research, lays full focus on the HDPE. It is unfortunate that PET can't be used in this project, as it is in abundance in Esperanza and it would be better if both plastics could be used. However omitting PET funnels the options and thereby the research. All the parameters for the machine, the mould, etc., can be optimized for HDPE.

The different PET mixtures supposed to result in the best washing and drying methods. However these mixtures haven't been tested, due to the unsuccessful reprocessing of the PET. HDPE is far less susceptible for water than PET. HDPE absorbs 0,005 - 0,01 % of its own weight in water (24 h) and PET absorbs 0,14 - 0,18 % of its own weight in water (24 h) ("CES EduPack 2017," 2017). In addition the reprocessing process of PET is affected more by moisture than the reprocessing process of HDPE as the recycled HDPE is already semi-cristaline and it doesn't become brittle as PET. Herefore the washing and drying methods are not significant for the testing of the HDPE.

Four different mixtures of HDPE will be tested.

1) HDPE (caps)
2) HDPE (jugs)
3) HDPE (mixed, 50% caps - 50% jugs)
4) HDPE (virgin)

Testing these four different mixtures of HDPE will give insight if mixing the caps and jugs influences the strength of the material. The virgin HDPE is tested in order to get information about the degradation of the recycled HDPE. The yield strength and e modulus will be extracted from the tests.

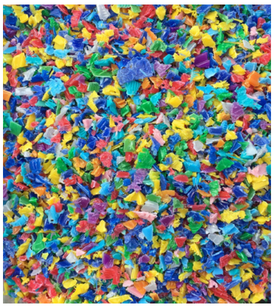


Figure 3.22 HDPE(C)


Figure 3.23 HDPE(J)


Figure 3.24 HDPE(M)


Figure 3.25 HDPE(V)

The self made injection moulding machine is not as sophisticated as the industrial machines that normally are used to produce plastic products. Therefore even more deterioration can be expected, caused by impurities and the lack of control over the injection speed, mould temperature and so on. The results of the different mixes HDPE will be compared with the mechanical properties found in CES EduPack 2018. The different mixes will be injection moulded into dog bones. These dog bones will be subjected to a tensile strength test. These tests will be performed with the Zwick Z010 (Figure 3.26.

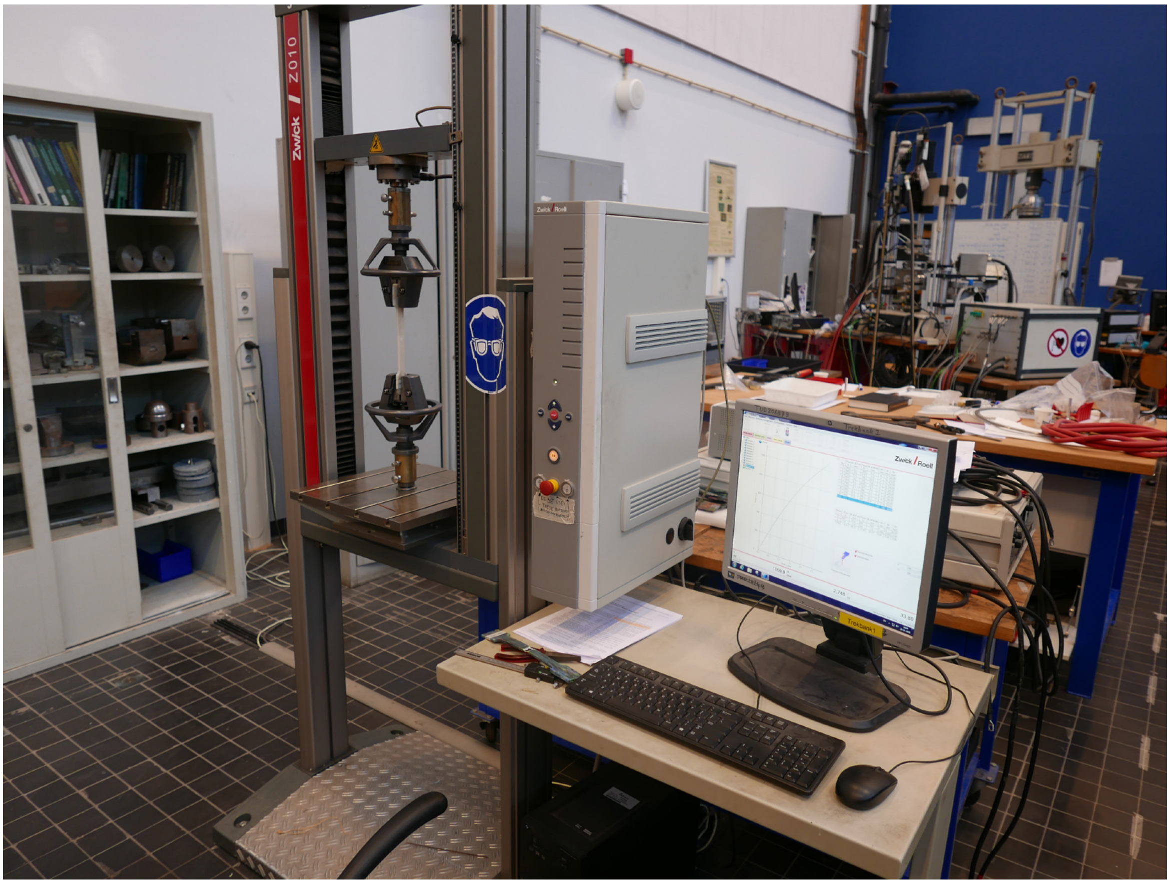


Figure 3.26 Zwick Z010 testing setup

3.3 HDPE STRENGTH TESTS

3.3.1 INTRODUCTION

The recycled HDPE is reprocessed using a self made low tech injection moulding machine. Recycled plastic usually has reduced mechanical properties caused by UV degradation and contaminations. In addition the use of a low tech machine causes further degradation of the mechanical properties. The aim of this project is to use this recycled HDPE for bamboo houses and other structures. Herefore it is crucial to test its mechanical strength. The testing will be will be performed with a Zwick tensile strength test machine. Dog bones (Figure 3.27) are fixed into the machine and the machine will stretch the dog bones with a speed of 5 mm per minute. These tests will determine a stress-strain diagram, from which the yield strength and the Young's modulus can be derived (Kopeliovich, 2014).

The Yield strength can be calculated by dividing the maximum standard force [N] at the yield point by the initial area of the cross section [mm^2] of the dog bone:

$$\sigma = \frac{F}{A}$$

From point 0 to A in Figure 3.28 HDPE behaves as a linear elastic solid (Milisavljevic-syed & Petrovic, 2012). At this point the Young's modulus is equal to the stress [N/mm2] divided by the strain [%]. The Young's modulus for these tests will be calculated between 0.2 to 0.5 strain.

$$E = \frac{\sigma}{\varepsilon}$$

Point B is called the yield point and from this point the plastic region starts. From point B a neck is formed and the HDPE will stretch substantially. The neck will continue to narrow until the dog bone brakes at point C. At point C the ultimate strength and the elongation at break can be found (Milisavljevic-syed & Petrovic, 2012).

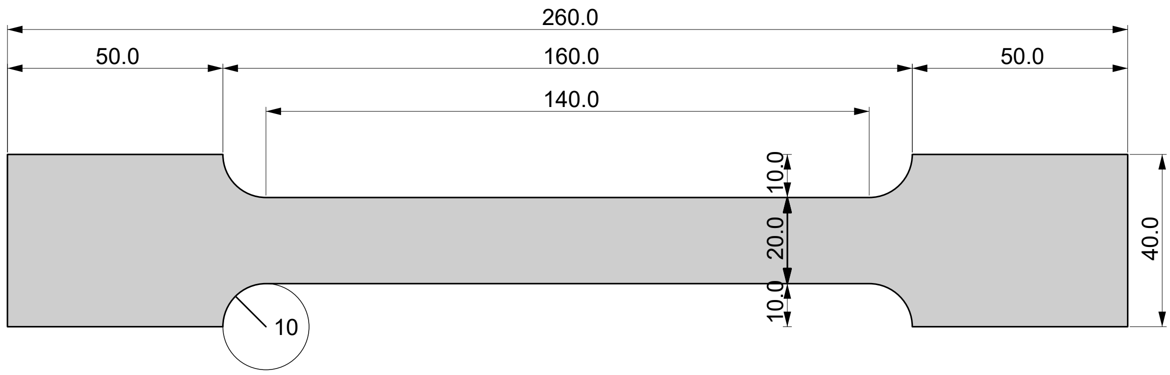


Figure 3.27 Dog bones with dimensions

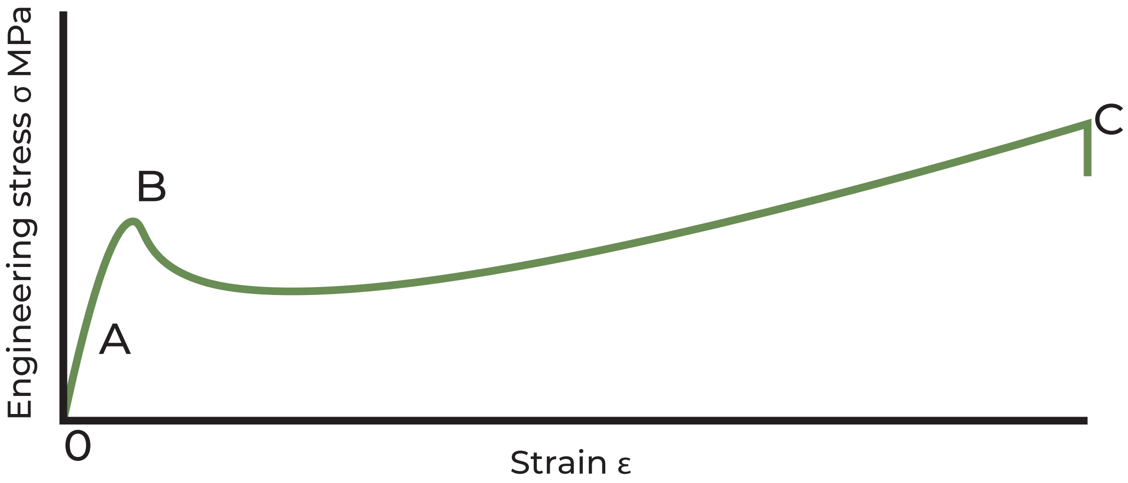


Figure 3.28 Stress-Strain curve for Polyethylene (PE)

It is difficult to make a distinction between recoverable (elastic) and unrecoverable (plastic). The recoverability of HDPE is dependent on the temperature and upon the time allowed for recovery (Milisavljevic-syed & Petrovic, 2012). In Central America it can be very humid and warm, herefore it is important to build in a safety factor. The final connections will be slightly over dimensioned to conclude the degradation of the plastic due to UV radiation.

The results of the tests will be compared to the mechanical properties of HDPE found in CES EduPack 2017 (Figure 3.29). The degradation of the recycled HDPE using a low tech machine can be determined in this manner.

Mechanical properties	
Young's modulus	1.07-1.09 GPa
Yield strength	26.2-31 MPa
Tensile strength	22.1-31 MPa

Figure 3.29 Reference data for HDPE according to CES database

3.3.2 HDPE (C)

The HDPE (C) mixture consists out of only caps. All the HDPE is injection moulded at a temperature of 275 °C at the nozzle and 250 °C in the barrel. These numbers are particular for the used injection moulding machine, as the machine is not sophisticated the numbers can differ from the actual temperatures. The tests are performed with a speed of 5 mm per minute.

Yield strength = 20,68 MPa
Young's modulus = 0,83 Gpa

The dog bones behave like a elastic solid until the yield point and the yield strength is comparable to the theoretical mechanical properties. However in the plastic region the samples loses strength quickly and no neck is formed. All five dog bones started to broke in the middle (Figure 3.33).

Figure 3.30 HDPE(C)

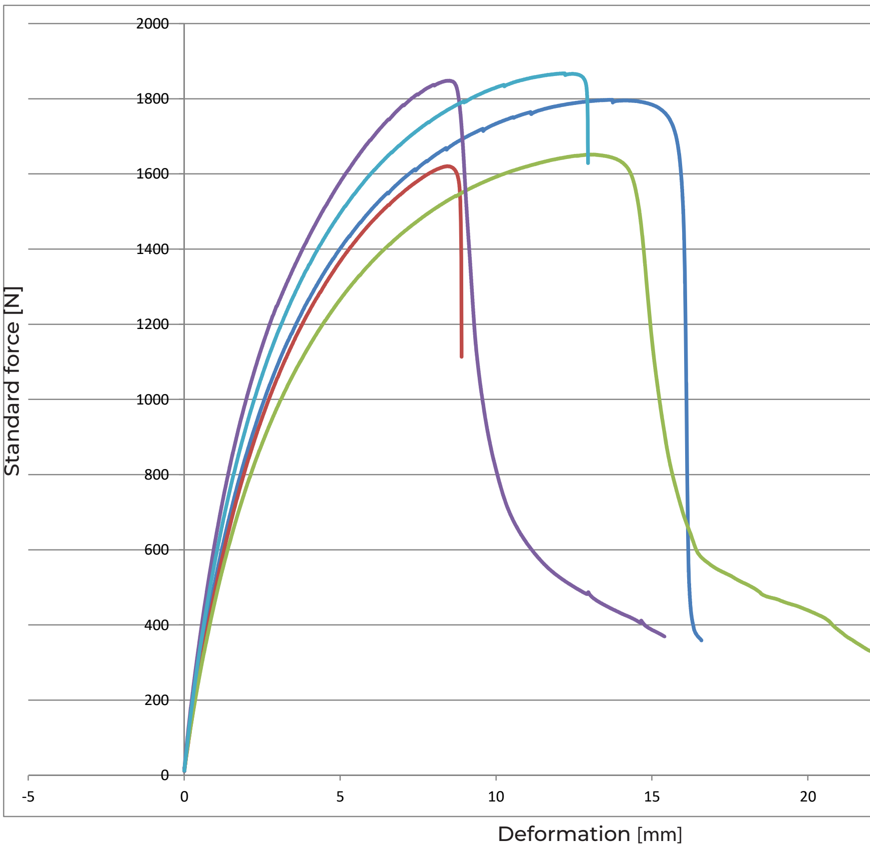


Figure 3.31 Standard force [N] - Strain [mm] HDPE (C)

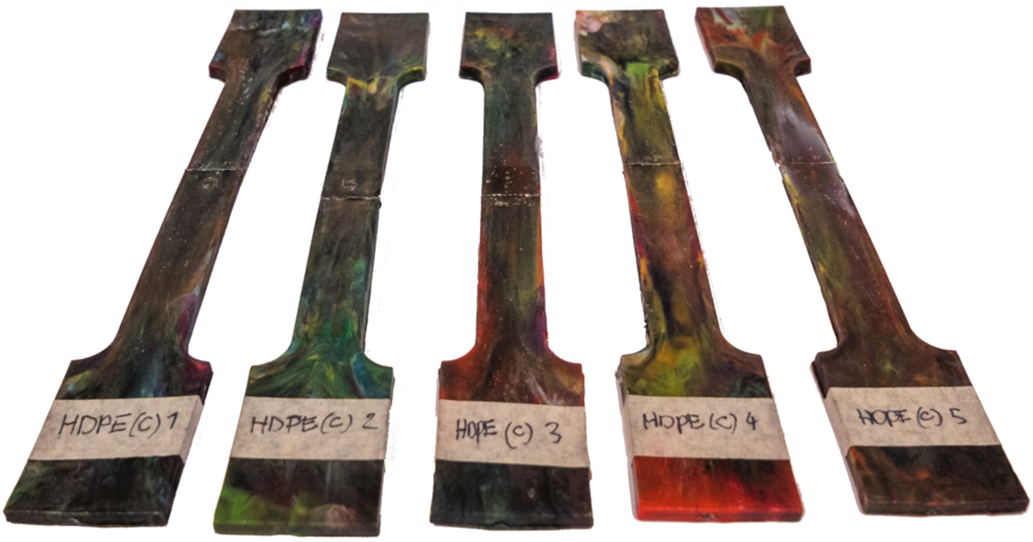


Figure 3.32 HDPE (C) before test

Figure 3.33 HDPE (C) after test

3.3.3 HDPE (J)

The second mixture consist out of milk jugs. A material which is equal to the water jugs that are used in Esperanza. Contaminations can be seen clearly, as the material is white.

Yield strength = 22,02 MPa
Young's modulus = 0,85 Gpa

Three of the five dog bones behave like a elastic solid until the yield point and the yield strength is comparable to the theoretical mechanical properties. However in the plastic region the samples loses strength quickly and no neck is formed. All five dog bones started to snap in the middle. The other two show normal plastic behaviour after the yield point, one more than the other. In sample 2 a neck is formed (Figure 3.37).

Figure 3.34 HDPE(J)

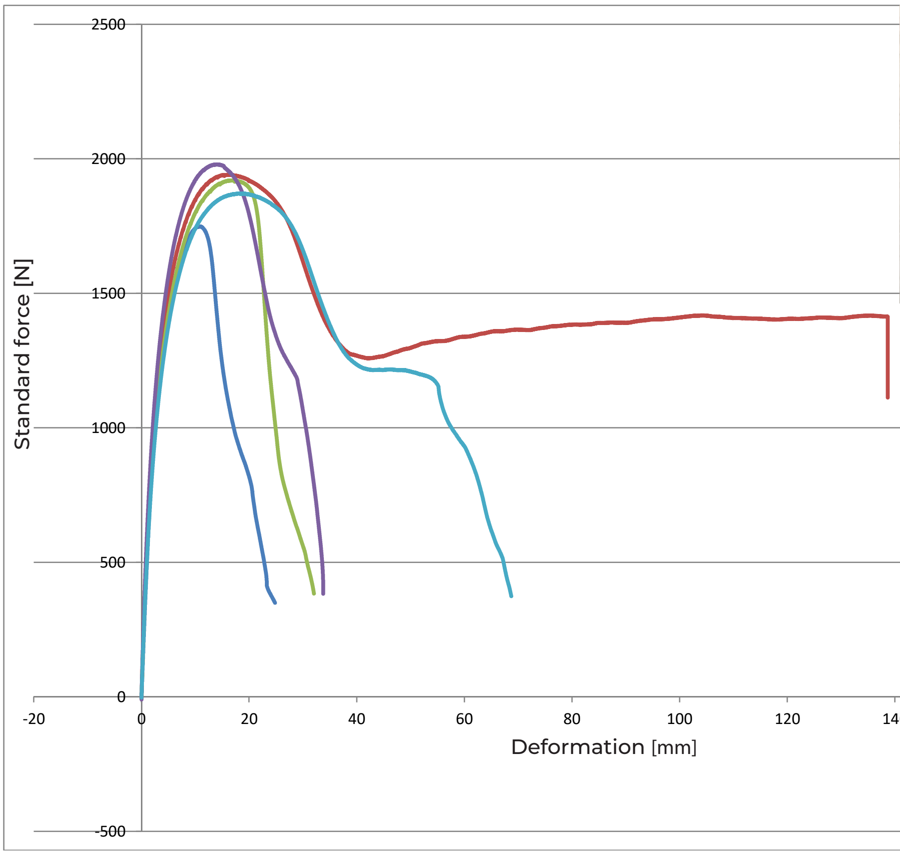


Figure 3.35 Standard force [N] - Strain [mm] HDPE (J)

Figure 3.36 HDPE (J) before test

Figure 3.37 HDPE (J) after test

3.3.4 HDPE (M)

The third mixture consist out of a mix of caps (50%) and milk jugs (50%). The goal of this mixture is to test the effect of mixing different forms of HDPE. A huge advantage would be, if the mixing would not make a difference in the mechanical properties.

Yield strength	= 21,82 MPa
Young's modulus	= 0,95 Gpa

Again all dog bones behave like a elastic solid until the yield point and the yield strength is comparable to the theoretical mechanical properties. However in the plastic region the samples loses strength quickly and no neck is formed. All five dog bones started to brake in the middle. The yield strength of the five dog bones is very similar, however the strain [mm] where the F_{max} is reached differ.

Figure 3.38 HDPE(M)

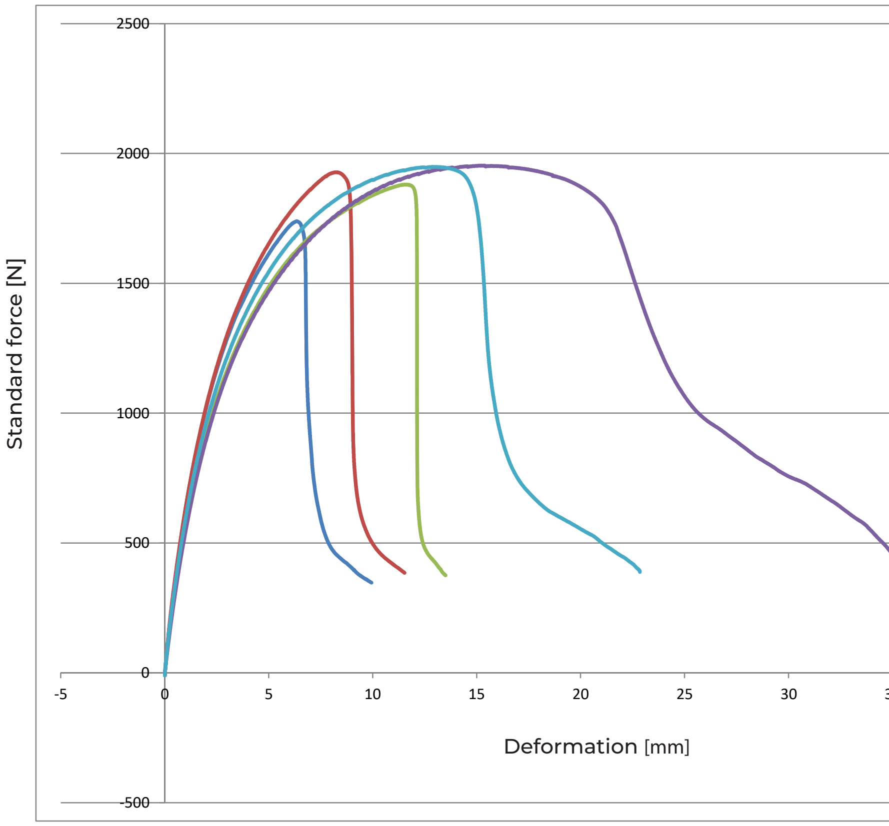


Figure 3.39 Standard force [N] - Strain [mm] HDPE (M)

Figure 3.40 HDPE (M) before test

Figure 3.41 HDPE (M) after test

3.3.5 HDPE (V)

The fourth mixture consist out of virgin HPDE pellets. Degradation of the recycled HDPE can be expected. Therefore virgin HDPE is tested in order to get insight of the grade of degradation. Also in the virgin dog bones contamination is found on the dog bones (Figure 3.43)

Yield strength = 20,71 MPa
Young's modulus = 0.84 Gpa

Again all dog bones behave like a elastic solid until the yield point and the yield strength is comparable to the theoretical mechanical properties. The virgin HDPE tends to behave more in a plastic way after the yield point (Figure 3.42). However the yield strength is very similar to the recycled HDPE mixtures.

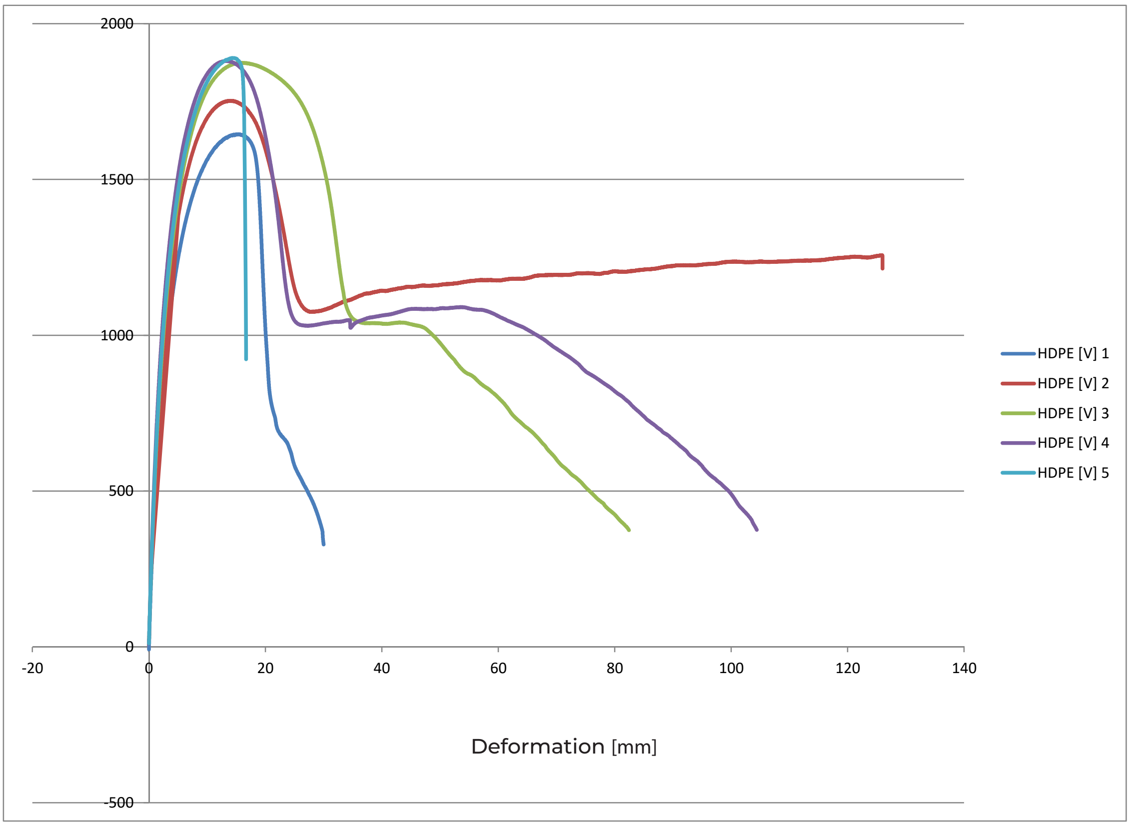


Figure 3.42 Standard force [N] - Strain [mm] HDPE (V)

Figure 3.43 HDPE (V) before test

Figure 3.44 HDPE (V) after test

3.3.6 CONCLUSION HDPE TENSILE STRENGTH TESTS

Testing the recycled HDPE in a tensile strength test was crucial to determine the quality of the recycled plastic. Especially because of the low tech manner by which the HDPE dog bones where produced. A drastic reduction of the mechanical properties was expected. Drastic reduction of the mechanical properties would result in a unsuitable material for structural use.

Against expectation the results are promising. The yield strength and the Young's modulus of the four different mixtures is calculated and compared with the values found in CESEduPack 2018 (Figure 3.45). In addition dog bones made from HDPE virgin pallets are tested to get insight of the degradation of the recycled mixtures.

The yield strength of the test specimens is very consistent, showed in the standard deviation of the tested dog bones. The consistency helps validating the test and it is important concerning the production of consistent connectors. Until the yield point the test specimen behave very similar to the Stress-Strain curve of Polyethylene (Figure 3.28). The average yield strength has a decrease of 18% compared to the theoretical yield strength of HDPE. Making the recycled HDPE very suitable for the bamboo connections. When comparing the recycled HDPE with the virgin HDPE the results are very similar. These unexpected results are against the assumptions of the decrease in mechanical properties when recycling plastic. However the test results show that there is no drastic decrease of mechanical properties.

The Young's modulus of the different mixes are even more similar to the theoretical Young's modulus of high density Polyethylene. The Young's modulus has a decrease of only 10% compared to the theoretical values.

The results show that the jugs are performing better than the caps. Herefore the mixture of caps and jugs is performing slightly better than the only cap mixture.

