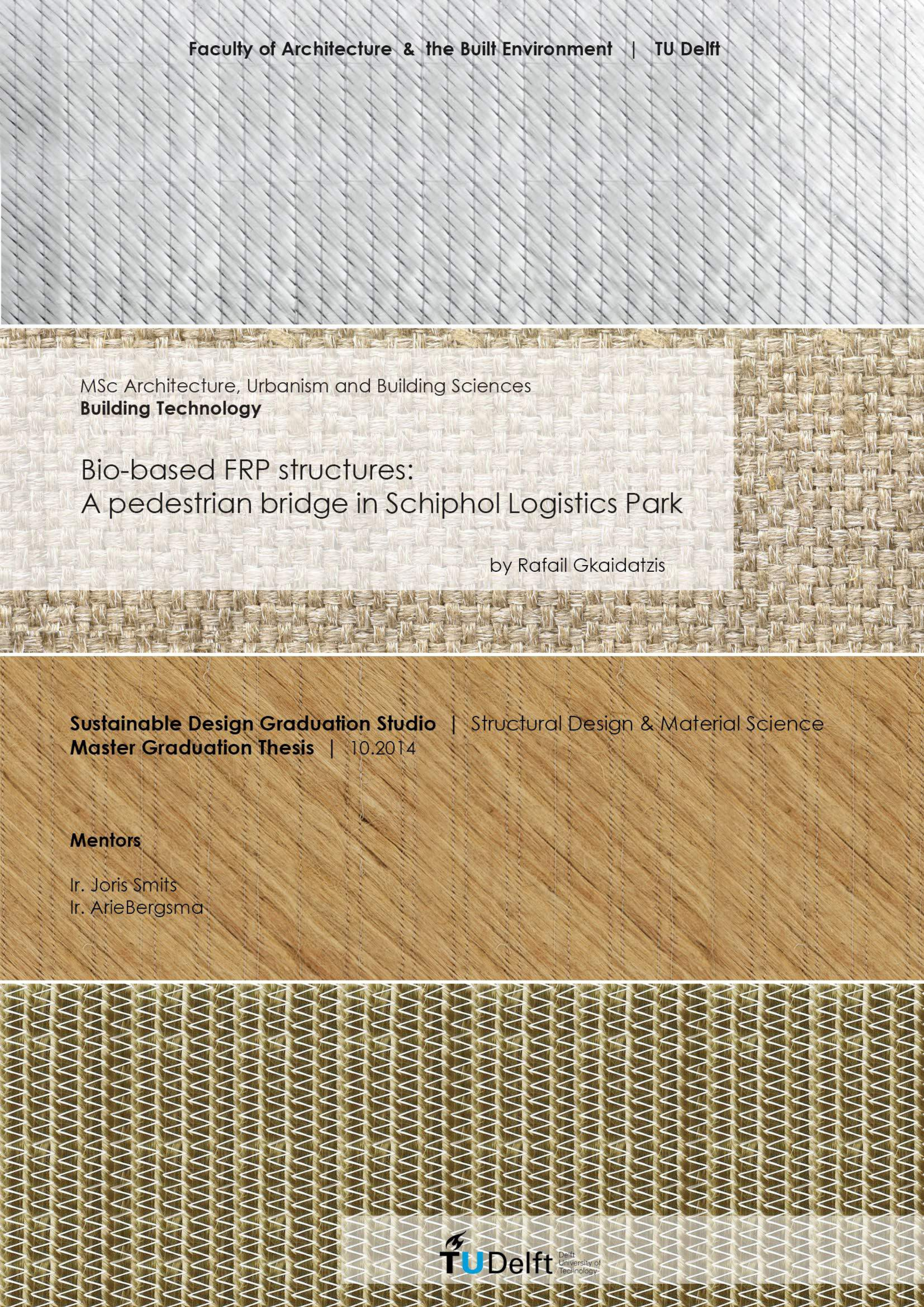

Faculty of Architecture & the Built Environment | TU Delft

MSc Architecture, Urbanism and Building Sciences
Building Technology

Bio-based FRP structures: A pedestrian bridge in Schiphol Logistics Park

by Rafail Gkaidatzis

Sustainable Design Graduation Studio | Structural Design & Material Science
Master Graduation Thesis | 10.2014

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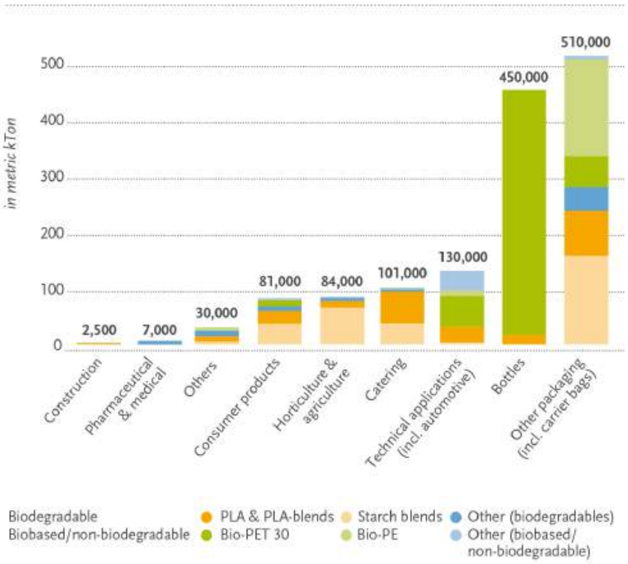
Introduction

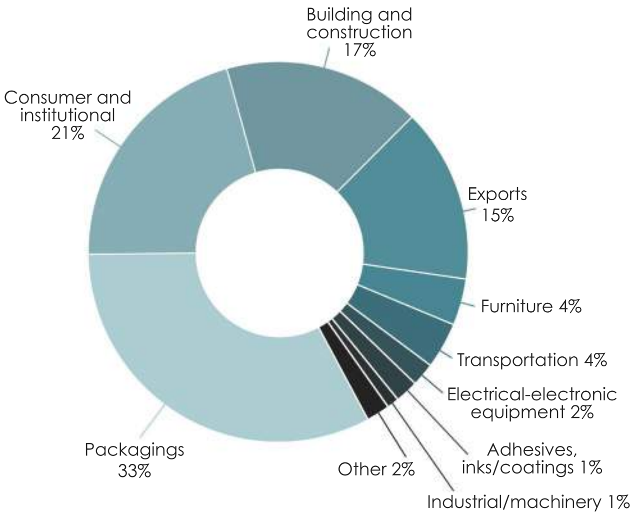
1.1 Problem definition

Plastic industry ranks third in the world amongst all other industry with composite plastic materials being already part of our everyday life, and having entered nearly all major industrial, commercial and domestic sectors. However, the utilization of long-lasting polymers for short-lived applications (packaging, catering, surgery, hygiene) is not a wise practice as the majority of the synthetic polymers is produced from petrochemicals and is not biodegradable. These persistent polymers became source of environmental pollution, harming wildlife when they are dispersed in the nature.

