Weaving Willows

Optimalisation of the weaving of willow branches to create a tensile fiber strong enough for a structural material

Master Thesis

Isa Heeling
2023/2024

Msc Building Technology
Technical University of Delft

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Mentors:
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Marcel Bilow - Façade & Product Design

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Abstract

Almost 40% of annual gas emmissions globally are produced by the construction sector. Due to the housing crisis of the Netherlands, the ministry of Housing and Spatial Planning wants to build almost a million dwellings before 2030, double the number of dwellings normally built in the same period. With that come greater gas emmisions. This growing amount of emissions however, can decrease drastically by using local and natural materials instead of the often used steel or concrete.

This research therefore aims to explore the potentials of natural local fibers for structural materials within new architecture. The use of these materials could reduce the carbon emissions greatly, while also bringing back the local identity of a place, that is now mostly lost due to a lot of generic, one-size-fits-all architecture.

This research begins with the investigation of local, natural materials that already have been introduced as building materials in the Netherlands historically and evaluates other natural fibers and their availability. The research soon delves into willow fibers and their properties and potentials. The final results provide an insight into the structural properties of different species of willow, a design for a structural element, its potential implementations within architectural projects and the possibilities of using this fiber on a big scale.

Content

1. Introduction

The introduction forms the base of this thesis and explains why the research that has been done is relevant. In chapter 1.1 the relevance of the subject is introduced. Next chapter 1.2 states the problem that is derived from that. Chapter 1.3 picks up on this problem and discusses the aim of the research. In chapter 1.4 the main- and subquestions are discussed. Lastly, the methodology and planning are outligned in chapter 1.5.

1.1 Introduction & Relevance

The Housing Crisis

There is a housing shortage in the Netherlands. Now, the estimated shortage lays at around 220.000 dwellings. However, due to the growing amount of households in the Netherlands, with the estimation being over 600.000 households in 2030, this shortage will continue to grow (*Wind, 2023*). To stagnate this the Dutch ministry has made plans to build over 900.000 dwellings before the year 2030 (*Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023*). Right now, the number of houses being built every year lays steadily at around 70.000, in order to reach the goal of 900.000 houses in 2030, this number has to grow to about 120.000 (*CBS, 2022*).

Global Energy and Process Emissions

This growing building industry due to a housing shortage, which is not limited to the Netherlands, reflects back to the amount of embodied energy and CO2 emitted into the world. At the moment, the building industry encompassed 37% of the worlds embodied energy, and 40% of the CO2-emissions that are process related (*Figure 1*). With the growing amount of houses being built, his number will only rise if we do not build more environmentally friendly (*United Nation Environment Programme, 2022*).

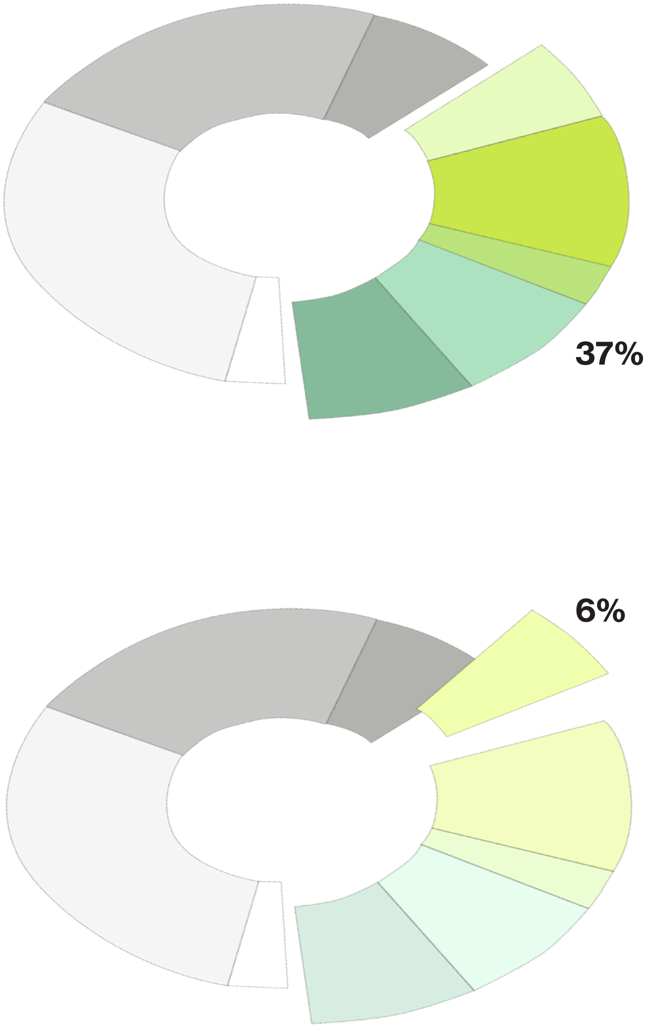


Figure 1: Share of global emissions due to building industry and construction industry in 2021. Own image, information: United Nations Environment Programme, 2022

The use of Timber within Construction

Building with biobased materials such as timber in construction is a more environmentally friendly way of constructing than building with concrete or steel. According to a case study done by Vukotic et al, the amount of embodied energy that is put into a building can decrease by building with timber instead of the standard steel and concrete (*2010*). The results of this case study state a difference of 37% between building with steel and building with timber, although this number can slightly vary per structure.

When using timber within construction, mainly slow growing wood is used. This slow growing speed makes the timber stronger, harder, more durable and grow straighter when compared to fast growing trees. Since the rise of the use of steel and concrete within the building industry, timber has been used less in constructions.

Since it became clear how polluting the building industry is, the use of timber within construction is on the rise again. However, with wood resources deminishing and restrictions imposed on cutting down trees in natural forests, the search for a different natural material which is also renewable and widely available has started again (*Xiao et al., 2008*).

Biobased Materials

Natural fibers, most of which on their own are not suitable as structural materials due to their low mechanical properties, have mostly been used for non-structural applications. However, due to new technological advances and machineries, research shows promising results in the creation of structural bio-composites and hybrid structures (*Bambach, 2018*).

A biobased product that is suitable as a structural material on its own is bamboo. For centuries, bamboo has been used within construction. It is the fastest growing woodlike plant in the world, with a 300% faster growing speed when compared to other plants and timber. It especially has a large tensile strength and, for a hollow material, a relative large compressive strength as well. However, in most instances, bamboo is used on its own for tensile applications and combined with materials such as clay or concrete for more compressive appliances.It grows in tropical and sub-tropical regions and for it to be used in the Netherlands, has to be exported and travel half the world. A transportation which would cause large emissions when done on a great scale.

Local Approach

Using local materials can enhance the effect of a building being more climate neutral, due to the little energy used in transportation. Not only that, it also makes buildings 'belong' more in a certain place (*Majerska-Pałubicka, 2020*). Like stated before however, most locally available fibres are not strong enough on their own to function as a structural element. Here in the Netherlands, a material that is as fast growing and as strong as bamboo is not available. We could however, make an attempt to create them by making bio-composites and hybrid structures that enhance the strengths of different natural materials.

Different researches show that the natural fibers that are abundantly available could be used within bio-composites and hybrid structures, preliminary research and case studies for that have already been done. However, on a big scale these structures are not implemented due to the fact that the processes still have some challenges and are not implemented commercially (*Zanetti et al., 2023*). In order to create fibers comparable in strength to that of bamboo within a bio-composite or hybrid structure they need to be grouped in such a way they hold the forces together. This can be done by either bundling or weaving fibers, depended on the type of structure it is needed for. The best way to do this has not been found yet when thinking about factors like geometrical freeform, automation, choice of material and variability of a material.

Local Structural Bio-Composites

The possible implementation of structural bio-composites consisting of local materials within architecture has several advantages.

First, with the use of local materials, the identity of a place is reflected in its buildings and thus forms a sense of them belonging there. Not only that, the use of local resources and production also leads to more job opportunities for people in the country and could have a positive influence on the country's economy.

Second, with the use of not only local, but als bio-based materials, the ecological footprint of a building can decrease significantly. Currently, structural elements have a high influence on the environmental impact of buildings. The materials used, the process to shape the material into the thing needed, the transport, all lead to a high energy consumption right now. If multiple things out of this equation could lessen by using innovative structural composites built out of local produce, the total energy consumption of a building process could be reduced.

1.2 Problem Statement

In the coming seven years, the government plans to build almost a million new dwellings to cater to the growing amount of households in the Netherlands. However, the construction of these dwellings would contribute heavily to the countries' total anual gas emissions and energy consumption, mainly from the production of materials such as steel, aluminium or concrete and the transportation of building materials. Not only that, the use of these 'global' products diminishes the connection with the location the building is constructed on. The use of local natural products within the building industry creates the opportunity for a type of architecture with a local identity and a circular construction that is returned to nature when its lifespan has been exceeded.

1.3 Design Assignment

This thesis aims to explore the possibilities of using local bio-based materials as grouped fibers within structural composites and the potential of expanding the implementation of these composites on a bigger scale. Based on this, the design assignment can be described as follows:

"Create a structurally optimised woven or braided natural fiber made out of Dutch produce that can be manufactured with existing machinery and operations."

1.4 Research Questions

To conclude the Problem statement and in order to reach the final goal of the upcoming research, a research question has been formulated:

How can the evaluation of braided or woven fibers, consisting entirely of Dutch natural materials, lead to wide spread use within structural bio-composites?

In order to answer this research question, three subdivisions are made within this research with each their own subquestions.

1. Local Natural Materials

SQ 1: What can we learn from the use of local natural materials in vernacular architecture in the Netherlands?

SQ 2: Which local natural materials are available in the Netherlands and which of them could be used as a structural fiber?

2. The Weaving and Braiding of Natural Fibers

SQ 3: What historic and current developments regarding bio-composites made from local biobased materials are there?

SQ 4: What different techniques and machinery are available for the braiding and weaving of natural fibers?

3. Optimisation for Local Fibers

SQ 5: What are the considerations and requirements when creating structural fibers out of willow and what are the possible configurations?

SQ 6: What are the possibilities of using willow as a strutural fiber on a bigger scale?

1.5 Methodology

Literature Research

Throughout the entire research process earlier done research and existing papers, journals and books related to the subject of this thesis have been analysed. Literature research has mainly been done in order to gain more insight on natural fibers, the availability of them, the available machinery and techniques for braiding and weaving fibers.

Research by Design & Research by Elimination

Considering the insight on natural fibers and their availability, the most abundant fibers in the Netherlands will be further analysed in order to prepare the materials for testing. Different species of material will be tested, as will certain woven and braided configurations. Analyses and comparisons on testresults regarding the

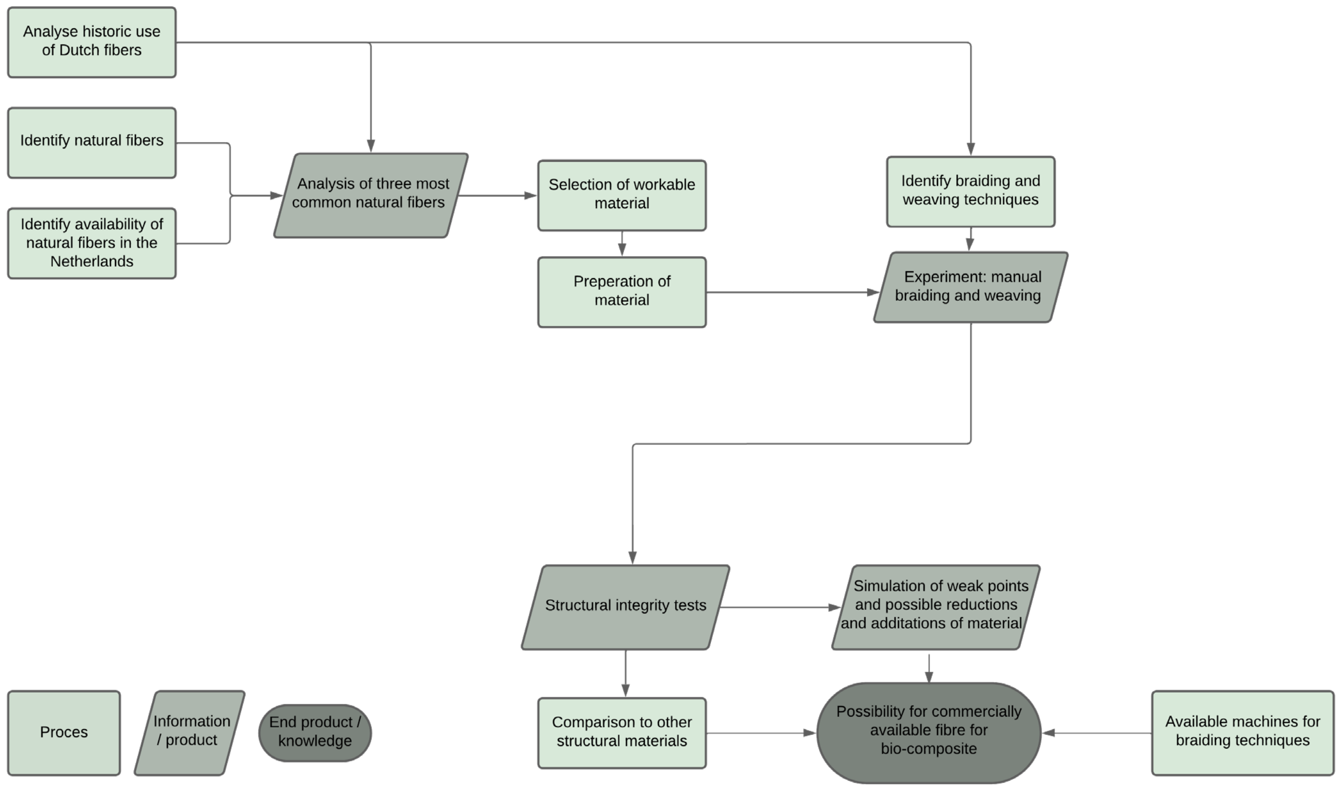


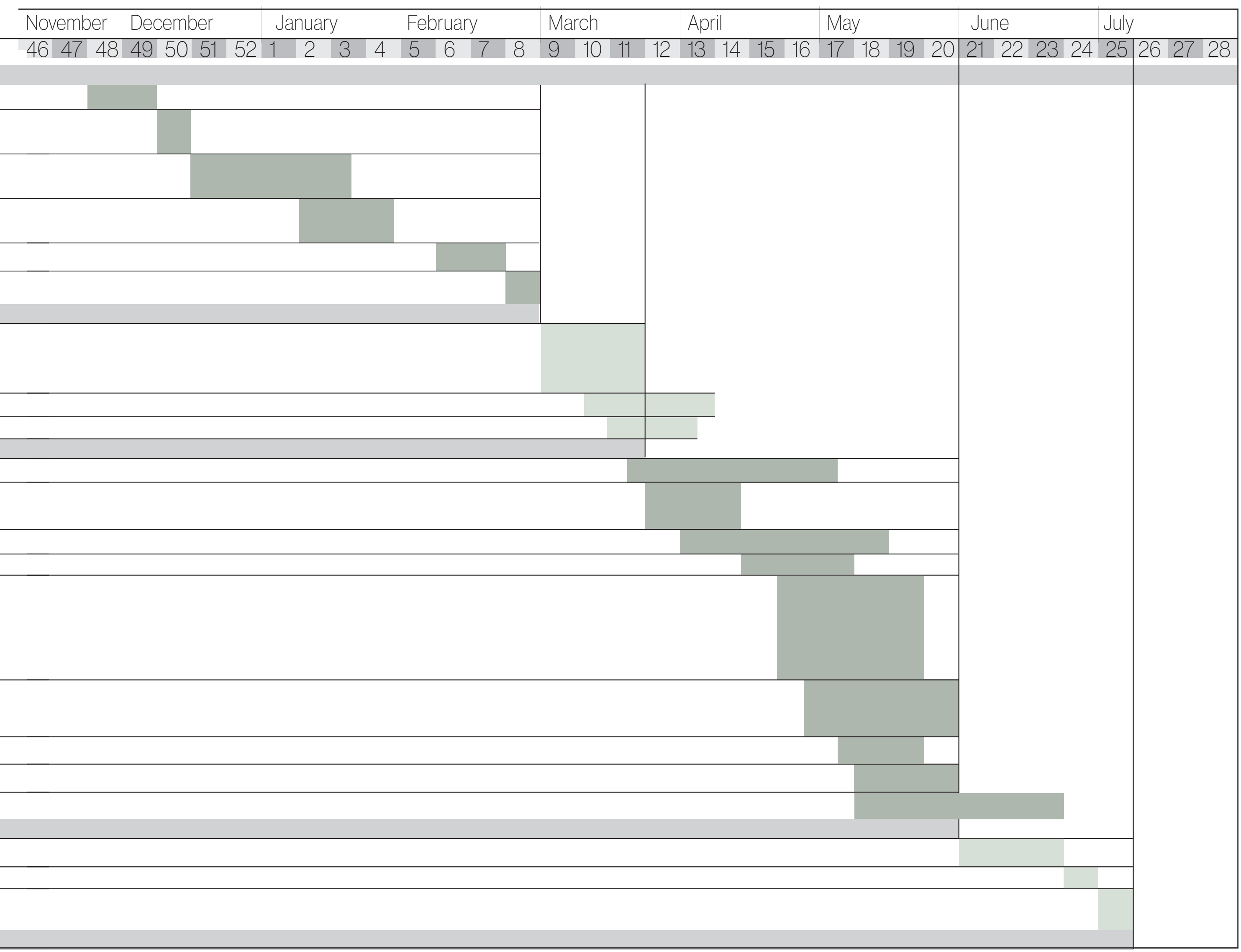
Figure 2: Methodology Framework, own work

braiding and weaving limits and possibilities and on structural integrity tests of the materials will be made to determine which materials and configurations hold the most promise to be used as a structural material.

The best performing products will be compared to existing structural elements and possible industrialisation methods and implementations are considered. After this, a consideration is made if these local fibers are indeed possible to be used as structural fibers for bio-composites and hybrid structures in a wide-spread use.

A framework for this methodology can be seen in figure 2. The planning for the entire process can be found on this page and the next.

Phase	Weekly program
P1	
Research	Biocomposites
	Hybrid structures
	What kind of local natural materials have been used throughout history?
	Natural fibers
	Machineries and techniques
	P2 presentation
P2	
Preparation Experiment	-Straw, willow and reed -Braiding possibilities -Weaving possibilities
	-Selection of material
	-Preperation of material
P3	
Experiment & analysis	-Experiment 1a: manual braiding/weaving
	-Analysis of the possible machineries in the Netherlands
	-Experiment 1b: Structural testing of 1a.
	-Interview experts on material
	-Experiment 2: Create configuration Tensile strength comparisons
	Analyse and determine weak points and opportunities of material
	Research industrialisation possibilities
	Research implementation possibilities
	Design and make possible implementation model
P4	
Design & deliverable	Finalize report
	Make P5 presentation
	P5 presentation
P5	


November December January February March April May June July
46 47 48 49 50 51 52 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28

2. Historic use of local biobased products

With the use of biobased, local building materials in housing, the identity of a place can become more prominently visible again. Buildings have become standardized and the ideology of a building 'belonging' in a certain place has become less important due to globalisation and mass production of the modern-day building industry (Majerska-Pałubicka, 2020). Moreover, as explained before, these biobased materials have a lesser ecological footprint than that of steel and concrete.