	Yield strength	Young’s modulus
HDPE (C)	20.68 MPa ± 1.66	0.83 GPa ± 0.13
HDPE (J)	22.02 MPa ± 1.16	1.16 GPa ± 0.08
HDPE (M)	21.82 MPa ± 0.90	0.90 GPa ± 0.09
HDPE (V)	20.71 MPa ± 1.31	1.31 Gpa ± 0.06
CESEduPack 2018	26.2 - 31 MPa	1.07 - 1.09 GPa

Figure 3.45 Results of the tensile strength tests

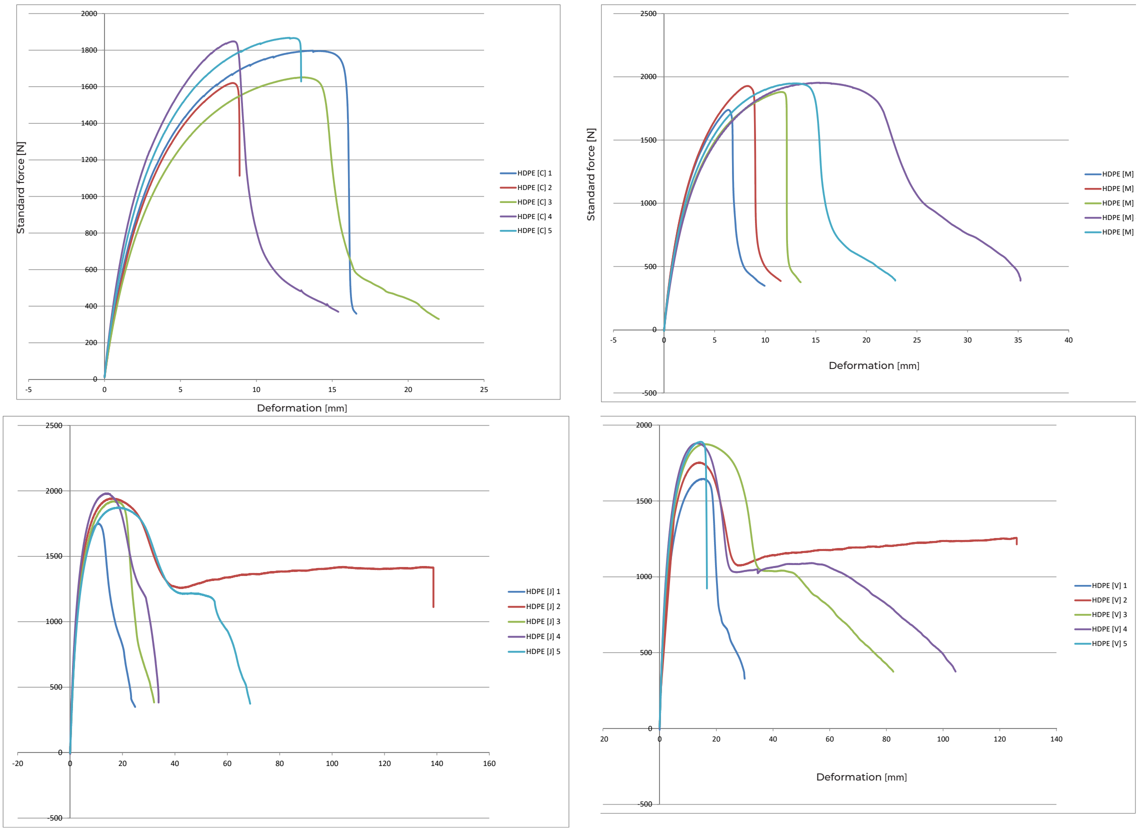


Figure 3.46 Results of the four different HDPE mixtures

In contrast to the consistency of the elastic behaviour of the HDPE before the yield point, the behaviour in the plastic region is less consistent. Only sample HDPE (J) 2 and HDPE (V) 2 have formed a neck in the plastic region. The other samples show more rapid failure. This abrupt failure is probably caused by air bubbles in the area where the plastic flows from the nozzle into the mould. Unfortunately this is a weakness of the low tech production process. Herefore it is crucial to subject the connectors to a force that does not exceeds the yield point of the HDPE. This can be managed by designing the bamboo connections in a way that the bamboo takes up most of the forces. Temporary high stresses can be taken by the plastic in case of a impact force, caused by for example wind. HDPE can be tested in a tensile strength test unto 25 mm per minute (Milisavljevic-syed & Petrovic, 2012). But the permanent high loads should be taken by the bamboo.

All in all, the results show that the produced material can be suitable for the connectors.

3.3.7 HDPE CREEP TESTS

Creep is the tendency of a solid material to move slowly or deform permanently under the influence of long-term mechanical stresses. It can occur as a result of long-term exposure to high levels of stress that are still below the yield strength of the material. Creep is more severe in materials that are subjected to heat for long periods, and generally increases as they near their melting point. Making it important to test the creep behaviour of the recycled HDPE as the connectors have to endure the hot climate of Nicaragua.

The rate of deformation is a function of the material's properties, exposure time, exposure temperature and the applied structural load. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function.

The creep behaviour of the HDPE is tested with a set of 6 dog bones. The tensile strength of the first dog bone is tested to set a reference. A maximum standard force of 1671,88 N, equal to a stress of 19,05 N/mm^2 is tested for the first specimen (Figure 3.47).

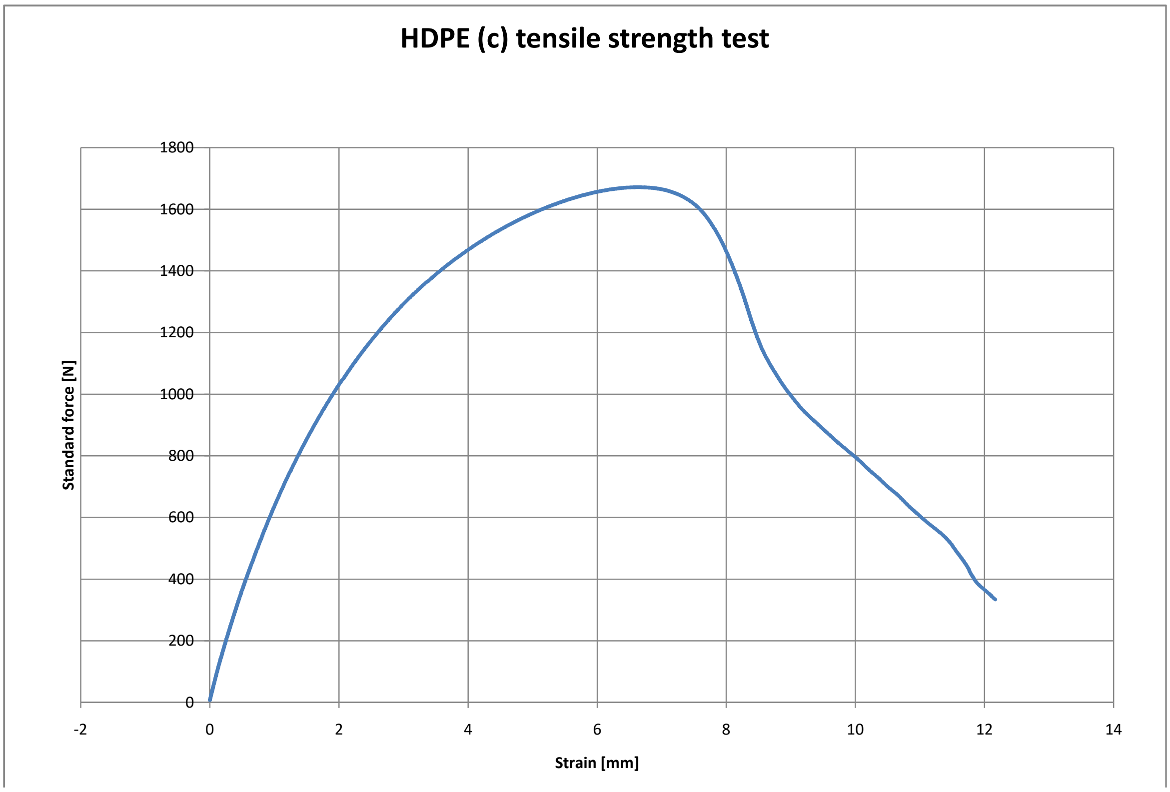


Figure 3.47 HDPE (C) tensile test reference for creep test

The remaining 5 specimen will be subjected to a decreased amount of stress over a longer period of time. With this method the tendency of creep can be tested for the low tech recycled HDPE. The second specimen is subjected to 1400 N around 85% of the maximum standard force. A standard force of 1400 N is equal to a stress of 16,29 N/mm^2 (Figure 3.48). An abrupt failure occurred at a strain of 6,21% 137 seconds and no neck is formed.

The third specimen is subjected to 1350 N around 81% of the maximum standard force. A standard force of 1350 N is equal to a stress of 15,46 N/mm$^{2.}$ (Figure 3.48). An abrupt failure occurred at a strain of 9,07% after 582 seconds and no neck is formed.

The fourth specimen is subjected to 1325 N around 79% of the maximum standard force. A standard force of 1325 N is equal to a stress of 15,10 N/mm$^{2.}$ (Figure 3.48). An abrupt failure occurred at a strain of 13,03% after 1568 seconds and no neck is formed.

The fifth specimen is subjected to 1300 N around 77,75% of the maximum standard force. A standard force of 1325 N is equal to a stress of 14,80 N/mm$^{2.}$ (Figure 3.48). After 3200 seconds the test stopped and a strain of 10,79 % was reached. The graph shows that the strain would eventually be greater than the results of the previous test specimen, which where subjected to an higher standard force.

The last specimen is subjected to 1200 N around 72% of the maximum standard force. A standard force of 1200 N is equal to a stress of 13,89 N/mm$^{2.}$ (Figure 3.48). After 3200 seconds the test stopped and a strain of 7,74 % was reached.

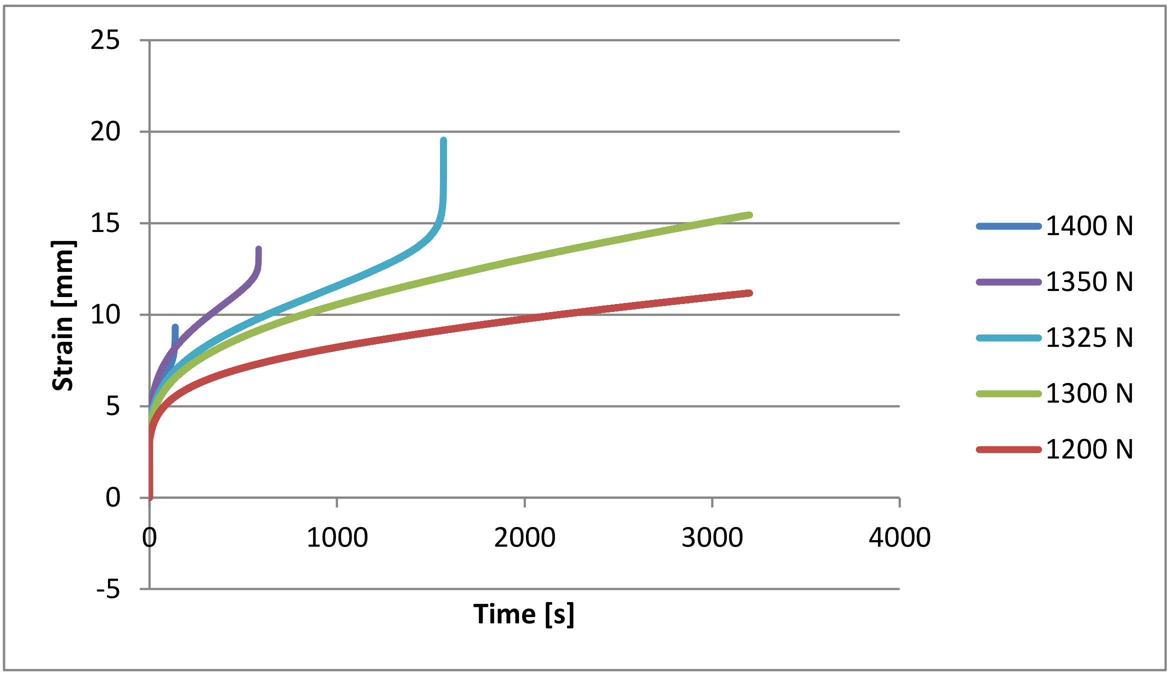


Figure 3.48 HDPE (C) Creep test

3.3.8 CONCLUSIONS HDPE CREEP

The tests definitely show an increase in the maximum strain as the applied stress decreases and the recycled HDPE has the tendency to creep. However a test of 3200 seconds is too short for the test specimens subjected to 1300 N and 1200 N to show results (Figure 3.46). In order to get complete results the dog bones should be tested over a longer period of time to find the stress level where the HDPE doesn't deform permanently. This doesn't mean that these results are useless.

The goal of the HDPE tests was to get insight of the quality of the recycled HDPE. The results show that the recycled HDPE can be used structurally, when constructed in the right way. Before use further tests are recommended. When using recycled HDPE it is important to know its limits. Creep will eventually result in permanent deformation. Permanent deformation needs to be prevented. Figure 3.31 shows that the stress-strain curve is linear up until around a standard force of 1200 N. In this case 1200 N is equal to 13.88 N/mm^2. The elastic region is determined by the region where the stress-strain curve is linear (Figure 3.49). When stresses stay below this value, no permanent deformation will occur in the HDPE. As it is very hard to precisely find the exact location of this elastic region, in combination with the small deviation of the tested mechanical properties, it is from importance to build in a security factor. To be safe a maximum stress of 7 N/mm^2 should ensure a safe construction.

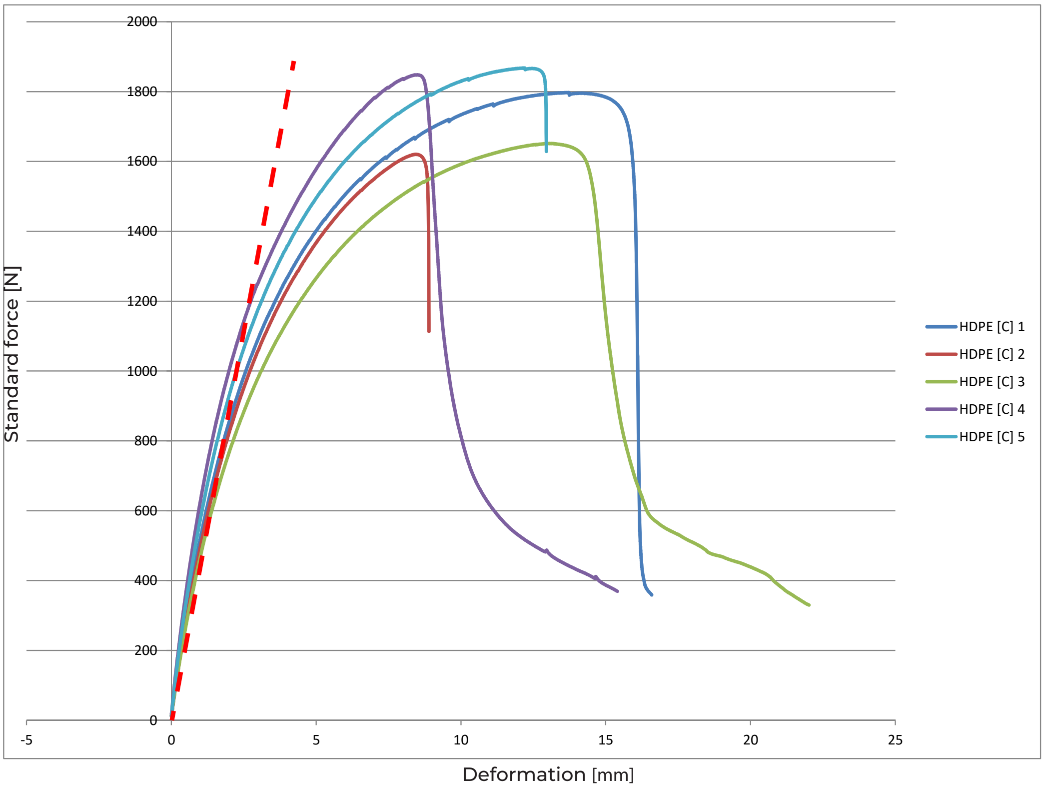


Figure 3.49 HDPE (C) Red dotted linear line

Figure 3.50 HDPE (C) Dog bones before creep test

Figure 3.51 HDPE (C) Dog bones after creep test

3.3.9 HDPE PIN COMPARED TO STEEL SCREW THREAD M10

In the Bamboo Factory steel M10 screw threads are used to construct the structure. Herefore the strength of the M10 will be a reference point for the requirements of the mechanical properties of the plastic connections. A HDPE pin with a diameter of 22,9 mm (Figure 3.53) is compared with a steel M10 screw thread with a diameter of 10 mm (Figure 3.54). A three point bending test is performed on the two elements. The objects are tested with a speed of 5 mm per minute with a maximum deformation of 20 mm. The HDPE pin behaves like a elastic solid before the yield point. The average yield strength of the two pins is 6.5 MPa. This is significantly lower than the yield strength of the M10 screw thread. The screw thread has a average yield strength of 29.5 MPa. However this the reason why the HDPE pin has a larger cross section. The average maximum standard force [N] subjected to the pin is around 2700 MPa compared with the 2200 Mpa of the screw thread. The elastic behaviour of the HDPE differs from the steel behaviour, however this test shows that the HDPE pins definitely can endure a significant amount of stress. Making it usable as a constructive material for the connectors.

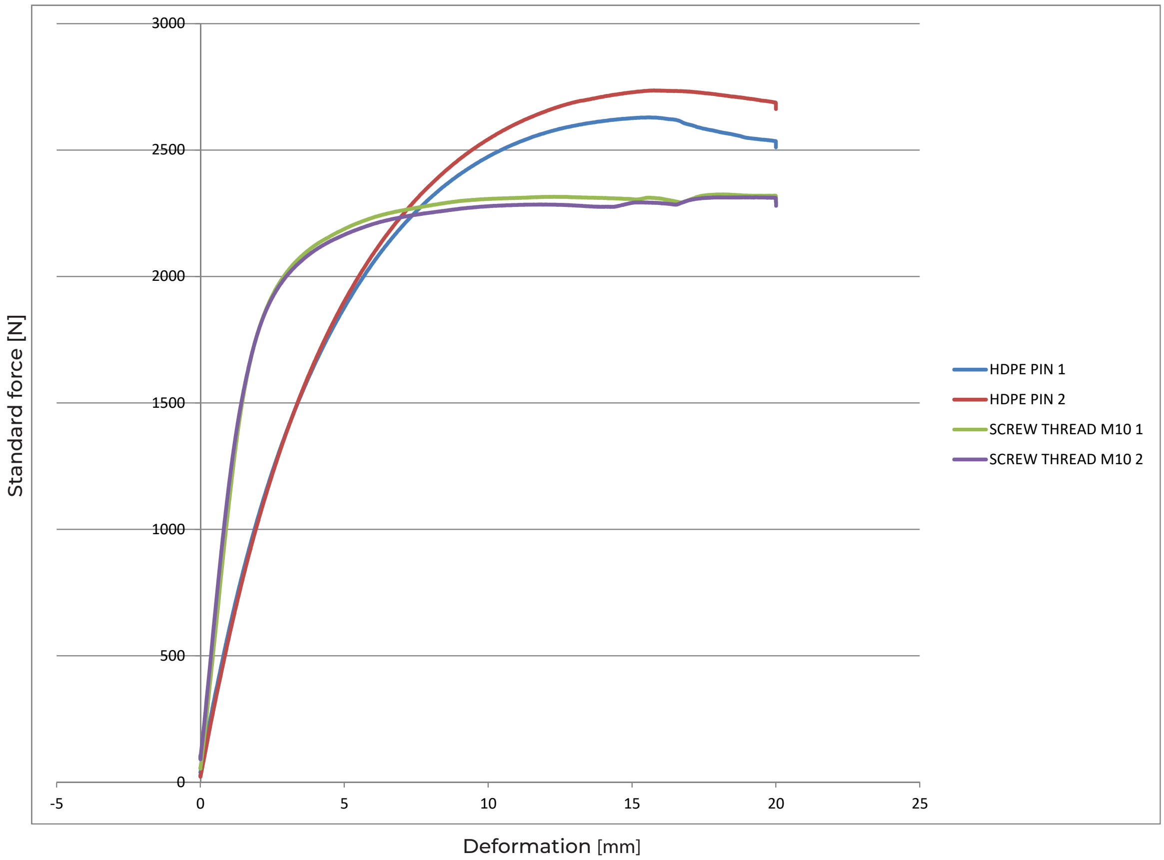


Figure 3.52 Standard force [N] - Strain [mm] HDPE (V)

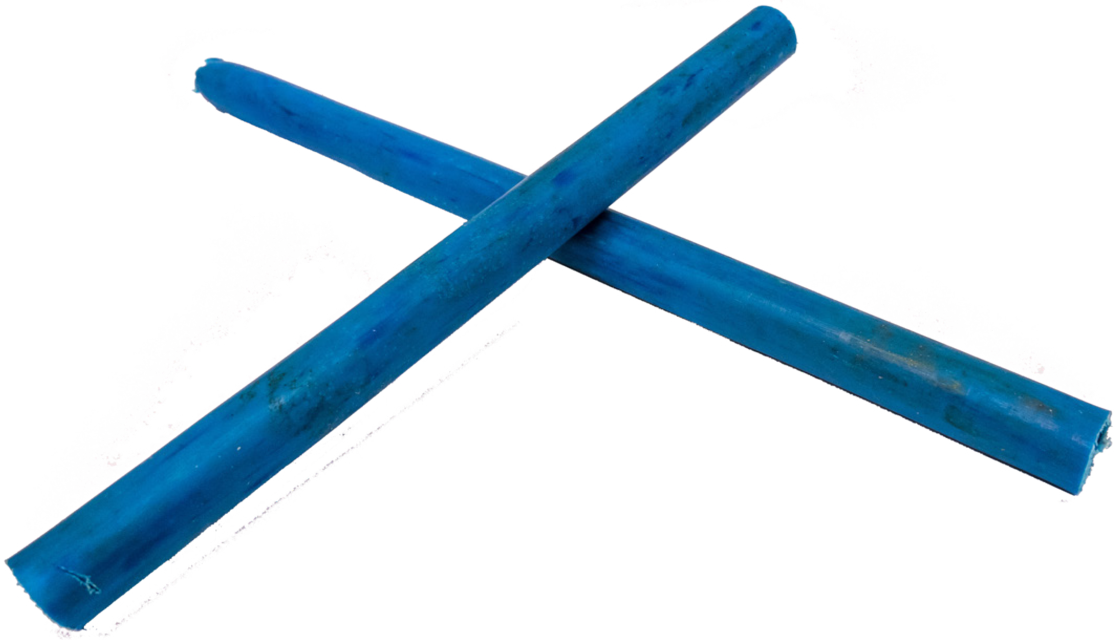


Figure 3.53 HDPE caps compressed into a pin

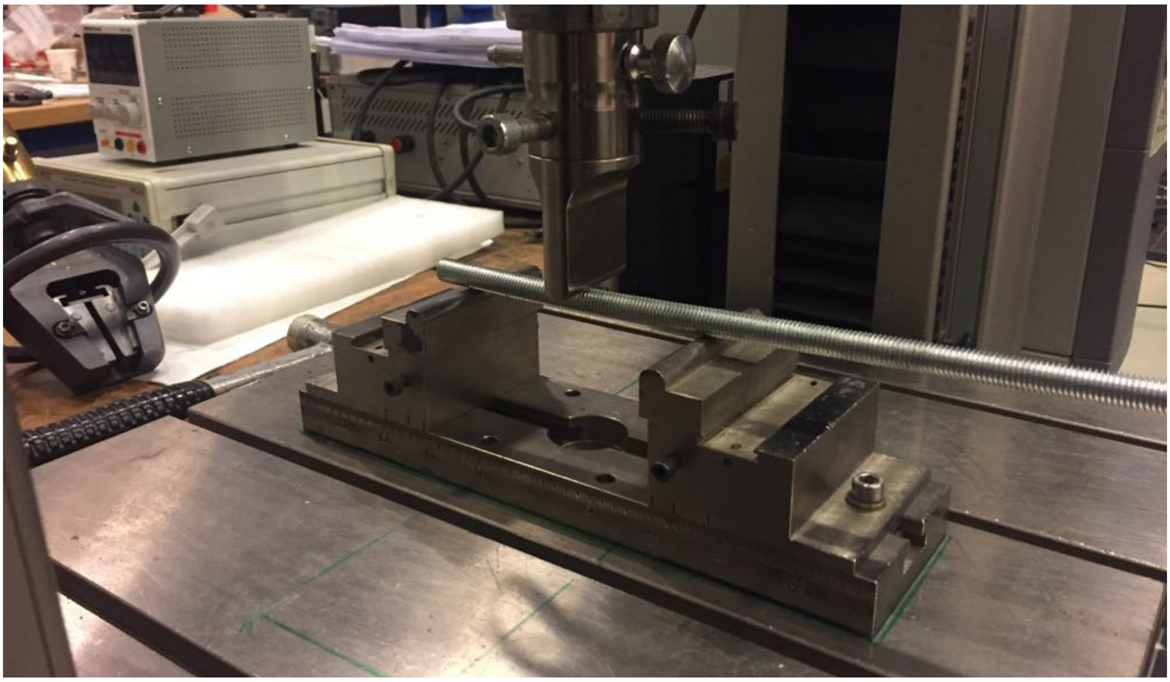


Figure 3.54 Screw thread M10 three point bending test.

4. DESIGN

4.1 DESIGN BRIEF

4.1.1 INTRODUCTION

Building method
The plastic connection need to be able to construct the essential connections to enable one to construct a bamboo structure. Difficulties with the varying diameter and shape of the bamboo has to be solved within the connection elements. A demountable set of connection is essential. As the durability of the plastic is expected to be shorter than the life expectancy of the treated bamboo.

Production process
In order to produce recycled plastic connectors the production techniques need to be relatively simple. No high tech and sophisticated tools are available. A system or a combination of systems need to be found to process plastic waste like bottles, jugs and caps into a new product. Therefore I refer to precious plastics whom made 4 easy to use machines in order to process plastic from waste to product.

Requirements connectors
1) Low tech machinery
Electricity is very scarce. Thus, the machines need to be able to run on either solar collectors or a small generator. The generators run on gasoline, making it expensive and unsustainable. Thus, solar collectors are preferred. The production should be manageable by low-skilled people.

2) Minimize amount of tools, and quick easy to use elements
When constructing a bamboo structure a minimized set of tools will speed up the construction, especially when you need to climb up high in the structure. A minimized set also makes it more feasible for the low-income people.

3) Cheap
As most inhabitants of Esperanza and the R.A.A.N. region live under the extreme poverty line (less than 1$/day). The connections should be close to free. An advantage is that plastic can be found basically everywhere for free. However, the process of turning plastic waste into a product will cost manpower, time and energy.

4) Durable
Today, the traditional connections and the bamboo that is used to build houses, lasts for 3-5 years. The new set of connections need to last at least 5 years. To improve on the situation.

5) Easy to replace/burglar proof
Assuming that properly treated bamboo lasts for 30-50 years, it is to be expected that the plastic connections will have to be replaced in time. Therefore, a demountable connector need to be designed. However, stealing is a regularly activity in the Esperanza community. Detachable connection has to be weighed against a burglar proof connection.

4.2 PROTOTYPES

4.2.1 LIST OF PROPERTIES

In order to evaluate prototypes, a list of relevant properties is made. These properties are derived from the requirements.

There are 2 categories for each prototype which will indicate the pros and cons of the connections.

1) Production
2) Construction

The connections will be reviewed using a table (Figure 4.1). This table will indicate the quality of the elements, the tables are not be 100% decisive. An additional explanation will be added to further describe the advantages and disadvantages of the connections.

All prototype will be 3D printed in order to thoroughly test the different connections. By doing so, the connections can be physically tested. The physical models are mostly important for the construction aspect. Properties as the strength, amount of tools needed, demountability and construction speed can be checked.