Under the environmental awareness of the recent years, environmental friendly materials are gradually emerging worldwide. Efficient utilization of plant species through the use of their smaller particles and fibres in order to develop eco-friendly composite materials is certainly a rational and sustainable approach. In this way, natural substances can be turned through appropriate processes into composite polymer products based on renewable raw materials and thus replace conventional fossil fuel-based polymers.



1.2 Global production capacities of bioplastics 2012 (by market segment)
Source: European bioplastics, Institute of bioplastics & Biocomposites
(http://en.european-bioplastics.org)



1.1 The distribution of major markets for plastics
(http://www.plasticsbusinessmag.com)

These polymers that are based on renewable raw materials found a variety of applications in different sectors. The automotive industry, for instance, is a sector that made important steps on replacing gradually the conventional plastics with natural fibre-reinforced polymers on vehicles. Other industries that invested on this bio-plastic technology include packaging, catering, agriculture, telecommunications and medical.

However, in the building industry the use of such bio-based polymers is still in an early state of development. According to the graph 1.2 for the year 2012 for construction sector the global production of bio-plastics was 2.500 Ktons holding the lowest position compared with other sectors. The specific application of these bio-plastics in the building sector include insulation products, cladding components for façade, flooring and connections.

As far as load-bearing applications are concerned, the use of environmental friendly polymers is even more limited as composites used for structural elements consist either of man-made fibres with increased environmental impact or petrochemical resins.

1.2 Goal of the research

It becomes clear that advanced plastics are increasingly preferred by the building industry as they show high future potentials. However, the high environmental impact of such fuel-based plastics makes necessary their replacement from more eco-friendly plastics with similar properties. In that sense, the goal of this graduation project is to prove that the utilization of composite polymers based on natural and renewable raw materials for lightweight load-bearing applications is feasible and thus take a step towards the introduction and establishment of such plastics in construction.

As the orientation of the project is on load-bearing structures a main aim is to convince that the mechanical properties of biocomposites are comparable with conventional composites and thus prove their capability to receive the loads of a structure. Important is also to research the lasting properties and the durability of these materials (UV, moisture, fire resistance) through time under the continuous exposure to environmental conditions.

1.3 Research question

Are composite polymers based on renewable raw materials able to fulfil the structural requirements of a lightweight loadbearing structure, such as a pedestrian bridge?

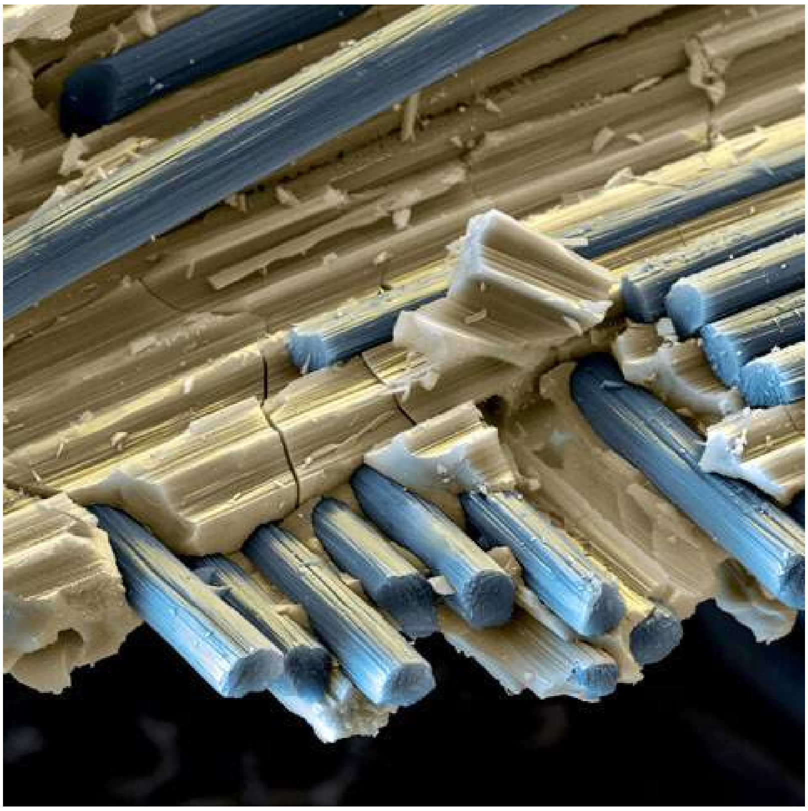
Under this general research question, further subquestions can be the following:

- What are the mechanical properties of natural fibre-reinforced polymers?
- What is the most appropriate combination of renewable raw materials in order to get a composite with the optimum structural behavior for a pedestrian bridge?
- What are the loading requirements the design criteria for a footbridge?
- What could be the cost of such a structure?
- Are there any clients in the Netherlands to absorb this kind of product in the market?

1.4 Introduction to fibre-reinforced polymers

Fibre-reinforced polymers (FRP) are composite materials composed of a polymer matrix which is reinforced with fibres. The fibres can be out of glass, carbon, basalt or aramid, although other fibres such as paper, wood or asbestos have been also used. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic, while phenol formaldehyde resins are still in use. Both fibres and the polymer matrix exhibit significant different physical and chemical properties but when combined together they create strong and rigid composite materials.

More specifically, the polymer matrix surrounds and supports the reinforcement by maintaining its position while the reinforcement gives its special mechanical and physical properties in order to improve the properties of the final product. In this way, the matrix which is a relatively tough but weak material is reinforced by the fibres that mechanically optimize the strength and elasticity of the polymer. In general, the plastic resins are strong in compression forces and relatively weak in tensile strength while fibres are strong in tension but tend not to resist compressive loading. The combination of these two materials and properties leads to the development of a new composite material that can resist both compressive and tensile forces.



1.3 Scanning electron microscope image of a fibre reinforced composite composed of carbon fibres (in blue) and silicon carbide (in brown) (http://www.pbs.org/)

1.4.1 Natural fibre-reinforced polymers and biopolymers

Composite materials are already a part of our everyday life, and have entered nearly all major industrial, commercial and domestic sectors. Although several studies have proved that fibre-reinforced plastics perform better in terms of CO2 footprint in comparison to traditional building materials such as steel and concrete, the majority of these plastics is based on non-renewable sources. Fibre-reinforced polymers used in structural applications are normally composed of synthetic fibres, such as glass and carbon combined with petroleum-based resins.

Thus, materials based on renewable raw resources have entered the composite industry and found application in various products. Natural fibres replaced successfully other artificial fibres and new types of resins based on natural substances have been introduced in the market aiming to reduce the environmental impact of composite plastics, as well as their embodied energy.