This chapter looks closer at the locally available materials that have been used in the Netherlands since prehistoric times, back when people built their houses with the materials that were available to them and used them in a way that enhanced the peoples culture and worked for the climate of a place (Zhai & Previtali, 2010). Chapter 2.1 focusses on the different materials historically used in the Netherlands. Next, chapter 2.2 discusses the usability and availability of Dutch timber

2.1 Dutch Vernacular Architecture

Since ancient times, humanity has recognized the necessity of shelter to shield themselves from natural elements. Back then, the absence of professional architects necessitated them to design and construct their shelters on their own. This type of architecture is called vernacular architecture, which literally translates to the 'native science of building' (*Oliver, 2006*). Spanning different cultures, terrains, available resources, and climates, vernacular architecture manifests in many ways worldwide (*Zhai & Previtali, 2010*).

The Dutch Climate

Beck et al. (*2018*) describes that the world can be divided into five climate classes according to the Köppen-Geiger system; continental, dry, polar, temperate and tropical, as can be seen in figure 2. These categories further subdivide into thirty distinct subclasses, with the Netherlands typified by a Cfb climate, known as 'Temperate Oceanic Climate' or 'Marine West Coast'. This climate is characterised by its cool summers and mild winters with its mean annual temperature being between -3 °C and 22 °C. In this relatively cold climate, massive building envelopes are preferred over lightweight ones, as these have more thermal mass. Additionally, architectural design emphasizes maximizing solar exposure, with openings positioned on the southern facades to optimize solar gain.

Used Building Materials

Vernacular architecture is not only dependant on climatic factors but also heavily influenced by material accessibility (*Zhai & Previtali,*

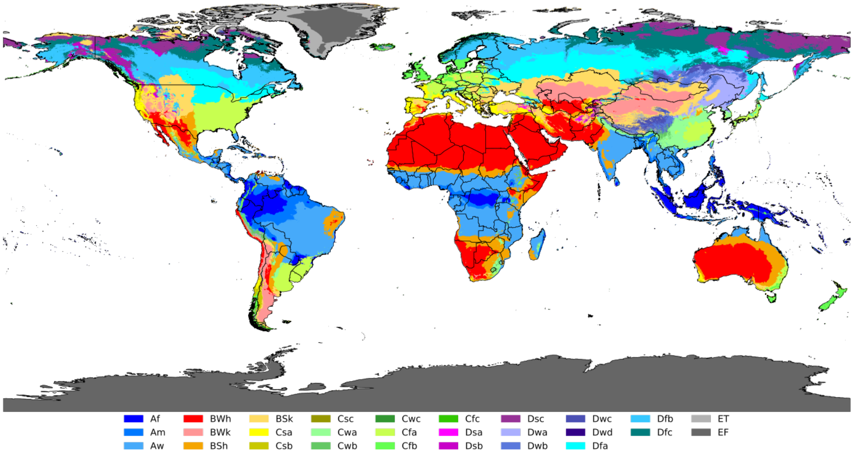


Figure 3: The world map shown as is according to the Köppen-Geiger model, with the Netherlands shown as a Cfb climate class.Beck et al., 2018

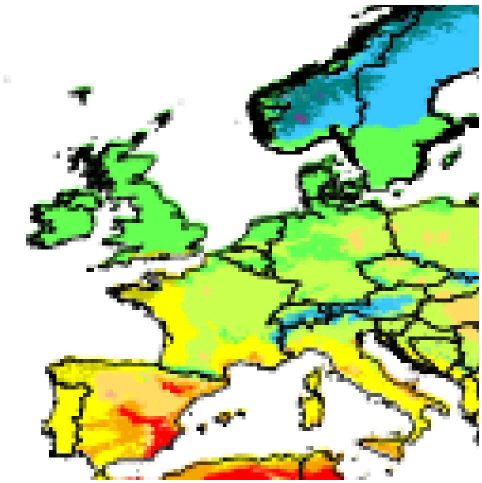


Figure 4: A close-up of the Netherlands within the Köppen-geiger model

2010). This is why even though stone and brick have a higher thermal mass, most dwellings in the prehistoric times in the Netherlands were comprised of wood, typically oak or pine, in conbination with loam – materials readily obtainable in the region. Moreover, the construction of the building is cost-effective and less time consuming than when constructed out of stone (*Lemmers, 2018*). Roof structures predominantly consisted of reed, straw or turf. An example of such a structure can be seen in figure 3. Note that this is a reconsruction, and not an exact replica of a historic dwelling, since these were not preserved due to the nature of the materials that were used.

Nowadays, there are little examples of these earlier vernacular architecture. Factors such as storms, fires, material deterioration, and increasing affluence within the country prompted a gradual transition towards the utilization of stone and bricks from the 16th century onwards (*Van Tussenbroek, 2017*).

Most buildings that are being built today resemble little the prehistoric buildings that had been tailored to work well in this specific climate with the available materials of the region. Dwellings are mass produced, looking almost identical to one another (*Majerska-Pałubicka, 2020*). This could be changed with the use of the materials that were used in the ancient times. Not only did those work well in the climate of the Netherlands, but they are also locally sourced and can be found in abundance. With modern technology, challenges like decay of materials and a faster production could be tackled.

Figure 6: Reconstruction of Dutch metholithic dwelling, De Raaff, 2020

Figure 5: Dutch prehistoric dwelling in stone-age, Lemmers, (2018)

2.2 Dutch Timber

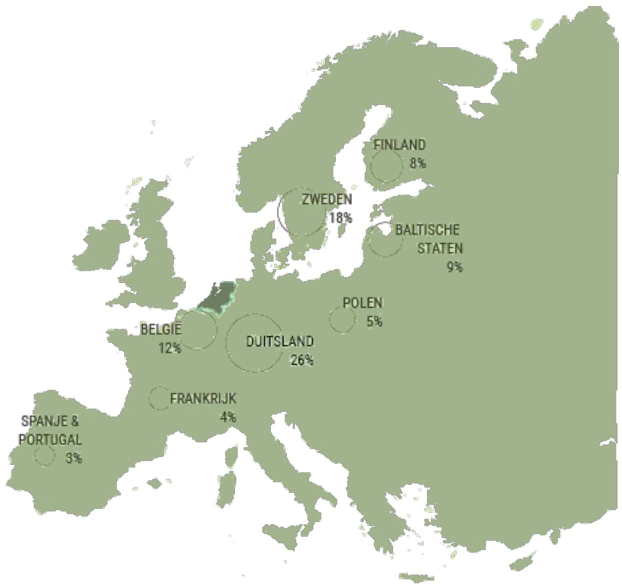
Timber has played a big role in construction since ancient times. In earlier eras, local wood, predominantly oak, pine, and willow for temporary structures, served as the primary construction material due to its accessibility and ease of manipulation*(Lemmers, 2018)*.

Oak and pine are both still one of the most used timbers used in construction, which are the most encountered trees in the Netherlands (*Team, 2023*). Pine, a fast-growing softwood is easy to work with due to its straight grain. It is also cost-effective, thanks to its abundant availability. Oak is a slower growing hardwood. Although it is more challenging to work with, remains popular for its robustness and structural integrity

Nowadays, only 8% (390.000 m2) of timber used in construction annually comes from the Netherlands, the rest is imported from other parts of the world, with Europe as main importer with 82% (*Circulaire Bouweconomie, 2023*). Figure 4 shows from which country exactly the wood comes from. The reason for this can be easily explained by looking at the use of the landscape of the different countries.

The Netherlands, a small country with a very high density of population, uses only 11% of its surface area as forests (*Oppervlakte Bos in Nederland, 1970-2021, 2023*). In Germany and Sweden, the European countries where the Netherlands gets most of its timber from, the land covered with forests encompasses 32,7% and 68,9% respectively of the total area (*Centraal Bureau voor de Statistiek, n.d.*). Another important detail to note is that only a small portion of the forest area can be used for the construction industry. Most of it is used for recreation and conservation of the biodiversity.

To become more self-sufficient and use less CO2 that is emitted by transportation, Van Dillen Bouwgroep (2023) has plans to create 'Building Woods' in the Netherlands. Forests, specifically intended to later become structural materials, will be planted on fields and pastures. This way, biodiversity can grow, CO2 emissions can be absorbed and building materials could be sourced more locally.



Conclusion

Dutch traditional architecture mainly used the materials timber, loam, turf, reed, or straw. Of those, only timber was used as a structural material.

Now, timber is a material that is still being used in construction, often to build more climate neutral when compared to the use of steel or concrete. The two most promising types of Dutch structural timber are oak and pine. However, the possibility of using Dutch timber as a main source is limited right now due to the forest area of the country. ‘Building Woods’ could be a solution of this; however, we would always be partly dependant on foreign timber.

3. Natural Fibers

This chapter focusses on different natural fibers and their materialistic properties in chapter 3.1. Later, it compares the potentials of the three most common and promising local natural materials and their historic uses. This part is divided in three chapters, one for each natural fiber. Chapter 3.2 focusses on willow, chapter 3.3 on reed and chapter 3.4 discusses straw. With all this general knowledge about the three materials, one is picked to be analysed further in depth in the next chapters.

3.1 Properties of natural fibers

There are three different kinds of natural fibers; animal, plant and mineral fibers. Then, within the plant fiber category, six sub-categories can be detected: leaves, grasses, stems, fruits, seeds and wood. An overview and some examples of natural fibers can be seen in figure 7. Tabel 1 shows the material properties for some of the most commonly used natural fibers.

A lot of the materials that fall under one of these categories can be, and have been used, within the building industry. However, a lot of these fibers, such as straw and reed, were not suitable as structural materials due to insufficient techniques of the earlier days. There was also never an incentive for the use of these materials, when building materials such as concrete and steel did the job. Now, it has become clear just how polluting the building industry is, with 40% of the total CO2-emission in the world coming from that sector (*United Nation Environment Programme, 2022*). With the use of natural fibers with construction, this number can be significantly decreased.

Natural fibers are biodegradable, renewable, and mostly found in abundance in the world and thus cheap (J*ohn & Thomas, 2008*). However, the process to be able to use the natural fibers as a structural material has not

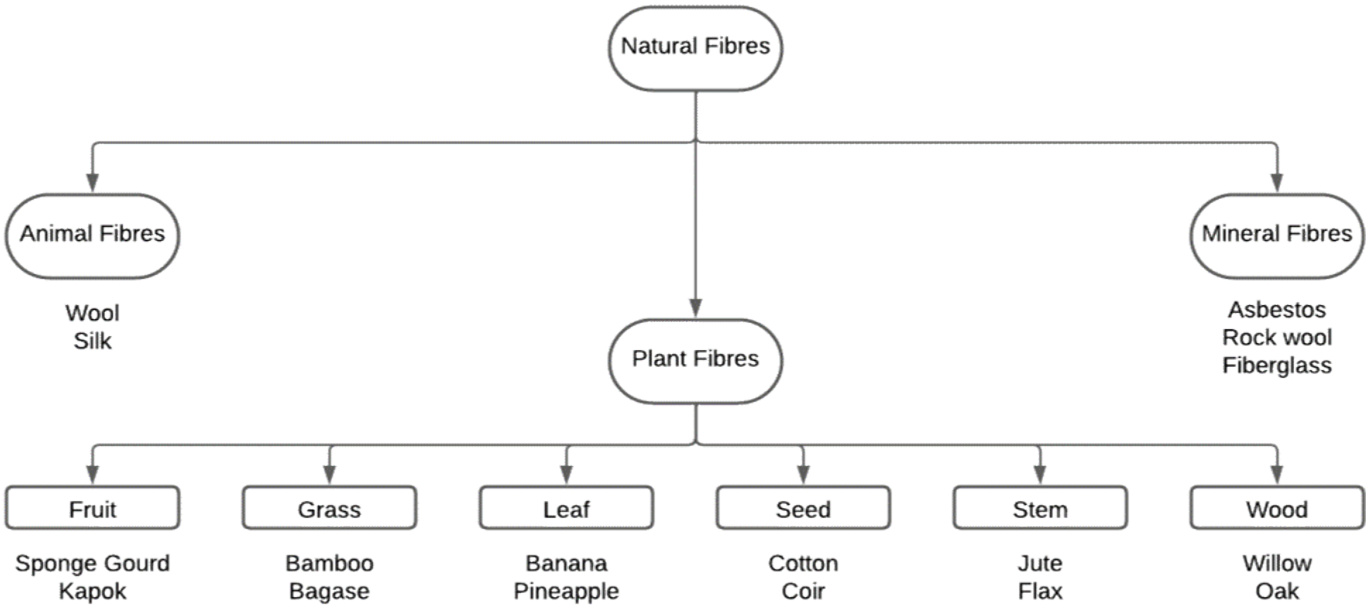


Figure 7: Classification of natural fibers, own work

yet been perfected, making the actual usability of the products low.

Before the creation of a bio-composite made up of natural materials, the fibers have to be purified and separated from components of the fiber that work against things like adhesion, such as the wax and proteins (*Nagalakshmaiah et al., 2019*). After this preliminary work of the purification of the fibers, all moisture has to be removed in order to make the fibers bond to the matrix. Currently, the creation of these bonding materials out of renewable resources remain limited and are not commercially available (*Fowler et al., 2006*).

This table shows different natural fibers that have been introduced to the building industry and their properties. Most of these fibers however, do not grow or only grow a little in the Netherlands. Since this Thesis focusses on local natural materials from the Netherlands and to see the possibilities of using those fibers within structural bio-composites on a big scale, the focus for the coming part of this chapter will be on the three most abundant natural fibers in the Netherlands. These are: Willow, Reed and Straw. The materials have been further analysed and their potentials for structural applications are discussed.

Fiber name	Classi-fication	Density Kg/m3	Young's modulus GPa	Tensile strength MPa	Availability in NL Kg/year	Price EUR/kg	Durability risks
Hemp	Stem	1,47e3-1,51e3	55-70	550-890	14,1e3	0,56-1,70	Flammable
Flax	Stem	1,42e3-1,52e3	27-80	750-940	10,1e3	0,66-2,34	Flammable
Jute	Stem	1,44e3-1,52e3	17-55	400-770	-	0,11-0,34	Flammable
Ramie	Stem	1,45e3-1,55e3	44-128	500-820	-	1,28-2,13	Flammable
Cotton	Animal	1,52e3-1,56e3	7-12	360-660	-	1,53-4,43	Sunlight Flammable
Kenaf	Stem	980-1,05e3	35-47	390-780	-	0,34-0,56	Flammable
Coir	Fruit	1,15e3-1,22e3	4-6	125-205	-	0,11-0,34	Flammable

Fiber name	Classi-fication	Density Kg/m3	Young's modulus GPa	Tensile strength MPa	Availability in NL Kg/year	Price EUR/kg	Durability risks
Wool	Animal	1,28e3-1,34e3	2,3-5	50-290	-	1,76-3,54	Sunlight
Bamboo	Grass	600-800	15-20	160-320	-	1,14-1,71	Water Flammable
Willow	Wood	310-380	7,1-8,7	53,1-64,9	Abundant	1,71-2,28	Water Flammable
Reed	Grass	130	6,5-9,7	75 -185	Abundant	1,10	Sunlight
Straw	Grass	90-160			Abundant	0,14	Flammable
Abaca	Leaf	1,15e3	41	857	-	n.a.	Flammable
Silk	Animal	1,26e3-1,35e3	5-25	340-720	-	22,2-52,8	Sunlight

Table 1: Material Properties of natural fibers, own work

3.2 Willow

There are about 350 different species of willow (*Salix*) that grow all over the world, with hybrid species not taken into account. Nine of those occur naturally in the Netherlands (*figure 8*). However, in the 19th century over fitfy new species were introduced to the country for basket weaving purposes (*Zwaenepoel, 2020*). These trees now thrive in the Netherlands due to their preference of wet soil and somewhat cold climate. Although these different species of trees all belong to the same family, they have different material properties and their strengths, compositions and densities differ greatly from one another.

What the different species do have in common is the amount of growth the trees go through each year. Willows are fastgrowing trees and their branches can grow over 1.2 meters every year, and with perfect conditions this growth can be up to three meters. When maintained they need to be trimmed at least once every two years, if not every year. The trees grow in abundance in the Netherlands, and thus their cuttings are as well.

According to professional Tree Worker Nino van de Rijzen these cuttings mostly end up as waste and go through the woodchipper. After which people mostly use them as animal bedding, a baselayer for a garden or simply compost them. The traditional use for the treecuttings; the craftmanshift of weaving of baskets or hoop-making, has been mostly lost since they no longer created any economic benefits (*Hoop Making, n.d.*). Although there are very few people left with the knowledge to make them, the traditinal techniques for the weaving and knotting of willowbranches could prove to still be useful in creating structurally strong fibers.

Willow in Vernacular Architecture

Willow has had multiple historic uses. Within architecture it was mostly used for the thatching of roofs. Here, smaller dried willow-branches were bundled together and layered on top of one another in an angle on the underlaying structure of roofs in order to shed water away from the inner structure (*Mac Coitir, 2020*). In ancient structures, this was not only done for the roofs, but for the walls as well, since they were built in a spehrical manner (*figure 5*). Another way willow was used was within wattle and daub constructions. Here, timber frames support the structure, while willow is woven inbetween the timberframes to fill up the non-structural parts of the façade. The willow is then covered with a mudmixtu-re to protect it and the inside from water and wind.

The most prominent way of using willow in history however, was with basketry weaving (*Bunn, 2013*). Due to the inherint flexibility of

Salix Alba
White Willow

Salix Aurita
Eared Willow

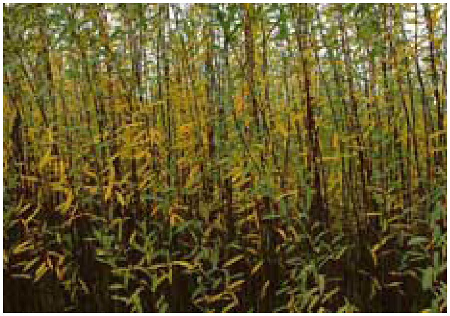
Salix Caprea
Pussy Willow

Salix Cinerea
Grey Willow

Salix Cinerea Oleifolia
Grey Willow Subspecies

Salix Pentandra
Bay Willow

Salix Purpurea
Purple Willow



Salix Purpurea lambertiana
Purple Willow Subspecies

Salix Repens
Creeping Willow

Figure 8: The nine native willowspecies of the Netherlands

the material, willow can be bent into different shapes, even at hard angles, and tightly wound together, without losing much of its strength. Willow has a low density, perfect for creating the small, lightweight structures that basketry offers.

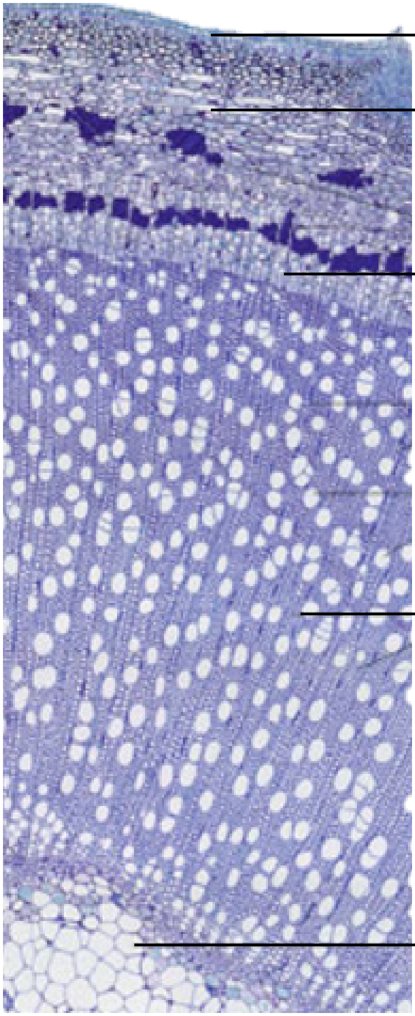


Figure 9: Microscopic view of willow, horizontal section. Karp,

Cellular level

Although the material properties of willow species differ greatly, on cellular level they look similar to one another, a microscopic view of a section of a willowtree can be seen in figure 9. The three main contents of the cellwalls of willlow include hemicellulose (24-30%), cellulose (35-60%) and lignin (17-26%). The rest of the components consist mainly of oils, ash and proteins (*Peng et al., 2010).* These contents can be seen in all plantfibers.