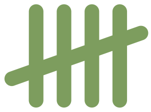
The properties for producing the prototypes is mainly based on the drawings and theory.

	○●●●●	○○●●●	○○○●●	○○○○●	○○○○○
Amount of Elements	One Element	Two Elements	Three Elements	Four Elements	Five or more
Volume (cm3)	0-20	20-40	40-60	60-80	80-100
Simplicity Mould	One Part	Two Parts	Three Parts	Four Parts	Five or more
Strength	Rigid	Fixed	Average	Loose	Very Loose
Amount of Tools	One Tool	Two Tools	Three Tools	Four Tools	Five Tools
Demountable	Very Burglar Proof	Burglar Proof	Average	Permanent	Very Demount-able
Essential Connections	All	-	Two	-	One
Construction Speed	Very Fast	Fast	Average	Slow	Very Slow

Figure 4.1 Table of properties

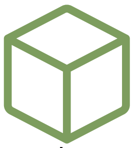
PRODUCTION

Indicates the amount of elements per connection. Fewer elements makes the connection easier to make.



Amount of Elements

Indicates the amount of plastic that is needed per connection. Less plastic makes it easier to collect and cheaper, thus more feasible.



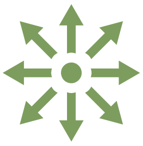
Volume

Indicates the simplicity of the mould. A simple mould is easier to use, will be durable and it will cost less.

Simplicity Mould

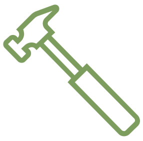
CONSTRUCTION

Indicates how rigid the concerning connection is.



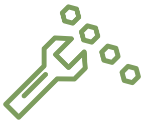
Strength

Indicates the amount of tools needed to fasten one connection. Fewer tools makes the connection easier and quicker to construct.



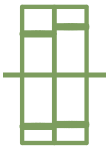
Amount of Tools

Indicates how demountable the connection is. Connections need to replaced when broken. Although in a village like Esperanza the connections need to be burglar proof.



Demountable

Indicates if the connection is able to facilitate all the essential connections.



Essential Connections

Indicates the time it takes to construct one connection. Long construction time is costly.

Construction Speed

4.2.2 PROTOTYPES

PIN PRESSURE CAP

Production
The quite large elements are easier to make due to a lack of small details. The simple form results in a relative simple mould with a low amount of elements.

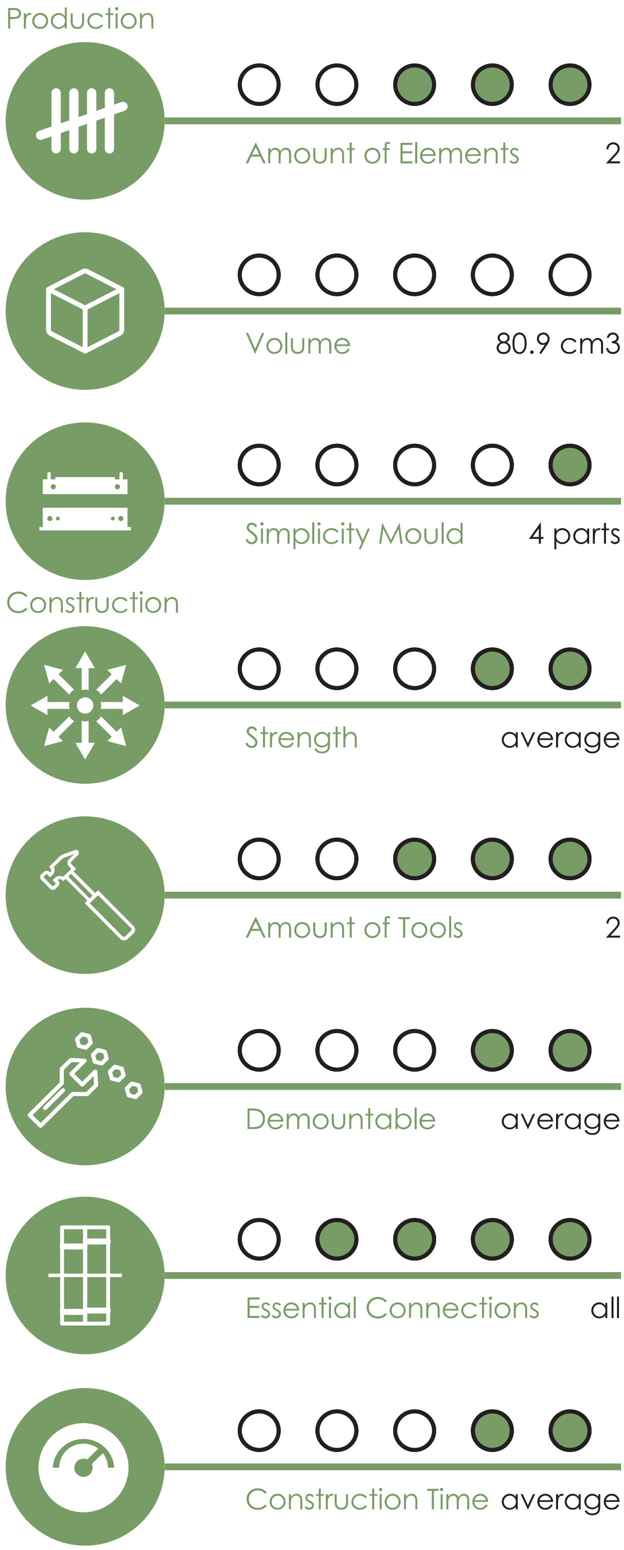
The pin can be produced in lengths of 6 meters, this makes it quick and easy in production. The pins will be cut later on in the construction process.

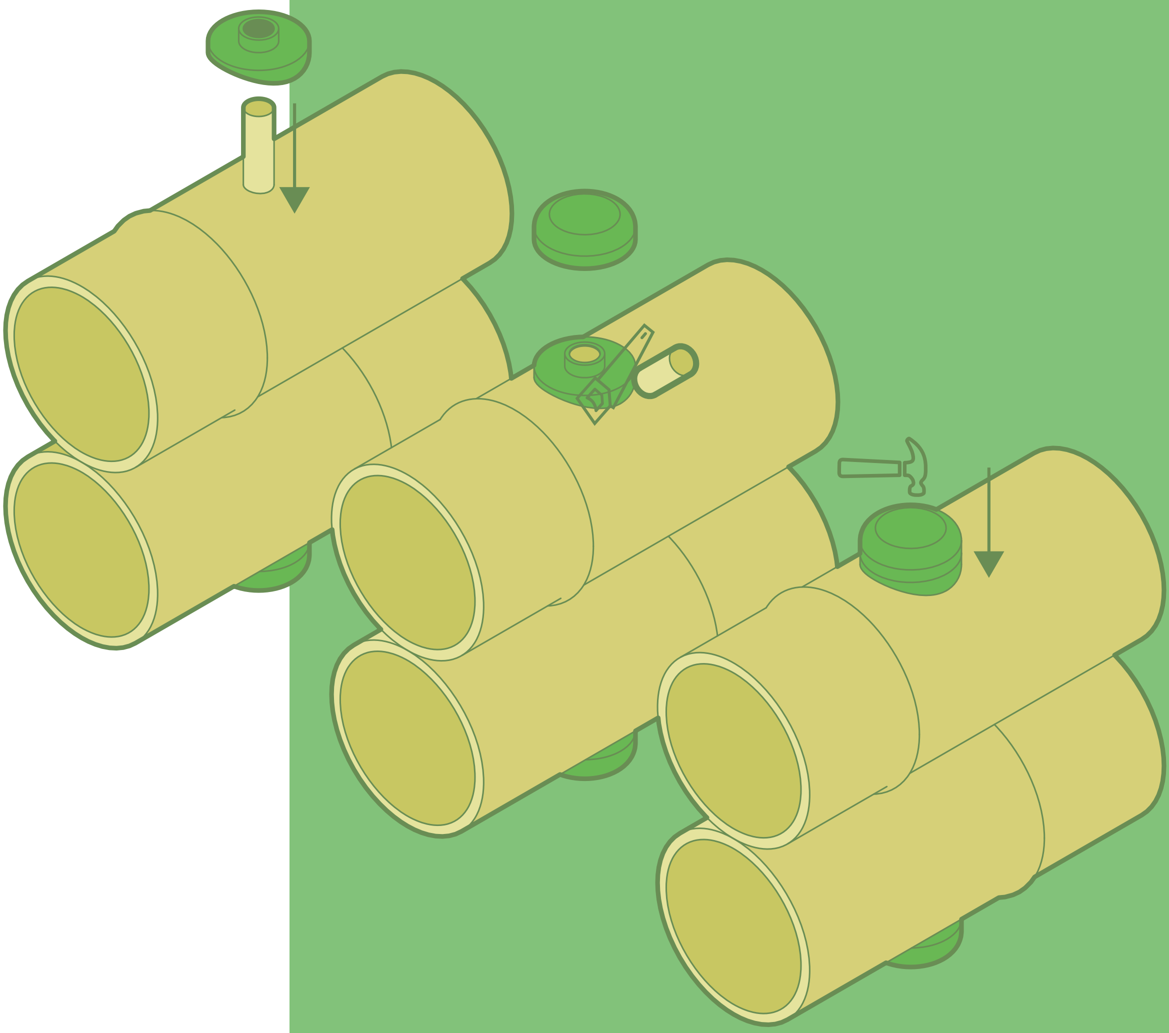
Construction
The first element can be slit over the pin. Cutting the pin flush to the element, makes it unnecessary to measure the length of the pin. This will ensure a perfect connection. Lastly mount the cap by hitting it with a hammer. The cap squeezes the connection even more firm and simultaneously it protects the other parts from the elements. To mount this element a saw and a hammer are needed.

Advantages
Low amount of elements and relatively simple elements. Quick and easy to mount.

Disadvantages
Further development needed to ensure a tight and rigid fit with the pin. An extra element has to be made to facilitate the perpendicular connection.

Figure 4.2 Pin pressure cap model





PIN SOLO CAP

Production
The simple shape of the element and the fact that the connector consists out of only one element, makes the mould and the production process quick and easy.

Construction
The pin needs to be cut correctly in order to make a proper connection. Once installed the element can not be removed easily, therefore recutting the pin is difficult. Once the pin is cut correctly de cap can be fixed by hitting it with a hammer. For this connection a hammer and a saw are needed.

Advantages
Only one element makes it easy to produce and construct.

Disadvantages
The pin needs to be measured and cut correctly. Recutting is hard, therefore it's hard to tighten the connection after the bamboo has shrunk. An extra element has to be made to facilitate the perpendicular connection.

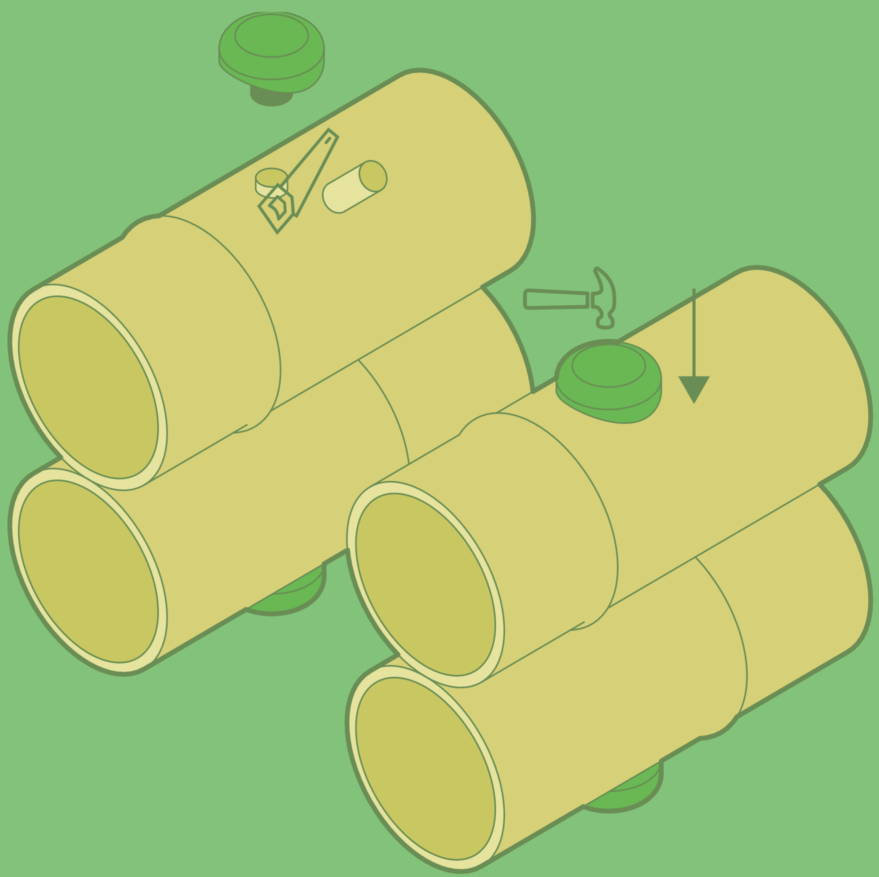
Figure 4.3 Pin solo cap model

Production

Amount of Elements	○ ● ● ● ●	1
Volume	○ ○ ○ ○ ●	60.2 cm3
Simplicity Mould	○ ○ ● ● ●	2 parts

Construction

Strength	○ ○ ● ● ●	fixed
Amount of Tools	○ ○ ● ● ●	2
Demountable	○ ○ ○ ○ ●	permanent
Essential Connections	○ ● ● ● ●	all
Construction Time	○ ○ ○ ● ●	average



PIN NAIL CAP

Production
This connection consists out of two elements, more elements result in a longer production time or more complex moulds. However the elements are simple.

Construction
This simple method of a wedge is often used in bamboo connections. The first element is slit onto the pin and then cut flush. By hammering the small pin into the connection the first element is fixed to the pin. A additional cap can be mounted to protect the other elements.

Advantages
This connection is very sturdy and it can be tightened afterwards. The connection is quick and easy to mount.

Disadvantages
High amount of elements. An extra element has to be made to facilitate the perpendicular connection.

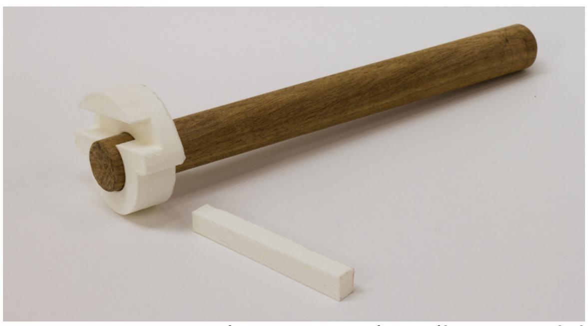


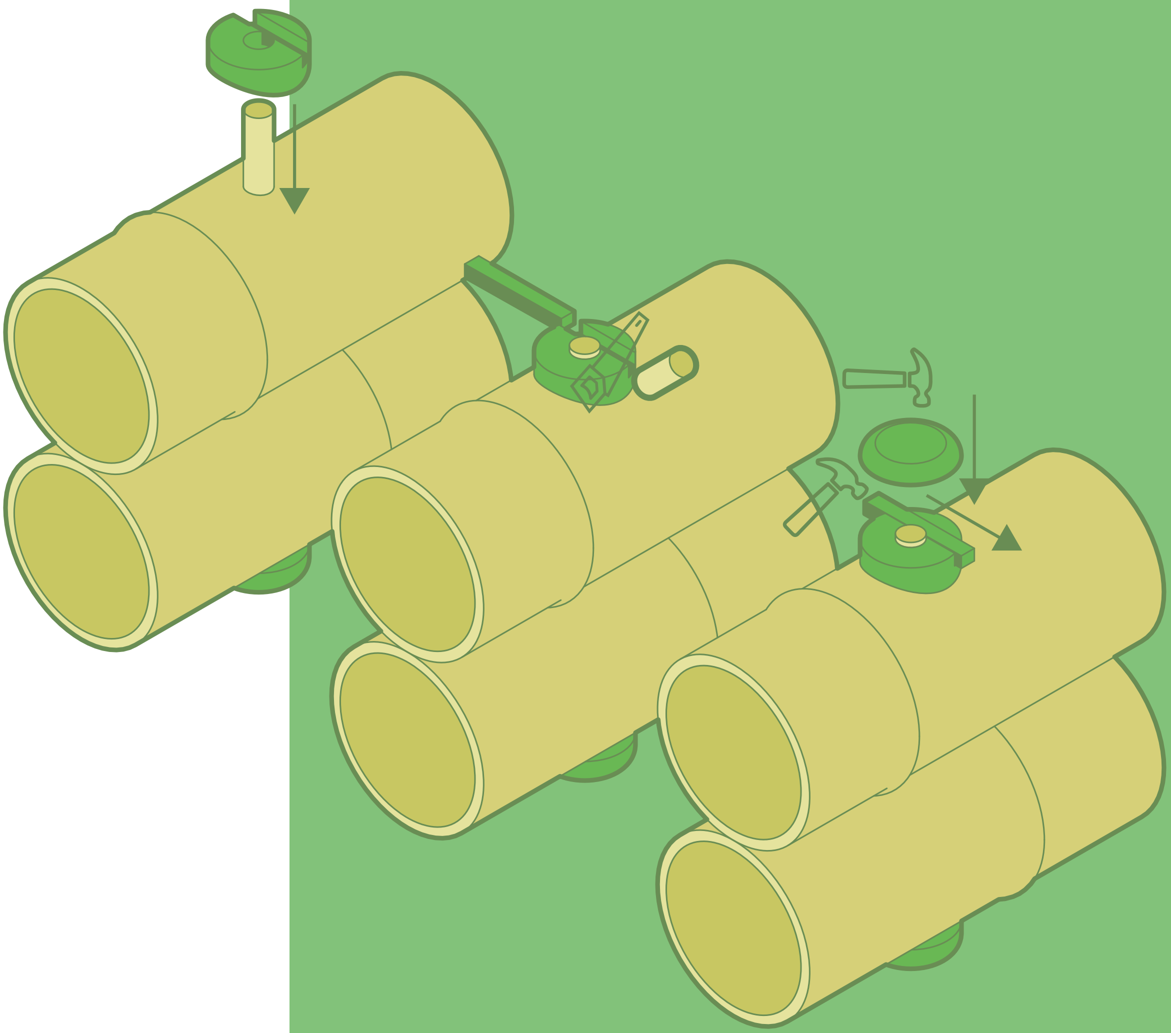
Figure 4.4 Pin nail cap model

Production

Amount of Elements	○○○●●	3
Volume	○○○○○	83.9 cm3
Simplicity Mould	○○○○○	5 parts

Construction

Strength	○●●●●	rigid
Amount of Tools	○○●●●	2
Demountable	○○●●●	burglar proof
Essential Connections	○●●●●	all
Construction Time	○○○○●	slow



TUBE SOLO CAP

Production
Only one element makes the production process quick and easy and the mould is relatively simple. Again the pin can be extruded in pieces of 6 meters, therefore the production speed is high.

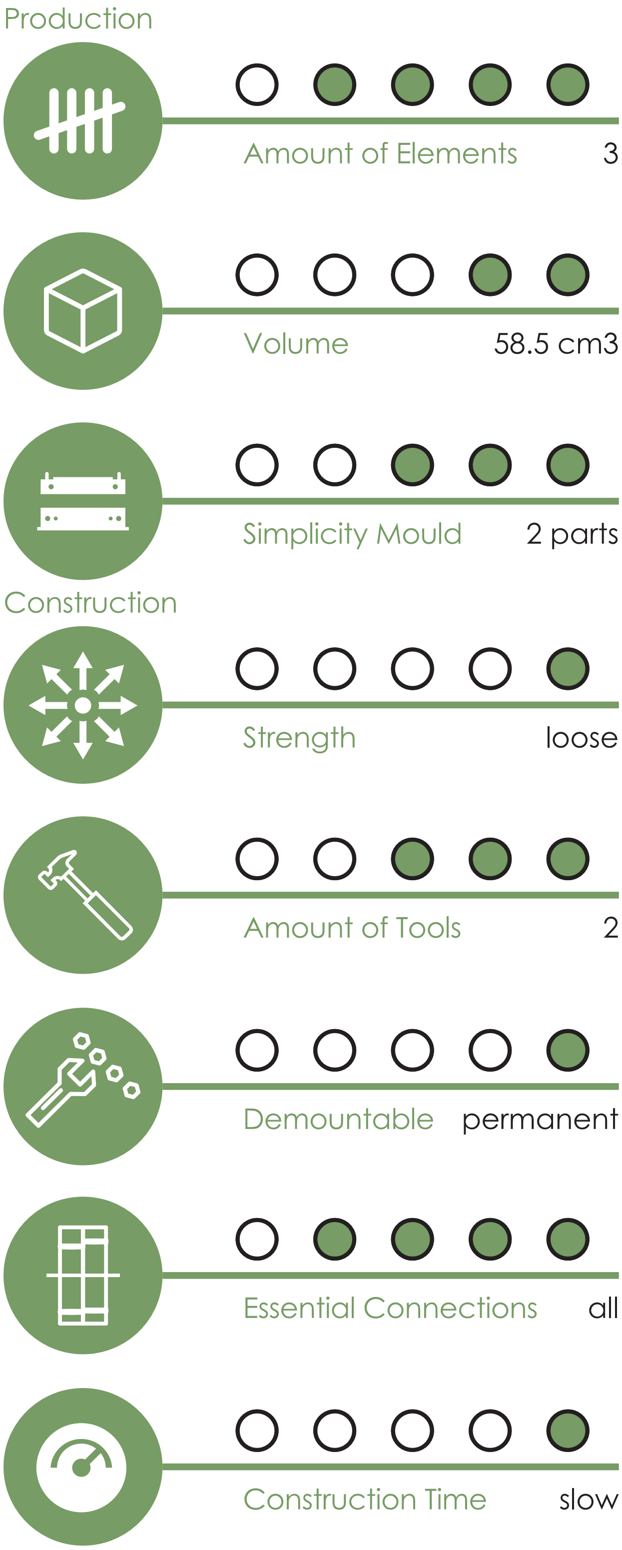
Construction
In order to make a tube from the extruded pin, a hole has to be drilled. It is hard to recreate the same hole in the middle of the pin each time. This extra action is not desired. Furthermore the pin will be weakened by the hole and removing material from the new elements results in waste.

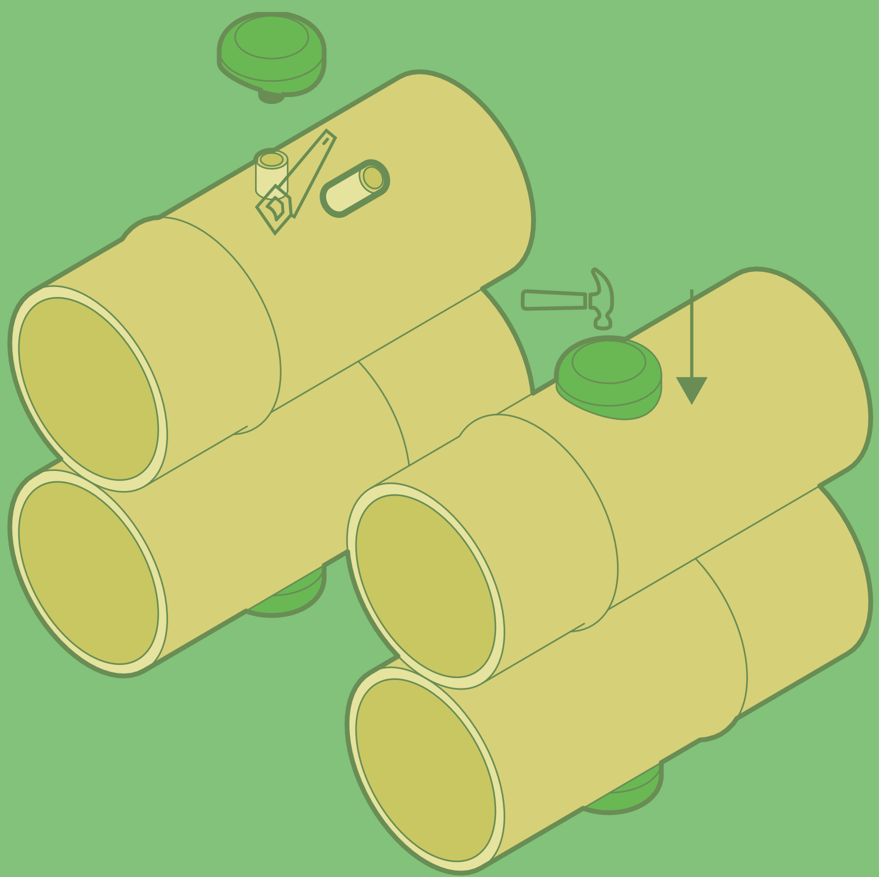
Before sliding the element over the tube the tube has to be measured correctly and the tube can't be adjusted easily after placement.

Advantages
Low amount of elements and quick to mount.

Disadvantages
Waste is created by drilling a hole in the tube and simultaneously the pin is weakened. An extra element has to be made to facilitate the perpendicular connection.

Figure 4.5 Tube solo cap model





TUBE SMALL PIN CAP

Production
Only one element makes the production process quick and easy and the mould is relatively simple. Again the pin can be extruded in pieces of 6 meters, therefore the production speed is high.

Construction
In order to make a tube from the extruded pin, a hole has to be drilled. It is hard to recreate the same hole in the middle of the pin each time. This extra action is not desired. Furthermore the pin will be weakened by the hole and removing material from the new elements results in waste.

Before sliding the element over the tube the tube has to be measured correctly and the tube can't be adjusted easily after placement.

For this connection a saw and a hammer are needed.

Advantages
Low amount of elements and quick to mount.

Disadvantages
Waste is created by drilling a hole in the tube and simultaneously the pin is weakened. An extra element has to be made to facilitate the perpendicular connection.