Natural fibre-reinforced polymers (NFRP) are composites consisted of a polymer matrix made from petroleum but the reinforcement consists of natural fibres, usually extracted from plants, which are encased in the matrix. These fibres reinforce the polymer and decrease the environmental impact of the composite as they come from renewable sources. Additionally, natural fibres are cheaper than artificial manmade fibres, as usually they remain as a waste sub-product, and have a high stiffness per weight (higher than glass), which results in lightweight components. Natural fibres are characterized by low density, characteristic that makes them important for the automotive industry, while they are biodegradable, non-toxic and present high insulating properties.

Biopolymers (or organic plastics) are synthetic materials manufactured from vegetable substances, such as starch or cellulose, instead of petrochemicals like polypropylene (PP) which was largely used the recent years. Biopolymers are biodegradable composites as long as their compostability is verified by the European Standard EN 13432.

1.4 Bioplastic products based on renewable raw natural substances

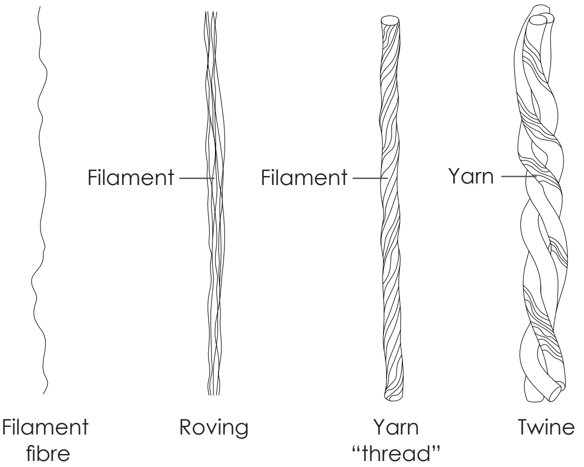
Fibres

2.1 Fibres

Fibres are generally classified in inorganic fibres (made from glass and carbon), polymer fibres (synthetic fibres), metal fibres and natural fibres. All man-made fibres are also referred to as chemical or synthetic fibers. Synthetic fibres, excluding only carbon fibres, are made from solid raw materials by production methods based on melting and stretching processes. One the other hand, natural fibres such as wool or plant fibres already occur in the form of fibres and so they are collected and refined in order to become an industrial product. The majority of fibres, apart from glass and metal, consist of bundles of tiny fibres that are visible through the microscope.

2.1.1 Basic terminology

An individual fibre is known as a filament, whereas a bundle of parallel filaments is known as a roving. When the bundle of the fibres is twisted, the result is a yarn (or thread). A twine is made from several twisted yarns. Rovings are typically used as raw material for reinforcement in polymer composites. One the other hand, yarns are used for making woven or knitted fabrics.

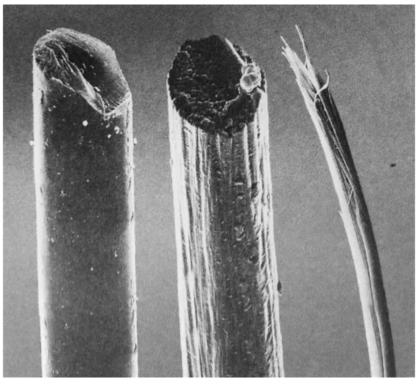


2.1.2 Mechanical properties

Compared with their length, fibres have a very small cross section, the diameter of which varies depending on the type of the fibre. For instance, the diameter of synthetic fibres is between 5 and 24 μm, while natural fibres can be up to 500 μm.

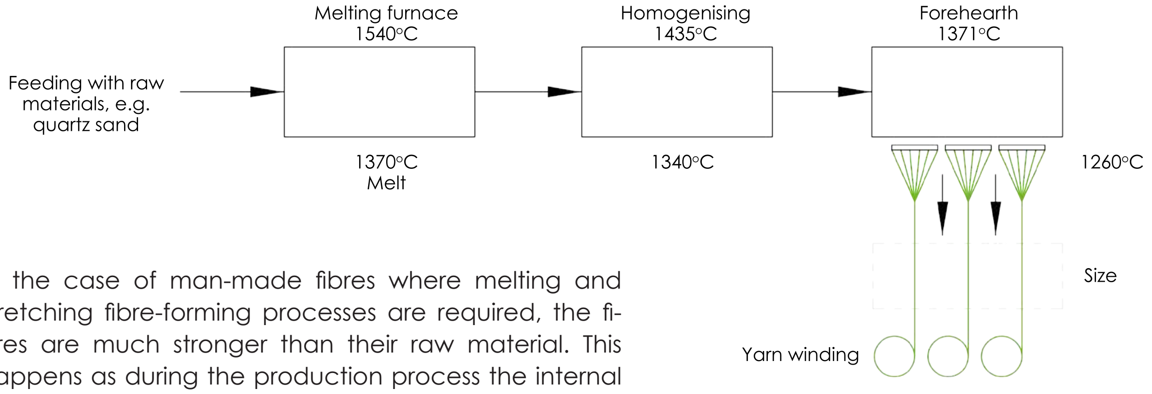
The diameter is an important parameter for the structural capacity of the fibre as it influences their strength. Thus, fibres with small diameter are stronger. However, this strength is mainly in the longitudinal direction as fibres are frequently sensitive to transverse compression. The more pronounced is the longitudinal orientation of the microstructure in the fibre, the weaker are the mechanical properties in the transverse direction.

Natural fibres	**Organic synthetic fibres (polymer fibres)**
Flax	Polyethylene (PE)
Sisal	Polyamide (PA)
Hemp	Polyimide (PI)
Jute	Polyacrilonitrile (PAN)
Ramie	Polytetrafluoroethylene (PTFE)
Banana	
Asbestos	Aramid
Metal Fibres	**Inorganic synthetic fibres**
Steel	Glass
Aluminum	Carbon
Copper	Basalt
	Ceramic



2.1 Glass, carbon and aramid fibres viewed under the microscope (up).
(In: Knippers, J,, Cremens, J., Gabler M., Lienhard J. *Construction manual for polymers + membranes*. Munich: Institut für international Architektur-Dokumentation)

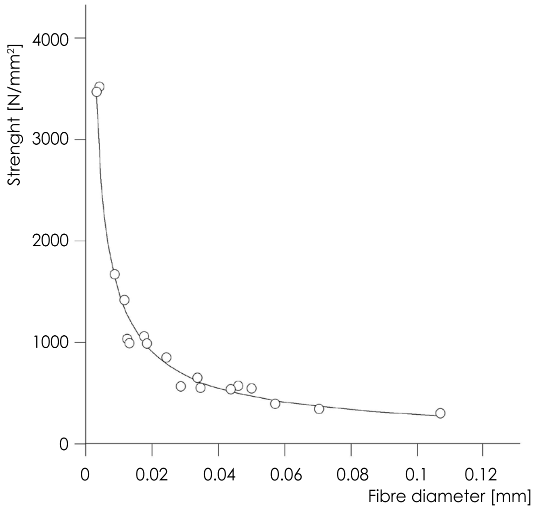
2.2 Carbon fibres under the microspope
(http://www.formula1-dictionary.net/carbon_fiber.html)