Within plants, the three main compartments have the same use. The outer cell walls consist of lignin, which provides strength and stability to a plant. It is hydrophobic, making the cellwalls waterproof, preventing excessive softening of the plants tissues in case of extremely wet periods. Lignin is also resistant to degradation and protects plants from decay, especially in wetland areas. Within the cellwalls, surrounded by the lignin, cellulose can be found, which not only provides strength and rigidity, but also plays a role in the watertransport of the plant: they form the vessels which are responisble for taking mineral and water from the roots to every part of the tree (*Cosgrove, 2005*). Hemicellulose is located around the cellwalls in a more random manner and helps the cellulose bind to one another and contributes to the flexibility of the cells. Hemicellulose molecules can also retain and absorb water molecules, which is especially useful in extreme periods of drought or wetness. Since the cellwalls provide the strength, rigidity and stability, the closer the cells are packed together, the stronger that part of the wood is. As is visible in figure 9, the cells are closest together close to the bast, for protection and suppliance of minerals and water, and in the heartwood. The softwood is weaker, which means it could be densified.

Working with Willow

Willow is a fastgrowing species of tree, growing up to three meters every year. These growings are mainly cut during the winter, between december and april, when there is no new growth and little foliage. If the trees are cut after the start of spring, and new foliage has started to break through, this can be unhealthy for the tree due to the loss of its saps at the places of cutting.

After cutting the branches should be dried for a period of time. This is because willowbranches have the unique ability to continue to grow after being cut off when exposed to humidity. This drying period has a minimum of six weeks, after which the cuttings are still flexible enough to work with. When dried for a longer amount of time, say a year, the branches have to be stripped from their bark (*Bunn, 2016*). This is neccesary in order for the willow to have more grip once woven. The bark of willow is smooth and slippery, causing early deformations. The bark can be removed by submerging it in boiling water for about 8 hours. This submerging in water also helps recreate the inherent flexibility of the willow.

This flexibility is crucial when working with willow. On its own, the branches do not have the strength it takes to perform well as a structural material. The variability of each branch in size and strength also makes it difficult to create homogeneous materials. In order to create consistent strength and stiffness within this material, the fibers have to be grouped together. This grouping of branches can either be done by parallel allignment and by braiding or weaving.

Both of these options have their advantages and disadvantages. By parallelly alligning the branches, the material keeps its maximum tensile strength, making it the strongest possible option. However, by weaving there is a greater geometrical freeform, in which the material can be lain out in desired shapes and bond better with needed adhesives and itself. Earlier research states that the weaving of fibers can decrease its strength by almost 30% (*Lee et al., 2002*). To see whether this would be the case with willow fibers would have to be tested.

3.3 Reed

There are six different type of reed, a plantfiber which can be classified as a grass. However, only two species are frequently mentioned in researches on material properties: Common Reed (*Phragmites Australis*) (*figure 10*) and Giant Reed (*Arundo Donax*). They are the most common species, and thus the most used (*R. Malheiro et al., 2021*). The giant reed, as the name already suggests, usually has a diameter that is two to five times as big as the one of the common reed (2,5-5,0 cm, compared to 1,0-2,5 cm), which gives both species very different material properties. Giant reed grows mostly in southern Europe and the middle East, whereas common reed also grows in northern Europe and thus the Netherlands. Giant reed is commonly used as a building material, whereas that is more limited with common reed.

Reed is a versatile plant, which grows in abundance near wetlands all over the world. It can be used for vernacular practices such as the weaving of baskets of music instruments, but also as a building material, although mostly as thermal insulation or roof cladding and not as a structural material (*Herbig & Zamolyi, 2013*). The grass-like plant grows near water and is fastgrowing, with the harvest being around 15 tons of material per hectare per year (t DM/ha/y) (*Van der Sluis et al., 2013*). Although here in the Netherlands the amount of wetlands is large, consisting of 16% of the entire territory, (*Best et al., 1993),* about 75% of the reed that is being used within architecture in this country comes from other countries.

Figure 10: Reed after cutting

Since only Common Reed grows abundantly in the Netherlands and this research focusses on local material, for the rest of this chapter only common reed is discussed.

Reed in Vernacular Architecture

Despite there being little evidence in the matter, it is believed that reed and other grasses have been used within architecture in Europe from as early as 5500 BC (*Herbig & Zamolyi, 2013*). This is when the first known large houses were being built in Europe, mainly consisting of wooden posts, wooden boards and a grassy thatched roof. Although little remains from these first settlements, this assumption can be made with confidence. Before there were regulation matters, or drainage of swamps, a lot of northern Europe consisted of large marshes, with reed growing everywhere, making it the perfect building material (*Zhai & Previtali, 2010*).

The thatch consisted of dried reeds, that were bound together and put on top of a frame, that was made out of timber. Next, the tatch was tied to the frame with other flexible fibers such as willow or coconutfiber, depending on what grew in the area (*Herbig & Zamolyi, 2013*). Reed thatch was not only used as cladding for roofs, but was also used in façades, as it provided good thermal insulation and protected against the wind (*Zhai & Previtali, 2010*). In South-Eastern Europe proof of building practices using reed within façades dates back 9000 years (*Z. Tokay, 2005*). Larger trees, with a diameter of 15-20 centimeter made up the skeleton of the buildings. Reeds were then knitted and woven through the vertical supports like mats, and formed the horizontal support for the dwellings. This was then covered with mortar to create a unified wall.

Reed was also used for building temporary shelters in these marshy areas, where shepards frequently built shelters for themselves and their cattle as they were on the move (*Herbig & Zamolyi, 2013*). More proof of these shelters can be found, as they were being built well into the 19th century, and drawings and pictures can be found as can be seen in image 6.

Cellular Level

Like all plantfibers, reed consists of cellulose, hemicellulose and lignin. Reed consists of more than 50% cellulose, around 25% hemicellulose and 12% lignin (*Wöhler-Geske et al., 2016*). The high amount of cellulose within this plant creates a strong fiber in comparison to other plants of its size (*Albrecht et al., 2023*). Reed also produces wax molecules, which lay on the outer surface of the reed stems in an organised matter, this is known as the Epidermis layer (*figure 11*). The epidermis protects the plant against water, and makes it almost completely water resistant, but susceptible to fire. In the Perenchyma, cells are less densely packed compared to other parts of the stem. This part, and the hollow inside, can be densified to make the material stronger.

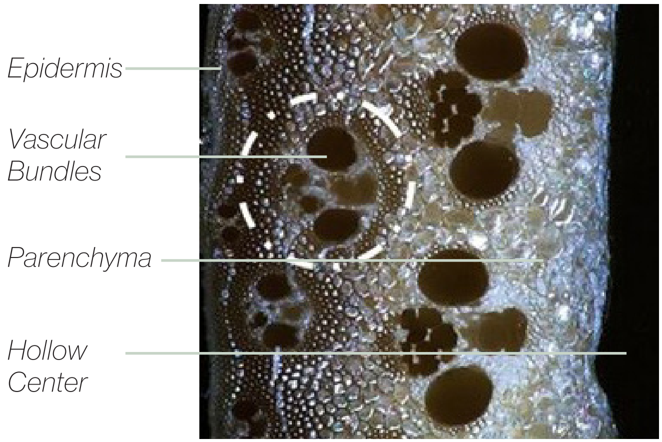


Figure 11: Microscopic view of reed, horizontal section. Albrecht et al., 2023

Working with Reed

Reed is a fastgrowing plant and can grow more than three meters in a single season (| *Concord, MA, n.d.*). Reed stems are mostly harvested in late winter or early spring, when there are no new growings, which is the least harmful for the plant, and gives it the opportunity to continue growing that same year.

Despite the plants level of cellulose, it is still not strong enough to work as a structural material on its own due to its small size. The grass has a diameter of around 1,5 centimeter and a thickness of the stem of about 2 millimeters, with the inside being hollow (*Albrecht et al., 2023*). In order to make a stronger material, the reed stems have to be grouped together. However, the waxy outer layer makes it difficult for reed to bond to one another and the adhesives (*Ghaffar et al., 2017*). So, this waxy layer has to be removed without it having drastic concequences for the rest of the material properties.

First, after cutting the stems, they have to be dried for at least a week, in order to counter water absorption (*Pandiarajan & Kathiresan, 2018*). After this, the stems are soaked at 60 degrees Celcius in a mild alkaline solution (0,1 mol/L NaOH) for about 30 minutes. After this, they are thouroughly rinsed until the pH of the water is back to neutral (*Albrecht et al., 2023*). When the time, temperature or amount of alkaline solution exceeds the minimum it needs in order to remove the wax layer, lignin and hemicellulose are also removed, weakening the material yet again. When all processes have been done sufficiently, the stems can be bundled and densified via pressing. This causes the hollow inside and the parenchyma to flatten, without the material losing its cellulose and thus structure, creating a denser and stronger material.

3.4 Straw

Straw is a byproduct of different crops. There are more than twenty different kinds of straw. However, most straw that is produced in the Netherlands is wheat straw (*Stro Als Biobased Bouwmateriaal, n.d.*). Wheat grows on a clay underground, a material that can be found in the ground in a little less than half of the Netherlands. After being harvested, the stems are left. These stems are harvested themselves and then dried in straw bales (*Straws | Feedipedia, n.d.*) (*figure 12*). After which, it is mostly used as ground covers in stables, mulch in agriculture and as building material.

Wheat straw is mostly planted in early fall, from mid-september to early october and harvested by late summer the next year, creating a yearly growth cycle (*NNFCC The Bioeconomy Consultants, n.d.*). In that time the plant grows to between 80-150 centimeters in height, and has a diameter of around three millimeters (*Neudecker et al., 2023*).

Figure 12: Drying straw bales

Straw in Vernacular Architecture

One of the earliest ways people created simple houses was by the use of mud blocks (*Hu, 2023*). Mud, a material found near river banks, was an often used building material as it could by found at every human settlement. Mud on its own cannot form building blocks for housing, as can crumble and crackle when it dries and shrinks uneavenly due to variable water absorption. By adding straw into the mixture, the mud can bind itself to the straw and dry evenly because of its shear strength. Together it forms a functioning façade which also provides thermal insulation.

Its availability, small size and shear strength seem to be the main reasons that straw is used within construction. It can not only be found in building blocks made from mud, but also as building blocks on its own. Here, dried straw bales in the shape of cubes are stacked upon one another and covered in soil to protect it from rain (*Hu, 2023*). Due to the compressional forces placed on the strawblocks, they are densified and create a strong material that perform well thermally. However, it creates very thick walls, with width-dimensions sometimes being over a meter, which in modern day architecture is not common or desirable.

Cellular Level

Straw consists for 33% of cellulose, 24% of hemicellulose and 15% of lignin (*Greenhalf et al., 2012*). This is comparable to the consistencies of wood. The plant has a good impressive strength, stiffness and buckling strength especially when its ratio between its diameter and height are taken into account. Just like with reed, the outside of the stem is covered in a waxy layer, that protects the plant against water. The rest of the plant, when looking at microscopic level, has a lot of similarities to that of reed. However here, the vascular bundles are more densely packed, making them stronger and less susceptable to damage when densified.

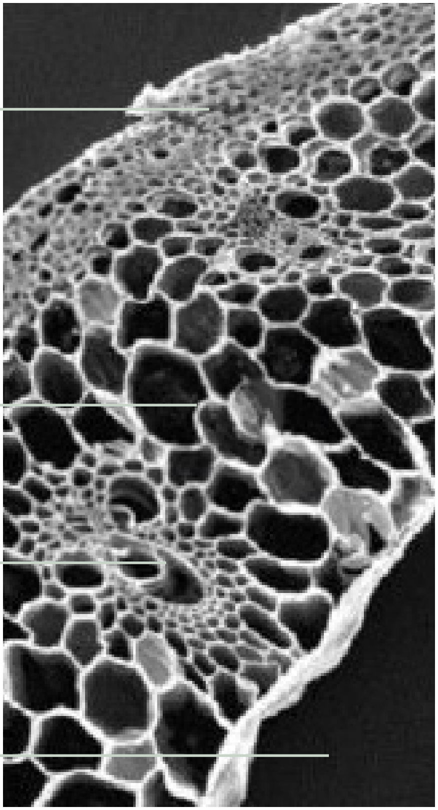


Figure 13: Microscopic view of straw, horizontal section. M, E. M., & R, E. D. (2016

Working with Straw

In order to perform best as a structural material, the straw should be dry, with moisture content being no higher than 20%. In order to bear loads, the straw should be densly compacted (*Cascone et al., 2019*). The two main challenges to create a functioning structural material out of straw are its low density and wax layer. The removal of a waxy layer on plants in order for it to be able to bind with adhesives has been discussed earlier in chapter 3.3, where it works in the same way. In this case straw would be exposed to a mild alkaline solution in order to get rid of the wax.

After its wax removal the straw can be pre-compacted by pressing it between paper sheets, this also removes the water residue from the alkaline treatment (*Neudecker et al., 2023*). These pre-compacted strawstems are laid out next to one another, rolled up and are then put in a mould in order to undergo the hot-pressing method.

When harvested, the dry straw has a density between 97,5 - 177,2 kg/m^3 (*Zhang et al., 2012*).

Conclusion

After a densification process with stems first treated with alkaline, this density grows to around 1050 kg/m^3 (*Neudecker et al., 2023*). This is an improvement of more than 600%. The alkaline treatment and densification have a negative effect on the amount of lignin and hemicellulose that can be found in straw. However, the ratio of cellulose within the straw, which is the molucule most responsible for the strength of the material, grows due to the processes. This causes the tensile strength of straw to have grown from 75 MPa in the raw material to 220 MPa in the treated material, a growth of almost 300%. The treated stems show better chemical properties compared to the most common timber used within the building industry in the Netherlands, oak and pine, which respectfully have a tensile strength of 95 MPa and 91 MPa (*Büyüksarı et al., 2017*) (*Büyüksarı, As, Dündar, & Sayan, 2017*).

The three most common natural fibers with structural potential are reed, straw and willow. Reed and straw have to, before being workable, undergo several pre-treatments in order to get rid of their waxy outerlayer and densification processes because of their hollowess which are complicated chemical processes. Willow does not need this pre-treatment and only has to dry for a period. Above that, the material is also more flexible and less susceptable to breakage when woven due to the way the cells are packed together. In order for it to have a better grip after being woven, the material has to be submerged in boiling water for a few hours. After this it is ready to be used. Due to its less complicated process, and the availability and low cost the material can be aquired for this research, the rest of this thesis will be mainly focussed on willow.

4. Working with Natural Fibers

Natural fibers, such as straw, reed and willow have been used in the building industry since the prehistory. However, this was not as a structural material, and always as cladding, filling or insulation (Lemmers, 2018). Recent innovations and techniques and the reimagining of older ones have made it possible to use natural fibers as a construction material as part of a composite or hybrid structure.

To see whether this process is nessecary or useful for working with fibers, this chapter 4.1 dives deeper into what a bio-composite consists of and chapter 4.2 discusses the process to create one that is applicable in architectural projects. Next, chapter 4.3 focusses on different projects and materials that have undergone such processes. Because of the flexible properties of willow, more research has been done to understand more about weaving techniques in chapter 4.4 and different machines that are now on the market which have the function of braiding fibers are discussed in chapter 4.5.

4.1 Structural bio-composites

A structural composite is a material that is composed of two or more components which have different chemical and physical properties. The combined materials produce a composite with enhanced mechanical properties, such as a higher strength, durability or stiffness. The materials used within a composite serve as either a binder, which binds the materials together, or as reinforcement, which provide the composite with its strength or stiffness (*Blok et al., 2019*).

Willow within a structural composite

Willow as a material has been used as a building material within architecture. However, this has never been done in a structural way. Although willow has a high tensile strength, of which there are little quantitative values available, the material has a very low compressive strength of around 26,0 MPa (*Salix Alba, Granta Edupack*). Note that with the more than 350 different species of willow that exist, and those all having different material properties, this is an average and can vary per species. Compared to white oak, which has a compressive strength of 51,0 MPa (*American White Oak Wood, n.d.*), the strength of willow wood is only half. Moreover, the willow that is being researched is the byproduct that comes from trimming the trees themselves. These branches are thin and could not form columns or beams on their own and would have to be grouped together to become strong enough to hold down forces. These branches could then be used within construction to transfer tensile loads. However, for the compressive loads that buildings undergo, willow is not strong enough. In order for the material to be able to be used within construction, it should be combined with another material that could transfer compressive forces.

Obstacles of bio-composites

In bio-composites, a natural fiber is often combined with a polymer that either softens or hardens when exposed to heat, depending on the function of the composite. The advantage of using bio-composites in structures are the sustainability properties of the natural fibers. The materials are recyclable, biodegradable and often have a quick growth cycle time, creating an almost never-ending supply (*Bambach, 2018*). Architects are however, also faced with certain issues when using bio-composites in their design. The use of natural polymers as adhesives is very limited. Natural fibers and adhesives are variable, causing uncertainty in properties such as strength, density and stiffness, depending on growing conditions, processing methods and harvest period. The durability of these natural composites is often lower than that of materials like steel and concrete due to the sensitivity to UV radiation and moisture (*Ariadurai, 2013*).

Coatings, additives and other treatments can protect the materials and quality control can ensure a good performance. These extra steps however, can be susceptible to inaccuracies and extra costs and labour which reduces the collective incentive to design with such materials. Once the process is more automated, certain bio-composites could be mass-produced, lowering their prices and creating more opportunities for the materials being used in the building industry (*Nagalakshmaiah, 2019*).

4.2 The Making of Bio-Composites

Based on techniques that have been used and are being used for the processing of plastics, bio-composites are also formed. Depending on the materials used, there are four different techniques to create bio-composites They are discussed in this chapter, together with an analysis of their functionality regarding willow.

Compounding and Extruding

The most common techniques include the compounding and extruding of the fibers and binders (*Fowler et al., 2006*). Here, the thermoplastic -or matrix- is heated until it melts. Then, the fibers and other additives are added in order to improve the traits of the final product. When these materials have been properly mixed, the mixture can be extruded into the final product, cool down and harden (*Fowler et al., 2006*). This method works especially well with long fibers. With willow, the thin branches would be lead into the machine in long bundles, where it would mix together with a matrix to properly bind them together. This could be a thermoplastic, or a more natural binder. The newly made composite material would exit the machine in long strands. Due to the heating the material becomes flexible, which can be enhanced with moisture afterwards. Now, by hand or possibly with another machine, it can be lead through a frame, into the wanted shape.

Thermoplastic Injection Molding

Here, instead of being extruded, the mixture is injected into a mold and then cooled. Once it's cooled, the object van be removed. This way, the mold can be reused (*Thermoplastic Molding: Process, Types, Materials, and Applications, n.d.)*. With willow, this would be harder to perfect. The long fibers are flexible, but not as bendable that they can securely and snugly fit into a mold unless the fibers are made smaller and are splintered.However, by doing that, you lose the initial benefit of the flexibility of the material, and are limited to the shapes that the mold can make.