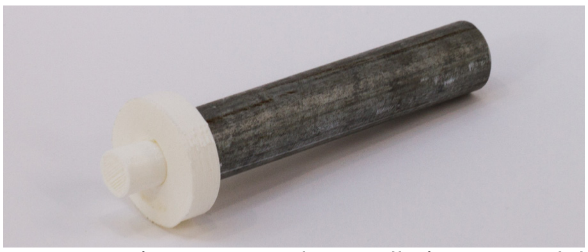
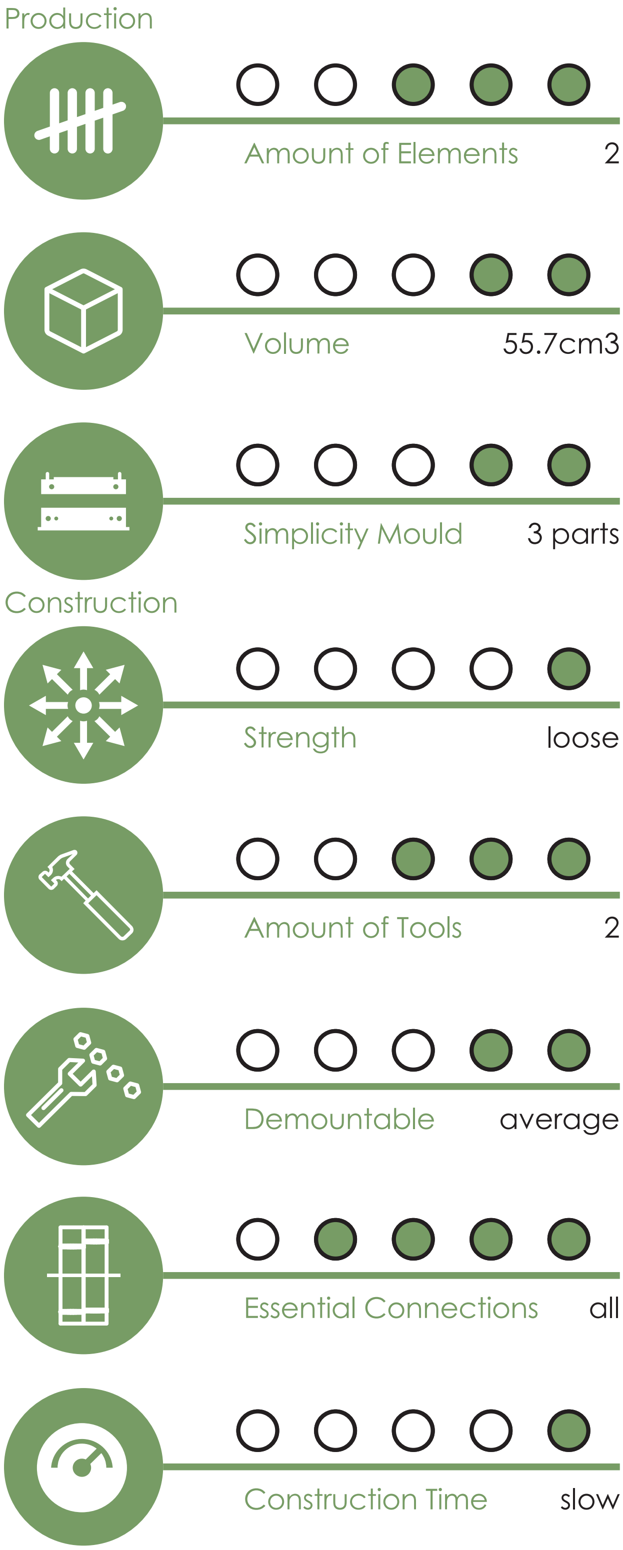
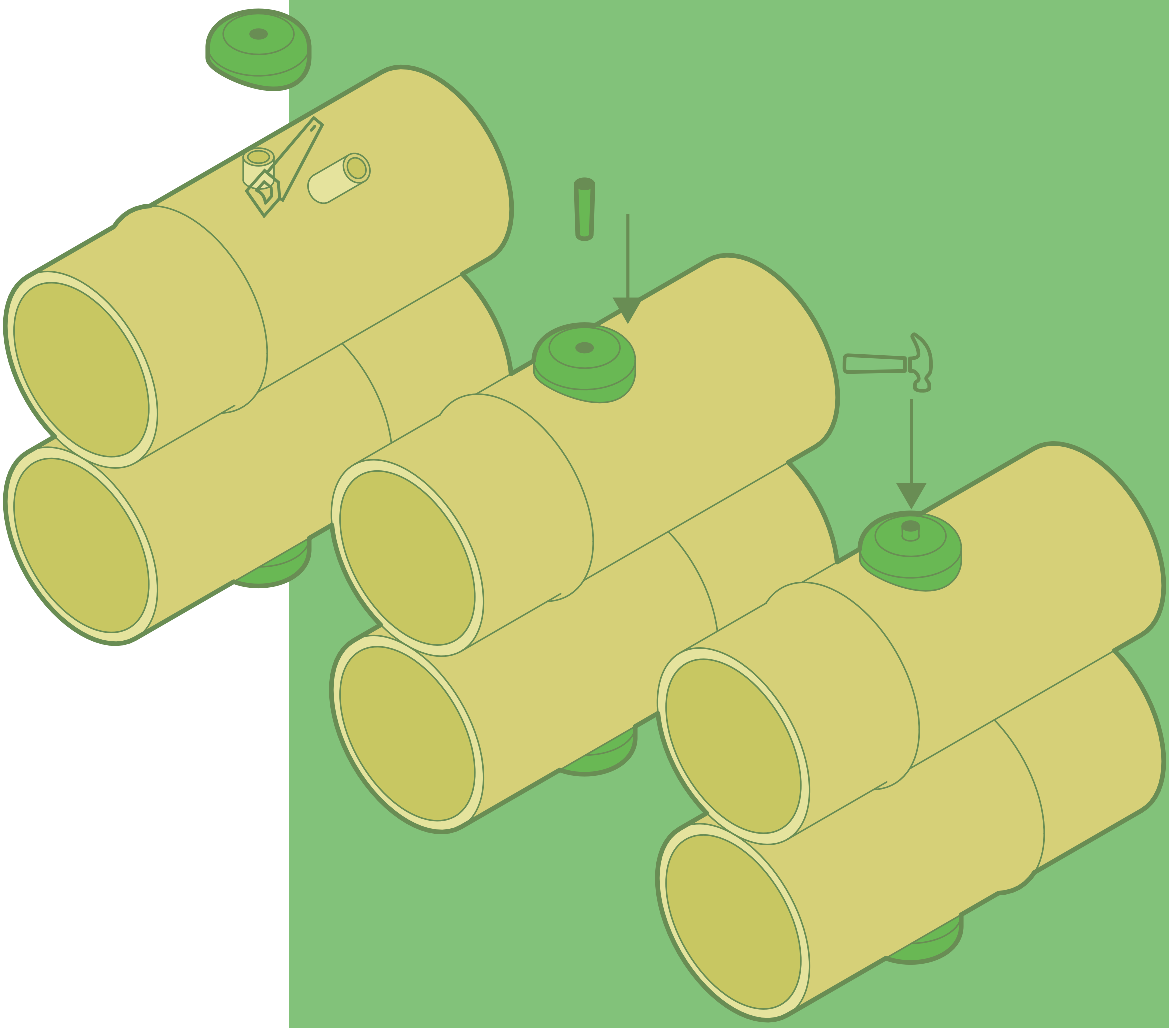


Figure 4.6 Tube small pin cap model





TUBE PIN CAP

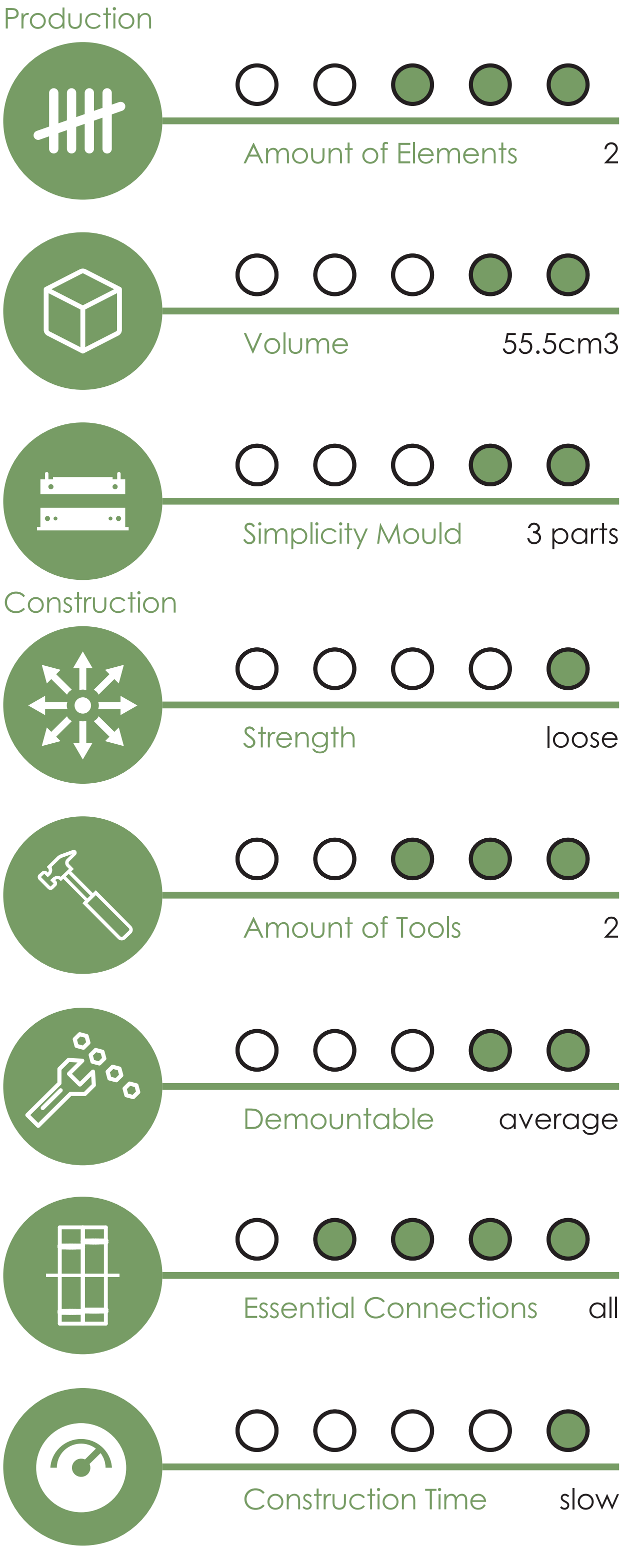
Production
This connection consists out of two simple elements and the total volume is relatively low.

Construction
The construction time of this connection is longer due to the extra step of drilling the hole in the pin, in order to make a tube. However the other actions are very low tech.

When hammering down the pin into the connection, one has to be care full not to break the tube.

Advantages
Low amount of plastic needed and the connection consists out of simple elements.

Disadvantages
The acquirement of drilling a hole in the pin, makes this connection slow to mount and the tube is weakened. An extra element has to be made to facilitate the perpendicular connection.



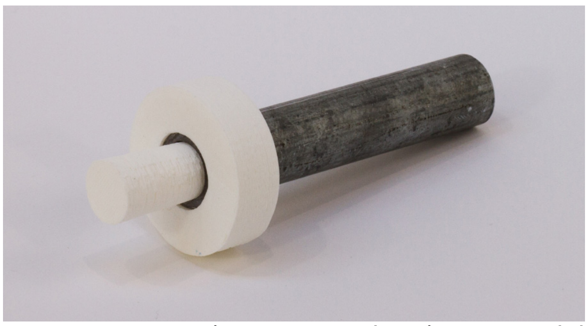
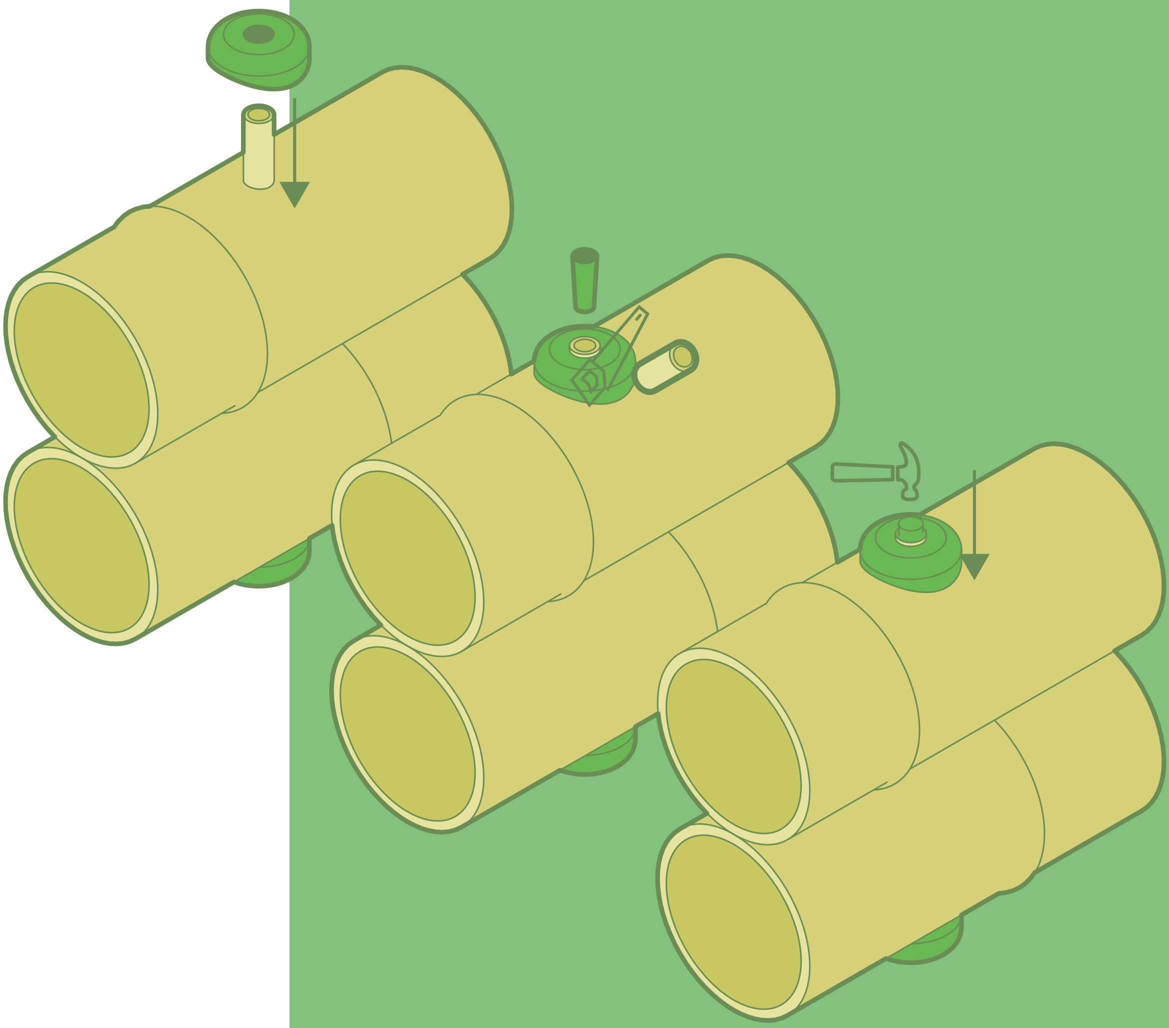


Figure 4.7 Tube pin cap model



STRAP HELMET SYSTEM

Production
Producing this connector requires a very complex mould that is hard to inject properly. The teeth and the length of the strap makes the production difficult. In addition the mechanism to tighten the strap is also complex. The complexity of this connection makes it unreliable

Construction
This connection is quick and easy to use. The strap is tightened by twisting the connector. The varying diameter of the bamboo is integrated in the teeth system.

Advantages
No extra tools are needed.

Disadvantages
The teeth are small and thin, therefore this connector is vulnerable. In addition this connector doesn't facilitate the three essential connections.

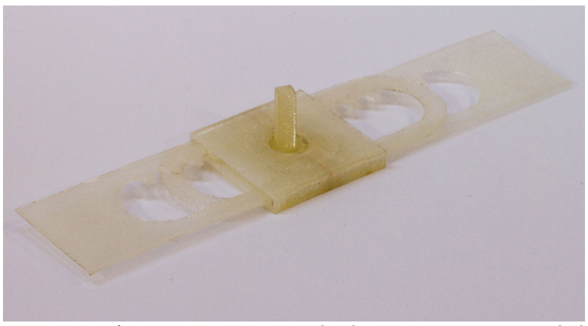
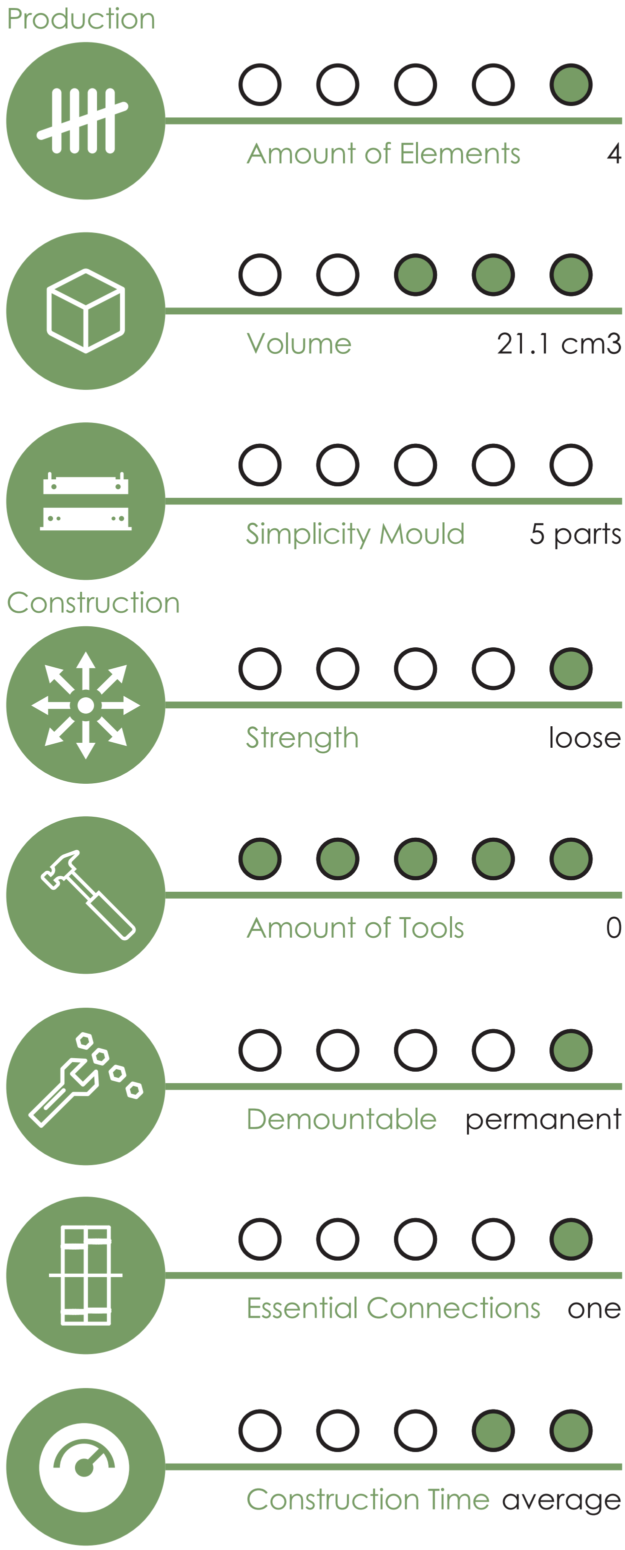
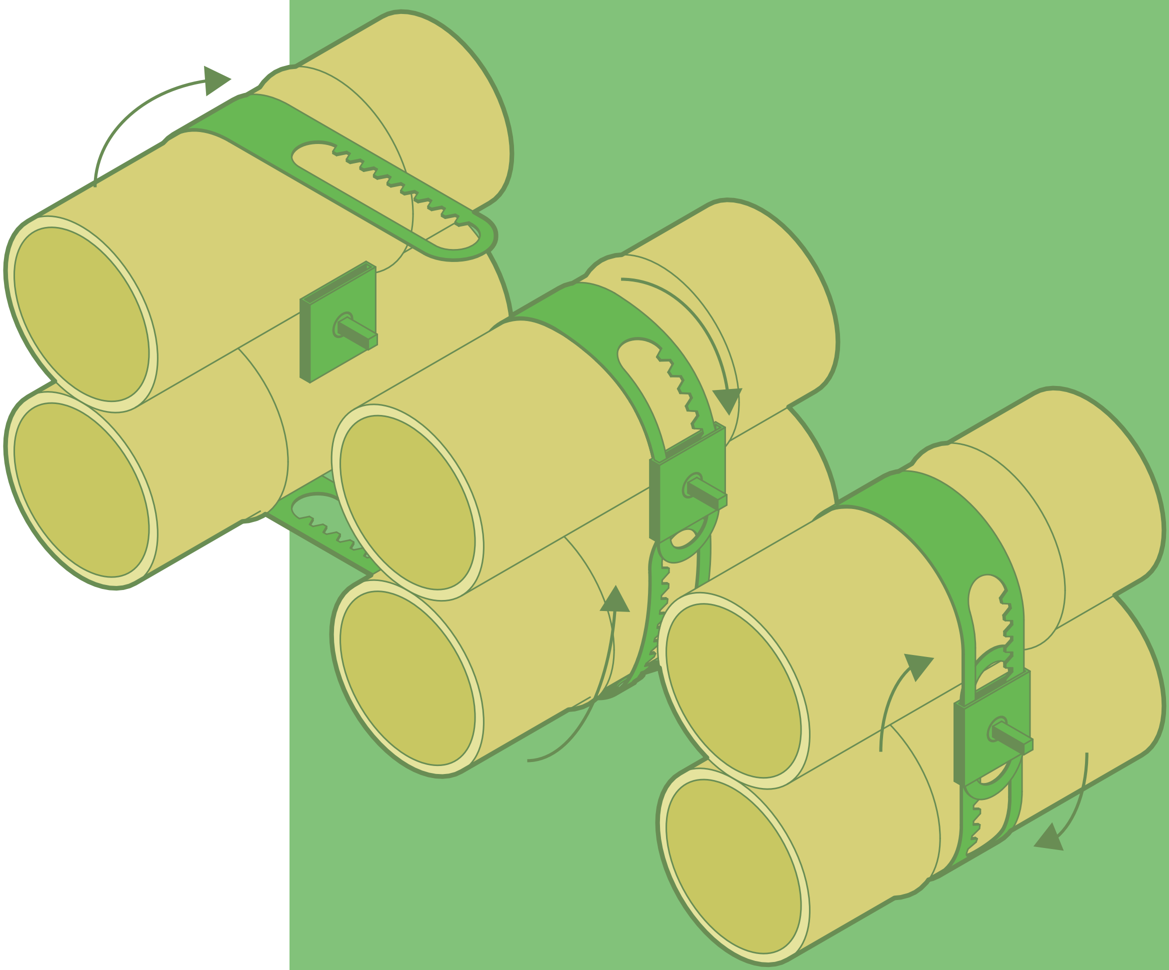


Figure 4.8 Strap helmet system model





STRAP BUCKLE

Production
Very simple to make. But it's also very cheap to buy normal buckles and then ship the buckles to the project location. However the strap is very difficult to produce. PET has to be very thin in order to be flexible. A thin thickness requires a very high pressure when extruding the plastic.

Construction
The strap buckle connection is similar to a belt. It is very easy and quick to tie. The simplicity of this connection makes it very easy to steal and next to this the connection is not very strong.

Advantages
Very quick and easy to produce and construct.

Disadvantages
Not burglar proof and it's a weak connection. In addition this connector doesn't facilitate the three essential connections.

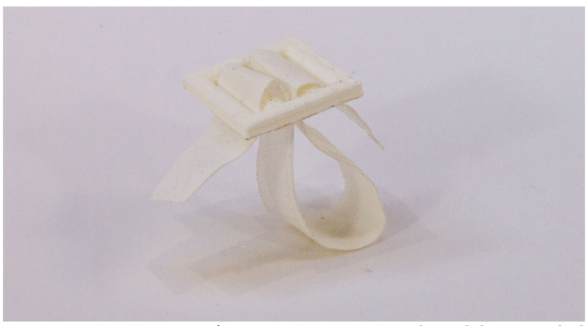
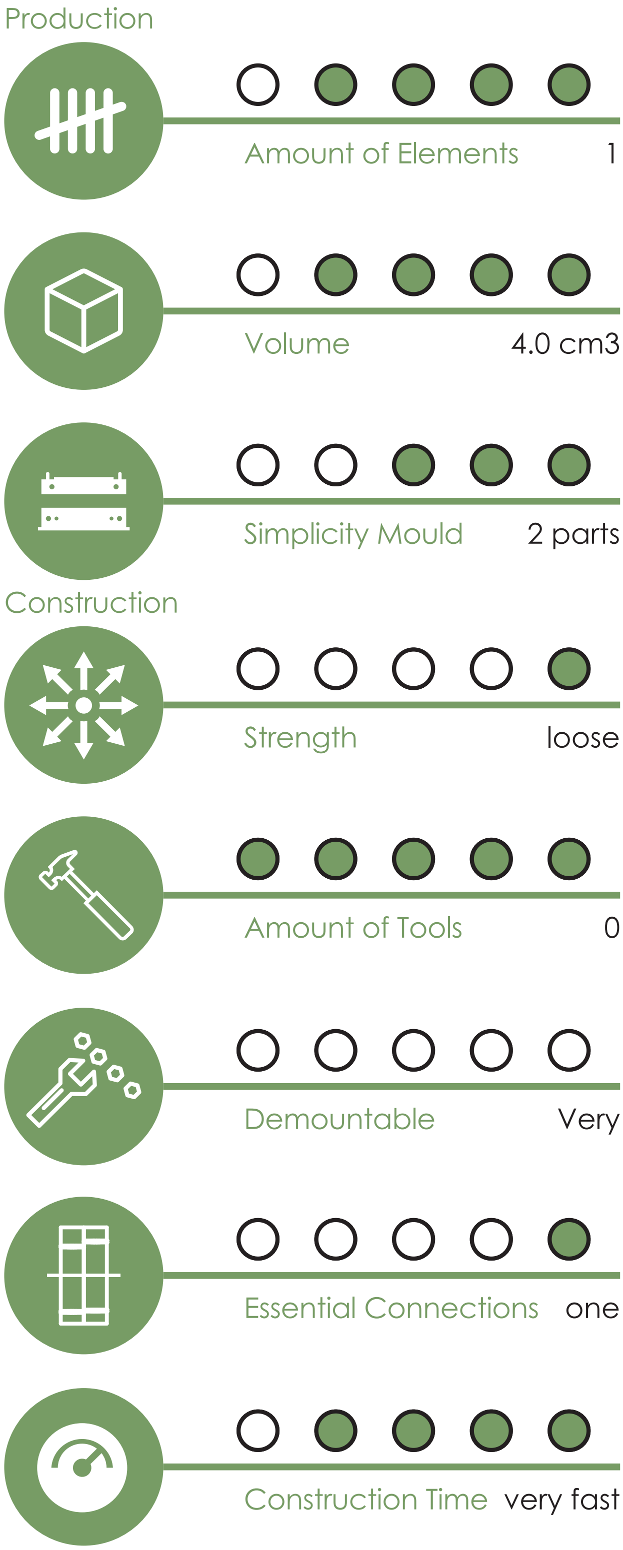
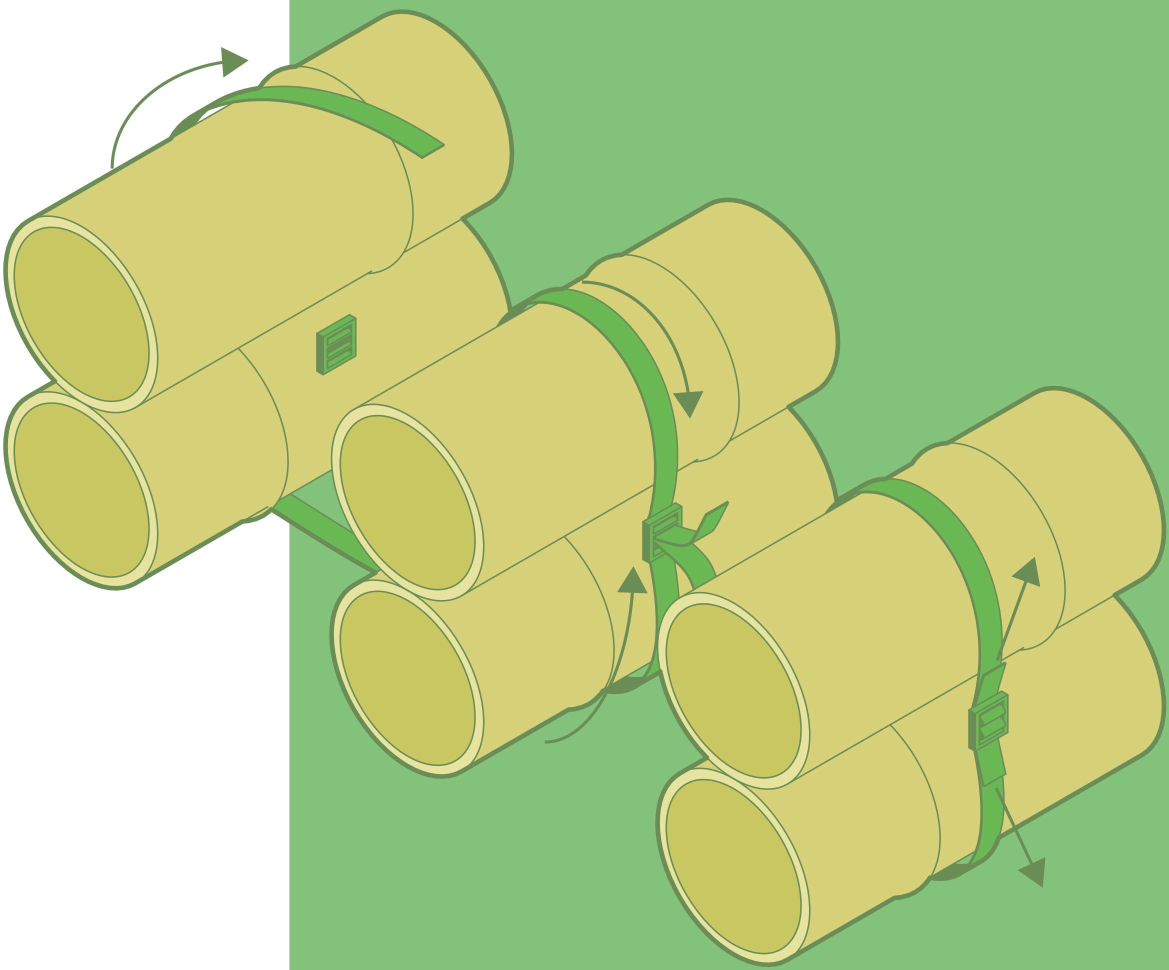