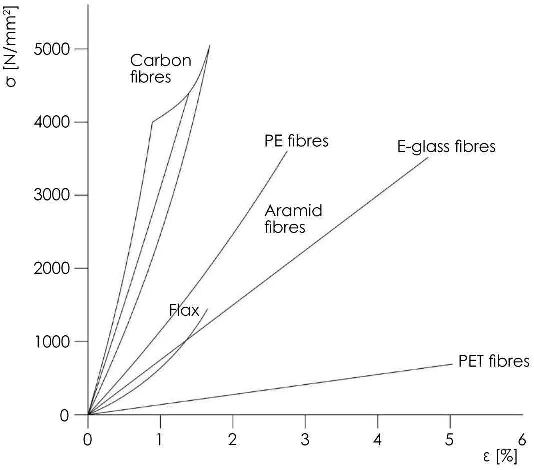


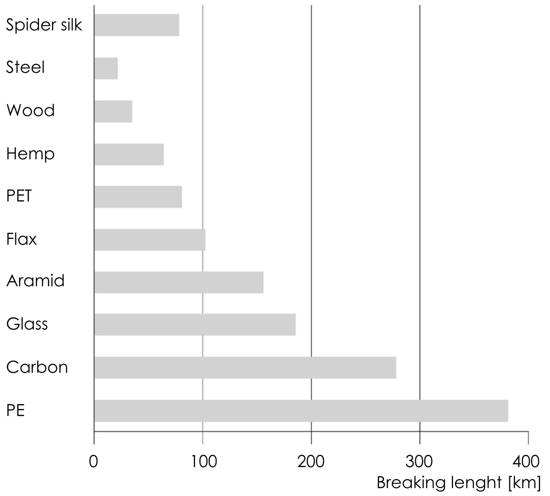
2.3 Production process of typical glass fibre

In the case of man-made fibres where melting and stretching fibre-forming processes are required, the fibres are much stronger than their raw material. This happens as during the production process the internal structure of the fibre becomes aligned in the longitudinal direction which improves the strength of the material. In doing so, compression of air inclusions is crucial as it reduces the negative effect that such flaws have on the strength in the longitudinal direction of the fibre.

As the application of fibres varies, different requirements, such as strength, buckling sensitivity or low self-weight, comply with different uses. For instance, considering only the tensile strength, carbon fibres show the highest values. However, they are relatively sensitive to buckling.







Specifically for lightweight loadbearing applications the most important property of a fibre is its' specific strength which is expressed by the relationship between strength and self-weight (strength-to-weight ratio). The specific strength is also indicated by the breaking length which is the theoretical maximum length that a vertically suspended fibre, supported only at the top, could reach before breaking under its own weight.

For fibres that are used as embedded reinforcement in polymer matrixes the elastic modulus is of high importance. Therefore, fibres with minimum elongation and thus high elastic modulus are preferred as low elastic modulus values lead to excessive deformations of the component. Additionally, thermosets that are normally used can only get a limited amount of elongation and break before the soft fibres have reached their maximum tensile strength. Thus, tensile strength has in most of the cases secondary priority.

2.2 Textiles

Textiles are semi-finished products made from woven fibres. They are mainly used as primary products for membrane fabrication and as reinforcement in polymer composites. The most crucial property of the textiles that are used in construction is obviously their loadbearing behavior which is determined by the orientation of the fibres, their waviness (undulation) and the weight per unit area (g/m2).

With the development of different textile technologies such as weaving, knitting and braiding, a huge variety of textiles for specific applications is now available. The most common textiles for fiber-reinforced composites are woven fabrics, non-crimp fabrics, complex mats, braids, chopped strand mats and fleeces.

2.4 Fabric woven with carbon fibres in twill weave.
(http://www.hccomposite.com/en/catalog/34/1969.html)

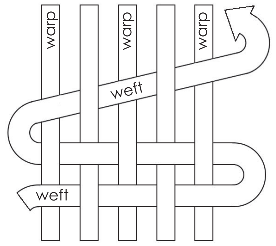
2.2.1 Woven fabrics

Woven fabrics are produced by weaving technics, which are systems of threads crossing at right angles. The warp threads are parallel to the longitudinal direction, fixed to the weaving loom and the weft threads pass perpendicularly above and below the warp threads.

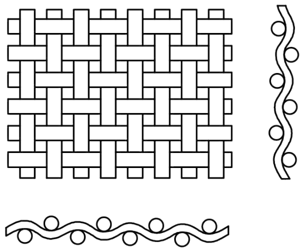
Different arrangements of the fixed warp threads during the weft insertion produce various types of weave with different mechanical properties each. Fabrics are also characterized by the weaving density, which is expressed by the number of (warp or weft) yarns per unit length. The specific terminology for used in textiles is tows per centimeter. The weight and the thickness of the fabric are also influenced by the dimensions of the filament, which together with the weaving pattern plays an important role in the stiffness and the strength of the woven fabric. The three main types of weave are plain, twill and satin weave.

Plain weave is the simplest and tightest type of weave. In this style of weave each warp fibre passes alternately under and over each weft fibre. The fabric is symmetrical, with good dimensional stability and reasonable porosity. However, compared with the other weave types is the one which is the most difficult to drape, whereas the high level of fibre crimp imparts relatively low mechanical properties. With large fibres this weave style gives excessive crimp and therefore it is not generally used for very heavy fabrics.

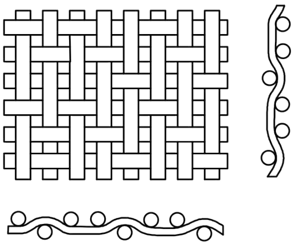
Twill weave is produced when one or more warp fibres alternately weave over and under two or more weft fibres in a regular repeated manner. This produces the visual effect of a straight diagonal rib to the fabric. This type of fabric is more water-resistant and has better drapeability than the plain type. In addition, because the stain in the warp direction is lower than in the plain weave, twill is stronger and stiffer.



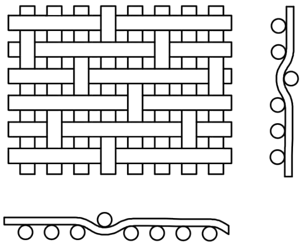
Plain



Twill



Satin

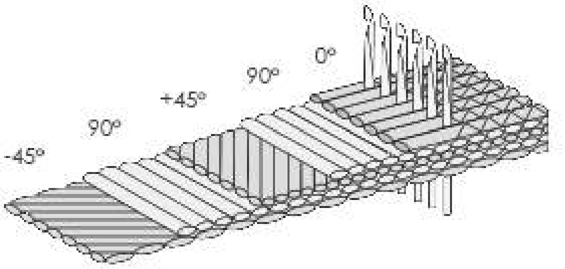


Satin weave is fundamentally a twill weave that is modified to produce fewer intersections of warp and weft. After each course, the change is shifted accordingly by at least two steps. Satin weaves are very flat, have good water-resistance properties, good mechanical properties and an excellent degree of drape. Due to its' great drapeability, satin weave textile is optimum as reinforcement in fiber-reinforced polymer components with complex and tight curvatures in three directions.