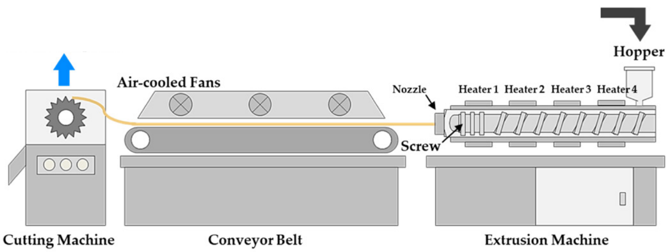


Figure 14: Compounding and extruding

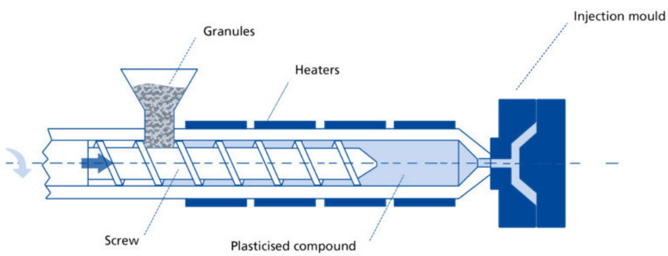


Figure 15: Thermoplastic Injection Molding

Hot Pressing

This method relies on low-pressure presses of the fibers and matrix into the mold. An advantage of this technique is that different elements such as fastening materials can already be inserted into the mold before the hot press, creating a precise component with less steps (*SMC Hot Pressing, n.d.*). The hot pressing method can also be used in order to densify a material (*Jakob et al., 2022*). With wood, this happens transversially. First the wood is heated up to a temperature where the wood can plasticize. In the mean time, the wood dries out due to the heat it is subjected to and its cellulose cells rearrange, causing its tensile strength and modulus of elasticity to increase. This method forms panel-shaped materials. With it you lose the inherint flexibility of the willow and the unique architecture it could create.

Film Stacking

Lastly, this method is advantageous when there is a high fiber volume required in order for the bio-composite to function well. Here, matrix and fiber layers are alternated, heated and then compressed into a mat, without the fiber losing its material properties (*Huerta et al., 2022*). With these thicker panel-like materials however, the same happens as with hot-pressing; the willow loses its flexibility and the possibility of creating unique shapes.

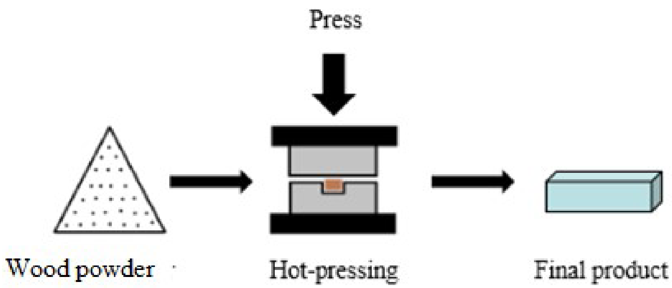


Figure 16: Hot Pressing

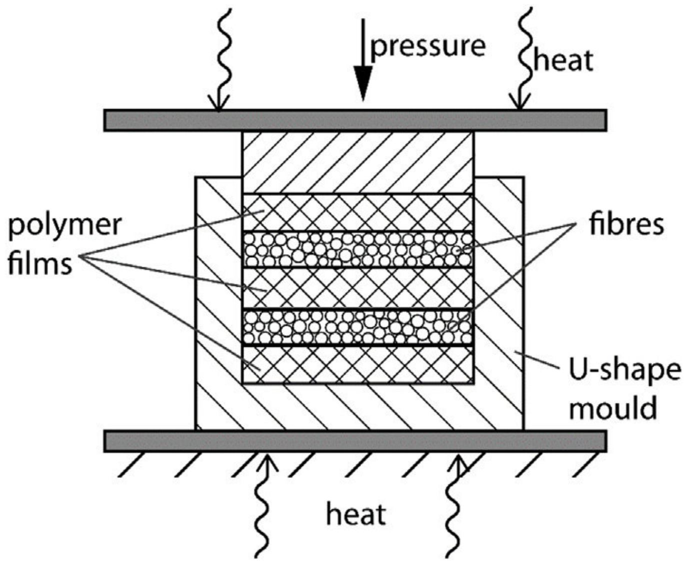


Figure 17: Film stacking

4.3 Reference Projects

In order to gain a better understanding of the possibilities of the earlier described natural fibers and materials within the building industry, the coming chapter discusses historic and modern-day inventions and developments regarding bio-composites and hybrid structures made with these fibers and the materials described in the chapter of vernacular architecture. The focus of these references lays mostly on the use of materials that are available in the Netherlands, because of the historic use of local materials, knowledge, techniques and machinery to use these materials and fibers are already mostly available in the country, or on projects with or similar to willow.

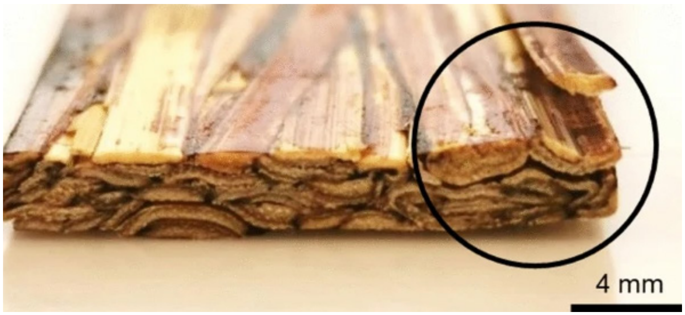


Figure 18: Beam made from reed with adhesion problem Albrecht et al., 2023

Reed Beams

Reed has often been used within architecture, although not as a structural material. The interest in this specific material is new due to the search to a new bio-based load-bearing structural material (*Albrecht et al., 2023*).
Reed, on its own, has a very low mechanical strength and easy combustion, making it a hard material to use with in construction (*Malheiro et al., 2021*, and table 1). However, new research shows that when reed is prepared in a certain way, its strength compares to that of bamboo, another naturally sourced structural material (*Molari et al., 2021*). By removing the outer wax of the reed and the silicon, the adhesion of the reed and matrix material can be enhanced (*Albrecht et al., 2023*). Once the stems are prepared, they are lain parallelly aligned together with a resin adhesive. With the 'hot pressing method' the stems and adhesive form the beams. Results of the case study of Albrecht et al. show promising results, with the strength of the beams being comparable to that of wood-based composites. The process to create these beams has not yet been perfected, as the adhesive fails depending on the pre-treatment of the stems (figure 18). However, the experimental research seems promising and might have the result that reed will become more attractive as a construction material.

Turf Blocks

When turf is dried and pressed together, it can be formed into building blocks. These building blocks could form the structural walls of a shelter (R*omankiewicz, 2023*). This building method was mostly used in the north-western part of Europe, an example of a structural façade made from turf can be seen in figure 19. Even though the material is compostable and the use of it contributes to a lower CO2 emission level within the building industry, there are problems associated with the material causing it to not be regarded as a renewable raw material and as a possible base for a composite or hybrid structure in this research: the formation process of turf is very slow, which means that the supply is finite. With most of the available turf having been used as a fuel for most of the 20th century in the Netherlands, it has been fully excavated (*Groene Bouwmaterialen, n.d.*). Creating a hybrid structure or composite consisting of only local natural materials is therefore not possible with turf.

Figure 19: Façade made from turf Romankiewicz, 2023

Half-Timber Construction

An example of a hybrid structure consisting of timber, loam and straw is a half-timber construction (*Schittich, 2005*). An example of such a structure can be seen in figure 20. Here, the roof and floor loads are carried by timber frames. Loam and straw are combined into a composite, which is used to fill up the non-load-bearing parts of the construction. A half-timber structure performs best with a high-density timber (*Okabe et al., 2004*). When looking back at the most common woods in the Netherlands, oak and pine, their densities can be compared. The density of oak is between 850-1,03 kg/m3, whereas the density of pine is between 400-600 kg/m3, according to the software of Granta Edupack. The combination of loam and straw with oak would perform best in this case.

Figure 20: Half-timbered house Craven, 2019

4.4 Weaving techniques

As shown in the previous chapter, a lot of natural fibers have been introduced as structural materials as part of a bio-composite or hybrid structure. However, issues and unknowns lay not only in the material selection, but mostly in the process of the creation of the composite, the collaboration between the different elements and the geometrical freeform of the construction. The following section focusses on some different machines and techniques in order to get a better understanding of their operation.

Mad Weave

The first technique to be discussed is the Mad Weave technique. This is a basketry technique that weaves in three directions that creates an almost continuous surface, an example of a result of this weaving technique can be seen in image 21. The surface or sphere that can be created with this method is strong due to the surface area of the material. However, when using less flexible materials, corners of this weave can be challenging (Gailiunas, 2011). Another thing that might be an issue with this technique is that there are inflexible rules with the weaving, which causes limitations is the geometrical freedom of the design and final product.

Bamboo Splitting

A technique to create more flexibility and bending possibilities that is widely used for bamboo is the splitting of the bamboo poles. Especially willow, which is flexible compared to a lot of materials, but still has its limitations, might be able to benefit from this technique. Here, V-shaped cuts are made into the bamboo poles to make it smaller and thus more flexible (Doha2O, 2021). However, the material does get weaker, so multiple poles should be tied together when bended in order for the structure to remain standing.

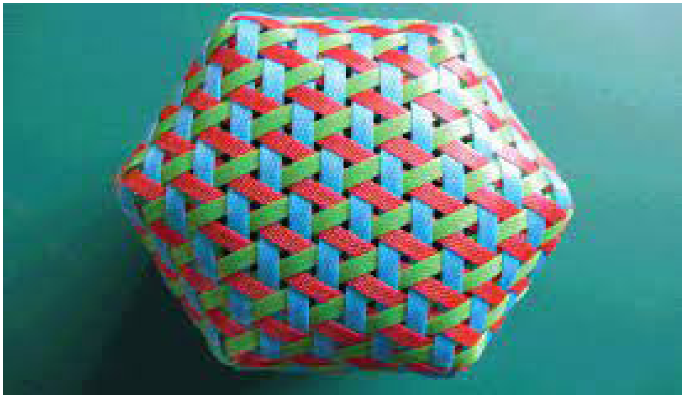


Figure 21Mad weaving Technique

Figure 22Bamboo Splitting

4.5 Potentials of Braiding Machines

Hexagonal braiding

A possible machine that could be used in order to braid single strands of fibers into stronger groups is the Three-dimensional Hexagonal Braiding Machine. This is a technique now used on textiles, but could technically be used for bigger fibers like willow and reed. This machine is equipped with bobbins, which have the fibers on them, put in a hexagonal grid (Emonts et al., 2021). These bobbins can rotate and move all throughout the grid, while the fibers are being braided. Due to the fact that the all the machines are controlled by individual motors, there is a lot of flexibility in the geometrical freeform as well as the control over the tension in the fibers and the speed.

Rotary Braiding

Another machine that already has been used within light composite materials is the Three-Dimensional Rotary Brading Machine. This machine can make three-dimensional structures from two-dimensional braids (Emonts et al., 2021). The difference between the Hexagonal and Rotary machines is that the bobbins on the Rotary machine are stuck on a track, resulting in a lower geometrical freeform.

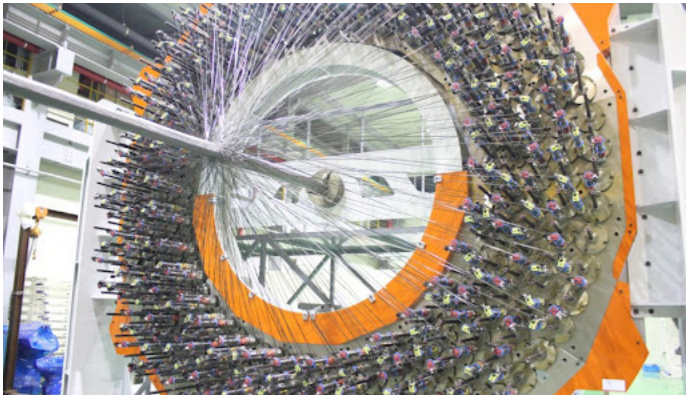


Figure 23Hexagonal Braiding

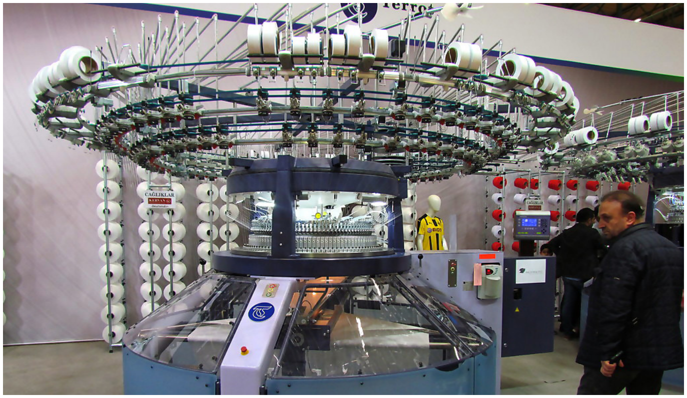


Figure 24Rotary Braiding

Circular knitting machine

There are also circular knitting machines, which are mostly used in the industry for the knitting of socks, shirts andsweatshirts. This machine could perhaps create ‘knitted’ hollow columns or beams. However, the flexibility of the machine is low; you are limited to the size of the diameter of the machine which are usually not bigger than 75 centimetres (Catcheyes, 2023).

Two axis machine

The two-axis machine that was used for the project of Intertwig – ReGrow Willow is also promising. Within the machines, poles were placed around which the willow is woven by a machine that can move freely in the x- and y-axis (Zanetti et al., 2023). However, limitations still exist in the z-axis, making the geometrical freeform limited for now.

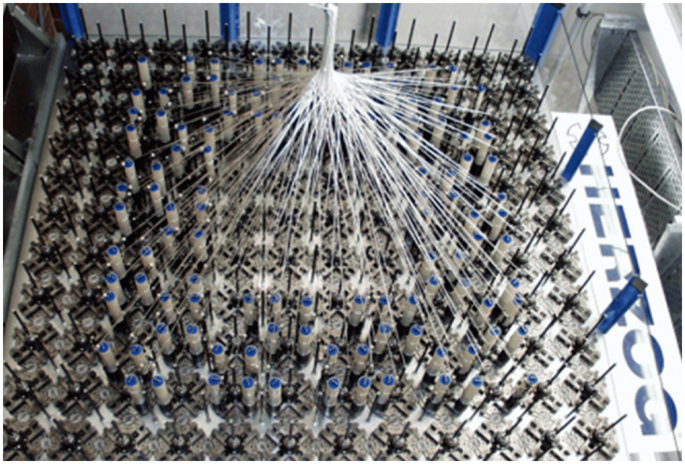


Figure 25Circular knitting machine

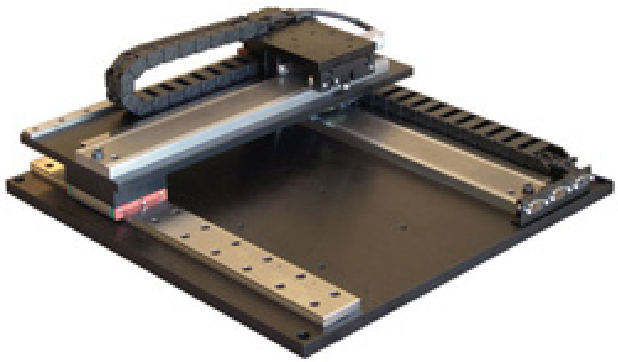


Figure 26Two-Axis machine

Conclusion

As stated in an earlier chapter, willow is a flexible material that works well in distributing tensile forces. However, in order for it to be used as a structural material, it should also be able to withstand compressional forces. The material that should be combined with willow should thus have a high compressional strength.

The creation of a completely natural biocomposite made out of willow and an adhesive proves to be difficult, since reliable natural adhesives are hard to find. Not only that, the freeform of the material decreases as well. Instead, ways could be found where willowfiber on its own could form a structural element.

Considering the properties of willow, a process in order to improve its strengths might be nessecary in order for it to perform well as a structural element. Experimentation with hot-pressing willow and its change in properties should be done at a later stage of this research.

Most machines available for weaving and braiding fibers are for microfibers, which willowbranches are not. In order for the material to be able to be used industrially, the fibers should be split and thinned.

5. Experimentation

To get a feeling of the workability of willow and its structural potentials with weaving and braiding the fiber, I started experimenting with three different species of willow, to also gain an understanding in the different properties of each. Chapter 5.1 discusses the three selected willowspecies and their availability. Next, chapter 5.2 shows the transport of the used materials to the workspace, which is then shortly discussed in chapter 5.3. Chapter 5.4 discusses the preperation that was done in order for the material to be ready for use. After this, chapter 5.5 explains the experiment methodology. Lastly, chapter 5.6 explains in detail the different experimentation done with the willowbranches.

5.1 The Material

Figure 27: Salix babylonica

There are over 350 different species of willow, like discussed before. Not all these different kind of trees can be discussed in detail in this one thesis. Taking into account certain aspects from the different species such as flexibility, historic uses and the availability of these species in order to do experimentation, the focus of the workability of willow focusses solely on three species: the Salix Babylonica (Weeping Willow), the Salix Caprea (Pussy Willow) and the Salix Purpurea (Purple Willow).

Salix Babylonica

The weeping willow is not a native species in the Netherlands, but has migrated over the world from eastern Asia. Today it can be found all over the country, often near a riverbank. The tree grows to a height of 15 meters at maximum in a period of 15 years. Every year, leaf stems can grow from 1,2 to 4 meters, both when the tree is fully grown or still young (*Greene, 2017*). The branches grow vertically upwards for half a meter before they bend downwards and grow towards the ground due to gravitational forces. This creates relatively straight stems that are easy to work with and weave when compared to branches with kinks. A problem with this tree however, arises due to its extremely fast growing rate. This fast growing rate results into a low density wood, with a density of around 350 kg/m^3, compared to the average density of willow wood being 500 kg/m^3 (*Orwa et al., 2009*) (*Editor Engineeringtoolbox, 2023*). This causes the tree to perform worse under tensile stresses compared to other species of willow and wood in general.

Studies show however, that costwise the weeping willow would perform well as a structural material when compared to other woods. Even though more material would be needed in order to achieve the same amount of strength as other wood, the costs would be lower due to its growth speed (*Larjavaara & Muller-Landau, 2010*). With the same cost of wood with a higher density, the wood with the lower density could thus achieve a greater strength.

Weeping willows do not grow in large quantities in the Netherlands. They mainly grow along riverbeds and are there for aesthetic pruposes. In order for the wood of the tree to be used in large quantities. special plantations should be made. Within these plantations the density of planting should not exceed 2200 trees per hectare, as that could compromise the growth of the plants due to their vast root system.

Figure 28: Salix Purpurea

Salix Purpurea

Unlike the Salix Babilonica and the Salix Caprea, the Salix Purpurea, also known as the Purple Willow, has more resemblence with a shrub than it does with a tree. The plant grows up to three meters tall on average (*USDA NRCS New York State Office et al., 2002*). Out of a single stump, a multiptude of branches grow, without them having sidebranches, an important characteristic for good weaving fiber (*Simpson, 1898*). The tree is resiliant and can overcome stem breakage and other mechanical damage. Moreover, it grows well in both wet and dry places, which is why this tree is often placed near riverbanks. They grow relatively fast compared to other trees, but slow when compared to othe species of willow. A maintained tree can grow around 30 centimeters to 1,2 meters each year, but it is best to trim it every two years to harvest more mature branches. When trimmed, the tree can be cut down all the way to the stump in early spring, providing new growth again less than a month after when the conditions are right.

Although the Salic Purpurea has the qualities of a well performing building material for woven structures, problems arise when looking at its occurance in the Netherlands. Due to its mentioned flexibility, resiliance and little branching, this tree used to be one of the main three species of willow that was used for basket weaving or more structural wickerworks like fences. However, this tree is now seen as an endangered species in the country. The Salix Purpurea, although one of the fewer species native to the country, occurs very rarely in six of the twelve provinces (*Maes & Maes, 2021*). This is mainly due to the fact that even in natural woodland in the Netherlands, there is no regulation regarding the planting of native trees. With forests thinning due to urbanisation or the use of the planting stock, other types of trees are allowed to be planted back, at the cost of the native trees such as the Salix Purpurea. In order for this species to be used within local architecture, without it having a negative effect on its occurance in the wild, 'Building Woods' as described in chapter 2.2 might be a solution. Not only could the cuttings of these trees be used as structural elements, they could also be cultivated and planted in natural woodland, decreasing its rarity. Purple Willows have a small root system, making a planting density of 20,000 plants per hectare possible, and with that producing a high quantity of usable stems (*Sulima et al., 2021*).