Figure 4.9 Strap buckle model





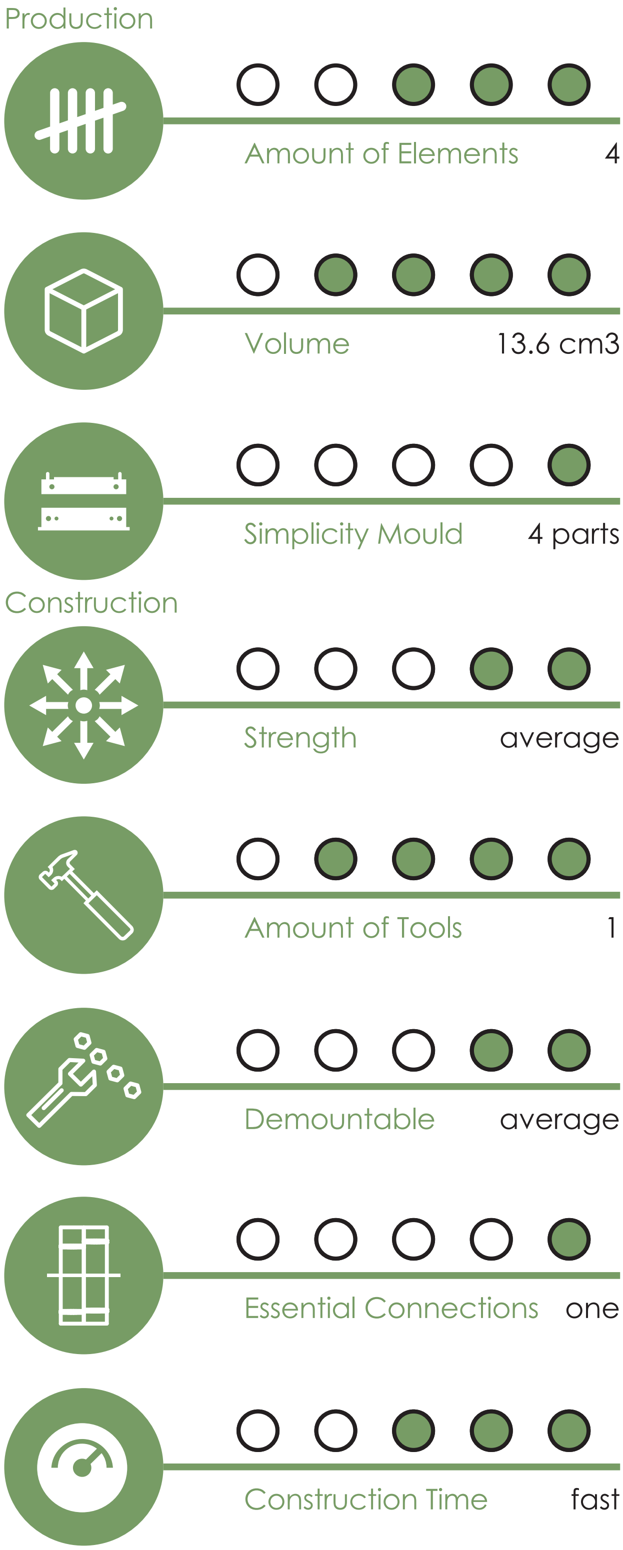
STRAP SLIDER

Production
The slider consists out of only two elements, however the elements contain small walls. Producing these elements with a injection machine requires high pressure.

Construction
The strap slider is very easy to tie, making it very demountable. The slider can be loosened in time to tighten the connection if needed.

Advantages
Quick and easy to construct and can be made with a little amount of plastic.

Disadvantages
The strap slider isn't easier to construct than the buckle. However it is harder to produce. In addition this connector doesn't facilitate the three essential connections. This makes the strap slider not suitable as a bamboo connection.



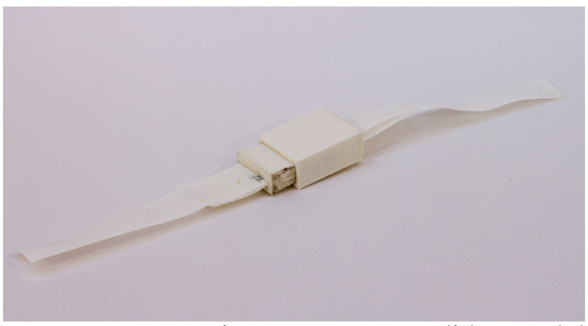
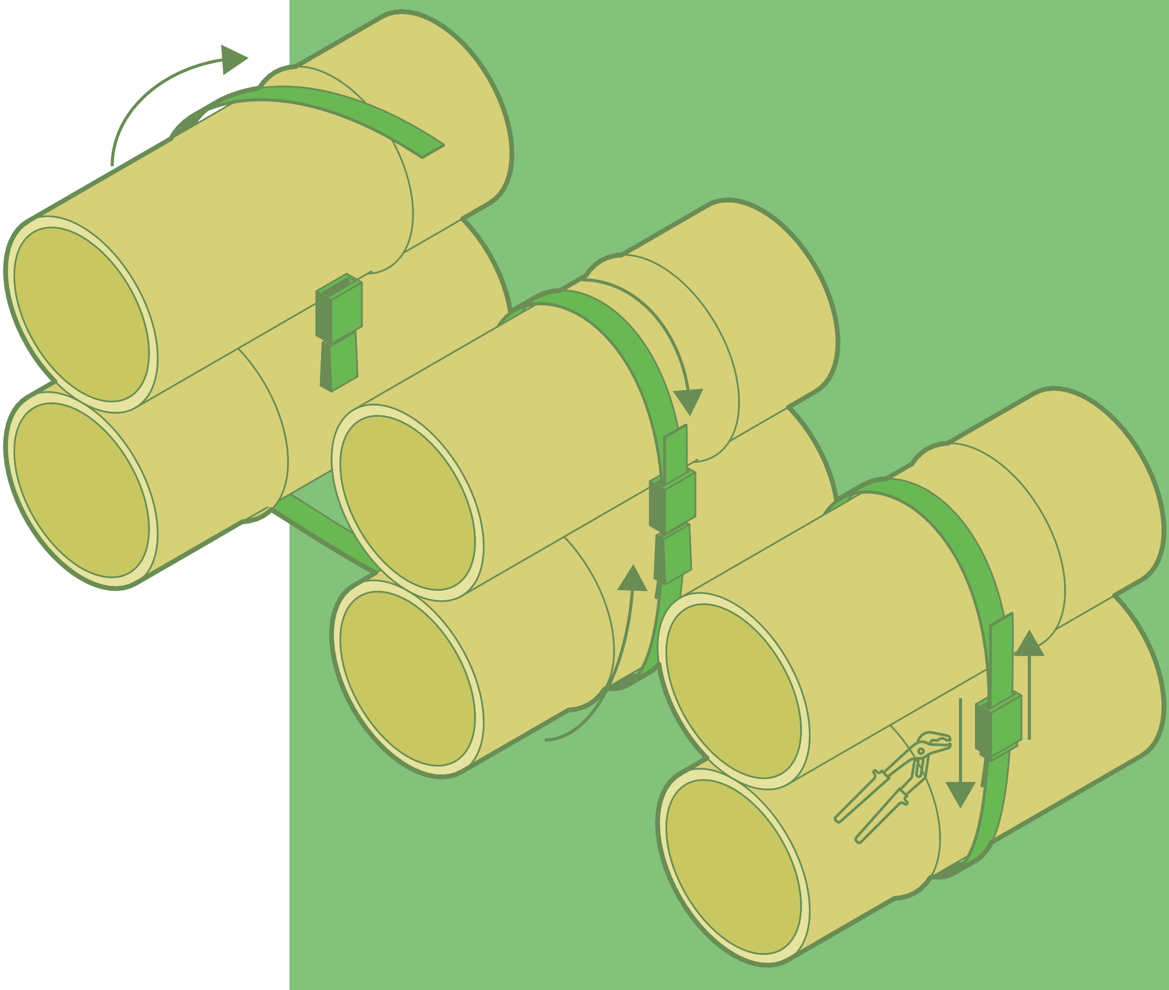


Figure 4.10 Strap slider model



4.2.3 ELABORATION ON PROTOTYPES

In order to elaborate on the prototypes the most important properties need to be pointed out. A low amount of elements, which results in a simple mould with few parts, is crucial for the production speed. The amount of plastic that goes into a part, is less important, when the amount of plastic available is sufficient. Using more plastic than needed is of course not desired, however saving on the amount of plastic is unnecessary. Especially when this will affect the strength and durability of the connection.

In construction it is most important that the connector facilitates all of the three essential connections. Also the connection needs to be strong and durable in the sense that it is burglar proof and simultaneously demountable, concerning the ability of replacing broken parts. The remaining properties are desired but not compulsory.

Essential connections

Concerning the ability of facilitating all the essential connections, the strap connections aren't doing so well. In order to facilitate the perpendicular connection and the crossing connection, multiple straps (Figure 4.11) or elements are needed. Except when using a lashing, however using a lashing in bamboo constructions is discouraged by the Bambú Natural project. Lashings are easy, quick and strong. But they are strong for only about 3 to 5 years, as they tend to loosen in time.

The pin and tube connections perform better as they facilitate the parallel and crossing connections. In order to facilitate the perpendicular connection, only one extra element is needed that holds two pins perpendicular to each other (Figure 4.12).

Figure 4.11 Crossing bamboo multiple straps

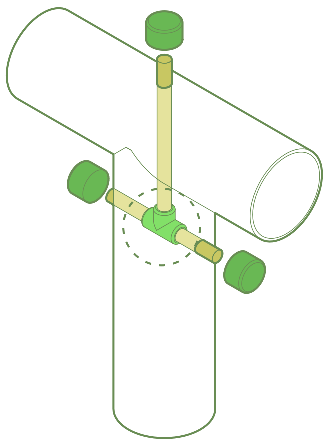


Figure 4.12 Extra element for perpendicular connection

Production

A small amount of elements and a simple mould decreases the production time. The production of a pin is relatively simple. The pins are produced by extrusion through a steel tube. Long pieces of about 6 meters can be made. This way a production line can be set up. A pin connection in combination with a simple connector would be feasible as a working connection.

Tubes can be made with the same pin, where holes are drilled in the ends after cutting the tubes to the desired length. Drilling the pins requires an extra action and more tools are needed. In addition the drilling has to be done precisely and it can weaken the pins.

PET and HDPE need to be very thin in order to be flexible. Therefore the straps should be thin. The production of a thin layer of plastic in an extrusion process requires high pressure, making it difficult to make with low tech machines. Producing it by injection moulding would be very time consuming and the use of a fixed size of the strap will result in a lot of waste. Also the buckle strap is very cheap to buy, so producing them with a low tech machine would be a bit cumbersome.

Construction

The pin connections are easy to mount, however the connections needs around three actions to install. Three actions is the average construction speed in the presented prototypes. The pressure cap and the nail cap result in a rigid connection.

As explained above, the tube need to be drilled, so that takes more time. The next steps are quick and easy. When designed well the pins that are hammered in the tube can form a strong and burglar proof connection.

The strap connection are very quick and easy to mount. However the buckle and strap connections need an extra element to make it a strong connection and burglar proof.

In order to make a decision on what type of connection is most suitable to act as a bamboo connector, tensile strength tests and 3 point bending tests will be performed on the pin and the strap connections.

4.3 PIN OR STRAP

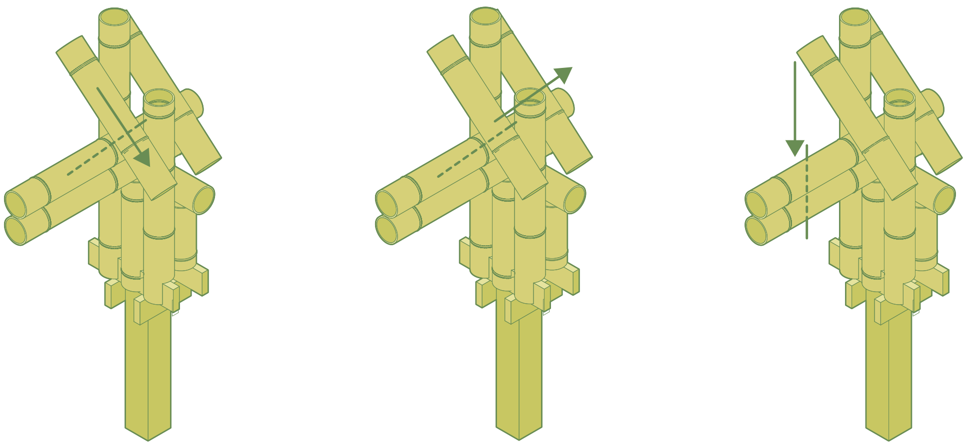
4.3.1 INTRODUCTION

As the list of existing jointing techniques shows that there are in fact two different types of bamboo connections. Firstly a strap around the bamboo, without adjusting the bamboo by for example drilling holes. Secondly a pin connection, where a hole is drilled in the bamboo to facilitate the connector. A combination of these two types can also be found.

In the Bamboo Factory steel bolts were used and herefore we drilled holes in the bamboo. The relative small hole didn't seem to weaken the bamboo in a drastic way. In order to get more insight of the advantages and disadvantages of the two types of connections a set of tensile strength tests will be done.

The three most common and important load cases will be tested.

1) Perpendicular to the connection
2) Parallel to the connection
3) Perpendicular to a beam



The initial tests will be performed on bamboos with a small diameter of around 20 mm. To be able to perform a quick first test, zip ties are used to represent the strap connection and a nylon m6 screw represents the pin connection. It is of importance to realize that the connections are not in scale. Therefore the results aren't scalable neither. This test will be used to get more insight of the behaviour of the two types of connections.

The three most common connections (Figure 4.13) will be tested in both a pin and a strap version.

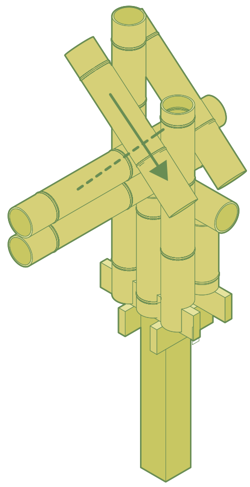
In the first tests the tensile strength of the pin and the strap connection is tested, the connector is perpendicular to the applied force. This is the most common load case occurring in a bamboo structure, this makes the perpendicular connection the most important. The importance of this connection makes the results of the first test very decisive for choosing the best type.

Secondly the crossing bamboo connection will be tested. In this test the connectors are parallel to the applied force, therefore the tensile strength of the connectors is tested. This type load case is less common in a bamboo structure. Mostly the bamboos are supporting each other and the connectors just holding the bamboos against each other. However some tensile strength is required when for example the roof is pulled by wind.

Lastly the beams will be tested. Traditionally bamboo beams are reinforced with so called 'Espiches'. Basically these espiches are wooden pins made from the wall of the bamboo. Holes are drilled diagonal through two or more bamboos and espisches are put in. The beams will undergo a three point bending test. Especially the bamboo stem itself will be tested in the three point bending test, as the connectors are on the outside of the test object. Herefore the effect of drilling holes in the bamboo and placing espiches will be tested. The results of the beam tests will be inferior to the first test, concerning the influence on the final decision, as the strength of the beams isn't depending a lot on the connectors

Figure 4.13 Three types of connections.

Force perpendicular to the connection



This load case occurs in all of the essential connections. Namely the two and three bamboos parallel or crossing and partly in the essential connection where two bamboos are perpendicular to each other. For this test three bamboos are connected with the pin and the straps. Steel plates are mounted to the bamboo in order to mount the test object into the zwick testing machine. Again this is a principle test, where the behaviour of the different connections is most important. No actual mechanical properties are calculated, as the bamboos varies in diameter, wall thickness and strength. However the measured data can be compared as the setups are identical.

Strap connection
Constructing the strap connection three zip ties are used (Figure 4.17). For this type of connection its hard to tighten the straps firmly. This results in a 'weak' connection. The bamboo slipped in between the straps, resulting in a F_{max} of 51,23 N (Figure 4.14).

Pin connection
A M6 nylon bolt and nut are representing the pin connection. A hole is drilled through the three bamboos and the bolt is put in (Figure 4.16). For this test it is important to know if the bamboo tears before the connector breaks. In the end the bamboo connection was deformed but still intact. The F_{max} of the pin connection was 1082,78 N (Figure 4.15). This means that the weakened bamboo with a hole still is much stronger than the strap connection.

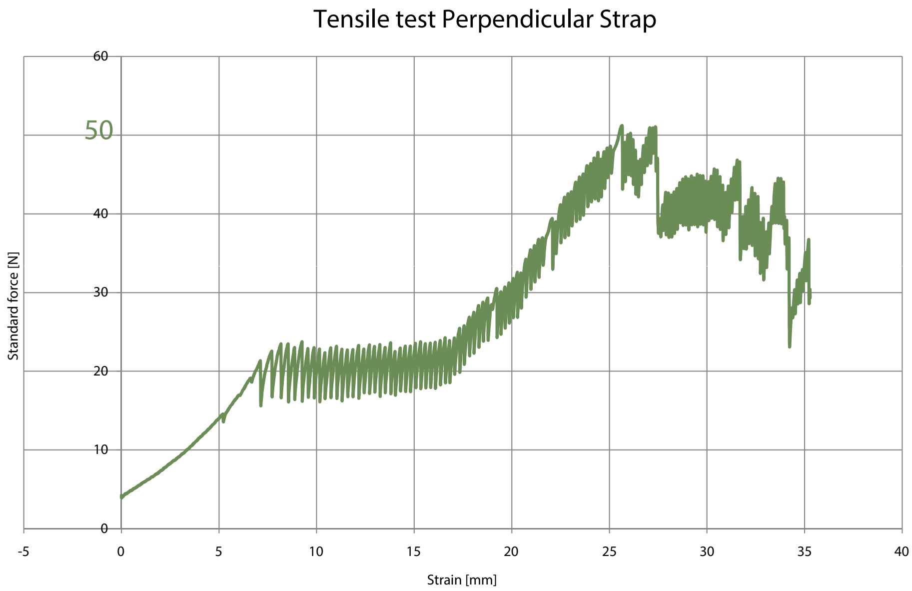


Figure 4.14 Results tensile strength test parallel strap connection

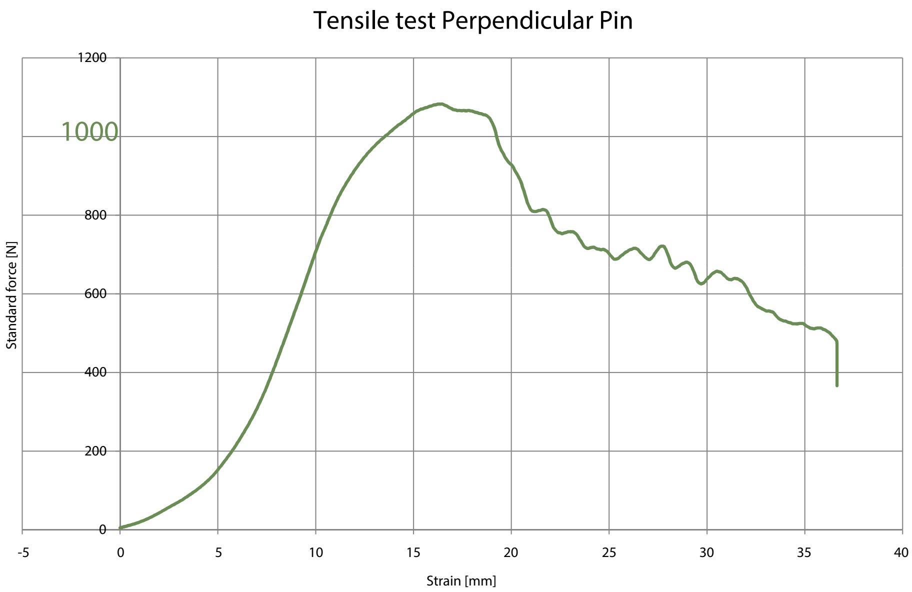


Figure 4.15 Results tensile strength test parallel pin connection

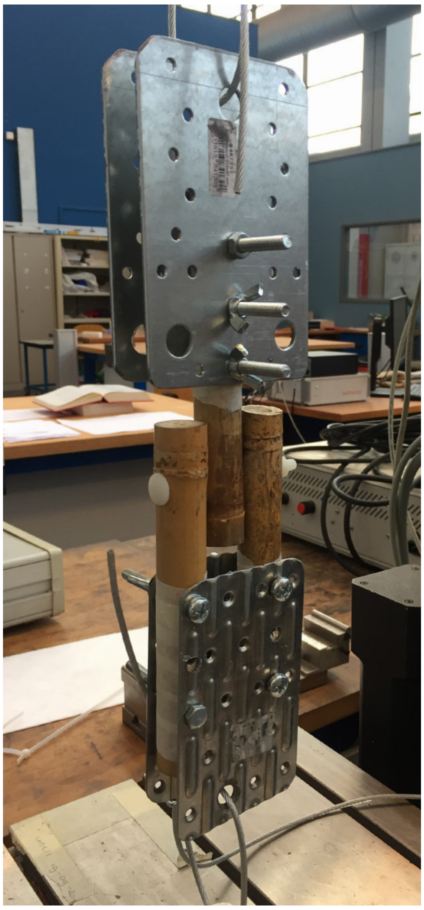


Figure 4.16 Perpendicular pin connection

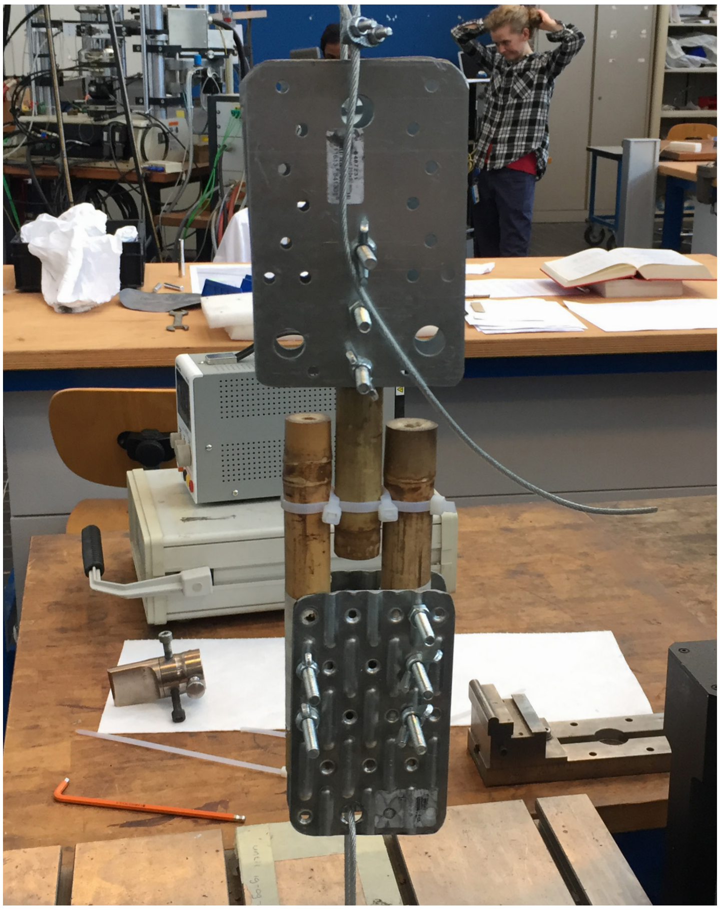
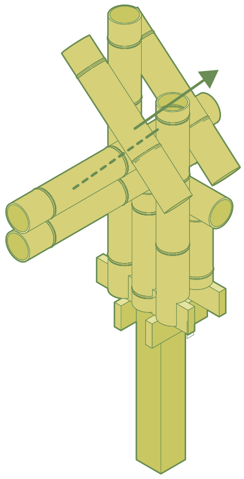


Figure 4.17 Perpendicular strap connection

Force parallel to the connection



This load case occurs mostly in the connection where two bamboos are perpendicular to each other. The tensile strength of the connector is also tested when for example the wind tries to lift up the roof. For this test two crossing bamboos are connected. Then cables are mounted to the bamboo in order to mount the testing object onto the Zwick testing machine. Zip ties prevents the cables from sliding. Again mechanical properties aren't the desired results of this test. It is of importance to be able to compare the two types of connections. An extra attention point is to check if the weakened bamboo by drilling a hole, cracks before the pin connection fails.

Strap connection
To mount the two bamboos firmly and to avoid the bamboos from twisting, three straps (zip ties) are used (Figure 4.20). During the test the bamboo remained undamaged and the zip ties failed at a F_{max} of 647,97 N (Figure 4.18). This shows that the strength of the strap is determinative until the bamboo fails before the strap. The failure of the bamboo will be tested in the next test.

Pin connection
A hole is drilled through the bamboos and a M6 nylon bolt and nut are placed in (Figure 4.21). During the test the bamboo didn't crack. The surly nylon connector was stretched until the maximum deformation of 70 mm was reached. The pin connection had a F_{max} of 862,60 N (Figure 4.19) . Meaning that the drilled hole doesn't affected the strength of the total connection negatively.