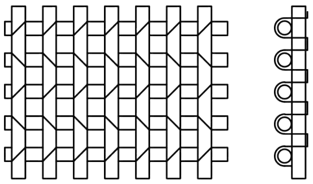
2.2.2 Non-crimp fabrics

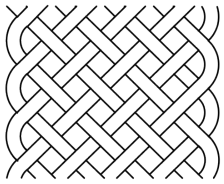
In contrast to woven fabrics, in which the fibres are interwoven, in non-crimp fabrics the fibres are in the form of fibre layers that are laid on top of each other with their fibres being fixed in position only by additional thin sewing threads (stitches).

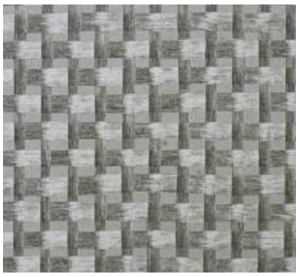
As no weaving occurs, the fibres of each layer are straight and not in an undulating form, which makes them stronger as reinforcement for fiber-reinforced polymers compared with woven fabrics. Another advantage is the flexibility in adapting the orientation of the fibres to the load-bearing direction as the fibres do not necessarily need to be in vertical arrangement but they can be incorporated at any angle. In a non-crimp fabric it is also possible to have not only two layers but several, the one above the other, which allows for multianglular arrangements. A typical application of this type of fabric is as reinforcement in textile-reinforced concrete.



2.5 Layers of a tetraxial (-45°, 0°, +45°, 90°) non-crimp fabric



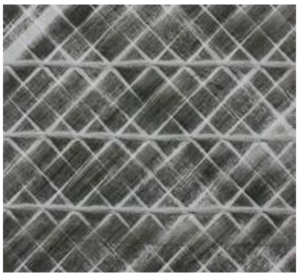




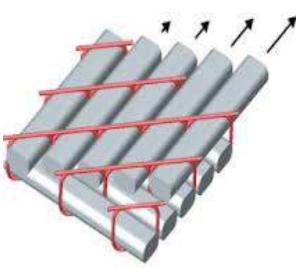
2.6 Plain

2.7 Twill

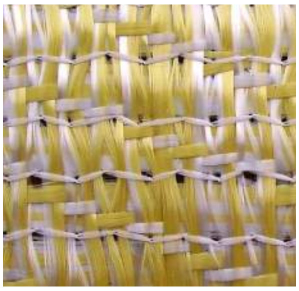
2.8 Satin



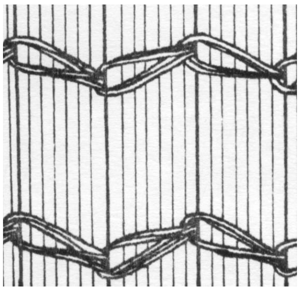
2.9 Non-crimp



2.10 Layers of a biaxial (0°, 90°) non-crimp fabric



2.11 Non-crimp fabric

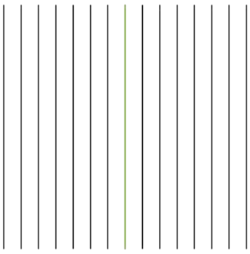


2.12 Detail of the stitch

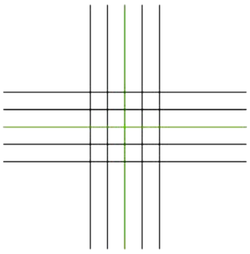
2.6-2.9
In: Knippers, J,, Cremens, J., Gabler M., Lienhard J. *Construction manual for polymers + membranes*. Munich: Institut für international Architektur-Dokumentation

2.10 http://www.utwente.nl/

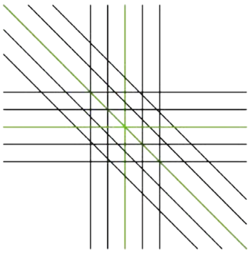
2.12 http://www.tech.plym.ac.uk/



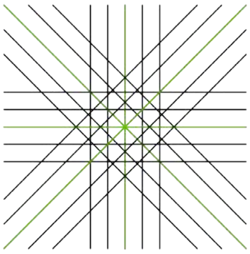
Unidirectional
0°
non-crimp fabric



Biaxial
0°, 90°
woven fabric



Triaxial
0°,+45°, 90°
non-crimp fabric

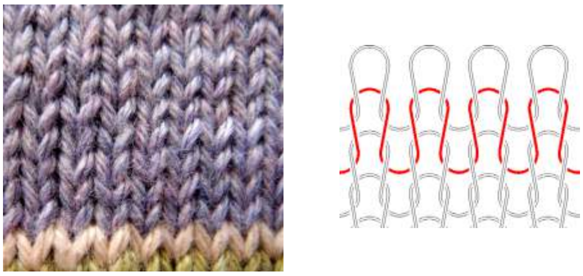


Tetraxial
-45°, 0°,+45°, 90°
non-crimp fabric

2.13 Carbon braid
(http://shop1.r-g.de)

2.14 Braiding
(http://www.makeit-loveit.com)

2.15 Random orientation in glass fibre chopped strand mat
(http://tienda.resineco.com/en/VI00005)



2.16 Knitting (http://en.wikipedia.org/wiki/Knitting)

2.2.3 Braids

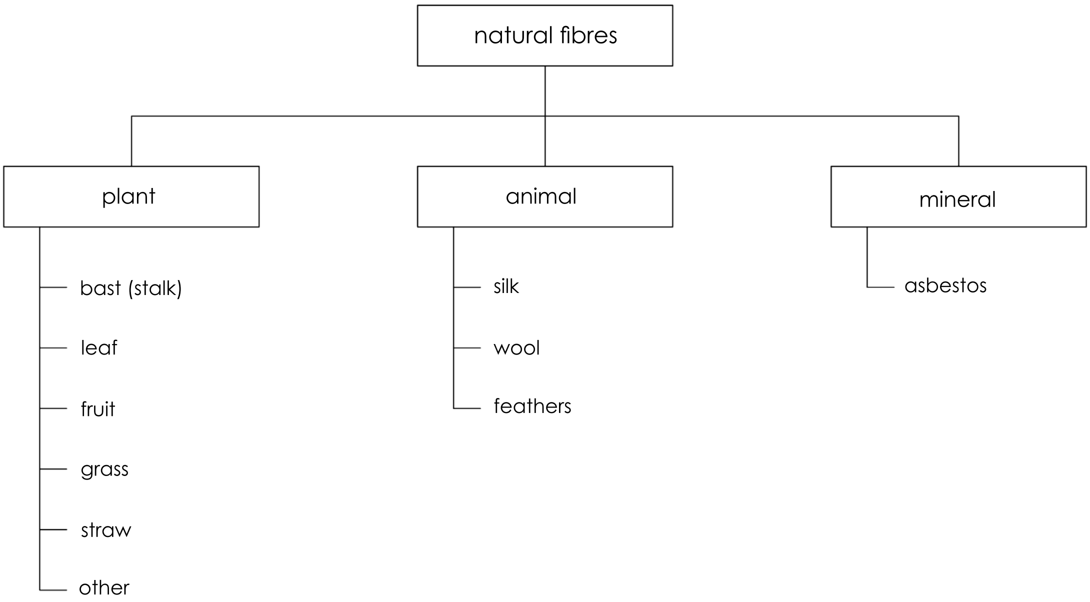
A braided textile is created by intertwining fibres from three or more yarns in such a way that they cross one another and are laid together in diagonal formation, forming a narrow strip of flat or tubular fabric. This criss-crossing arrangement of the fibres results in a higher friction force upon fracture and so in a better impact resistance. Tubular braids have the optimum form for elongated, three-dimensional composite applications such as tubes. For that reason, braiding is usually used as fibre-reinforcement for pipes.