Figure 29: Salix Caprea

Salix Caprea

Unlike the weeping willow, the Pussy willow is native to the Netherlands and can be found all over northern Europe. It can grow up to 12 meters in height in good conditions. When compared to other species of willow, in this case the Salix Babylonica and the Salix Purpurea, this species of willow is more sensitive to an exces of water and does not grow as close to riverbanks as the other two types do (*San-Miguel-Ayanz et al., 2016*). The tree can be seen as a fast growing tree , but its stems only grow up to 50 centimeters a year and should only be trimmed every other year, creating a lesser production quantity when looking at the other two types of tree. Due to this slower growth rate, the tree has a relatively high density and tensile strength.

As discussed in an earlier chapter, an advantage of working with willows is the fact that propegation is possible by planting cuttings of trees. With the Salix Caprea this only works oocasionaly (*Skálová et al., 2012*). With hardwood it is completely impossible, but it is possible to grow new trees from leaf droppings. The reasons for this still remain mostly unknown. It does however, make this tree less suitable to work with compared to the other ones, as with replanting hardwood branches you can skip a growthperiod of almost three years.

When looking at the branching of the tree, it happens in a more irregular way than the other two analysed trees. Where branches of willow trees grow downwards and those of the purple willow grow upwards without much side branching, the branching of the pussy willow happens in an irregular, forked way. The variating form of the branches makes working with the material hard. The tree mostly produces branching to the third degree. Here, the first degree are the main branches sprouting from the trunk, the second degree are the smaller stems growing from those branches, and from those stems the twigs grow (third degree) with the foliage. From the second degree on, the branching is less tortuous, making its workability better. The tree has a big root system, making a large planting density impossible. Each tree, especially when they are growing, should have at least 2,5 m2 of individual space.

Table 2 shows the availability and growth potentials in the Netherlands of all three species of tree. Comparing the growth speed, maximum trees that can be planted per hectare, replantation possibilities and usable branching within each cutting, the Salix Purpurea is the best option to be used in a big scale. Not only can a lot of plants be planted within a small area, the shootings from those plants are mostly straigt, with little sidebranching. Since this species of willow is also one that was often used within basket weaving, the hypothesis is that this type of tree also is best workability wise due to its flexibility. The strengths, another important factor in order for the material to be used within the construction sector, will be discussed in a later chapter.

	Salix babylonica	Salix Purpurea	Salix Caprea
Maximum height	15	3	12
Growth per year	1,2 - 4,0	0,3 - 1,2	0,5
Trees / ha	2200	20000	1600
Replanting cuttings	Possible	Possible	Not possible
Usable branching			

Table 2: Availability comparison of willow species

5.2 Transport of Materials

In order to gain acces to the materials needed I contacted several Tree Worker companies. There was one near Delft who was enthousiastic: Nino, from Rooibos Boomverzorging. He had several costumers during the period of experimentation who needed their willows trimmed down. Nino gave these trimmings to me in order for me to use them for the experimentation. As seen in figure 30, the transportation of these branches sometimes required some help. Luckily, often my parents or Nino himself were happy to help.

Despite the many different species of willow growing in the Netherlands, I only analysed the possibilities of three different species: the Salix Babylonica (Weeping Willow), the Salix Caprea (Pussy Willow) and the Salix Purpurea (Purple Willow). This decision was based on both momentarily availability, since Nino had trimmings of these trees, and also occurance of the species in the Netherlands.

Figure 30 Transport of materials

5.3 The Workplace

After initially starting the preperation of the experimentation at my parents' garden due to my own lack of an open space in Delft, my boss provided me with a garden near the center of Delft. This location was close to home, and close to the faculty, providing a great working space. The weather in april proved to make working in the open air hard, with temperatures barely rising above 12 degrees Celcius and a wetness that did not help. However, the shed in the garden provided a dry and warm place to work in and keep the materials when the weather was rough.

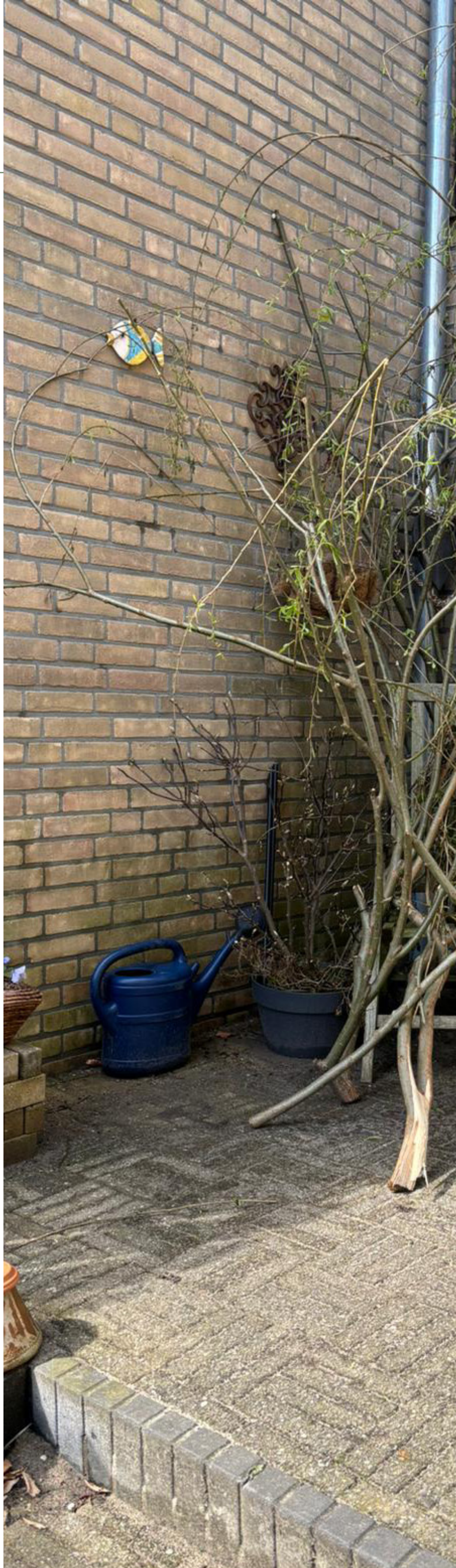


Figure 31 Workplace

5.4 Preperation

The three different species of willow arrived after one another, giving the opportunity to prepare them one by one. This also made the pros and cons of working with each material clearer, which will be discussed this coming chapter.

In order to be able to work with the different branches and being able to weave with them, the leaves, bloomings and side branches were cut away at the nodes. In order to lower the variability of the cuttings in this small a sample size and to get conclusive testresults in the end, the branches were then divided into three different groups, depending on size of the diameter of the branches. With the diameter being ‘X’, these three different groups are:

- 5 mm < X < 10 mm
- 10 mm < X < 30 mm
- X > 30 mm

The cuttings of the leaves, bloomings and branches that were either too short or too thin to work with were left alone in this experiment. However, a following chapter discusses possible uses for this restmaterial.

The different groups of each species of tree can be seen on the following page. Due to the material properties for Purple Willow and its little branching, there are no branches that fall under the second size group. With the Pussy Willow, the branches that fall within the thinnest size group are unusable due to the small lengths of them and the amount of foliage.

Figure 32: sidebranch at node, place of trimming

Figure 33: Group 1. Salix Purpurea

Figure 34: Group 3. Salix Purpurea

Figure 35: Group 1. Salix Caprea

Figure 36: Group 2. Salix Caprea

Figure 37: Group 3. Salix Caprea

Figure 38: Group 1. Salix Babylonica

Figure 39: Group 2. Salix Babylonica

Figure 40: Group 3. Salix Babylonica

5.5 Experiment Methodology

Willow is a material of which the properties are variable. This is due to the variating thickness, but also due to variating placement of the nodes and side branching. In order to see how variable this type of timber is, various branches from all three different kind of species of tree were tested in tensile strength and flexibility.

The main focus of the mechanical testing of the specimen is to examin the tensional properties of the materials. While there are qualitive results of the mechanical properties of willowtrees, no explicit quantitive results are available. There is also the question whether the different species of willow achieve different results. As chapter 5.1 concluded that availability-wise the Salix Purpurea would be best to be used as a building material in a big scale, this result might change when the species are compared in strength, an important factor when making structural elements.

The branches would be used for tensile strength testing. The specimens however, did not fit in the tensile testing machine due to the forces the specimen would be subjected to at the specimen grips. In order to get as close to finding out the tensile strength of the branches, they were subjected to bending tests instead. Specimens were subjected to both a four point bending test and a three point bending test.

The testing of the structural integrity of the different elements has been done at TU Delft, at the 3ME faculty with the Zwick 10 machine (figure 41). The set up of the four point bending experiment consisted of span length L of 100 mm. The loading noses were placed at equal distance from each other and the support wedges at a distance of 33 mm (a).

The results, which will be discussed later, show that with the four point bending tests, the specimen show failure in shear strength before they fail in tensional strength, making it nessecary to do testing with a larger moment arm, which is possible with three point bending tests. For the three point bending test the span length L also consisted of 100 mm. The loading nose was put in the middle, at an equal distance from both support wedges at a distance of 50 mm. Schematic overviews of the set ups can be seen in figure 42.

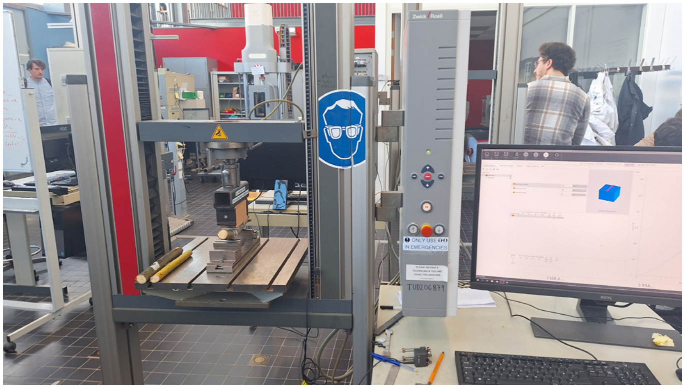


Figure 41: Zwick 10 machine

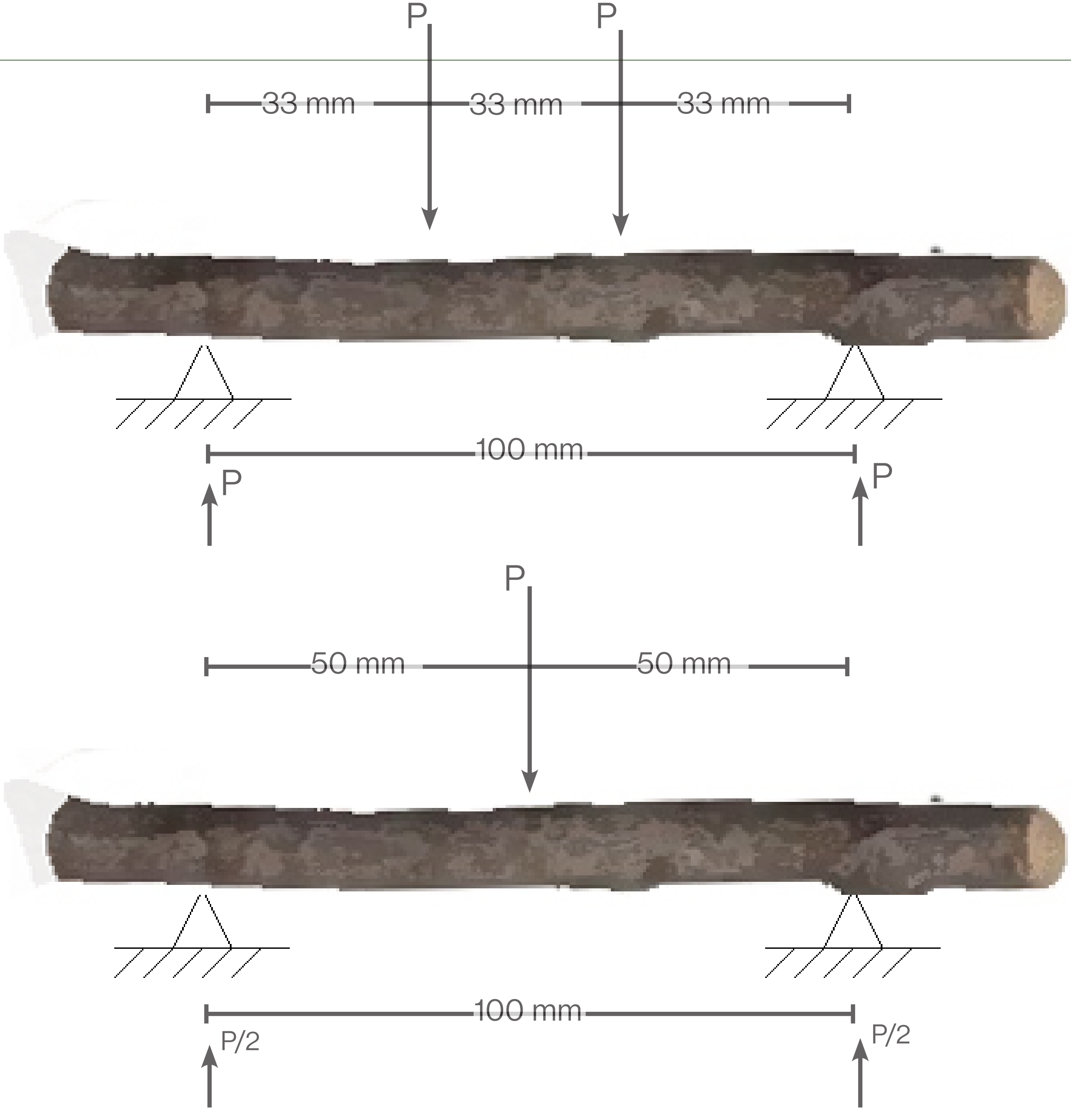


Figure 42: Schematic overview of bending test set-upof both 4-point bending and 3-point bending

Intermezzo - a visit to a basketry weaver

During the experimentation phase I visited Esmé Hofman, a basketry weaver living in Northern Netherlands. Since a project in highschool, where she analysed the traditional art of basketry weaving, she was sold. In 1997 she went to Germany to start a training which took her four years, to become the professional weaver that she is. Now she is one of the three remaining people in the Netherlands with the knowledge of this art.

Esmé mostly does repairs of antique wickerworks, makes regular basketry, but is mostly known for her fine work, which have been on display in different museums in the Netherlands and around the rest of the world. She shows me her piece de la resistance, 'Kegel I' (figure 118). In collaboration with Harmen Brethower, who is investigating all different kinds of traditional workings, she has created a cone, entirely made out of willow.

She showed me her process. First, she makes a design by hand, in which she

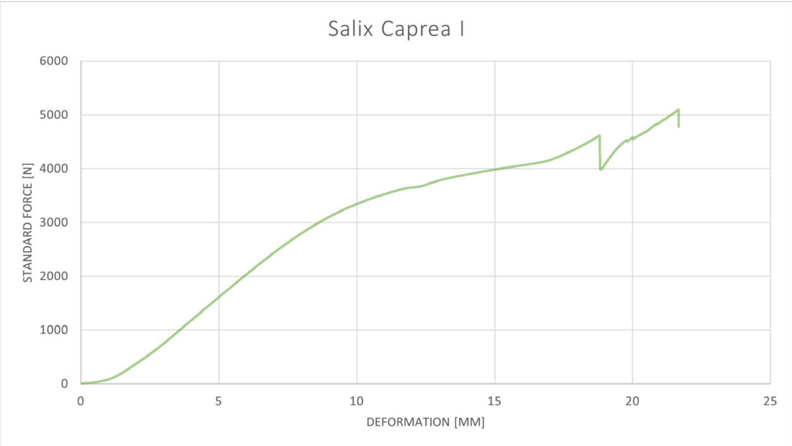
draws her design and calculates how much willowtwigs go into it. She handpicks willow-bundles at specific farms and gets a mold made out of wood. This mold is needed to properly tighten and shape the material in the wanted structure. Next to her workstation, a bucket of water is permanently filled, in which she then lays the willowbranches in order for them to soak for about six hours, although she mainly does that overnight. She then uses a wood splitter, with which she splits the branches into three or four. This makes them thinner and more flexible.

In order to still provide the strength for the structure needed, she sometimes layers the split trimmings over one another.

While being there, she showed me the basic tehniques, which are used throughout all her projects. The most important advice she gives, stated that you should always go with the natural torsion of the material, and weave in two different ways in order to provide stability.

Singular branches

Applied to the four point bending test are samples of each species of willow, with diameter X > 30 mm. The tests for the singular branches have been done in order to be able to make a comparison in strength of the initial wood and configurations made by the more flexible pieces. The graphs on the next page show the forces placed on the specimen versus the deformation due those forces. The tables underneath show the quantitive test results and the results after calculations. The formulas of these calculations and the values that cannot be derived from the graphs are on page 70. The results will later be compared to the ones derived from the tests of the woven configurations in order to see whether the material has potential to be used as a structural material when woven.