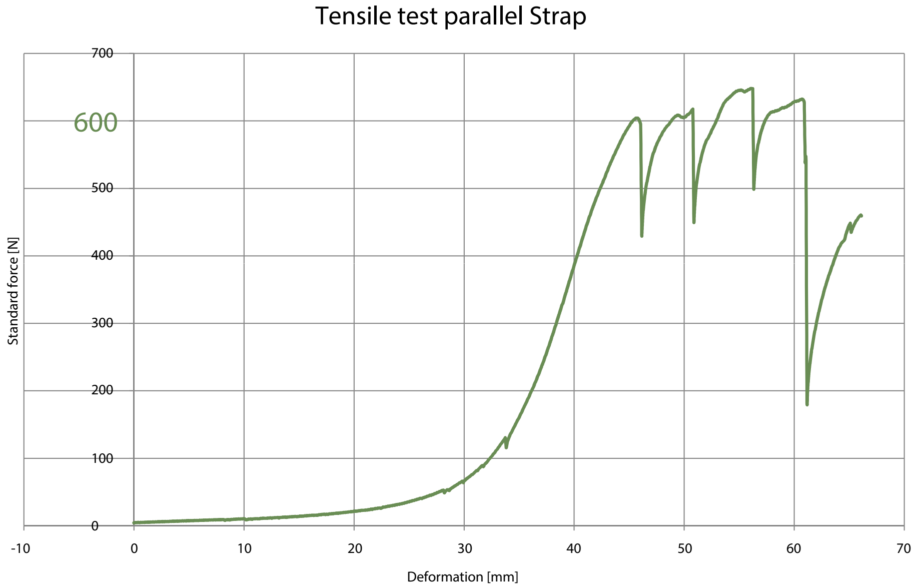


Figure 4.18 Results 3 point bending test strap connection

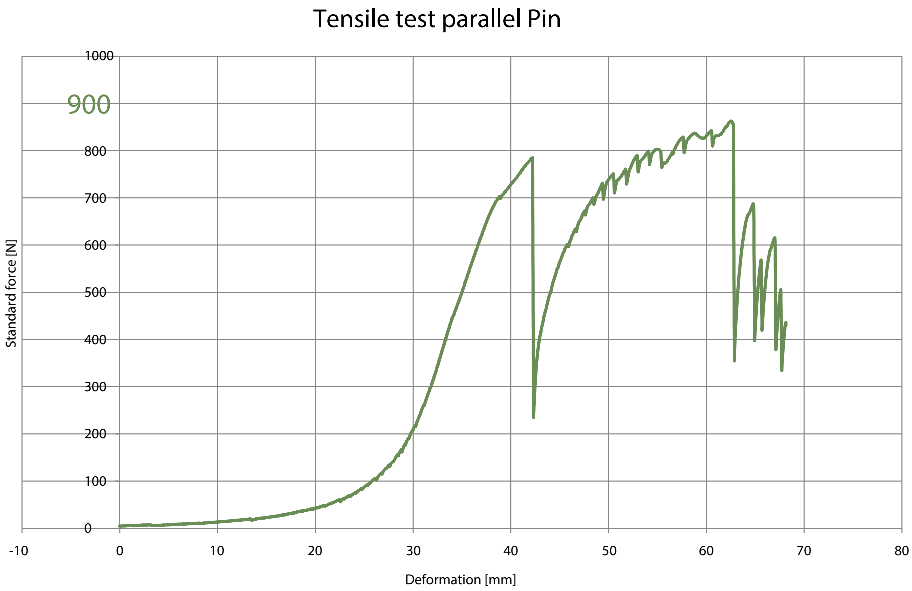


Figure 4.19 Results 3 point bending test pin connection

Figure 4.20 Parallel strap connection

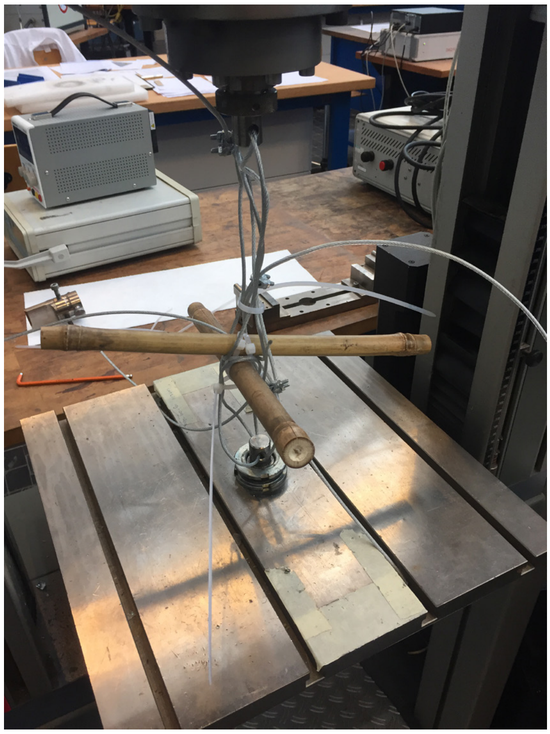
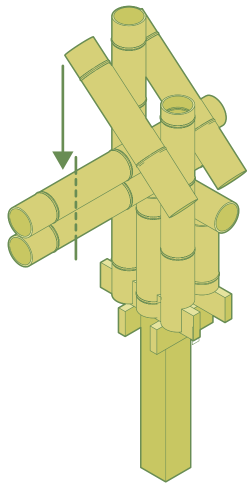


Figure 4.21 Parallel pin connection

Force perpendicular to a beam

A beam is of course a important element in a bamboo structure. Therefore the beam is also tested in this test. The connectors aren't really tested, as they are on the outside of the beams. However this test can give insight into the effect of the espiches. Two bamboos are connected with the connectors and then mounted into the three point bending setup. Wooden blocks and clamps are used to avoid the bamboo from twisting.



Strap connection
The two bamboos are connected with one zip tie on both sides (Figure 4.24). During the test the zip ties stayed intact, what confirmes that mostly the bamboos were tested. The strap beam endured a F_{max} of 2291,38 N (Figure 4.22).

Pin connection
Two M6 nylon bolts are drilled in the ends of two bamboos to make a beam. In addition diagonal holes are drilled through the two bamboos and tooth picks are put in. These tooth picks represents the espiches (Figure 4.25). Unfortunately the wooden blocks and the clamps couldn't hold the beam up straight and this resulted in a F_{max} of 1796,99 N. Further tests should involve a better setup in order to draw conclusions.

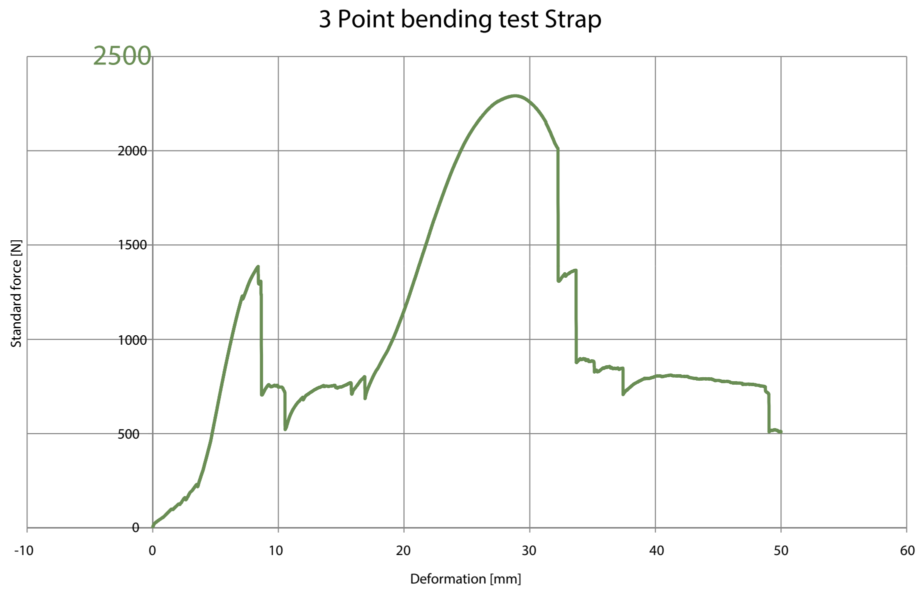


Figure 4.22 Results 3 point bending test strap connection

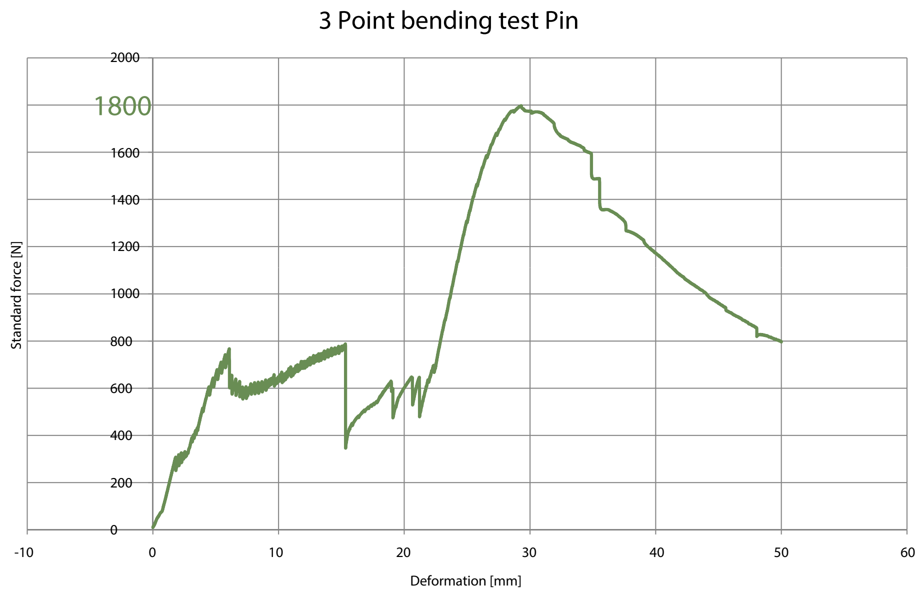


Figure 4.23 Results 3 point bending test pin connection

Figure 4.24 Beam strap connection

Figure 4.25 Beam pin connection

4.3.2 CONCLUSION ON PIN OR STRAP

Both the prototypes and the tensile strength tests show that the pin connection is the best option. The pin connection facilitates all the essential connections and this is crucial in order to act as a suitable connector. The pin connectors are relatively easy to produce, therefore the production time is short. In construction the connectors are performing quite similar. However the pin connection seemed the most rigid connection, which is also very easy and quick to construct. The only reason to not choose the pin connection, was the hole that needs to be drilled in the bamboo.

In the tensile strength tests the pin and strap connections are compared in order to see if the hole damages the bamboo in a way that it weakens the connection as a whole. The first two tests (parallel and perpendicular) showed that the bamboo itself can hold a lot more than the connectors, even when a hole is drilled through the bamboo. This means that the strength of the total connection is depending on the connectors and the hole in the bamboo has no negative influence on the total strength. However it is important to realise that the hole in the bamboo can enhance cracks in the bamboo.

The first test where the force was applied perpendicular to the connectors had clear results. In the strap version the bamboo could slide through the straps, as the straps are tied around the bamboo it is hard to get grip onto the bamboo. The pin version was around 21 times stronger than the strap version (Figure 4.14 and Figure 4.15).

The second test where the force was applied parallel to the connectors the zip ties broke. The nylon M6 bolt only stretched and could stand a bit more than the strap connection. In this case two different materials are tested, and you can't really compare these materials one to another. However what can be extracted from this test is that the weakened bamboo with the hole, again wasn't the weakest part of the total connection. The connectors are determining the total strength. For this test the pin connection had the best results.

The beams that were tested in the three point bending test, don't play a role in the choice between the pin and the strap connection, as the connectors had no influence on the results.

As the pin connection comes bests out of the test, the pressure cap and the nail cap will be further improved. Thereafter the two prototypes will be compared and the final type will be chosen.


Figure 4.26 Pressure cap

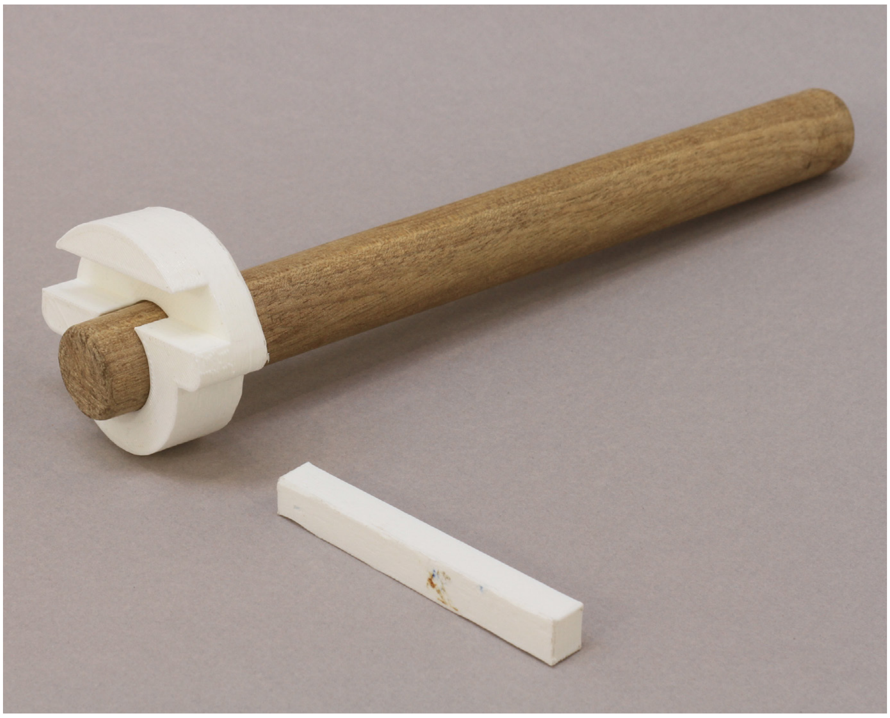


Figure 4.27 Nail cap

4.4 PIN CONNECTION

4.4.1 FURTHER DEVELOPMENT

Pressure cap 2.0

The pressure cap is improved in terms of strength (Figure 4.28). Notches are made in the thin part of the connector. When the cap is placed onto the bottom part the remained lips are pressed against the pin. This way the connector is mounted by the friction between the two elements.

Production

Concerning the production of pressure cap 2.0 the thickness of the lips needs to be considered. Lips of 1 mm thick will require high pressure in the injection machine. Multiple thicknesses of the lips will be 3D printed in order to see if the strength decreases. If not, thicker lips are easier to produce and thereby have the preference. Consisting of only two elements eases the production of the pressure cap. Few elements and relatively simple parts are needed for the mould.

Construction

Mounting the pressure cap is identical to the first version. However no hammer is needed. The cap can be mounted by hand. Minimizing the amount of tools needed is a coincidental benefit. A saw is still needed to cut the pin to the required length.

Nail cap 2.0

The first version of the nail cap had a weak spot. Plastic relaxes in time, therefore the slit for the pin opened. Causing the connection to loosen. To prevent the connector from opening, a extra cap is made (Figure 4.29). Which is mounted after the pin is hammered in the connector.

Production

This connection consists out of three elements, more elements result in a longer production time, more moulds or complex moulds. The shape of the elements are relatively simple.

Construction

Mounting this piece is easy. However a hammer is needed in order to place the pin firmly. When the pin is mounted the cap can be placed. The cap secures the connector and prevents the bottom part from opening.

Figure 4.28 Pressure cap 2.0

Figure 4.29 Nail cap 2.0

Pressure cap

The production time and the ease of mounting the pressure cap were decisive in choosing the pressure cap as the best option. However still a number of things needs to be figured out, tested and tried, before the final mould will be made.

Aspects that can be improved or need to be tested (Figure 4.30):

1) Thickness of the fingers
2) Do the fingers need to be tapered
3) Inner diameter of the cap
4) Diameter of the pin
5) Total volume of the connector

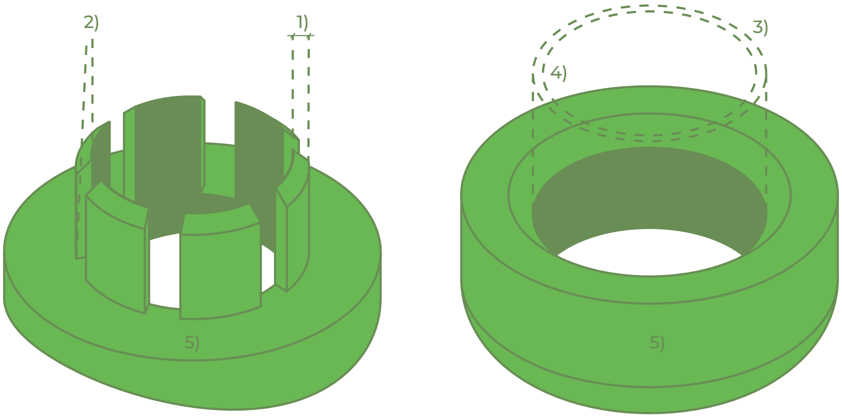


Figure 4.30 Parameters pressure cap

1) Concerning the ease of production the thickness of the fingers should not be to small. From experience an object with a thickness of 3 mm can be injection moulded. The prototype with a thickness of 3 mm provided the most strength and the fingers are thin enough to remain flexible. This flexibility is required for the friction that the connector needs to provide in order to form a rigid connection.

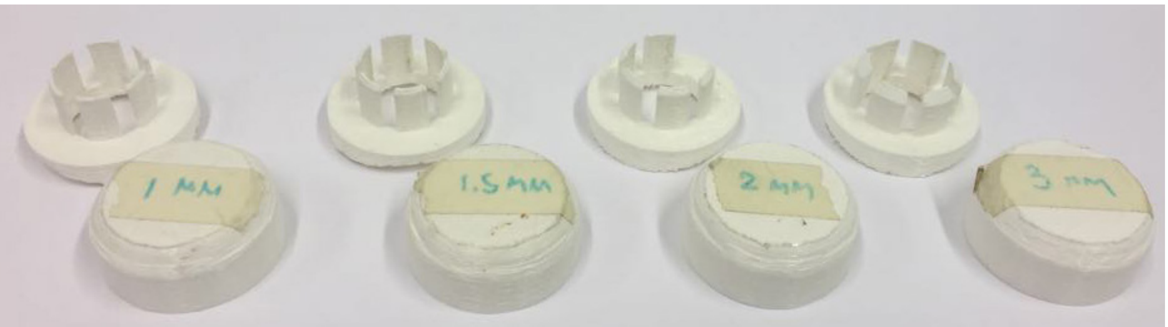


Figure 4.31 3D printed connector prototypes

2) Tapered fingers would ease the demountability of the connectors. The connector is performing better in terms of being burglar proof, when the fingers are not tapered. However the straight fingers still need to be tested in production. The connector with straight fingers can be difficult to remove from the mould.

3) Due to the print margins of the mould and the shrinkage of the HDPE after injection moulding, it is hard to calculate/predict what the final diameter of the cap would be. The cap should fit very firmly over the bottom part, however it needs to fit without breaking the elements. The right diameter needs to be found by testing different moulds.

4) The diameter of the pin is determined by the three point bending test. The strength of the pin is based on the strength of a M10 screw thread. With a safety margin to take into account the UV degradation of the HDPE, the diameter of the pin is 23 mm. The diameter of the bottom part of the connector is based on this diameter. The bottom part should be able to slide over the pin by hand, however it certainly should not be loose. This would result in a weak connection between the pin and the connector.

5) The total volume of the connector is important in the sense of contact area with the bamboo. When the connector is to small the stress on the connection would be to big and it could increase the likelihood of cracks in the bamboo. Secondly the volume determines the amount of plastic that is needed for a connector. A low amount of plastic would be easier to collect, however the amount of waste in Esperanza is sufficient. Bigger volume would mean a higher resistant to UV radiation as the outer layer would degrade first. Herefore decreasing the volume of the connectors is inferior to the mechanical properties and durability of the connectors.

4.4.2 TESTING TENSILE STRENGTH CONNECTOR

The pressure cap is based on friction. A tensile strength test is done on two connectors (Figure 4.33). These tests are performed with 3D printed pressure caps and a wooden pin. The injection moulded elements did not have the right margins to result in a rigid connection. The final moulds need to be improved to get the HDPE connectors working properly. 3D printed elements have a different surface than the injected elements, this could give different results. However, these tests give good insight of the performance of the pressure cap. The test results show that the pressure cap has a tensile strength of 500 N. The two test are very similar shown in Figure 4.32. The varying strain is caused by the steel cables. These cables needed to be pre tensioned. The cables were mounted differently. Therefore, the strain is different.

The pressure caps only need to keep the bamboo together, the bamboo takes all the high and permanent loads. A tensile strength of 500 N is sufficient to mount the bamboo.

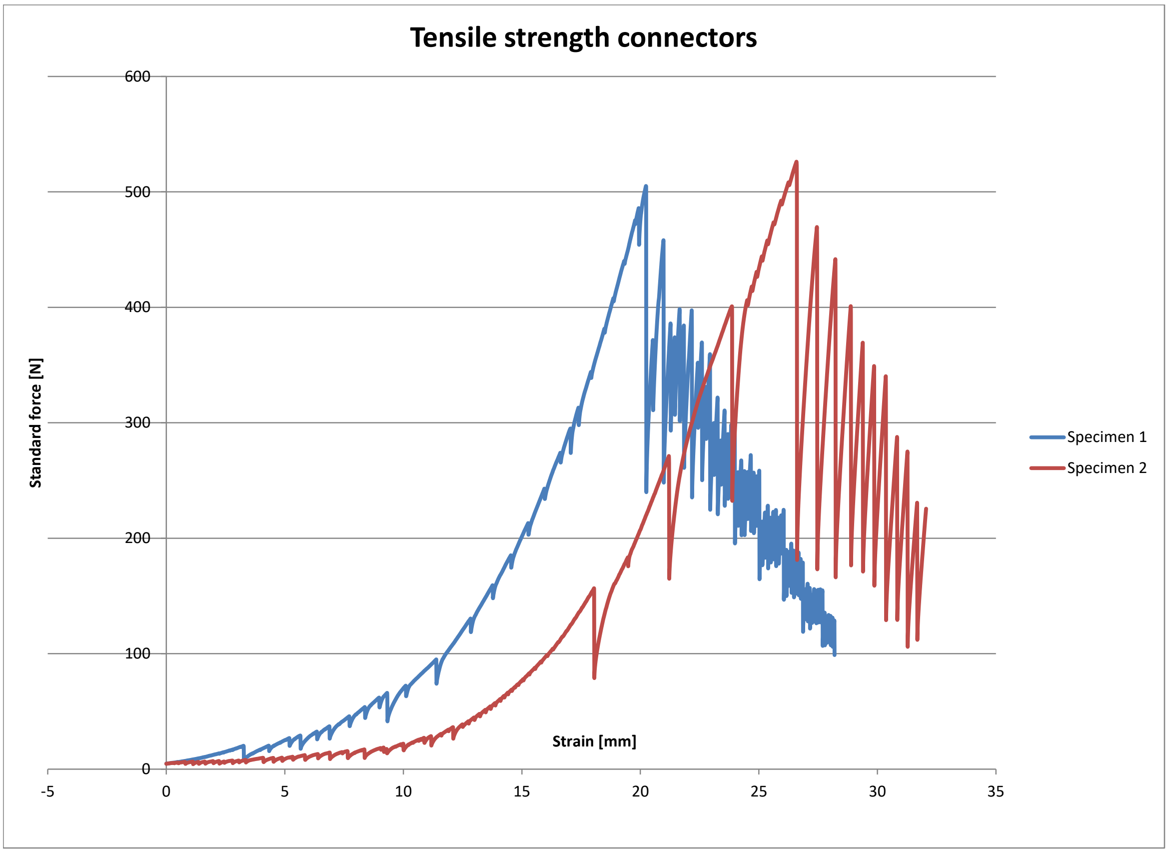


Figure 4.32 Test results Tensile strength test 3D printed connectors

Figure 4.33 Tensile strength test 3D printed connector s

4.4.3 ESSENTIAL CONNECTIONS - TWO BAMBOOS PERPENDICULAR

Until this point of the project the connectors didn't facilitate the essential perpendicular connection (Figure 4.30). Therefore, a connector is designed that is based on the pressure cap connector, which can connect two pins perpendicular to each other (Figure 4.35). To connect two bamboos perpendicular to each other, three pressure caps, two pins and a perpendicular connector are needed. Mounting the perpendicular connector is as easy and quick as the regular pressure cap (Figure 4.36).

Quite a few elements are needed to construct the perpendicular connection. Therefore, it is important to only use this type of connection when needed. In a lot of cases the horizontal bamboo can rest on the vertical bamboo without being connected to each other. The horizontal bamboo is mounted to a other bamboo with a regular parallel connector (Figure 4.34 on the right). During the design process of a bamboo structure it is important to use the strength of the bamboo. When designed properly the plastic connectors only keep the bamboos together and the bamboo is doing the hard work. Later on in this report a few rules will be described on how to use the plastic connectors efficiently.

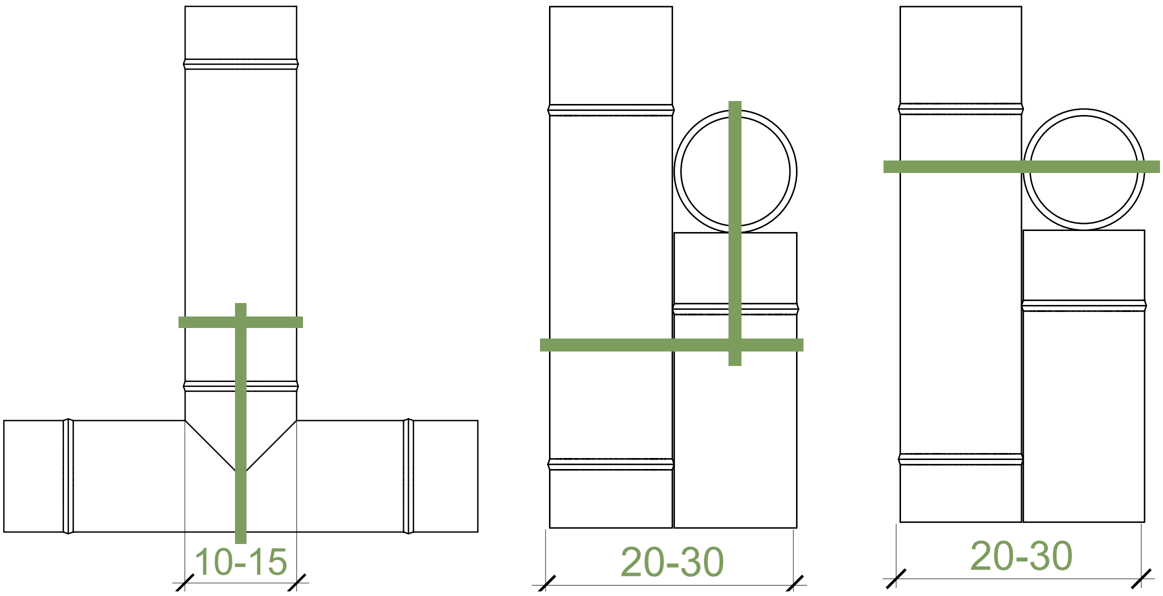


Figure 4.34 Perpendicular essential connection (left), alternative option (right)

Figure 4.35 Perpendicular essential connection model

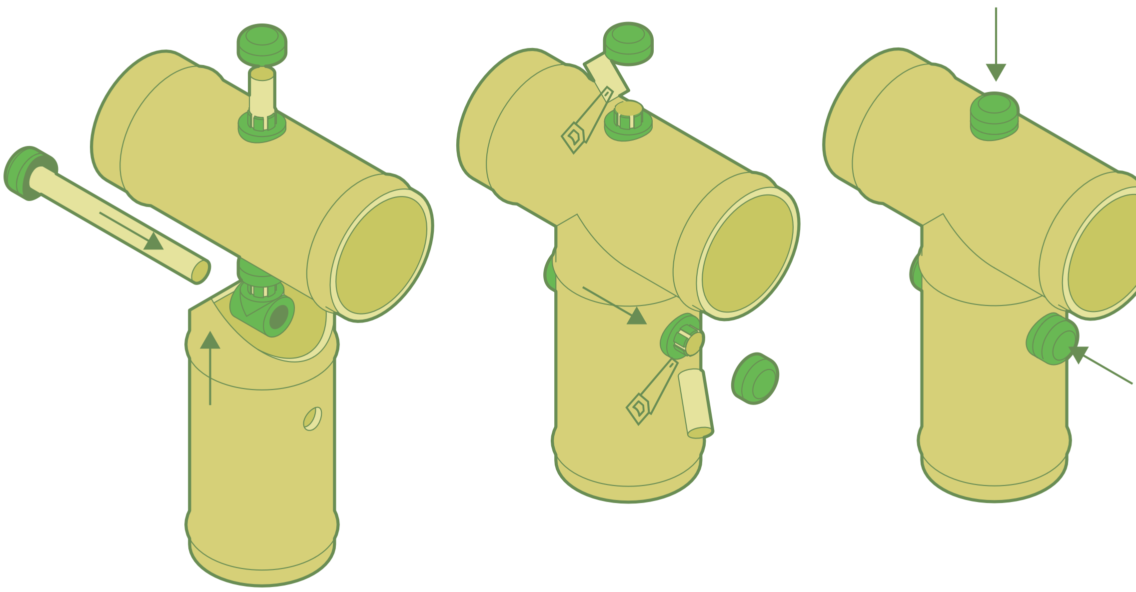


Figure 4.36 Perpendicular essential connection scheme

5. PRACTICE

5.1 BUSINESS MODEL

5.1.1 INTRODUCTION

At this point it is clear that a plastic connection for bamboo structures can be designed and produced, with a relatively simple injection moulding machine. The strength of the recycled plastic is tested and the results are put into the design process. However, it is possible to do this in the Netherlands, where we have the resources, the knowledge and the money to build such a injection machine. What steps need to be taken in order to enable local families to build their own bamboo house with the plastic connections?