2.2.4 Chopped strand mats and fleeces

In chopped strand mats the fibres that are bonded together have a random arrangement. Due to this random orientation of the fibres, composites that contain such fabrics show mechanical properties that are not dominant in any orientation. For that reason, they find application only in composites with low mechanical requirements. However, the fibres of chopped strand mats have the ability to adapt perfectly to the shape of the component as during processing when the fibres come into contact with the resin, the bonds are loosened. Additionally, such fabrics can be draped easily over curved shapes. Fine mats, also known as fleeces or non-woven fabrics, are used in the outer layers of a fibre-reinforced composite in cases where smooth surfaces are required. They have also application as core materials for infilling sandwich components.

2.2.5 Knitted fabrics

Knitted fabrics are produced by processes similar to hand-knitting mainly by forming loops or stitches. The application of these textiles as reinforcement for composites is limited as they do not have a dominant direction and thus they are only used as backing materials for other reinforcing fibres.



2.3 Natural fibres

2.3.1 Classification

Natural fibres refer to fibres that occur within nature, and are found in plants (cellulose fibres), animals (protein fibres) and minerals (asbestos). However, plant fibres are dominant in use as natural fibre-reinforcement for polymers.

Plant fibres are obtained from various parts of plants, such as the seeds (cotton, kapok, milkweed), stems (flax, jute, hemp, ramie, kenaf, nettle, bamboo), and leaves (sisal, manila, abaca), fruit (coir) and other grass fibres. Fibres from these plants can be considered to be totally renewable and biodegradable. Plant fibres, which have a long history in human civilisation, have gained economic importance and are now cultivated on a large scale globally

Animal fibres can be either fur/wool taken from hairy mammals, silk fibres secreted by glands of insects during the preparation of their cocoons or feather fibre like avian collected from birds. Animal fibres consist largely of particular proteins such as collagen, keratin and fibroin.

Finally, mineral fibres are naturally occurring or slightly modified fibres procured from minerals and they can be categorized into asbestos, ceramic fibres and metal fibres. Some types of mineral fibres are considered a possible carcinogen to humans. Specifically, the use of asbestos in forming fibres is banned in the EU and in Switzerland for its harmful effects on human health.

2.17 Mineral fibres under the microscope
(http://www.niehs.nih.gov)

2.18 Fibres of cashmere, silk, linen, cotton and polyester from left to right.
(http://www.alpacasocksrock.com)

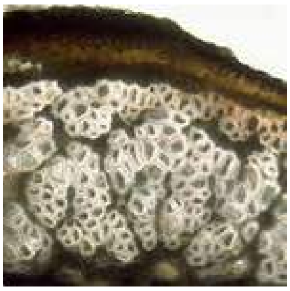
2.4 Plant fibres

Vegetation that produces natural fibres is categorized into primary and secondary plants depending on the utilization. Primary plants are grown specifically for their fibres while secondary plants are the ones where the fibres are extracted from the waste product.

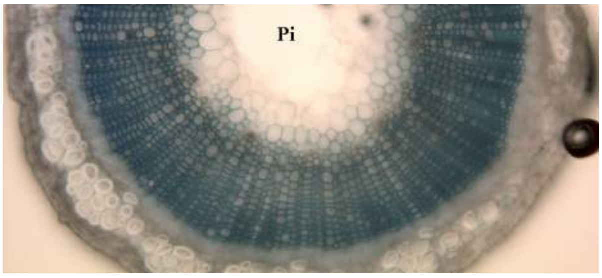
2.4.1 Bast/stalk fibres

In general, bast fibres (stalk fibres) such as hemp or flax show better mechanical properties and therefore are preferred from the building industry. In this plant category, the fibres are concentrated in the outer skin of the stalks supporting the conductive cells and providing strength to the stem. Each fibre contains individual fibre cells or filaments. The filaments are made of cellulose and hemicellulose, bonded together by a matrix, which can be lignin or pectin. The pectin surrounds the bundle thus holding them on to the stem. The length of these fibres is usually a few centimetres. Therefore, these fibres are characterized by high tensile strength and low elongation at failure. Straw fibres also belong in the same bast fibre family. Straw fibres are an agricultural by-product that is extracted from the dry stalks of mainly cereal plants. Straw makes up about half of the yield of cereal crops such as barley, oats, rice, rye and wheat.

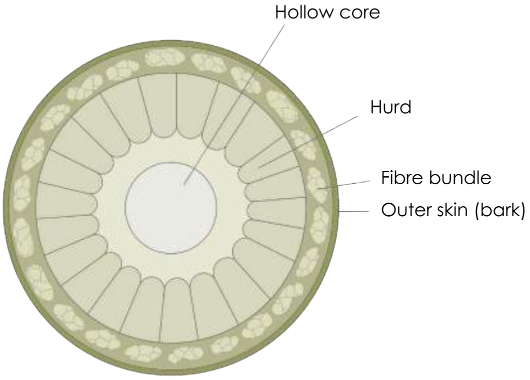
2.19 Flax stalks



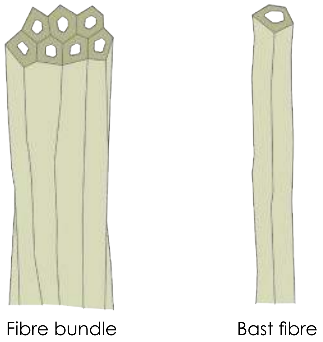
2.20 Hemp cross section



2.21 Flax stalk in cross section
(http://www.onetruepants.com)
(http://www.stemergy.com)
(http://greenclothing-style.blogspot.nl)



Flax cross-section



Flax

Flax, belongs to the family of the bast fibres and grows in cooler regions while it is one of the oldest fibre crop ever. It is the most commonly used material in composite area and especially as natural fibre reinforcement in the automotive industry. Short flax fibres are produced almost exclusively in Europe and they are mainly by-products of the production of long fibres from the textiles industry.