Graph 1: Deformation of Salix Caprea I

Figure 43: Salix Caprea I during bending test

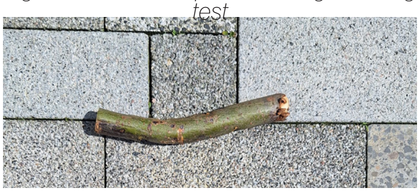
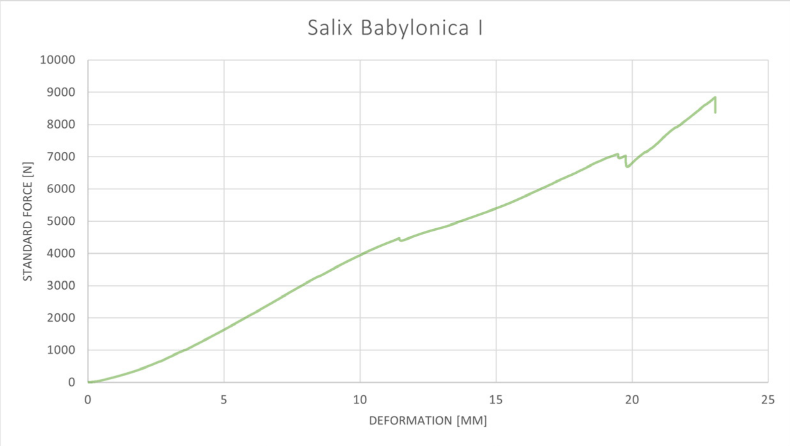


Figure 44: Salix Caprea I specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (MPa)	E (MPa)
Salix Caprea I	5094,69	21,66	4615,09	18,80	7,21	6,53	16.8124,77	63,43	33,29

Table 3: Testresults and calculation of Salix Caprea I



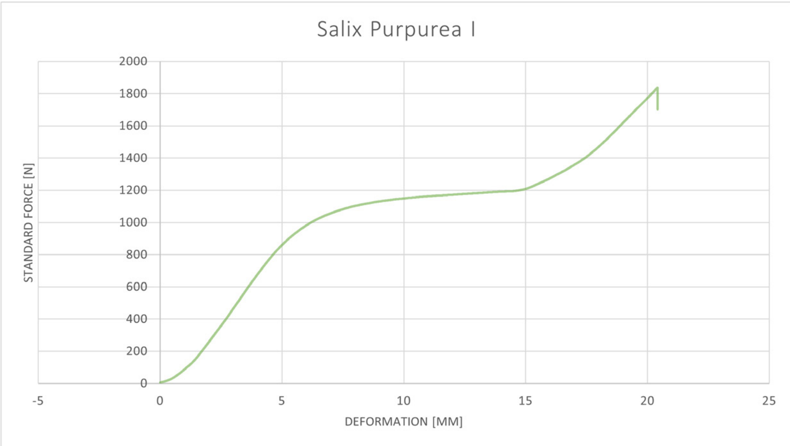
Graph 2: Deformation of Salix Babylonica I

Figure 45: Salix Babylonica I during bending test

Figure 46: Salix Babylonica I specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Babylonica I	8847,36	23,05	7087,97	19,47	12,52	10.03	291.962,88	110,14	54,3

Table 4: Testresults and calculation of Salix Babylonica I



Graph 3: Deformation of Salix Purpurea I

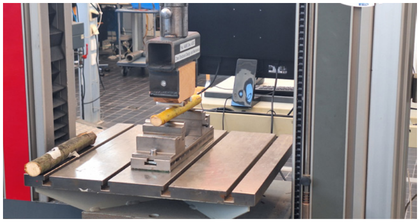


Figure 47: Salix Purpurea I during bending test

Figure 48: Salix Purpurea I specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Purpurea I	1836,87	20,40	-	-	2,60	-	60.616,71	22,87	12,74

Table 5: Testresults and calculation of Salix Pupurea I

The maximum moment can be calculated with the following formula:

Mmax = P * a

In which

Mmax	maximum moment	[Nmm]
P	Force	[N]
a	Momentarm	[mm]

The Bending stress can be calculated with the following formula:

$$\sigma = \frac{M * Y}{I}$$

In which

σ	Bending stress	[Nmm2]
M	Bending moment	[Nmm]
y	Distance to neutral axis	[mm]
I	Moment of interia	[mm4]

The moment of interia for tubular structures can be calclaed with the following formula:

I = π / 64 * d4

In which

I	Moment of Interia	[mm4]
d	diameter	[mm]

The tensile stress can ben calculated with the following formula:

σ = F / A

In which

σ	Tensile stress	[Nmm2]
F	Force	[N]
A	Area	[mm2]

The Youngs modulus can be calculated with the following formula:

E = σ / ε

In which

E	Youngs' modulus	[Nmm2]
σ	Tensile stress	[Nmm2]
ε	strain	[%]

The strain can be calculated with the following formula:

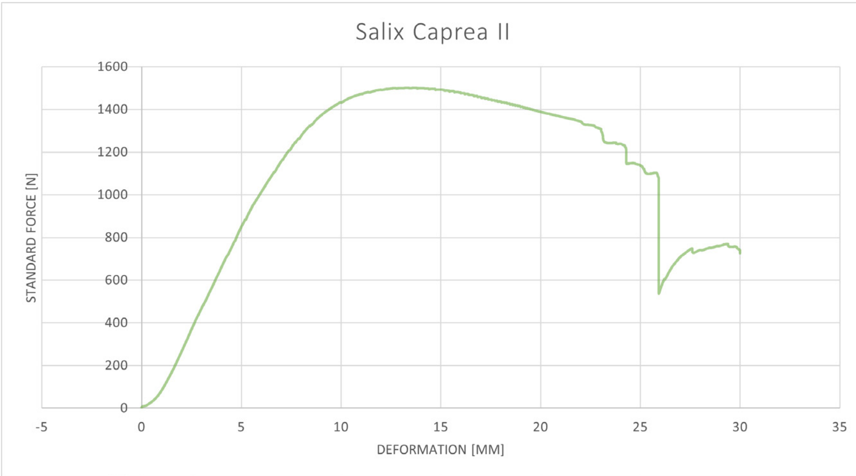
ε = ΔL / L0

In which

ε	Strain	[-]
ΔL	Deflection	[mm]
L0	Original length	[mm]

As stated before, the four point bending tests resulted in failure because of shear in the first specimen of the Salix Babylonica, as is visible in figure 49. In order to reduce the chances of failure happening due to shear instead of bending, three point bending commenced. This setup is used more often in order to study the flexibility in a smaller structure. Moreover, due to the flexibility of the materials tested, a longer momentarm is preferred. Results of the three-point bending tests of the singular branches can be found below.

Figure 49: Salix Babylonica I shear failure



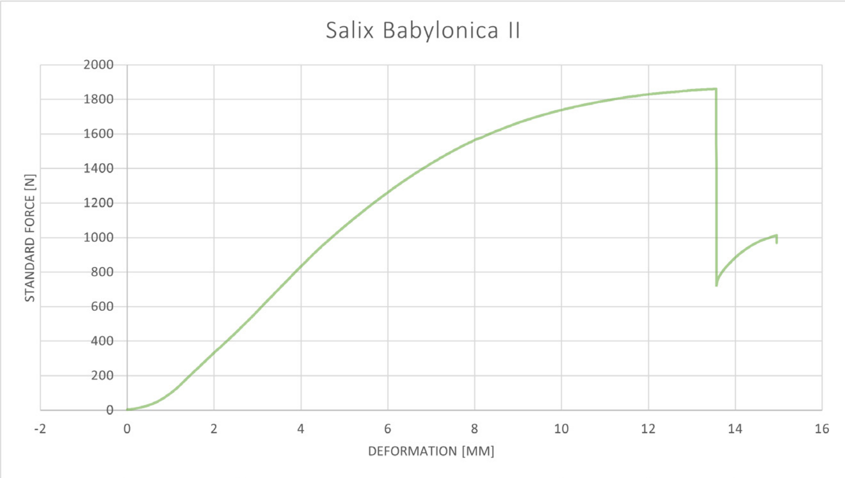
Graph 4: Deformation of Salix Caprea II

Figure 50: Salix Caprea II during bending

Figure 51: Salix Caprea II specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Caprea II	1500,19	14,09	1103,71	25,79	2,12	1,56	.37.504,75	14,15	15,05

Table 6: Testresults and calculation of Salix Caprea II



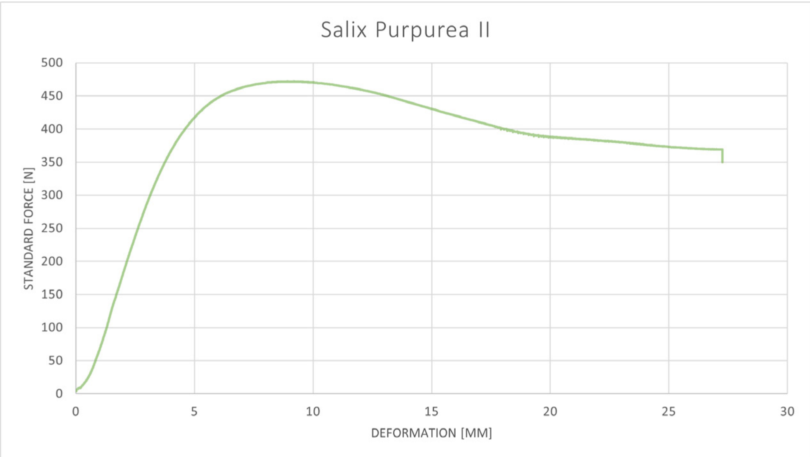
Graph 5: Deformation of Salix Babylonica II

Figure 52: Salix Babylonica II during bending test

Figure 53: Salix Babylonica II specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Babylonica II	1860,67	13,55	1860,67	13,55	2,63	2,63	46.516,75	17,55	19,4

Table 7: Testresults and calculation of Salix Babylonica II



Graph 6: Deformation of Salix Purpurea II

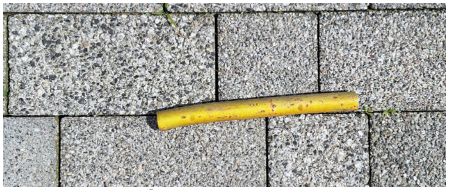


Figure 54: Salix Purpurea II specimen

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Purpurea II	471,77	8,90	370,60	26,01	0,67	0,52	11.794,25	4,45	7,53

Table 8: Testresults and calculation of Salix Pupurea II

After the three point bending tests for the singular branches of the biggest size group had finished, it became clear that it would not be possible to do these same bending tests for singular specimen of the other size groups. This is due to the fact that the machine has a limit on the amount of deformation that is allowed to occur due to the forces projected on the specimin. The deformation cannot exceed 30 millimeters. This formed a problem for the specimen out of the first and second size group; due to the inherint flexibility of willow a bigger deformation than 30 millimeters would occur before permanent material failure.

Figures 55, 56 and 57 show close ups of the specimens Salix Babylonica I, Salix Caprea II and Salix Purpurea II after testing. The first sample has not failed due to a failure in bending capacity, but in shear strength. The Caprea II shows a tear in the middle of the wood, exactly underneath the point of testing. With the Salix Purpurea, only a dent in the wood is visible and no tears can be found. When looking at the graphs of both Purpurea I and II there is also no breaking point visible. This is because both specimen did not fail. Both specimen bended to the maximum point of the machine and bended back to their original shape once the forces applied to them stopped. The only indication that they were put under stress are the small dents visible in the wood at the place where the loading nose was, as shown in figure 57. This elastic bending can be explained by the dryness of the wood.

For the results when working with willow, the branches have to be dried for at least a year before working with them in order for them to achieve their heart strength instead of their sap strength (*Leclercq, 1997*). The branches of the Salix Babylonica and Caprea were cut at the end of March (1 month before testing) and the branches of the Purpurea at the end of April (1 week before testing). The Salix Purpurea had less of a chance of drying, causing it to, instead of bend, compress. For a more conclusive testresult regarding the Salix Purpurea, new tests should be done after a longer drying period.

In graph 7 the deformation of the samples of all species of size group three are shown in correlation to the forces applied to them. The tested specimens can be seen in figure 55, 56 and 57. Important to note is that the first samples of each species were subjected to four point bending and the later tested samples to three-point bending. This last type of testing resulted in a better result of showing the tensile strength of the material because of the larger moment arm. That also results to an earlier point of failure, as is visible in the graph.

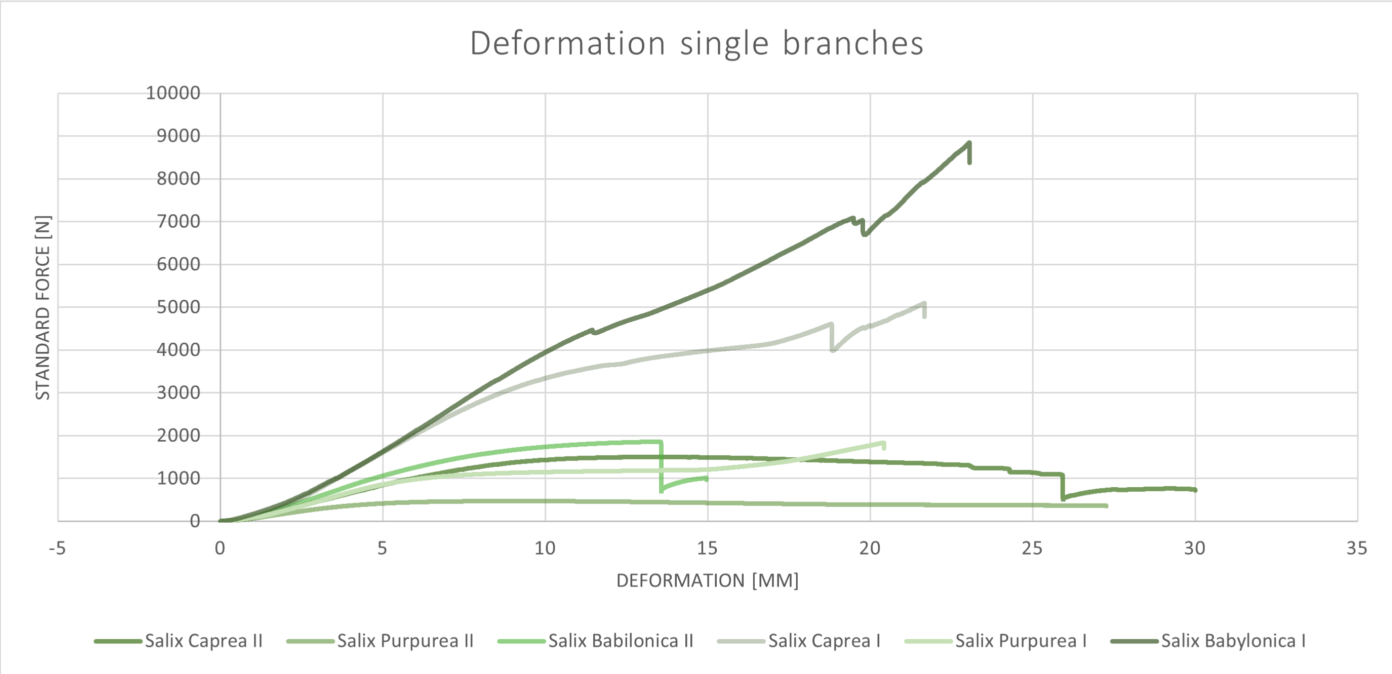
When looking at the results while only taking the three-point bending into account it seems that the Salix Babylonica and Caprea perform best in bending strength, with the peak forces being 1860 Newton and 1500 Newton respectively. Salix Purpurea can only handle a force of 470 Newton before it start to deform drastically (though elastically).

The results of these tests can be used later to compare the strength of woven configurations of thinner branches with the strength of that of the bigger branches.

Figure 55: Salix Babylonica I after shear failure

Figure 56: Salix Caprea II after bending test

Figure 57: Salix Purpurea II after bedning test



Graph 7: Deformation of all single branches

Figure 58: Salix Purpurea

Figure 59: Salix Babylonica woven

Figure 60: Salix Babylonica woven bending test

Figure 61: Salix Purpurea bundled

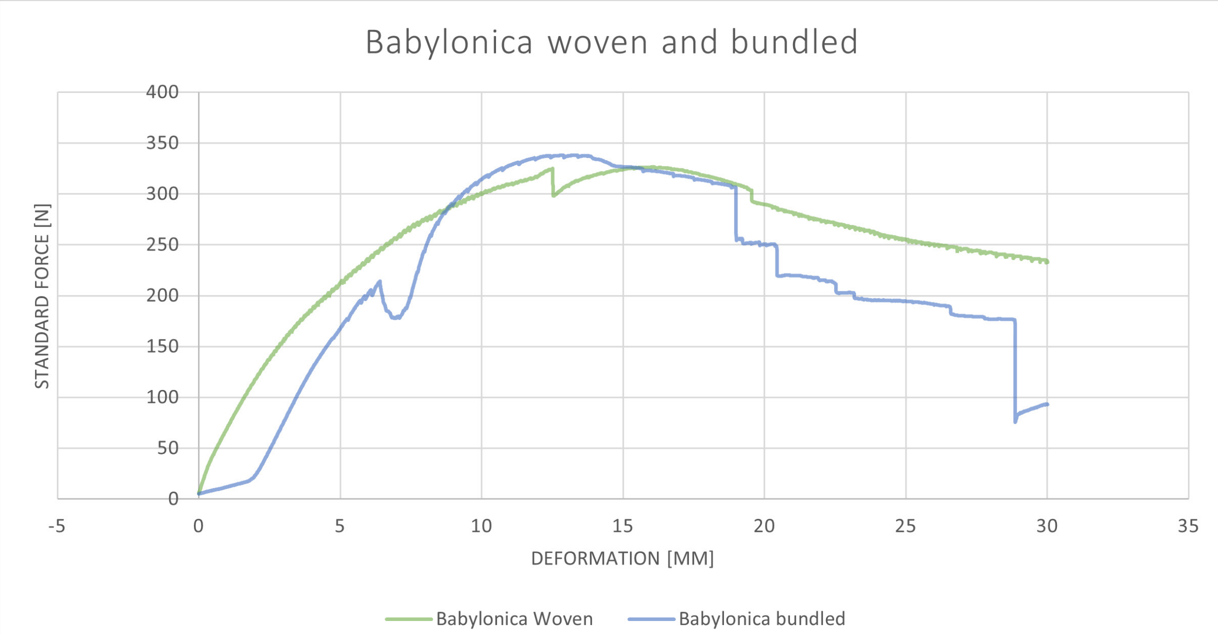
Figure 62: Salix Babylonica bundled

Figure 63: Salix Babylonica bundled bending test

Braided branches

In order for the willow branches to be used as a structural material, they have to be grouped, since bundled they are stronger. Earlier was stated that by parallelly alligning the branches, the material would keep its maximum strength. However, to create longer fibers and let the material bind to itself and work together as one, weaving is necessary.

Tests have been done to see how much of an influence the weaving has on the tensile strength of willow compared to paralelly alligned willow. For the first test, three strands of the middle size group (10 mm < X < 30 mm) are grouped together. This was done for the Salix Babylonica (Figure 59, 62) and the Salix Caprea, since the Salix Purpurea has little to no



Graph 8: Deformation ofwoven and bundled Salix Caprea

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Babylonica Woven	325,08	12,51	-	-	1,38	-	8127	55,19	11,03
Babyloicca Bundled	338,12	13,33	306,32	18,98	1,44	1,30	8453	57,40	10,8

Table 9:Testresults and calculation Woven and bundled

branching of this size. This is both done paralelly and in a single braid. The middle size was chosen due to the relation between its initial strength and flexibility when compared to the other groups: the largest fibers are strongest. However, weaving them by hand is impossible due to its inflexibility, even after soaking with the thought of increasing the inherint flexibility. The smallest fiber group on the other hand, is flexible but significantly weaker. Configurations of this group were made, as is visible in figure 58 and 61, but could not be tested due to the deflection limit of the machine and the flexibility of the thin material.

During testing, it was only possible to test either the Babylonica or the Caprea. Since the results of the testing of the single branches shows that the Salix Babylonica performs best, this species was chosen to undergo the second round of testing. In graph 8 the deformation due to a force of both the bundled and the woven fiber are visible. It is immediately visible when looking at the lines that the woven material works together in distributing the forces applied to it; the line is homogenous when compared to that of the bundled fibers. One dip can be seen when the maximum force was applied. This happened due to the positioning of the fiber on the machine, where it rolled over on its supports at this point. This would not be possible when the material is used within a construction.

When looking at the deflection in relation to the forces of the bundled babylonica, it shows a less homogeneous line. Here, the flat line in the beginning shows the fibers being pressed against one another. The second dip in the line shows that the fibers had started moving against one another and then forced to the same level. Where the woven material shows a slow decline of seemingly one material and not three different fibers, the decline of the bundled fibers happens more choppy as the branches break one by one. The woven fiber had, at the deflection limit, not reached its limit in bending yet.

Although the maximum force applied to the bundled fibers is a bit higher than that of the woven fibers, it is not a significant difference (4%). The behaviour of the material makes up for this small difference in strength and shows that the weaving of the material greatly improves the predictability of it. This predictability can be improved more with the combination of more fibers into one material. The variability of the material can be countered by the amount of that material being used within an element. For the next configuration of the material, there have been looked at ways to create a structure in which the amount of fibers can be easily increased, without much change in the weaving pattern.

Reciprocal tower

For this weaving configuration, inspiration has been taken from reciprocal towers, made from bamboo strips (image 64). By placing several strips of bamboo in a circular base and interlocking and interweaving them in opposite directions, a self-supporting hollow structure is formed (*Marketing BambooU, 2022*). In the case of bamboo, this structure can not only counteract tensile forces, but also compressional forces, as the wood has a relative good compressional strength. In the case of willow, where its compressional strength is small, this hollow structure forms an opportunity for it to be filled with a local natural material that performs well under compressional loads such as adobe or a clay-like substance.