Local people in Esperanza are not so fortunate to have the resources and money to set up such a production line. It's crucial that someone or a team, helps build the machine and goes there to transfer the knowledge that is needed to operate the process. This approach is similar to the Bamboo Factory project. Where a team of students connected to the TU Delft managed the entire project. The intention is that the local people will learn how to work with the bamboo and the plastic connections and that they eventually operate the process themselves. In that sense this project is a charity project where less fortunate demographic groups are being helped to start a business, and eventually it can help the whole community.

Setting up the production line is one step to achieve the goal. However, there is more that needs to be arranged. What is the best location for the production line in Esperanza, who is responsible for the production, how and who collects the plastic? In this chapter we will try to elaborate on all the aspects which are needed to make this project feasible.

Figure 5.1 Bamboo factory Workshop with locals of Esperanza

5.1.2 COLLECTING PLASTIC

Collecting the plastic is an essential step of secondary recycling. In order to transform HPDE into the connectors it is important to sort the HDPE and make sure that no other types of plastic are in the final mixture. Different types of plastic will change the melting temperature and will even possibly burn or not melt. After sorting the plastic the caps and jugs need to be shredded. This can be done with the shredding machine of precious plastics. Shredding the plastic enhances the melting process and simply cuts the plastic in small pieces to fit the injection moulding machine. Hereafter other contaminations like food, drinks and dirt need to be minimized. These types of contaminations can be removed by washing the collected and sorted plastic. The plastic will be washed with only water. Moisture is also a contamination in the reprocessing of plastic, therefore the washed HDPE flakes need to be dried. Preferably the flakes are dried in the shadow, as UV radiation degradates the plastic.

Collecting the plastic can be an activity that helps the whole community of Esperanza and surrounding villages. Plastic is scattered through the village and in the river. Collecting it will clean the village, making it better and healthier for the people and the environment. In addition most of the inhabitants of the R.A.A.N. region live under the poverty line of 1$ a day and a big part doesn't have a job. Collecting can be a way to earn some money. The production line that will eventually produce the connections can pay a small amount of money for properly collected HDPE. This way the project can provide money for people that don't have a job. Further sorting, shredding and washing will be done by the people that run the production line, in order to make sure that there is only HDPE.

5.1.3 REPROCESSING MACHINES

The HDPE is reprocessed with a relatively simple injection moulding machine. This injection moulding machine is based on a machine that is developed by Precious Plastics (Figure 5.2). It requires knowledge, time and money to build the injection moulding machine. For most local people in Esperanza and the R.A.A.N. region it is impossible to build such a machine. In order to make this project happen in Esperanza, a team has to go to there to transfer the knowledge and to build the machine. This can be done in collaboration with Bambú Social. Normally Bambú Social goes to Esperanza frequently as a continuation on the Bamboo Factory project. Last year a workshop is build. However, due to the unsafe situation in Nicaragua at the moment the next project is postponed. To check the feasibility of the project it is important to make a cost estimation. Therefore the cost of the machine is important, , but the running costs of the production line are even more essential.

In order to make the plastic connectors, at least two machines need to be build. A shredder is needed to shred the collected plastic and the injection moulding machine is needed to produce the connectors. The pin can be made by sliding a steel tube as a mould for the pin, into the injection machine. With this steel tube one can produce a pin with a maximum of 60 cm. A 60 cm pin is long enough to make all the connections. However the production time will be long, as all the pins would be made separately. In addition this will result in a lot of waste. Concerning the efficiency, building a extrusion machine would be better, but it is optional. The extrusion machine of Precious Plastics can produce pins with the length of 6 meter. Reducing the production time and minimizing the amount of waste.

Figure 5.2 Machines overview. (Precious Plastics, 2018).

5.1.4 MACHINE COSTS

	Total costs	Time
Injection moulding machine	€ 150, -	~7 days
Shredder	€ 300, -	~14 days
Extrusion machine	€ 250, -	~10 days

With a total of € 700, -the three machines can be build in around 14 days. The expenditures vary depending on the location of the project. The money needed for this project can be collected by fund raising. The production line in Esperanza could be a part of the next Bambú Social project. After building the machines and transferring the knowledge on how to operate the whole process, the production line should be self-sufficient. The energy consumption and production time need to be calculated in order to get a good overview.

5.1.5 ENERGY COSTS

Concerning the costs of the final connectors it is important to know the energy consumption and the production time of the machines. Once these aspects are known a final price per connector can be calculated. The total cost depends on the location, as energy costs rely upon the location as well.

The injection moulding machine has 4 band heaters (60 W per piece). Resulting in a energy consumption of 0.24 kWh. However when the barrel of the machine is heated it needs less energy to keep warm as it is well insulated with ceramic fibre insulation. In Nicaragua the base costs of energy is US $0.08 dollars per kWh (Marshall, 2018). Making the costs to run the injection moulding machine US $0,02 dollars per hour.

The electric motor of the shredder is less economical as it consumes 2 kWh. Resulting in US $0,16 dollars per hour.

Lastly the extrusion machine is basically a combination of the electric motor that is used for the shredder and the 4 band heaters that are used for the injection moulding machine. This results in a running cost of US $0,18 dollars per hour.

These energy costs will be used to calculate the costs of the final design. The energy costs will be calculated with the local energy price, which is depending on the location.

5.1.6 MOULD COSTS

Using the material Liqcreate Strong-X made it possible to cheaply produce and test multiple prototypes and shapes. This material is 3D printed and it costs around 10% of the price of CNC milled steel moulds. The 3D printed moulds are ideal for prototypes, however they can be injected around 100 times. As the moulds that will be used for the project in Esperanza should last for many years, a different type of mould needs to be made. Steel CNC milled moulds are a suitable solution. The two moulds shown in Figure 3.18 will cost around €900-1000.

5.1.8 LOCATION FOR THE PRODUCTION LINE

In Esperanza energy is produced by solar panels and small generators that run on gasoline. The use of the generators is undesired, as they are not sustainable and too expensive for the local people. When the machines are not used at the same time a maximum of 2.24 kWh is needed. Assuming that one solar panel produces 0,25 kWh in the full sun, therefore 9 solar panels are needed to power the production panel. When it is desired to run all the machines simultaneously 18 solar panels are needed.

When it is not possible to access 18 solar panels it is also possible to locate the production line in Waspam. Waspam is the nearest city that is connected to the electricity grid of Nicaragua. Collecting big amounts of plastic will be easier in Waspam, as there is more waste in the city. 2-3 times a week a boat passes by Esperanza from Waspam. Giving the opportunity to produce the connections in Waspam and then transport them to the smaller communities. This will simultaneously enlarge the amount of people that benefit from the project.

5.1.7 WHO IS RESPONSIBLE?

After building the machines and transferring the knowledge in Esperanza the team will leave eventually. But who is going to run the plastic recycling production line? For the Bamboo Factory a team was selected throughout the project. Each week a new group of locals would join the team to help and learn. From these groups the ones that worked hard, enjoyed the work and most importantly seemed responsible, were asked to join the group that would be responsible for the continuation of the Bamboo Factory. If this project will be realised in Esperanza, this will be the team that also operates the connector production line. In other situations it would be the one, which undertakes to build the machines and starts producing the elements. The drawings of the precious plastic machines are freely available on the internet, just like the drawings of the moulds of the connectors will be. This enables anyone with the required resources and skills all over the world to make a bamboo structure, that is constructed with the plastic connections.

6. FINAL DESIGN

6.1 HOW IT WORKS

6.1.1 INTRODUCTION

The goal of this project was to develop a set of connections that enables people in low income and remote areas, to build a house from bamboo that can last for 30-50 years. Therefore, it is important to give a comprehensive explanation on how to get the most out of the plastic connectors. It is important to show what kind of connections one can make and to list the strengths and weaknesses of the system.

6.1.2 PRESSURE CAP

Regular connection

The regular pressure cap connection basically consists out of 3 elements (Figure 6.1). The connection involves a pin that goes through the bamboo and the bamboo is fixed with a head that consists of two parts. The connection is based on friction, the first part of the head is slit over the pin. The pin is cut to length and hereafter the cap is pushed or hammered onto the bottom. The cap will compress the fingers of the bottom firmly to the pin (Figure 6.2). Resulting in a rigid connection. The regular connection facilitates the essential connections where 2 or 3 bamboos are parallel or crossing.

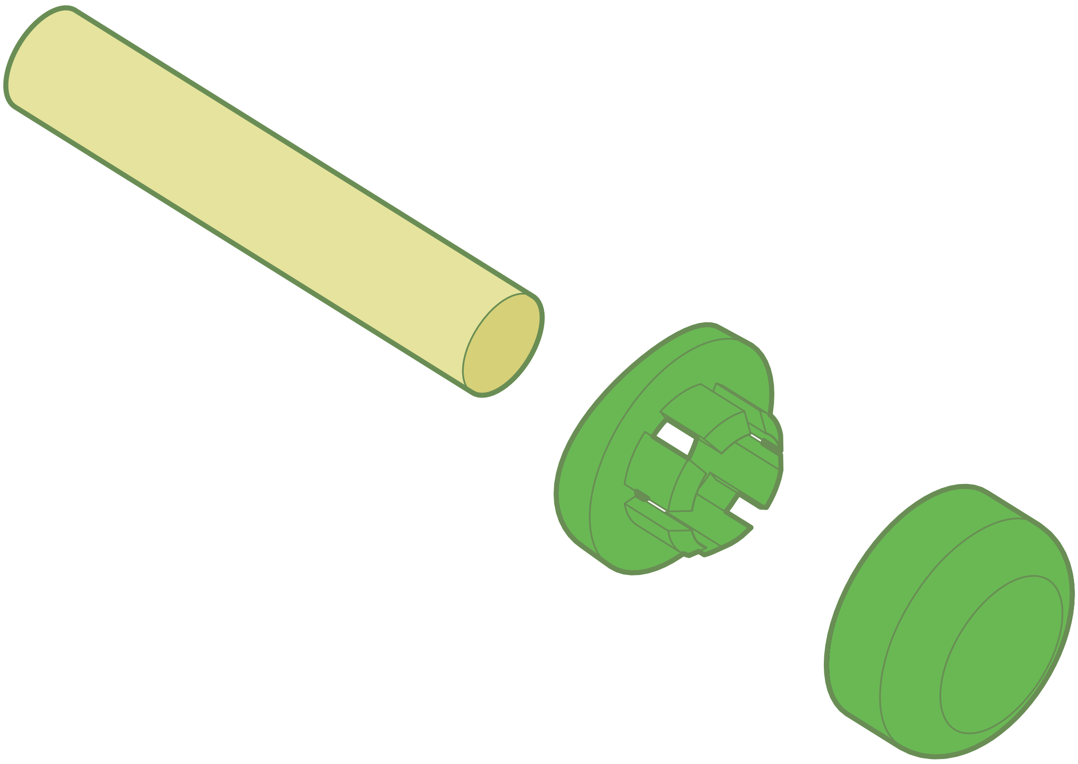


Figure 6.1 Pressure cap elements

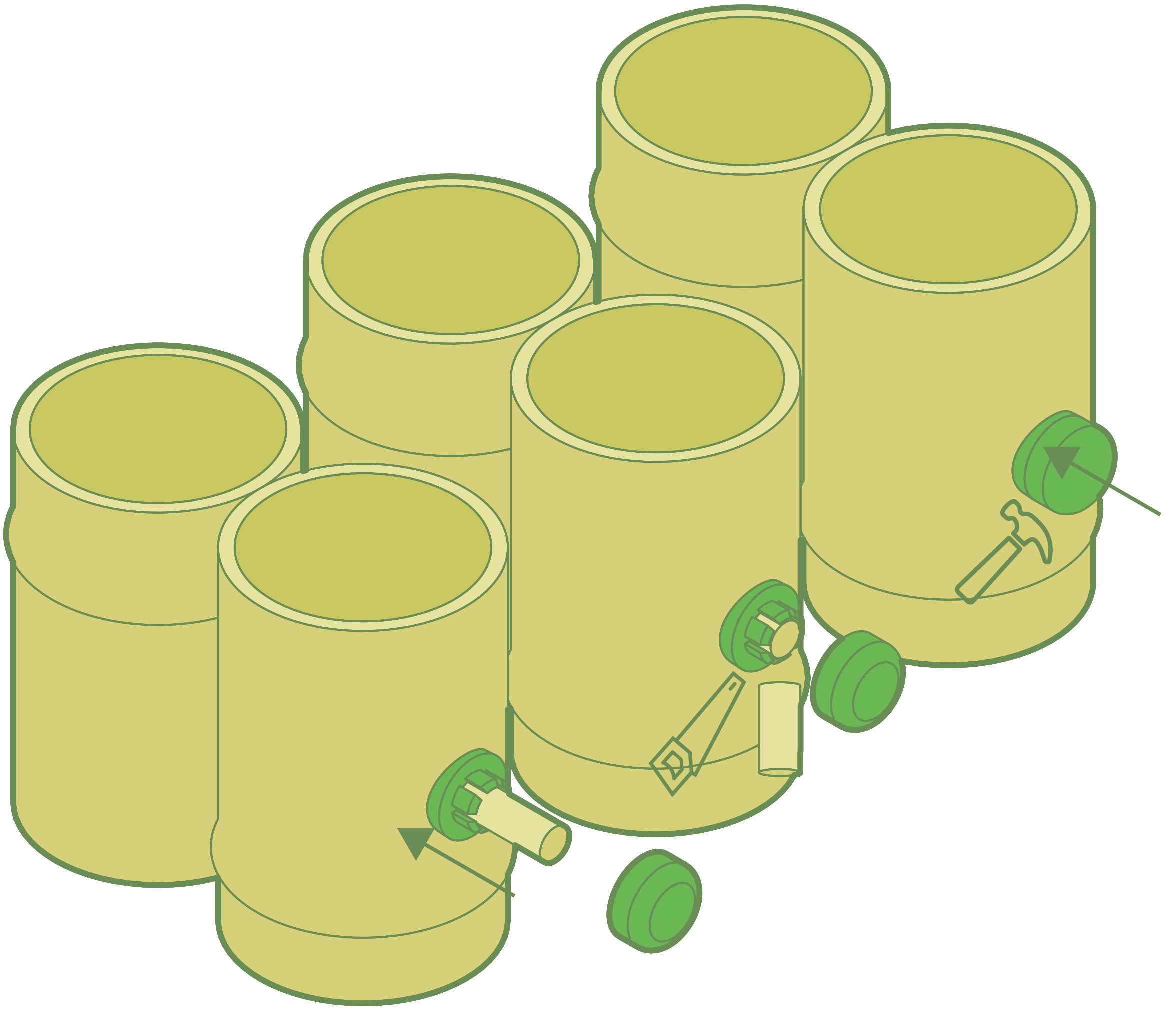


Figure 6.2 Regular pressure cap explained

Perpendicular connection
Concerning the essential connection where two bamboos are perpendicular to each other, a special element is designed. The perpendicular connector (Figure 6.3) is based on the pressure cap and therefore it also secures the pins with compression between the fingers of the bottom part and the cap. In order to place the connector, holes are drilled in the bamboo. Make sure that the holes are drilled close to a node, this prevents the bamboo from splitting. On the end of the vertical bamboo a 'Boca de pescado' is shaped in order to make a beautiful and stable connection to the horizontal bamboo, however this is optional. The two pins are secured with the perpendicular connection inside the bamboo. Lastly the regular connectors are placed to fasten the connection (Figure 6.4).

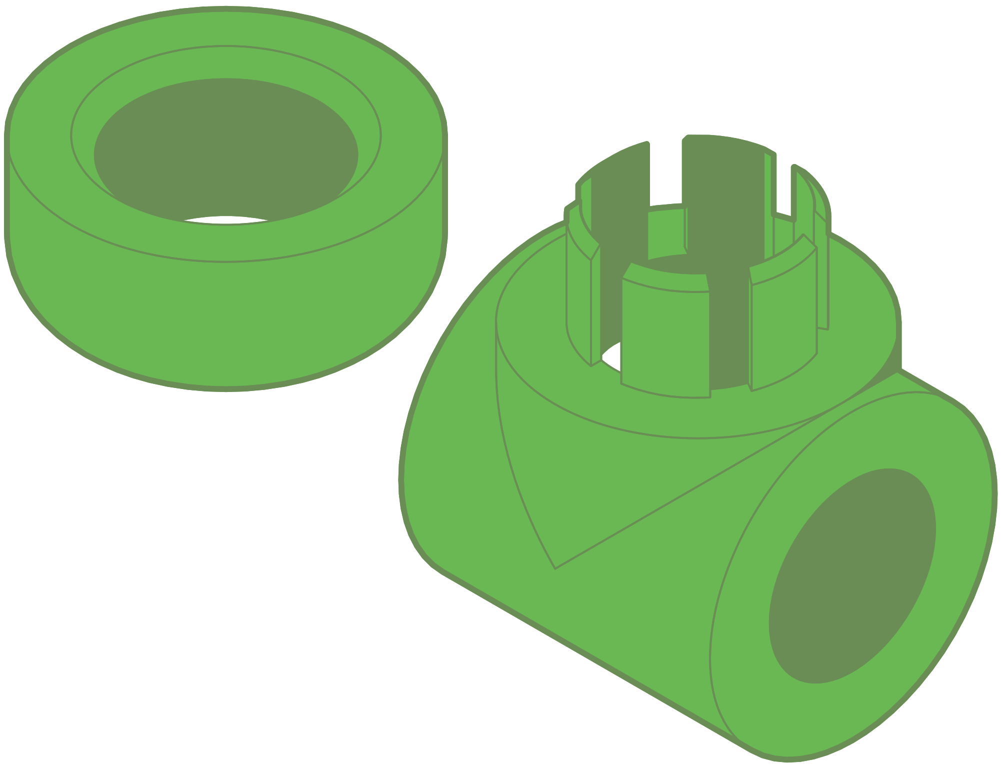


Figure 6.3 Perpendicular connection

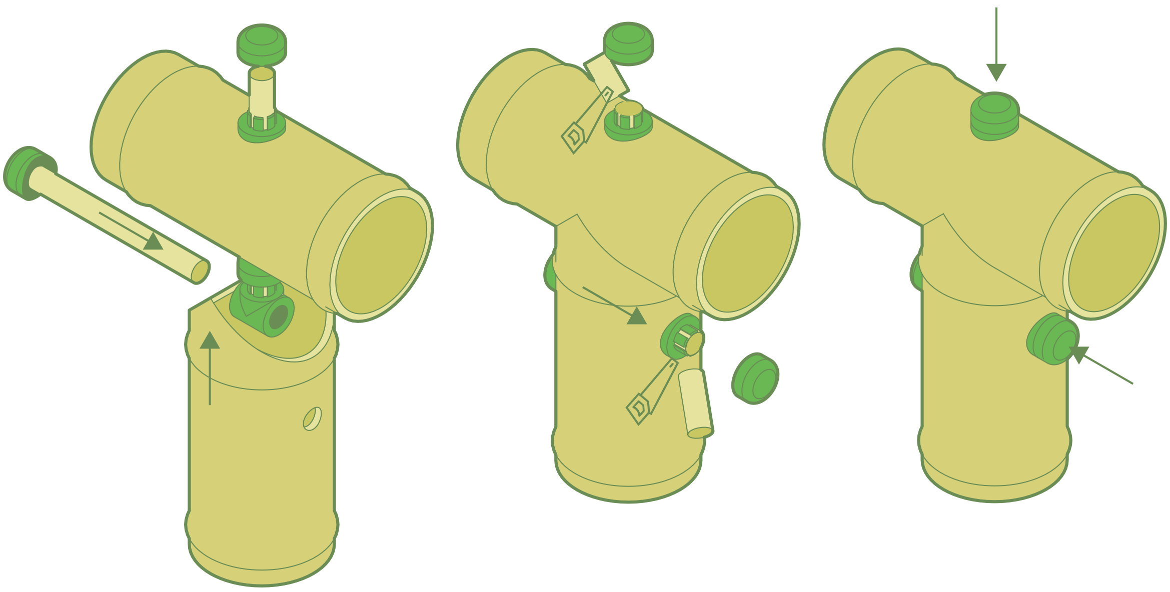


Figure 6.4 Perpendicular connection explanation

6.2 BAMBOO CONNECTIONS

6.2.1 INTRODUCTION

Making strong, durable and aesthetically pleasing connections is rather complicated, because bamboo is a natural material. Bamboo its strength is along its length on the longitudinal axis. For a strong and durable connection it is crucial to take advantage of the good properties of the bamboo. When the plastic connectors are used, it is essential to avoid big stresses in the plastic. The bamboo connections have to be designed and put together in a way that the connectors only keep the bamboo together, whereby the bamboo is taking all the forces. Therefore, a set of possible bamboo connections will be given. These connections will be based on the essential connections (Figure 6.5).

As explained in chapter 2.3 How to build with bamboo, the usage of pins tend to crack the bamboo, due to the forces on the transverse direction. Bamboo has nodes, it is important to use these strong spots, and make connections near the nodes. If it is impossible to achieve this on both sides, use wooden inserts or a fitting bamboo with a node. Make basic cuts. This doesn't require heavy equipment, a set of traditional tools will do. Bamboo doesn't last long when exposed to the elements. Keep the bamboo construction dry and out of the sun, using a big overhanging roof. Keep the bamboo from the ground to prevent moisture from the ground damaging the bamboo. This can be done by using a hard wood or concrete foundation. Keeping the bamboo dry and out of direct sunlight will simultaneously protect the plastic connectors.

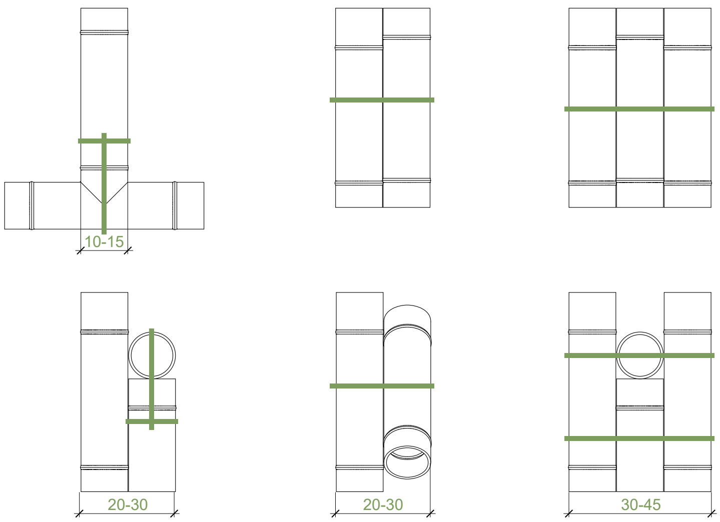


Figure 6.5 Essential connections

6.2.2 EXAMPLES OF BAMBOO CONNECTIONS

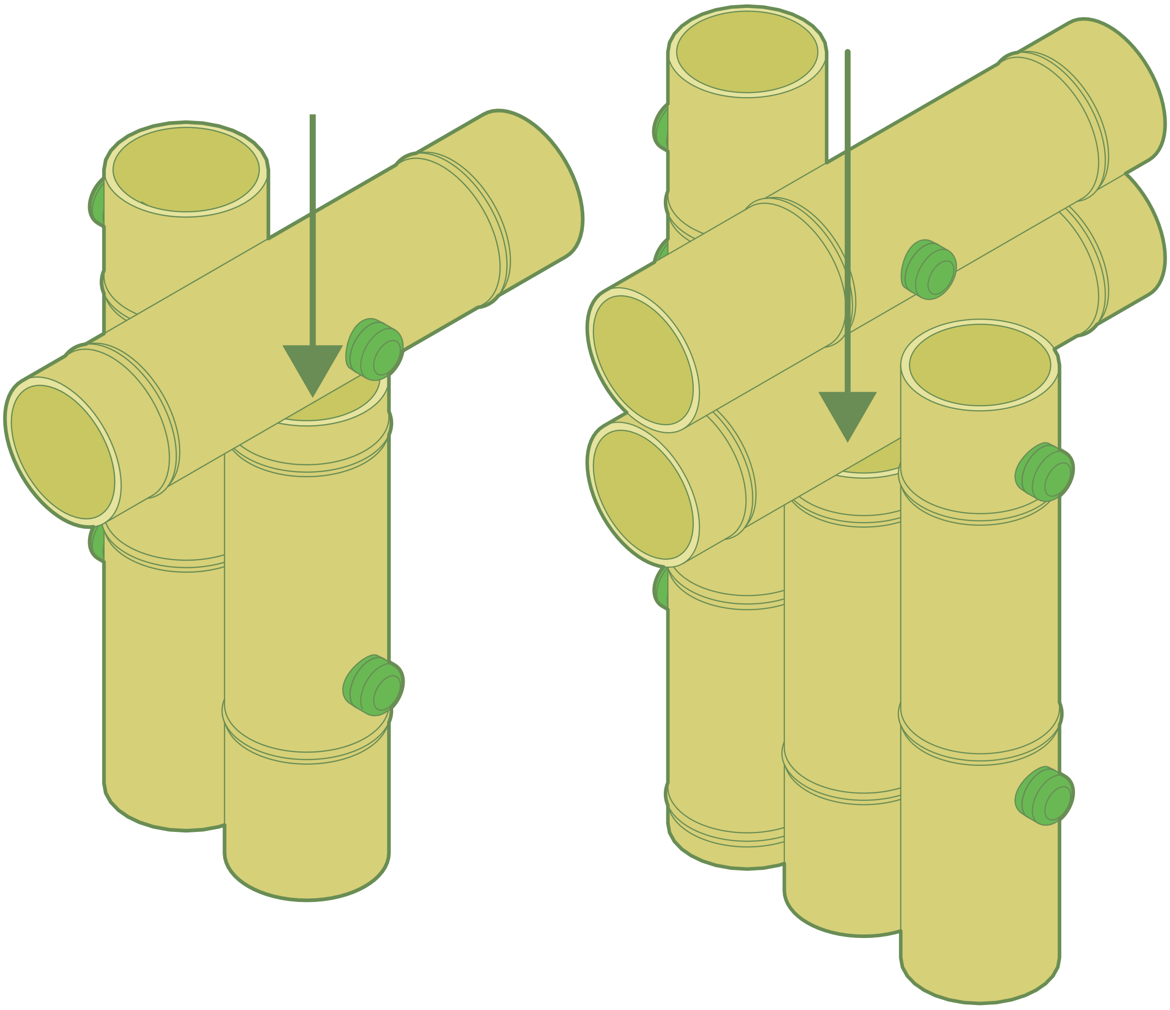


Figure 6.6 Suitable connections for columns and beams

In order to avoid large moments and stresses in the plastic connectors, the bamboo connections have to be build in a way that the bamboo is subjected to most of the forces. In Figure 6.6 and Figure 6.7 three options are given on how the connectors should be used. All the loads are transferred through the bamboo and the plastic connectors are just holding the bamboos together. The bamboo that is supporting the horizontal bamboos can be adjusted by cutting a 'boca de pescado' on the end. This supports the horizontal bamboo better and makes it aesthetically pleasing. However the use of two bamboos, one for taking the loads and the other for the support, makes the boca de pescado unnecessary. Therefore cutting a boca de pescado is optional, as it is also very time consuming.

For small spans it is often unnecessary to use two bamboos for a beam or column. However the use of more bamboos ensures that the plastic connections remains intact for a long time. When HDPE is permanently subjected to a load in a hot climate it would deform drastically. Therefore, the use of multiple bamboos is desired. Gadua Aculeata has a diameter of 10 - 15 cm. Smaller diameters can be used for columns and beams constructed from multiple bamboo. In Figure 6.7 it is shown how the bamboo is subjected to the permanent load, and the plastic connector only has to keep the bamboo together.