Hemp

It is also member of the bast fibres, specifically from the Cannabis family and similarly with flex, it is also grows in temperate regions. Hemp is mainly used as special cellulose for composites and insulating materials and has extensive application in the automotive industry. Since 1996, when the cultivation of low-narcotic hemp species was legalized in Germany, hemp received considerable even more attention for further development in the entire Europe.

Jute

Jute is the fibre type with the highest production volume and the one with the lower price compared to the rest of the natural fibres therefore it is considered as one of the most "exotic" natural fibres. Countries where the climate conditions are ideal for its growth are Bangladesh, India, and China.

Kenaf

Belonging to the genus Hibiscus, it is a relatively new crop in United States which shows good potentials for usage as reinforcement in composite products. Originally coming from Africa and Asia these plants reach height of about 4 meters. Latest innovations in decortication processes on the separation of the core from the bast fibres, have increased the interest on utilizing kenaf as fibre source.

2.22 Flax fibres

2.23 Hemp fibres

(http://www.baltic-flax.com)
(http://en.wikipedia.org/wiki/Hemp)

2.24 Jute fibres drying

2.25 Kenaf fibres

(http://en.wikipedia.org/wiki/Jute)
(http://ecotextiles.com.au)

2.4.2 Leaf fibres

The leaf fibres are hard, coarse fibres obtained from thick and fleshy sword-shaped leaves of monocotyledonous plants (flowering plants that usually have parallel-veined leaves, such as grasses, lilies, orchids, and palms), used mainly for cordage. These fibres, usually several feet long and stiff, are also called "hard" fibres, distinguishing them from the generally softer and more flexible fibres of the bast, or "soft," fibre group. The leaves are hand-harvested, and their fibre is separated from the surrounding leaf tissue by decortication, a hand or machine scraping or peeling process. Finally the fibres are cleaned and dried. Commercially useful leaf fibres include abaca, cantala, henequen, Mauritius hemp, phormium, and sisal while applications include ropes, and coarse textiles.

Sisal

Sisal fibres are extracted from the leafs of agave plants which are mainly flourishing in East Africa and South America. These stiff fibres are traditionally used in making agricultural twine and rope. Likewise other natural fibres sisal fibres are also used by the automotive industry as reinforcement for polymer composites.

Abaca

The Abaca or banana fibre is extracted from the banana plant and is durable and resistant to seawater fibre. Abaca being the strongest commercially available cellulose is produced in Philippines and Ecuador. In the past, it was the most chosen cordage fibre for marine applications due to its resistant to moisture. Having this special quality, abaca fibres are is used nowadays at the at the underbody covering part of cars which is exposed to moisture, weather conditions and ground stone impact.

2.26 Sisal plant

2.27 Sisal fibres cross section

(http://en.wikipedia.org/wiki/Sisal)
(http://www.intechopen.com/books)

Pineapple leaf fibre

Pineapple fibres belong to the family of the leaf fibres and are extracted from the plant of pineapple which is indigenous of tropical climates and mainly Indonesia, India, Brazil and China. It is rich in cellulose fibres and as the leaf fibres are a waste product they are relatively cheap. It is mainly used by the clothing industry but also as natural reinforcement for polymer composites.

Oil Palm

Oil palms, is vastly produced in South East Asia, particularly in Malaysia and Indonesia. Oil palm empty fruit bunch cellulose fibres are relatively a cheap waste product in the industry and therefore, it is of interest to utilize the cellulose fibres into beneficial products with higher commercial value. Such products include mattresses, fiberboards, insulating or paper products. However, research done on the mechanical properties of the fibres and the ability to be utilized as reinforcement for polymer composites prove that oil palm fibre is hard and tough and its porous surface morphology is useful for better mechanical interlocking with matrix resin for composite fabrication.

2.28 Sisal fibres
(http://www.bhtengda.com)

2.29 Abaca fibres
(http://www.save-on-crafts.com)

2.30 Pineapple fibres
(http://www.pixmule.com)

2.31 Oil palm fibres
(http://i00.i.aliimg.com)

2.32 Oil palm plantation in Malaysia. About 11% of the total land area in Malaysia (about 62% of the country's agricultural land) is devoted to palm oil.
(http://www.etawau.com)

2.4.3 Fruit/seed fibres

Fibres that are produced on the seeds of various plants have been called seed hair or seed fibres. The most important fibre of this class is cotton. Other fibres of this group (kapok, floss from milkweed, dandelion, and thistle fibres) are not generally spun into yarns, but are utilized mainly as staffing in pillows and mattresses, and for life belts
Seed fibres normally are light, hairy and relatively shorter compared to other fibre types.

2.33 Coconut fibre cells
(http://www.superstock.com)

2.34 Coconut fruit
(http://sanctuarysoil.com)

Coconut

Coconut fibre or coir fibre is one of the natural fibres abundantly available in tropical regions, and is extracted from the outer shell of the coconut fruit. There are two types of coconut fibres, brown and white ones which depend on the maturity of the coconut. Brown fibres are thick, strong and have high abrasion resistance while white fibres are smoother and finer, but also weaker. Applications vary mainly between objects of daily use such us brushes, ropes and mattresses. The material is also used for insulation, packaging and as upholstery padding for the automobile industry in Europe.

Cotton

Cotton is the most common seed fibre and is used for textile all over the world. Cotton is a soft, staple fibre that grows in a spherical form around the seeds of the cotton plant, a shrub native to tropical and subtropical regions around the world, including America, India and Africa. The fibre most often is spun into yarn or thread and used to make a soft, breathable textile. In comparison with other natural fibres, cotton is rather weak. It can absorb moist up to 20% of its dry weight, without feeling wet and is also a good heat conductor. Cotton is applied for the manufacturing of clothes, carpets, blankets, mobs and medical cotton wool.

2.35 Cotton fibres 2.36 Coconut fibres
(http://informedfarmers.com)
(http://www.ppfenterprises.com)

2.37 Cotton fibres in section and view through microscope
(http://www.swicofil.com)

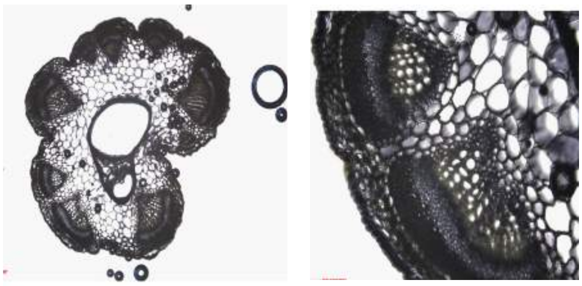
Others (wood/paper)

Wood fibres commonly refer to the tracheid cells which make up the bulk of the woody tissue in trees. These fibres are roughly tubular in shape, and are oriented parallel to the tree stem while their dimensions are quite variable. Wood fibres constitute the largest component of most pulp and paper products.