This shape has a low geometrical freeform as it can only be shaped in one way. However, when looking at possiblities of industrialisation, it creates opportunities. For automating processes and creating the fastest possible production of structural elements, the weaving pattern of the material must be continious and homogenious. It was also chosen with the help of Esmé Hoffman, an expert in weaving and basketry. She explained that to connect the different fibers in a way that lets them keep their initial tensile strength, as little weaving as possible should be done. Enough so that the materials bind together and work together as one, as was the case with the braided Babylonica, but not so much that they are put into a straining position.

Figure 64: Reciprocal tower from bamboo

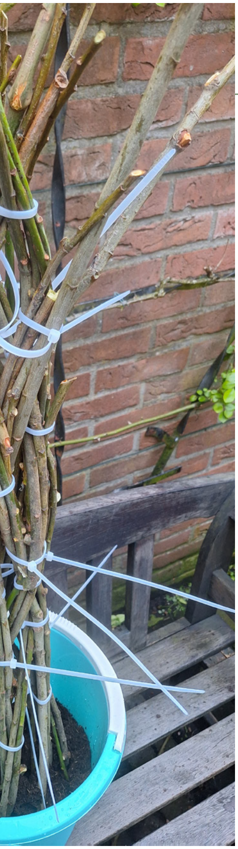
Figure 65: Salix Caprea Reciprocal tower, step 1

Figure 66: Salix Caprea Reciprocal tower, step 2

Figure 67: Salix Capr
step

The experiment for the reciprocal tower was done with branches of the Salix Caprea (Pussy Willow). The desicion for this was based on the fact that these were cut the most recent and thus still the most flexible. In reality, the branches should be layed out to dry for at least a year in order to avoid the possibilities of new growth. Then, after soaking in a bath of water for a week, the branches recover their original flexibility.

First, a bucket was filled with earth, in order to provide the willow with stability in its base. 24 branches were placed in the earth in groups of three. This was done in order to go against the variability of the willow; the more willow there is in one element, the better you can counter-act the variability. After this, three of the groups were twisted in a clockwise rotation, and three in a counter clockwise way. At the place of crossing another group the branches were interwoven alternating on the inside and on the outside to further improve the unity of



ea Reciprocal tower,
p 3

Figure 68: Salix Caprea Reciprocal tower, step 4

Figure 69: Salix Caprea Reciprocal tower, close-up

the structure. As can be seen in image 64, the bamboo strips used for the reciprocal towers have not been interwoven due to the unflexibility of the bamboo. The connection between the different stems have been made by the use of bolts. The willowbranches, which have a significantly smaller diameter, are bound together in order to create this connection. In this experiment this is done with the help of tie-wraps. However, this could also be done with rope created out of the smaller fibers of the willow.
A problem during weaving arised when the groups of branches started to slowly thin out due to thinning or ending of the stems. This was counteracted by introducting new branches to the configuration, binding them to the structure and continuing the weaving. By using branches of different sizes or starting the weave at an offset instead of at the underside of every branch, this method of adding branches to create a longer structure can be achieved, without creating weak points where multiple stems are at the same place.

The results of the tensile test of the reciprocal tower in relation to that of the test of Salix Caprea II can be seen in graph 9. At first glance it is visible that the singular branch of Salix Caprea II has a larger bending strength than the configuration of the smaller fibers.

It shows here that while the woven material does work as a singular material, as is visible in the straight line, it deforms under little pressure. This can be explained by the way the structure has been woven. The configuration creates a hollow structure, which could be filled with another substance that could distribute the compressional forces. Since here only the structural limits of willow itself is being tested, this structure remains hollow. With the forces being applied to it, the structure sags a bit and settles slowly into a flatter shape. This however, causes the test to stop before the material fails, since the maximum deformation has been reached. In the case of an actual tensile test the results might be different.

This proves the difficlties of working with the material by hand. The tensioning of the material when weaving it becomes increasingly harder when the fibers become larger, stronger and less flexible. In order to create more conclusive results about the strength of this configuration, another reicprocal tower was made wih the smallest size group (5 mm < X < 10 mm) of the Salix Purpurea, becase of availability. Graph 10 shows the reciprocal tower in relation to that of the test of Salix Purpurea II.

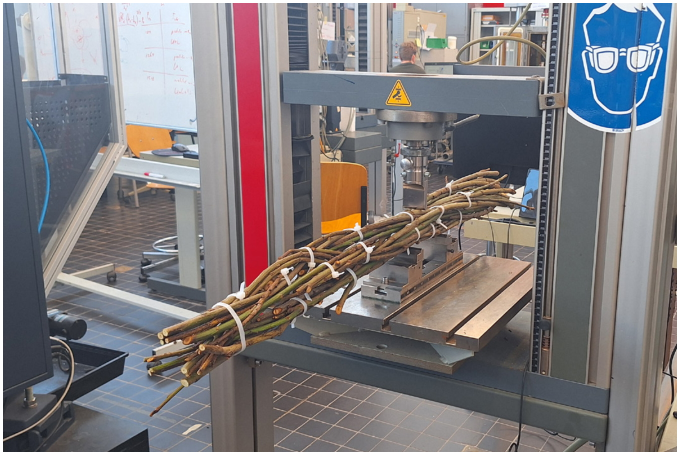
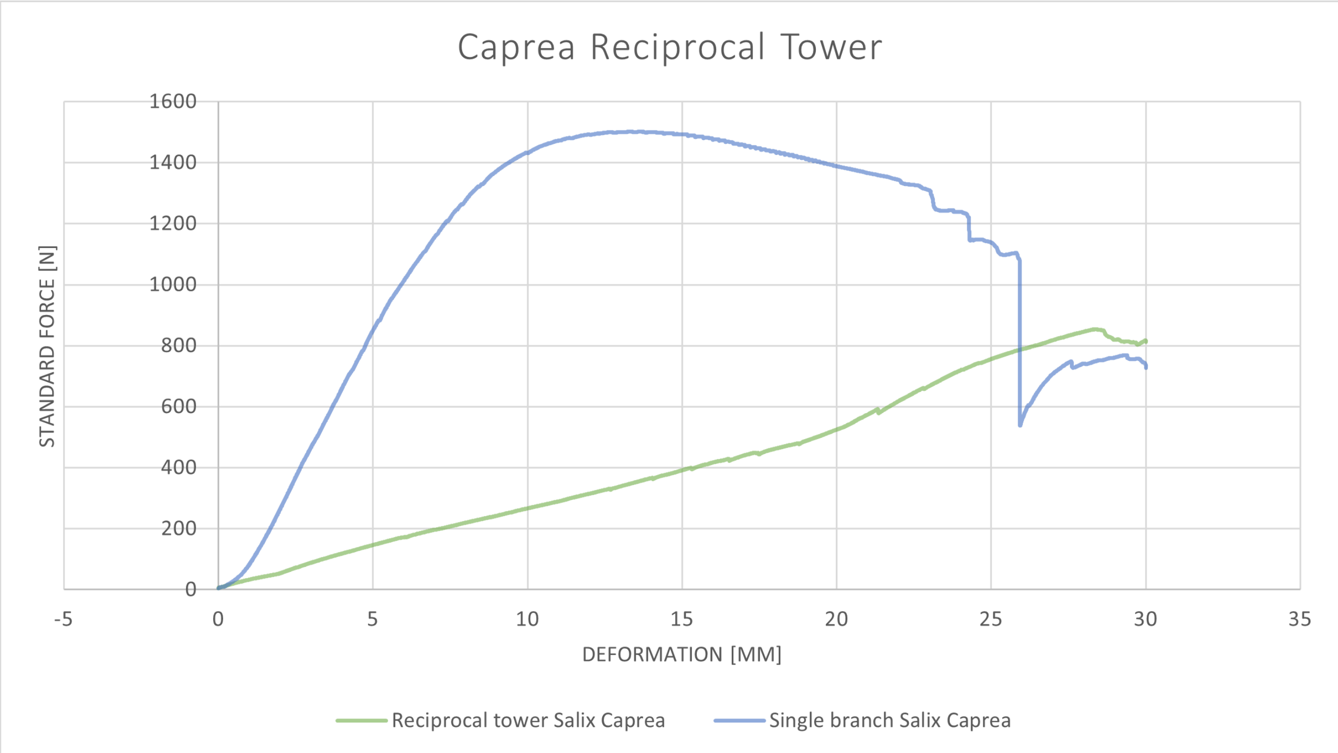


Figure 70: Salix Caprea Reciprocal tower, bending test

Figure 71: Salix Caprea Reciprocal tower



Graph 9: Deformation of Caprea Reciprocal tower and Caprea II

ID	F_{max} (N)	δl at F_{max} (mm)	F_{break} (N)	δl at F_{break} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Caprea II	1500,19	14,09	1103,71	25,79	2,12	1,56	37.504,75	14,15	15,05
Reciprocal Tower	853,67	28,39	-	-	0,45	-	21341,75	69,20	1,59

Table 10: Testresults and calculation Reciprocal tower Caprea

In both cases, the strength loss of that of the tower in relation to the singular branch of that same species is 43%. However, the size difference between the two towers is significant. The total area of the Reciprocal tower of the Salix Caprea is at least (24 branches, with the diameter of each branch taken at its minimum of 10 mm) 1885 mm^2, whereas that of the reciprocal tower made of salix Purpurea (24 branches, with the diameter of each branch taken at its minimum of 5 mm) has an area of 471 mm^2.

While the strength loss still is signifigant, it is less significant than that of the Salix Caprea species.

It shows that the smaller the fiber, the less significant the loss in tensile strength. This can be explained by the initial stress that is being put on the fibers. With the bigger fibers, the twists that have to be made in order to weave and braid the fiber are bigger in relation to their size than those with the small fibers. On top of that, the thinner strands are more flexible than the bigger ones, causing a smaller chance of breakage or splitting within the fibers while weaving.

With the testing, the same problems as with the other reciprocal tower arised: more deformation than 30 mm would occur before material failure due to the flexibility of the material. This results in a less conclusive value of the maximum stresses than when a structure fails.

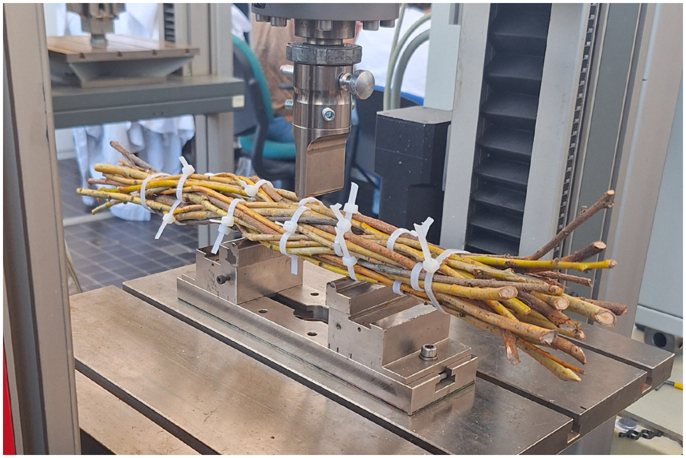


Figure 72: Salix Purpurea Reciprocal tower, bending test

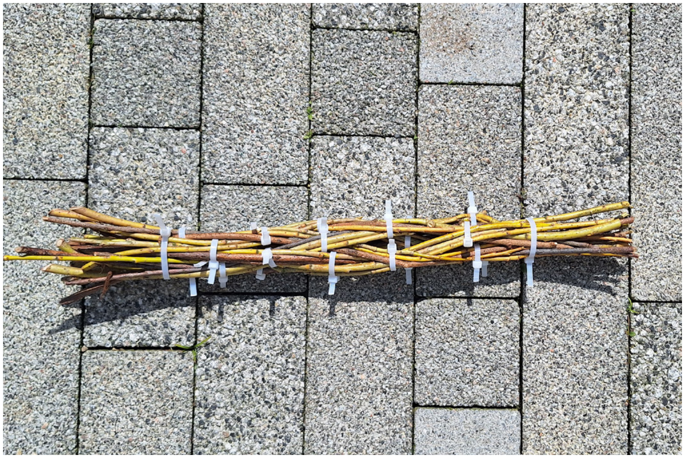
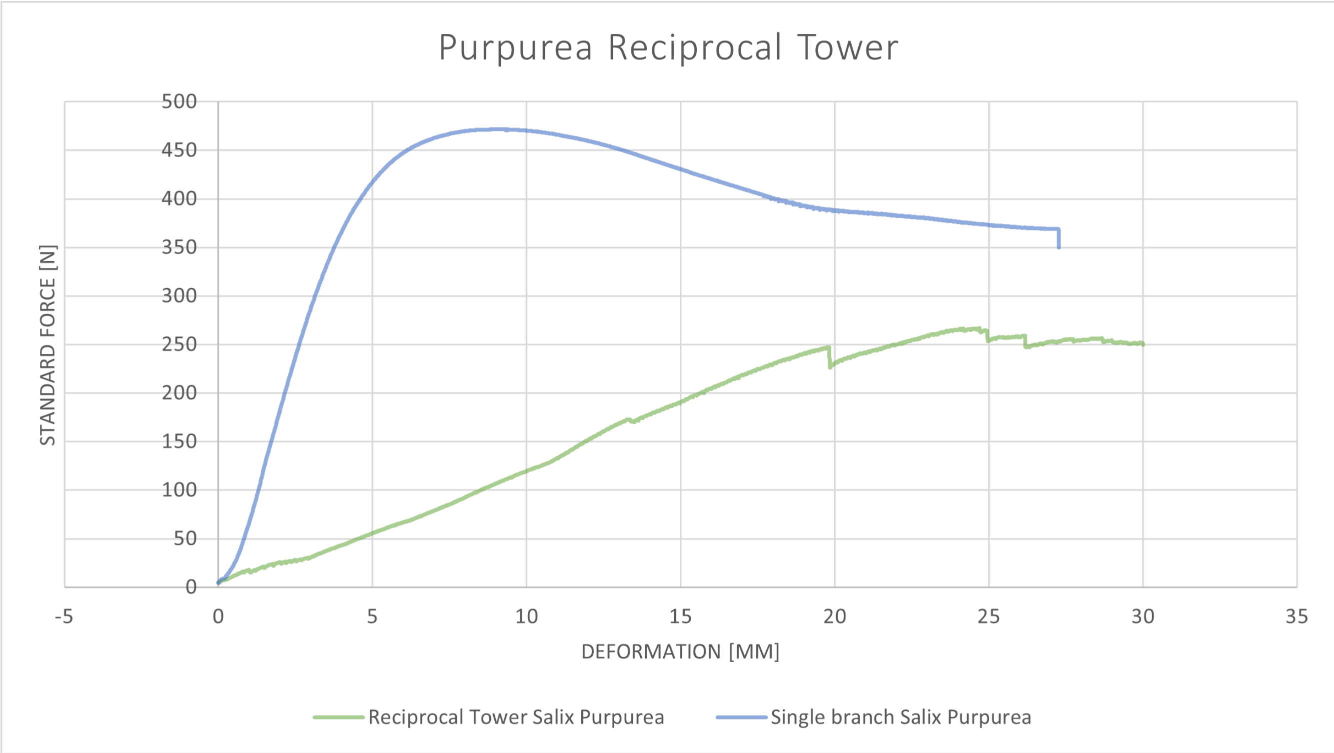


Figure 73: Salix Purpurea Reciprocal tower

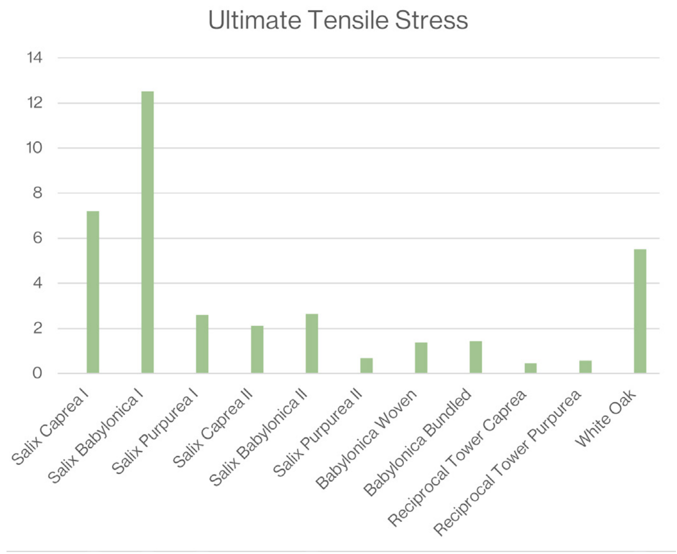


Graph 10: Deformation of Purpurea Reciprocal tower and Purpurea II

ID	F_{max} (N)	δl at F_{max} (mm)	F_{break} (N)	δl at F_{break} (mm)	$\sigma_{tensile\_ult}$ (MPa)	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (Nmm2)	E (MPa)
Salix Purpurea II	471,77	8,90	370,60	26,01	0,67	0,52	11.794,25	4,45	7,53
Reciprocal tower	266,75	24,69	-	-	0,57		6668,75	172,99	2,31

Table 11: Testresults and calculation Reciprocal tower Purpurea

Table 12 shows once more all data derived from the bending tests. Graph 11 shows the ultimate tensile stresses of each of the tested specimen and a comparison to white oak, an often used timber within the building sector, has been made (*American White Oak Wood, n.d.*). This graph shows great differences in strength, even within the same sizegroup. This big difference between the first and second specimen of the singular branches can be explained by the testing methods. The first samples were subjected to four-point bending, whereas the second samples were subjected to three point bending tests. The first three samples show not the tensile stress, but the shear stress and should thus not be taken into account when comparing different materials.



Graph 11: Ultimate tensile stresses specimen and white oak (matweb)

ID	F_{max} (N)	δl at F_{max} (mm)	F_{yield} (N)	δl at F_{yield} (mm)	**$\sigma_{tensile\_ult}$ (MPa)**	$\sigma_{tensile\_yield}$ (MPa)	Mmax (Nmm)	σ_{bend_ax} (MPa)	E (MPa)
Salix Caprea I	5094,69	21,66	4615,09	18,80	7,21	6,53	16.8124,77	63,43	33,29
Salix Babylonica I	8847,36	23,05	7087,97	19,47	12,52	10.03	291.962,88	110,14	54,3
Salix Purpurea I	1836,87	20,40	-	-	2,60	-	60.616,71	22,87	12,74
Salix Caprea II	1500,19	14,09	1103,71	25,79	2,12	1,56	.37.504,75	14,15	15,05
Salix Babylonica II	1860,67	13,55	1860,67	13,55	2,63	2,63	46.516,75	17,55	19,4
Salix Purpurea II	471,77	8,90	370,60	26,01	0,67	0,52	11.794,25	4,45	7,53
Babylonica Woven	325,08	12,51	-	-	1,38	-	8127	55,19	11,03
Babylonica Bundled	338,12	13,33	306,32	18,98	1,44	1,30	8453	57,40	10,8
Reciprocal Tower Caprea	853,67	28,39	-	-	0,45	-	21341,75	69,20	1,59
Reciprocal tower Purpurea	266,75	24,69	-	-	0,57		6668,75	172,99	2,31

Table 12: Testresults and calculation all tested specimen

Conclusion

Willow as a fiber show potential to be woven into a structural material, although not every species behaves the same. Structural bending tests show that the Salix Babylonica fibers perform best out of the three researched fibers.

Weaving the fibers does not result into a significantly weaker material, but instead makes the different fibers work together in distributing forces. Moreover, the variability of the material decreases due to the combination of strengths between the different fibers.

The ultimate tensile stresses of the different materials and configurations have been determined with bending tests. These results might be different when the structures are subjected to an actual tensile test. Especially in the case of the reciprocal towers, the hollow structure influenced the outcome of the test. This could be further explored in subsequent stages of this research.