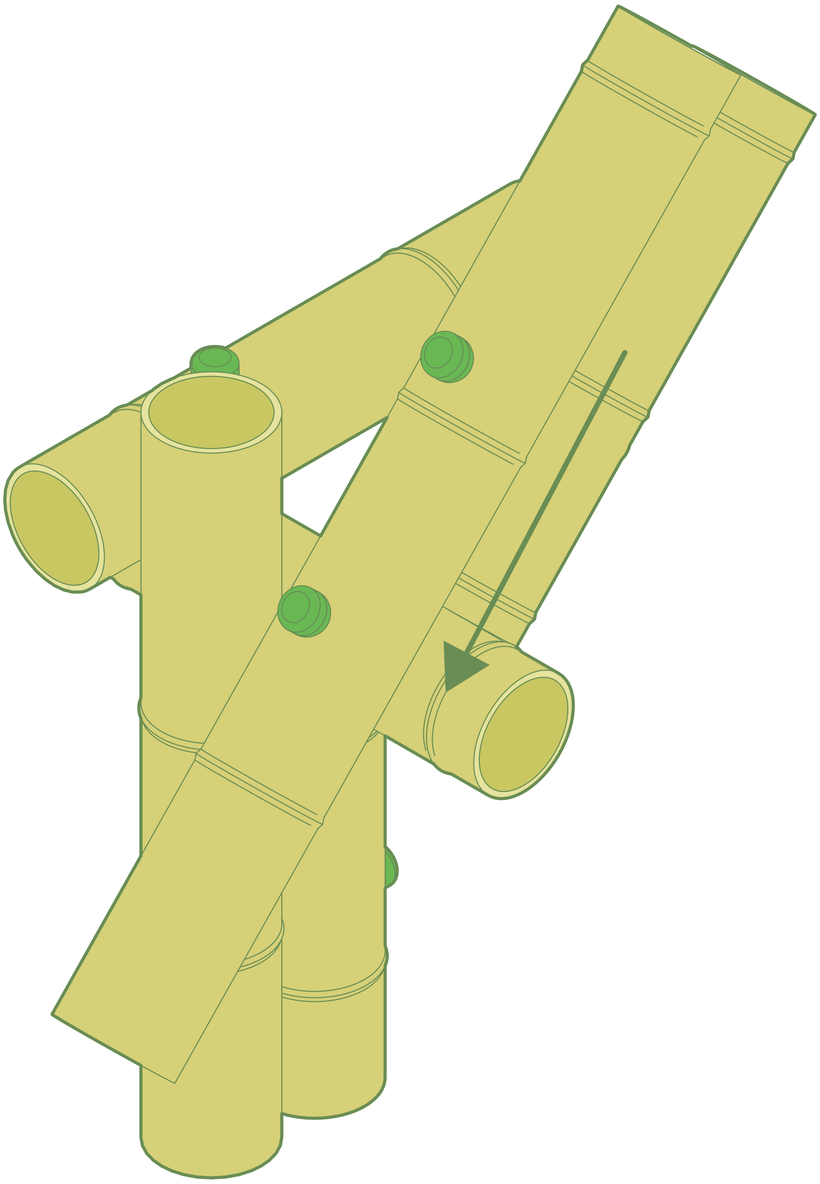


Figure 6.7 Suitable connections for roof beams

6.3 TYPICAL HOUSE

This project's main goal is to enable people in low income and remote areas to build their own houses from bamboo. When the bamboo is treated properly it can last for 30 to 50 years. When a typical house of a local in Esperanza (Figure 6.9) can be build with the essential connections explained before, the project is basically successful. In Figure 6.8 a design is shown of a bamboo structure, which uses the set of connections explained, that could meet the requirements of the typical house in Esperanza.

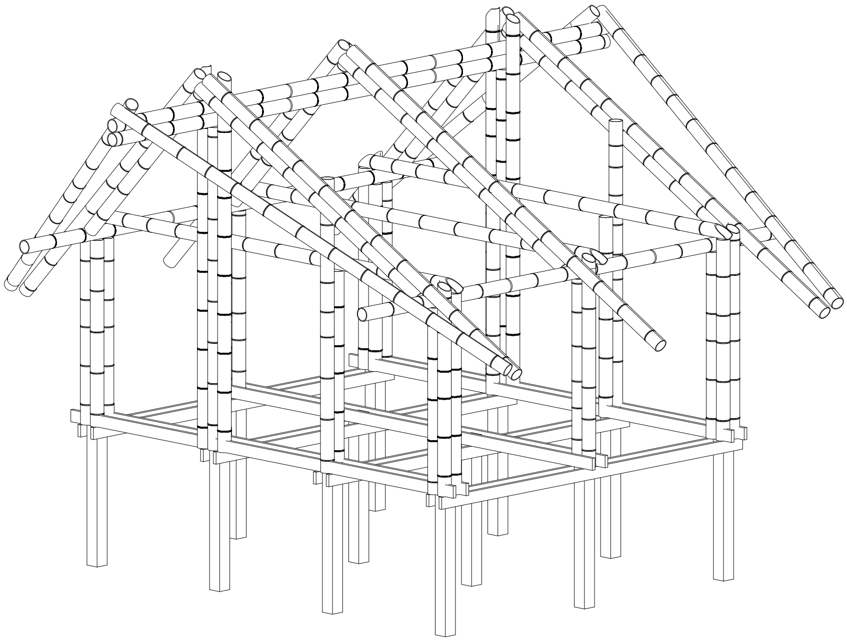


Figure 6.8 Design for bamboo version of typical house

Figure 6.9 Typical house in Esperanza

7. CONCLUSION

7.1 OBJECTIVES

7.3.1 INTRODUCTION

The objective consists of three main points;

(1) Designing a set of connections that enables one to build a bamboo structure with recycled plastic connection elements.

(2) Degradation of the mechanical properties of the recycled plastic can be expected, therefore the reprocessed plastic needs to be tested.

(3) The connections are produced with low tech techniques and extend the durability of the plastic waste and the bamboo houses.

The conclusions on these objectives will be described in this chapter. All three objectives are essential in the overall research. These objectives are decisive for this project to make it work in practice. However, a negative result in any of the aspects won't make the research fail. The main goal of this research is to get insight of the possibilities for recycled plastic in construction.

7.3.2 DESIGN

The final design enables one to build a bamboo structure with a low amount of tools and skills. It consists of a small amount of elements; namely the pin, and the two elements of the pressure cap. Making it quick and easy to produce and construct. In order to build with the plastic connectors, tools to make holes and to cut the bamboo are needed. These tools can differ depending on the location and the available resources. To mount the actual connectors a saw is needed in order to cut the pin. The pressure cap can be mounted by hand or with a hammer.

The self made injection machine has its defects. Herefore the connectors are designed to be producible with this low tech injection moulding machine. This results in simple and relative cheap moulds.

All in all, the design focus was to empower people that live in remote and low income areas with the ability to build their own bamboo houses with these plastic connectors. The result is a standardized set of only three elements which are relatively simple to produce and very easy to construct.

7.1.1 PLASTIC PROPERTIES

The second objective states;

(2) Degradation of the mechanical properties of the plastic can be expected, therefore the reprocessed plastic needs to be tested.

Multiple dog bones are injection moulded with the self made injection moulding machine. Three different mixtures of HDPE that can be found in Esperanza as waste, have been tested. Virgin HDPE pallets were tested to be able to compare it to the recycles plastic. This helped determine the degradation of the recycled plastic.

Drastic decrease of mechanical properties was expected for the tests, however the results are promising. The different mixtures perform consistently with high yield strength and Young's modulus. Especially in the elastic phase of the Stress-Strain curve the test specimens behave like normal Polyethylene. The average yield strengths have a decrease of 18 % in comparison to theoretical properties of high density Polyethylene.

The virgin HDPE performed similar to the recycled HDPE. From this we can concluded that the thermal degradation and the production technique have more effect on the degradation of the mechanical properties, than the UV degradation has. The tested mechanical properties show that the recycled plastic is very suitable for the bamboo connections.

After the yield point the dog bones behave less like the normal Stress-Strain curve. Only 2 out of 20 dog bones showed neck forming in the plastic region. The rest failed more abruptly. This abrupt failure is probably caused by air bubbles, caused by the low tech manner of injection moulding. This behaviour makes the recycled plastic unpredictable in the plastic region. Herefore it is important to know its strengths and weaknesses, when designing a bamboo structure with the plastic connections.

Figure 3.31 shows that the stress-strain curve is linear up until around a standard force of 1200 N. In this case 1200 N is equal to 13.88 N/mm^2. The elastic region is determined by the region where the stress-strain curve is linear. When stresses stay below this value, no permanent deformation will occur in the HDPE. As it is very hard to precisely find the exact location of this elastic region, in combination with the small deviation of the tested mechanical properties, it is of high importance to include a security factor. To be safe a maximum stress of 7 N/mm^2 should ensure a safe construction.

Finally a comparison with a steel screw thread M10 is made. A HDPE pin with a diameter of 23 mm and the screw thread were subjected in a three point bending test. The HDPE pin deforms more as it is more flexible. However, the maximum standard force [N] is higher than maximum standard force of the screw thread. These results show above expectations that the recycled HDPE is a suitable material for bamboo connections. However further research in UV degradation and further testing on mechanical properties as creep is required.

7.1.2 PRODUCTION TECHNIQUE

The third objective states;

(3) The connections are produced with low tech techniques and extend the durability of the plastic waste and the bamboo houses.

The plastic HDPE waste is reprocessed with a self made injection moulding machine based on a project called Precious plastics. This machine was the simplest way to transform plastic waste into a material that might be suitable for bamboo connections. Unfortunately an even easier and cheaper way, was not found. In order to enable people that live in low income and remote areas to build their own houses with the plastic connections, a 'production line' has to be set up. This production line consists out of 2-3 machines with a cost of around €700,-. Starting and funding this production line would be done in the form of a charity project. For Esperanza, this project can be included with the next Bambú Social project. This production line would be able to transform HDPE waste in the form of bottles, caps and jugs into usable connections for bamboo constructions.

7.2 FINAL CONCLUSION

7.2.1 RESEARCH QUESTION

“Is it possible to design **a set of plastic connections** that enables **people in low-income and remote areas** to build a **bamboo construction** that lasts for **30-50 years**? “

Methods on how to harvest and treat bamboo to make it last for 30-50 years, and how to build with bamboo to ensure the extended durability, are described in this paper.

A standardized set of connectors is designed. The simplicity and the small amount of elements takes away the need of sophisticated machinery. The plastic connectors can be mounted with only a hammer and a saw. The holes in the bamboo will be made accordingly, depending on the available resources. Minimizing the amount of tools needed will speed up the construction time and simultaneously makes this way of constructing even more feasible.

The recycled HPDE is tested on its quality. The mechanical properties show that the HDPE can take quite high tensile stresses, around 21 N/mm^2. In the elastic region the recycled HDPE performs very similar to regular HDPE. The elastic region is determined by the linear part of the stress-strain curve. However, the exact limit of the elastic phase is hard to determine. The limit of the elastic region of the tested HDPE (Caps) lays around 14 N/mm^2. If this maximum stress of 14 N/mm^2 is not exceeded, no permanent deformation will occur. As it is hard to determine the exact limit of the elastic region, it can be stated that a maximum permanent tensile stress of 7 N/mm^2 won't result in permanent deformation.

In the plastic region of the stress-strain curve the recycled HDPE performed less promising. Most of the times the HDPE dog bones failed abruptly. Where regular HDPE forms a neck and can have a elongation of around 1200%, the tested recycled HPDE had a maximum elongation of around 13%. In addition the HDPE has the tendency to creep under long term permanent high stresses especially in combination with high temperatures. Resulting in permanent deformation. In order to prevent permanent deformation it is important to construct the bamboo structures in a way that the bamboo takes all the high permanent loads. The essential bamboo connections, which are used to construct a whole bamboo structure need to be designed using this knowledge.

The plastic waste needs to be transformed into useful elements after it is collected, shredded and washed. In order to do this a relatively simple injection moulding machine is build. The machine melts plastic flakes, thereafter the molten plastic is injected into a mould. The pressure for the injection is provided by a lever and body weight. Once the machine is built the process is quite simple and the production could be operated by local people that live in Esperanza. However, building this 'production line' requires money. Therefore, the machines need to be build by a team in the form of a charity project. The total cost of around €700.- is unaffordable for a local. However, for a charity project this can be easily achieved. Realizing such a production line for a village as Esperanza can enable the whole community to build their own houses. Small reparation of the machines can be done by local craftsman.

To conclude, harvest and treatment methods are described to extend the life expectancy of bamboo to 30-50 years. HDPE waste is recycled with a low tech injection moulding machine and the quality of the HDPE is determined by testing its tensile strength and Young's modulus. The plastic connectors will always stay the weakest point of the connections. Therefore, high permanent stresses should be taken by the bamboo. Lastly, a standardized set of connectors is developed, that enables people in low income and remote areas to construct houses from bamboo using recycled plastic connectors. So it is indeed possible to design a set of plastic connectors that enables people in low-income and remote areas to build a bamboo construction. However, if the connectors lasts for 30-50 years hasn't been tested yet. Herefore, the UV degradation needs to be tested, which will be explained in the recommendations. Lastly, the connectors are developed to be demountable if needed. Therefore the connectors can be replaced if they don't last as long as the bamboo.

7.3 RECOMMENDATIONS

7.3.1 RECOMMENDATION FOR REALIZATION

Realization of the production line that is needed to transform HDPE plastic waste into bamboo connectors, will depend on further research. The recommendations for further research are listed below.

Building the machines: Depending on the location and the presence of skilled men, a decision has to be made on where the machines will be build. Some parts of the machine have special requirements. The barrel for example, is made out of a seamless precision steel tube. If these materials aren't available on the specified location, they should be collected by the project team beforehand. For very remote areas, a set of spare parts is recommended. Further reparations are rather simple and can be done by local craftsmen.

Improvements on the injection moulding machine: This project shows that the pressure cap can be produced with the injection moulding machine. However, some improvements still have to be made concerning large scale production. A jack system needs to be build, in which the mould can be placed quickly, and removed right after the injection of the plastic. When releasing the mould from the machine a clamp should keep pressure on the mould to prevent it from opening.

To scale up the production of the connectors, the extrusion machine and the shredder based on Precious Plastics needs to be made. The extrusion machine will produce the pins. The shredder will ease the processing of the plastic waste into washed, clean HDPE flakes.

Plastic properties: The overall quality of the HDPE plastic is tested. This is done with tensile strength tests, creep tests and a three point bending test. However, for a full understanding of the recycled plastic further research is required. To prevent the HDPE connectors from permanently deforming, the exact limits of the elastic region have to be tested and analysed. In addition, the UV degradation of the connectors need to be tested. Sunlight affects the mechanical properties of HDPE and eventually the plastic will become brittle. However, the solid shape of the connectors will make it last longer. The outer layer will act like a sacrificial layer. It can take several years to affect the actual connection.

Structural analysis: Constructing bamboo is mostly done without any structural calculations. Usually adjustments will be made during construction when necessary. However, a structural analysis of the essential connections could give insights on the behaviour and mechanical properties of all the connections.

Mould design: For this research Liqcreate Strong X is used to 3D print the prototype moulds. These type of moulds are ideal for prototypes, as they are relatively cheap. However, these 3D printed moulds can only be injected about 1-50 times, depending on the design. Therefore, a design has to be made for a mould that can be milled out of steel or aluminium, to ensure long endurance.

How to use: When the production line is up and running on the location, the plastic elements can be used by the whole community. Only a hammer, a saw and a tool to make holes in the bamboo are needed to construct a bamboo structure. It is of high importance to understand that the plastic connectors will always be the weakest element of the connections. Therefore, it is essential to prevent high permanent stresses in the plastic. Permanent high stresses will result in permanent deformation. In this paper a set of example connections is shown. In these 'standard' bamboo connections the bamboo takes all the permanent loads. The use of combined bamboo culms is often needed to avoid permanent stresses in the plastic connectors.

Bamboo naturally grows on every continent of the world except for Europe and unfortunately plastic waste can be found all over the world. Therefore, this project can be useful for setting up a production line that enables a community to build bamboo structures that last for 30-50 years and simultaneously clean the surroundings from plastic waste. By doing so, it provides jobs and improves the health of people, animals and the environment. To make sure that anyone can start a production line like this, the needed documents will be open sourced and free to download by the public.

8. CASE STUDY

8.1 SCHOOL ESPERANZA

8.3.1 INTRODUCTION

A possible continuation of the Bamboo Factory project and Bambú Social is a school in Esperanza. Ultimately, the goal is to house 240 students, give space to communal gatherings, harvest and purify rainwater, sanitize the toiletries and even use solar energy for future electrical needs. Poor governance, insufficient funds, a lack of teachers and other challenges create uncertainty for the realization of the project (Verhoeven, 2017). As a reaction to these uncertainties and for the gradual and continuous implementation of bamboo as a construction material, a construction principle was created. Several large open sheds are created, which can be connected, and provide an integral answer to the following strategy points that strongly influence the design:

-Flexibility in function and expansion
-Experience of design
-Construction in phases
-Climate responsive

The school in Esperanza could be a project to test the final connections. As the school will be constructed in phases, a part could possibly be a test setup for the plastic connections. The design is shown in Figure 7.1, Figure 7.2, Figure 7.3 and Figure 7.4.

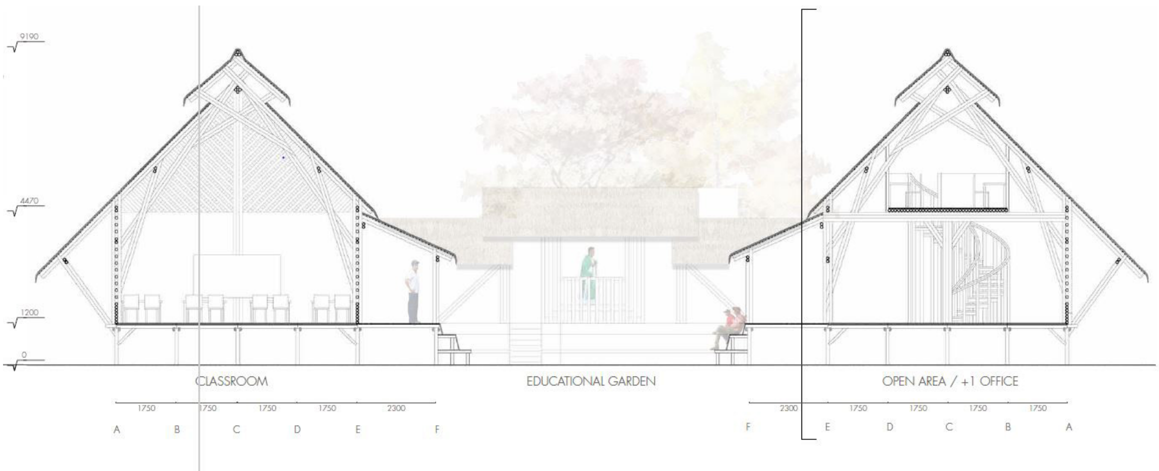


Figure 7.1 Design School Esperanza. (Verhoeven, 2017)

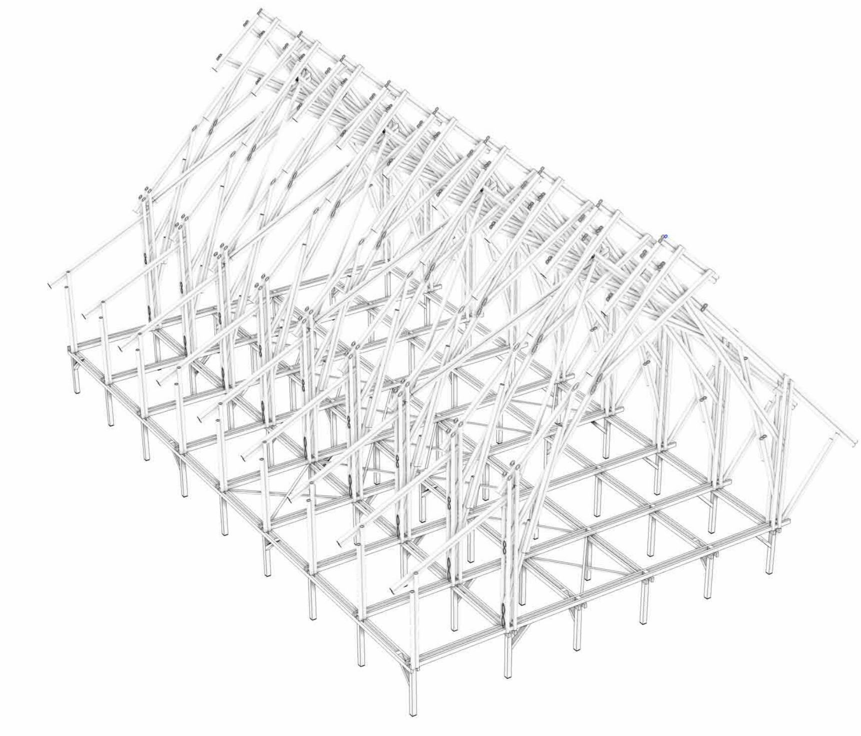


Figure 7.2 Design School Esperanza. (Verhoeven, 2017)

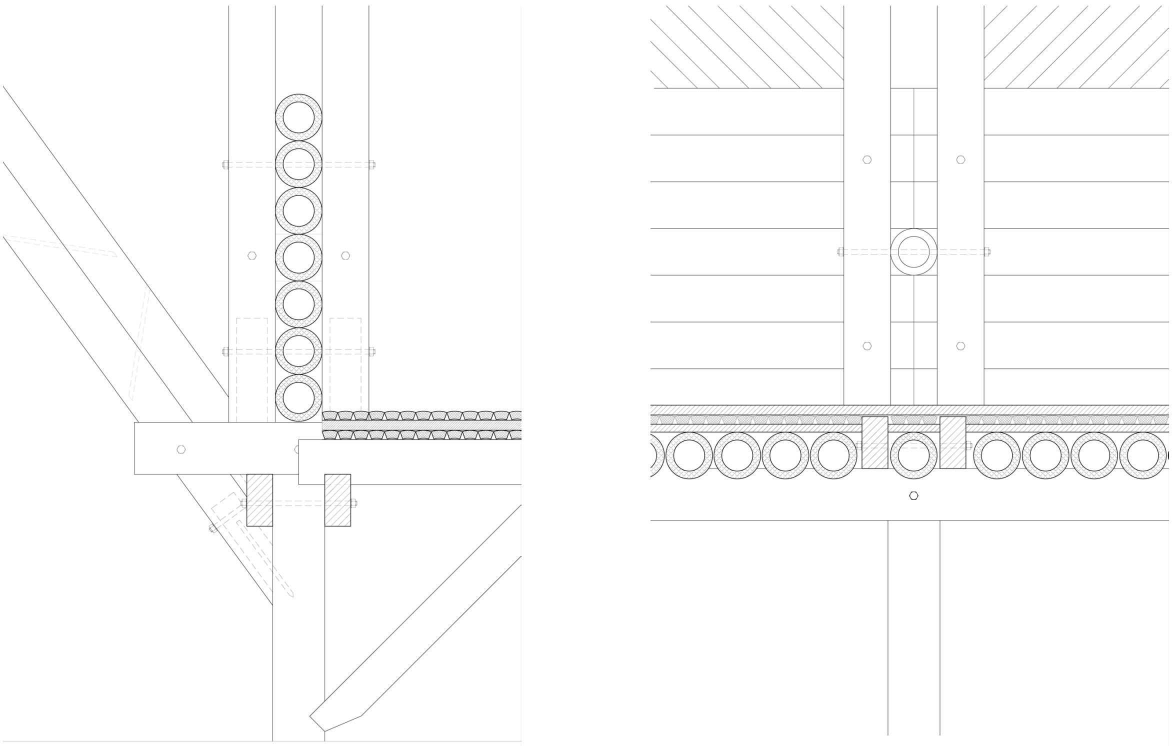


Figure 7.3 Design School Esperanza. (Verhoeven, 2017)

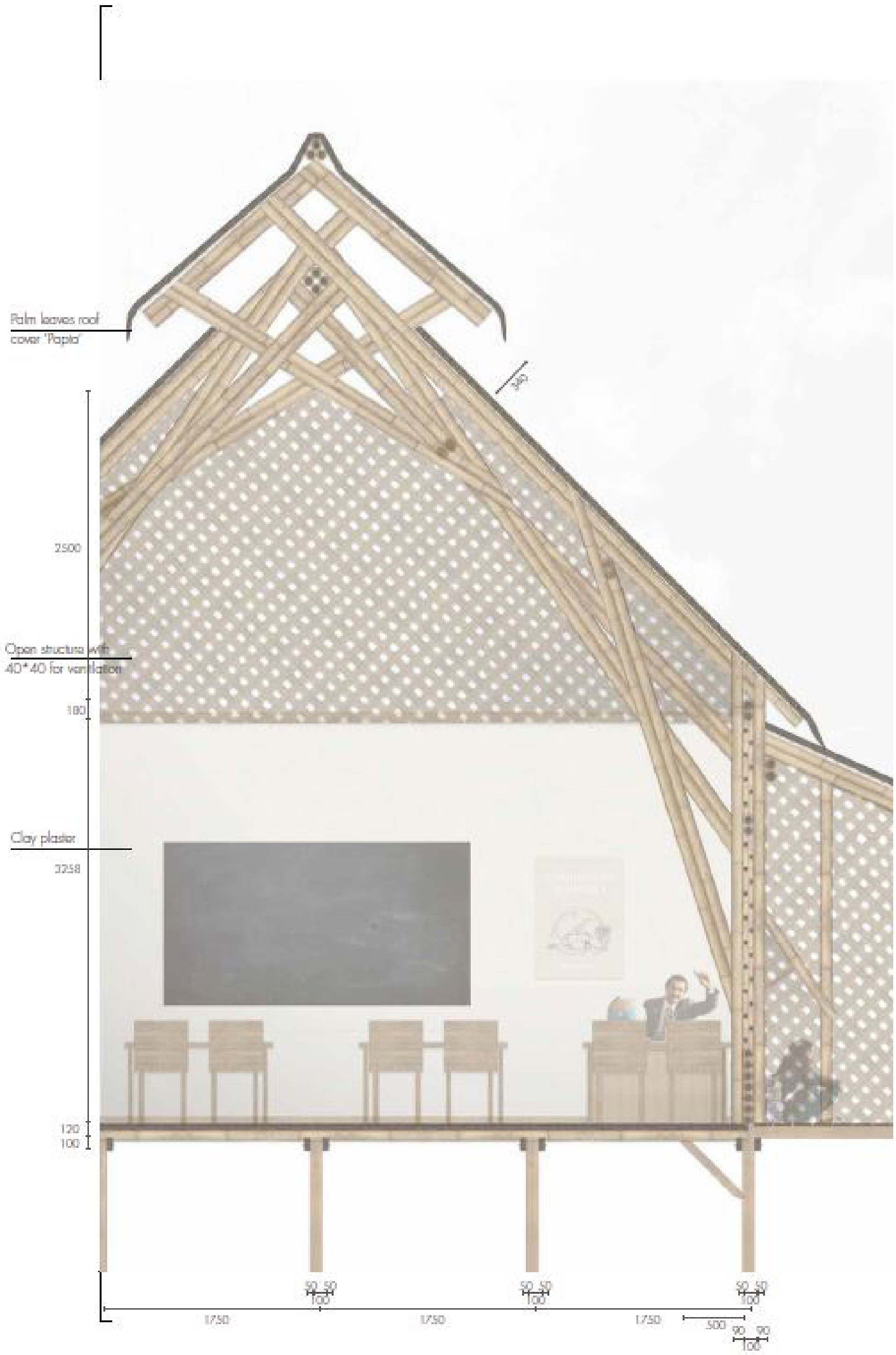


Figure 7.4 Design School Esperanza. (Verhoeven, 2017)

9. LITERATURE

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9.1 LIST OF FIGURES

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