Right now the results how that the material in this configuration is not strong enough yet to be used as a structural element, when compared to strengths of other known structural materials. Further research could look further into bettering the configuration and looking at ways to change the cellular properties of willowbranches.

6. Industrialisation and Implementation

Based on the findings of the experimentation in the last chapter, this chapter focusses on the possibilities of industrialising the structural configurations and the prospects of using the material on a big scale. Here, chapter 6.1 looks at possible workflows in order to industrialise the concept, where one option makes use of machinery, and another option looks at a climate neutral way of 'automising' the creation of the structural element. Chapter 6.2 showcases different example designs that can be made based on the configuration of chapter 5.

6.1 Industrialisation opportunities

The last chapter showed that in order to create a homogeneous structural material made out of willowfibers, fibers have to be combined. With the fibers woven into one another, they work together in distributing forces. The more fibers are combined within one structure, the less variable the material becomes.

In order to create a homogeneous material from raw cuttings of willow in a big scale, several steps have to be made. First, the cuttings have to be sorted in size. This way, the biggest fibers can be used in parts of the construction where the forces applied to it are biggest, and the smaller fibers can be used where there are less forces in play. Moreover, if the fibers are the same size, the process of weaving the fibers costs less effort. Fibers too thick to be woven can next be planted back into the ground, where they grow into new trees that can be used for willow production. In this way, with the planting of cuttings instead of seedlings, the growth period is cut shorter by two to three years. After this, depending on the optimised configuration of the woven fiber and the optimal size of them, the thicker branches would have to be split in order to make them more flexible. The flexible, equally sized fibers can then be coiled up and next be extruded into the shape of the final configuration. This chapter discusses these steps in detail, while giving possible machines to work with in order to show the workflow of industrialising the use of willow as a structural fiber.

Figure 74: Tree sorting machine, SMO

Size Sorting

Like was done with the experimental tests in the chapter before, the willowfibers should have to be sorted in size in order to decrease the variability of the fibers used. A machine that could be used for this is the Tree grading Machine designed by SMO (figure 74). This machine makes use of a camerasystem and measures things like length, thickness, whether or not there is sidebranching and curvature of the wood (*Tree Grading Machine – Machine Builder SMO (Belgium), n.d.*). After analysation the stems are sorted into different boxes and automatically logged. According to SMO the average person can sort up to 800 trees in size per hour. This machine can sort over 10.000 branches per hour, with only seven people supervising or operating the machine. This is an increase in production of 79%. A smaller model is also available on the market for smaller projects.

Splitting fibers

In order to create more flexible fibers and to be able to use willow branches that are to stiff to be woven due to their size, the stems can be split. Historically and still traditionally, this is done with a cleave (figure 75). This is a piece of hardwood or metal with either three or four sharp edges on one of its heads. These sharp edges can cut through the softer willow wood with a small force, usually a small push of the cleave is enough to cut through. An automated machine is not yet on the market at the time of writing, but could be devloped in the future.

Figure 75: Cleaving willow

Due to the splitting, the fibers become more flexible, but less strong. With the use of these small fibers, more material is needed to make an equally strong material as when working with bigger fibers. Small fibers however, do offer a greater geometrical freeform when woven and have the ability to be coiled, due to their flexibility.

Coiling fibers

To be able to work with the thin fibers, and create a material strong enough to function as a structural element, a considerable amount of fiber is needed. To create a larger structure, which is as uniform in its strength as possible, the fiber has to be coiled up to be able to be uniformly extruded into a rope-like structure.

This coiling can be done with several machines, although there are some requirements regarding the willowfibers. As the willowfibers are stand-alone branches and not spliced fibers, the supply to the machine should be in a straight line, and possible via a production line. The amount of fibers being stranded into one should be bigger than the minimum required, and fibers of differentiating lengths should be put into the machine in an offset in order to neutralise weak links at places where multiple branches end at once, as was shortly discussed in chapter 5.6.

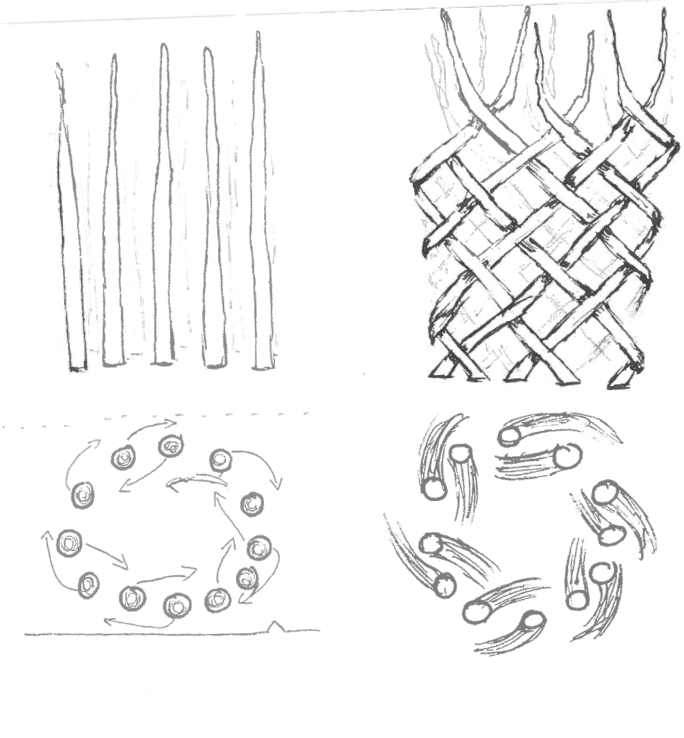
A possible machine that can be used for the coiling of fibers is the Robco T88, a stranding machine; which creates a continious strand of multiple fibers (*Twisters, Rope Making Machines and Winders - Robco Engineering, 202*4). Fibers can be supplied via a production liine and enter the machine through three reeve plates, which are slowly twisting around. This pretwists the fibers. Next the stranded fibers are tensioned and twisted further, and end up coiled on a wheel.

Figure 76: Robco T88

Replanting Willow Branches

Instead of going through the process of making coiled fibers out of willowbranches, and then extruding those fibers into or around a mold, the trimmed branches could also be propegated and turned into hyperorganisms. Most willow species have the unique ability to be grown from a cutting of a tree.

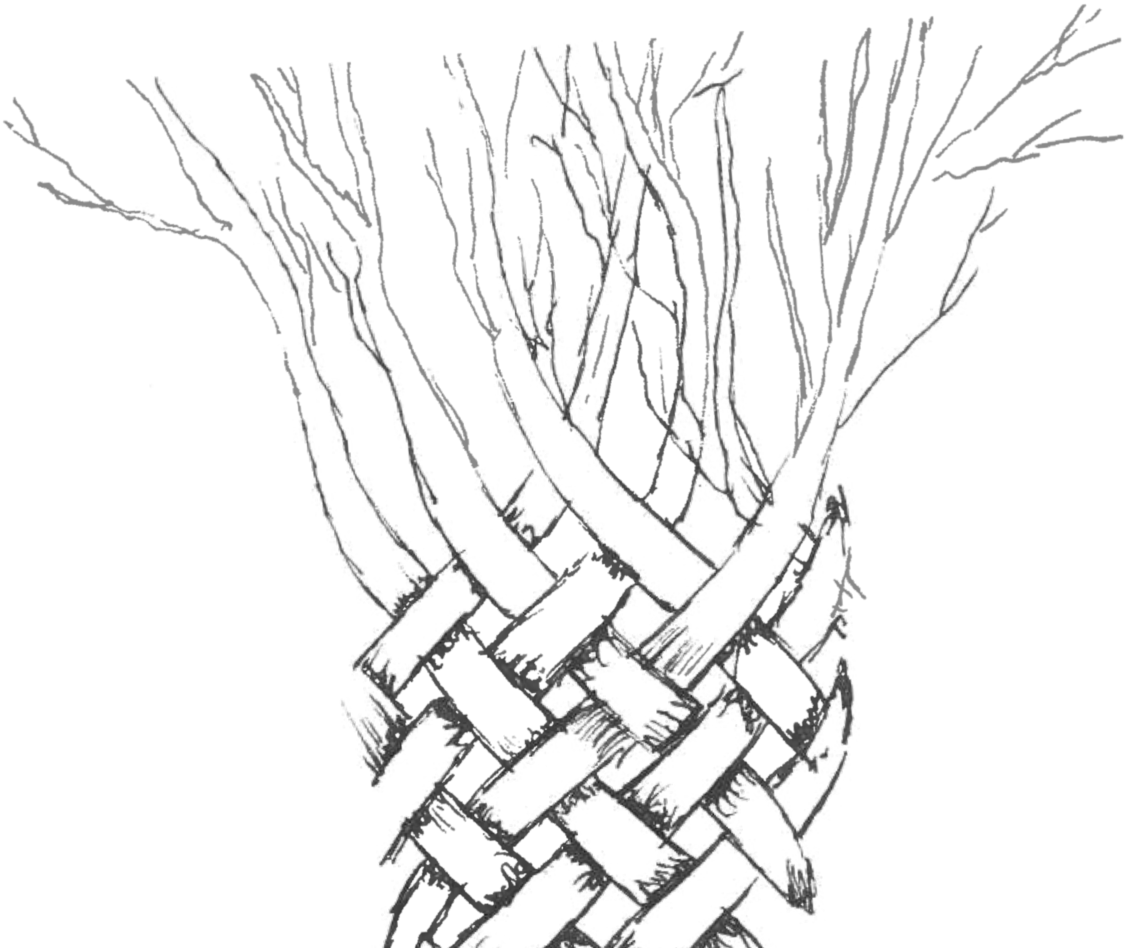
The best time to cut a willowtree is in the winter, when there are no new growings or foliage. Since the replanting of branches has to be done when the wood is still freshly cut, this trimming period should be during late winter or early spring when most frost has gone. This gives the new plant the best opportunities to develop (*Propagating Weeping Willows From Cuttings, n.d.*).



These cuttings, when being replanted, still have their inherint flexibility and can be bent into desired shapes, like the shape of a reciprocal tower as was done with cuttings in chapter 6.6. The bendability and bending strength of branches depends on the species of willow. Of the analysed species of willow, Salix Caprea cannot be propagated as a hardwood, so it is taken out of the equation. The Salix Babylonica has the highest bending strength (chapter 6.6) and the Salix Purpurea is the most flexible. The Salix Purpurea grows up to have more of a resemblance to that of a bush than to a tree, making it unsuitable for this practice, leaving the Salix Babylonica, the weeping willow. Further research could explore the exact possibilities of this tree species.

After being replanted and woven into shape, the branches continue to grow in both circumference and length, creating big coöperating systems over time, while the original geometric shape stays the same. First, the increasing circumference of the growing trees will press different branches against one another firmly; making it almost impossible to move the branches individually (*Löschke & Ludwig, 2016*). Then, while continuing its growth, the bark of both trees slowly merge together, after which the timber fuses and continues to grow as one. At the ends of the trees, new flexible young branching appears, which can be woven in a continuous shape and enable the structure to become as long as needed. Unwanted side branches can be trimmed from the tree and replanted on their own, forming their own structure over time. Over time, when the structure has reached the desired shape and size of the structural element, the willow can be cut, dried and used in construction.

The process for this system of creating structural elements out of willow goes slower than using coiled up fibers and industrialising the practice would not be cost effective due to the time intensiveness and plantation area needed. It would however, be a process that would need little to no machinery and simply time to grow, emitting almost no carbon into the atmosphere.



6.2 Potential implementations

An advantage of the configuration of the reciprocal tower is the geometrical freeform. Although limited in its tube shape, the material can be shaped into any form. The hollow structure offers possibilities where the different elements can come together and form a stronger supportsystem at bases. As a potential implementation I made a dome, supported by 12 columns made out of willow. At the base, where compressional forces are high, the material is covered and filled with an adobemixture, that helps distribute the forces.



7. Conclusions & Reflection

Conclusion

The main research question of this thesis is:

“How can the evaluation of braided or woven fibers, consisting entirely of Dutch natural materials, lead to wide spread use within structural bio-composites?”

This question can be answered by first discussing the sub-questions.

Local natural Materials

What can we learn from the use of local natural materials in vernacular architecture in the Netherlands?

The materials used within vernacular architecture was influenced by available resources, climate and culture. In the Netherlands this was reflected in shelter made out of timber, loam and grasses in ancient times and later stone. This resulted in a clear identity of places, which is now being threatened due to modernday, mass produced architecture.

Which local natural materials are available in the Netherlands and how could they be used as a structural fiber?

There are a multitude of natural fibers available in the Netherlands that have been introduced to the building industry. The three most commonly found analysed fibers in the Netherlands are reed, straw and willow. All three of these materials could in theory be used as a structural material, when prepared in the correct way. With all fibers a drying period is nessecary. After this drying period, willow is ready to be worked with. With reed and straw however, more processes are needed before they are workable. They have a waxy outer layer that has to be removed in order for it to be able to bind to adhesives and itself, and a densification process is neccesary due to the hollowness of the fiber. In order to enhance structural properties of the fibers, the fibers can be densified before working with them.

The Weaving and Braiding of Natural Fibers

What historic and current developments regarding bio-composites made from local biobased materials are there?

Historically, the utilisation of a material depended on craftmanship and availability of a material. Since timber and stone were used for structural elements, composites of natural materials were mostly used as fillers of walls. The basis of a composite remains the same: a mixture of fibers and adhesives.

A problem that arises with bio-composites is the creation of an adhesive that consists only of natural materials. The reed-beam for example makes use of a non-biodegradable resin. Adhesives that are completely green are not readily available on the market yet. Instead, ways could be found where willowfiber on its own could form a structural element.

What different techniques and machinery are available for the braiding and weaving of natural fibers?

Most machines that are available to weave or braid fibers exist for microfibers. In order for them to be usable for willow fibers, the willow should be split into thinner long fibers and then spliced together. Once coiled up in this way, they can be used in a braiding machine and braided into the shape or mold of the structural element.

Optimisation for Local Fibers

What are the considerations and requirements when creating structural fibers out of willow and what are the possible configurations?

Willow, like all natural elements is a variable material. In order to make it as reliable in strength as possible, as many fibers as possible should be combined within one element.

Another requirement is the amount of weaving or braiding of the willowfibers. In order for the fibers to retain most of its initial strengths. but still work together in distributing forces, the fibers should be woven together as little as possible.

What are the possibilities of using willow as a strutural fiber on a bigger scale?

Willow is a plant that occurs naturally in the Netherlands in many different shapes. In order for it to be used as a structural fiber on a big scale, a willow plantation would have to be made. Building Woods as an organisation would give the Netherlands the opportunity to grow its own building materials locally, while enhancing the biodiversity of the country.

The trimmings could be processed, sorted, split, coiled up and braided into structural elements. Another possibility is replanting the clippings of willow back in the plantation in the desired shape of the structural element. The willow would grow into that shape and could be cut after a period of time. This is a more time consuming process, but less harmful for the environment.

Based on the answers to these sub-questions, the main research question can be answered.

Main Conclusion

"How can the evaluation of braided or woven fibers, consisting entirely of Dutch natural materials, lead to wide spread use within structural bio-composites?"

Testresults derived from different woven configurations made out of willowfibers conclude that at the moment, wide spread use of this material within the constructionsector is not yet possible.

Testresults show that the difference in strength of a woven material compared to a bundled one is small. However, woven fibers distribute forces together, whereas bundled fibers do it individually, causing earlier breakage due to forces. The tests of the analysed configuration with most initial promise, the reciprocal tower, show little promise of trimmed willowbranches being used as a structural material on their own in the near future. With more structural testing, and analysing the tensile properties of the material, other conclusions could be derived.

Possibilities arise by splitting the big fibers into smaller ones and coiling up the fibers. With the use of thesse small fibers, a greater amount of material is needed in order for the material to be as equally strong as one made out of larger fibers. However, the smaller fibers offer a greater geometrical freeform since they are more flexible, opening up to new potential configurations impossible to make from the big fibers.

Discussion

This thesis has analysed the possibilities of trimmed willowbranches being used as structural material and the conclusion of this research is based on the results of experiments regarding this material. Other natural fibers might also perform well structurally in the same or a different way.

Due to the limited amount of time available, the research was narrowed down a lot in early stages of research. In the end, an analysis of the properties of three species of willow and their possible configurations were made. However, there are over 350 different species of willow available all around the world, of which around 70 occur in the Netherlands, it might be that another species has better availability, workability and material properties. Right now, the results show that the willow configurated in the way it was with this research, is not strong enough yet to function as a structural material. However, additions of a compressional strong material, which could resist bending might change this result and is something that could be further researched. The same goes for the possibility of densifying willow, although it is unknown how much this would change the flexibility of the material.

The experiments conducted were designed to be low-tech, because of the limited workspace and time, but also because the less extensive steps a process has, the better it often is for the environment. Due to its low-tech however, little thought was given at first at how the structural properties would be tested. A system in order to hang the specimen on the tensile testing machine was therefore not available and bending tests had to be conducted instead. This only gave an estimation of the tensile strengths of the configuration. Later research should be conducted where the relation between the shear and tensile strengths could be compared and confirmed.

Another subject that was disregarded within this thesis is the cost of creating the structural elements out of willowfiber. It is one thing that the potential structral material emits almost no carbon into the atmosphere, but the most prioritised factor in this industry is still the price. A structural element consisting entirely out of willow might be better for the environment than one made out of concrete or steel, if it is twice as expensive to make, no company will invest in the product. However, with the increasing costs of energy and thus the production costs of steel and concrete, a structural material with willowfiber could potentially be an interesting sustainable alternative for the industry.

Lastly, further research should be done to see the succesrate of replanting the willowbranches in a woven structure. With this initial tensioning of the fibers, it might be that some branches, due to the growing circumference die off. Whether this has big consquences for the final product remains unknown at the moment.

Reflection

The methodology of this thesis included a literature review, a research by design and a research by elimination.

For this thesis I aimed to explore bio-based, local materials to create structural elements for the built environment. However, the subject “biobased local materials” seemed so broad at the start, that to narrow it down, I looked at historic practices of Dutch architecture. Because of the little remains of this historic architecture however, this part of the research took longer than expected, without a lot of results.

After some initial literature reviewing, I had to make some decisions: I could not analyse every single natural fiber available in the Netherlands. In order to get some depth within this research, I had to decide which fibers had the most potential as a structural material. Moreover, an exploration had to be made to see what kind of configurations were possible for potentially used fibers. I did these two things simultaniously, which caused for a lot of research not being used in the end, since a lot of ways were not suitable for willowfibers. Looking back, that was time I could have spent on other types of the research or to go further in depth of the parts of the research. The insights however, did inspire some other parts of the thesis.

As I had decided at the beginning of the research that I wanted to research by designing and experimentation, instead of theoretical research, I had to find a way to get a hold of the material I was going to be analysing: willow wood. This proved to be harder than I thought it was going to be, both with getting the material in my hands and finding a place to work in. A thing I would not do again in later research is the waiting I did during this one. It caused unneccesary insecurities and stress. The research by design itself however, played a big part in the thesis. Due to little research available on the properties of willow, testing it myself was the only way to get information on its workability. I implemented the insights I had gained from literature research, talks with a treeworker and basketweaver into my experimentation.

The Building Technology track of TU Delft focusses on closing the bridge between engineering and designing, with the focus being on the future and sustainability. With the aim of this research being the creation of a structural material out of natural, local materials, it makes it the perfect fit. The project made use of hands-on experimentation and testing in order to gain a better understanding of materials, rather than just the use of theory. This gave a lot of extra insights, considering the little amount of available research about properties of willow. The steps I did could be easily repeated by someone else and could maybe encourage others to continue on with this topic.

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