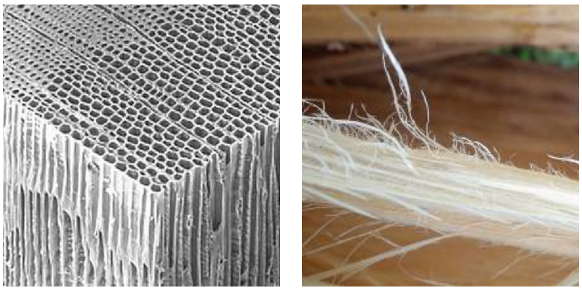
2.4.4 Grass fibres

Grass is an annual plants with bundles of elementary fibre cells and it can be found in large amounts. These elongated cells occur in different parts of plants, mainly in the stems and leaves of grass. The most important representatives in the group of grasses are ryegrass, trefoil and lucerne. Grass fibres cover a wide range of applications such as various domestic goods or handicraft items like hats and baskets.

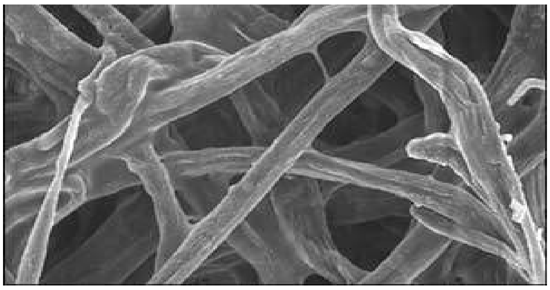
2.38 Grass stems in section 2.39 Triangular grass stem
(http://www.hiltonpond.org) (http://www.bibalex.org)



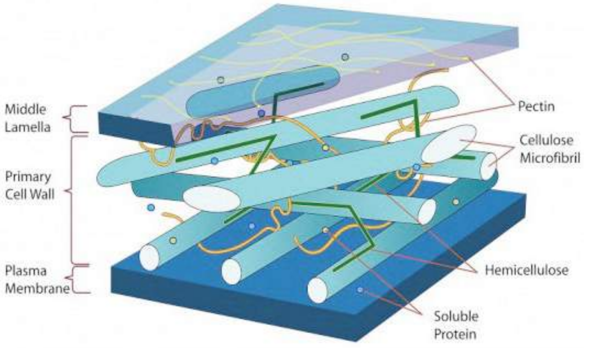
2.40 Cross section of a Trefoil stem
(http://www.intechopen.com)



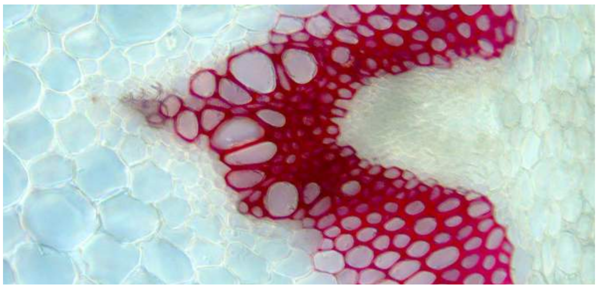
2.41 Wood fibres
(http://www.bc.org.nz/purpose.html)



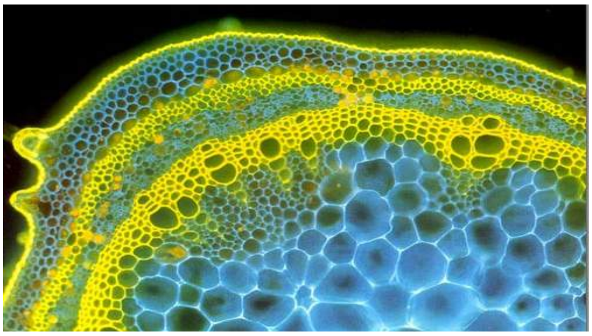
2.42 Cellulose microfibrils in the microscope (http://media.noria.com)



2.43 Section on the structure of a plant fibre (http://images.gizmag.com)



2.44 Lignin (red) keeps plant cell walls study and strong (https://www.sciencenews.org)



2.45 Section of soybean stem, stained with two fluoro chromes to show distribution of cellulose (blue) and lignin (yellow) (www.swicofil.com)

2.4.5 Chemical composition of plant fibres

In order to develop polymer composites from natural resources it is important to understand the microstructure and chemical composition of these fibres.

Natural fibres normally have rigid complicated structures, with crystalline cellulose micro fibril-reinforced amorphous lignin. Generally, natural fibres are composed of cellulose, hemicellulose, lignin, waxes, and some water compounds. However, cellulose, hemicellulose, and lignin are the major constituents with percentages that vary depending on the species and the variety of the plant, agricultural variables such as soil quality, the weathering conditions, the level of plant maturity and the quality of the refining process. Typically, natural fibres contain 60-80% cellulose, 5-20% lignin and moisture up to 20%.

Cellulose is an organic compound with the formula (C6H10O5)n. It is a polysaccharide consisting of a linear polymer chain of several hundred to over ten thousand linked D-glucose units organised into microfibrils. Cellulose consists an important structural component of the primary cell wall of green plants. It is the major component which is responsible for the tensile strength and stability of the natural fibre, while lignin can take the compression. Cellulose is by far the most abundant renewable material. Every year the photosynthesis produces more than 75 billion tons of cellulose on the basis of CO2 and water.

Hemicellulose is not a form of cellulose and the name is a misnomer. They comprise a group of polysaccharides composed of a combination of 5 and 6 carbon ring sugars. Hemicelluloses form the supportive matrix for cellulose microfibrils and they are very hydrophilic, soluble in alkali and easily hydrolyzed in acids.

Lignin is a complex hydrocarbon polymer with both aliphatic and aromatic constituents. They are totally insoluble in most solvents and cannot be broken down to monomeric units. Lignin is totally amorphous and hydrophobic in nature, while it is the compound that gives rigidity to the plants. Therefore, high consistency in lignin results in a high degree of lignification which results in stiffer, but at the same time more brittle, fibres.

The following table compares different portions of cellulose, hemicellulose, ligning and waxes in specific plant fibres.

Table 2.1 Chemical composition of different natural fibres

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Waxes (wt%)
Abaca	56–63	20–25	7–9	3
Bamboo	26–43	30	21–31	–
Coir	32–43	0.15–0.25	40–45	–
Flax	71	18.6–20.6	2.2	1.5
Hemp	68	15	10	0.8
Jute	61–71	14–20	12–13	0.5
Kenaf	72	20.3	9	–
Oil palm	65	–	29	–
Pineapple	81	–	12.7	–
Ramie	68.6–76.2	13–16	0.6–0.7	0.3
Rice straw	41–57	33	8–19	8–38
Sisal	65	12	9.9	2
Wheat straw	38–45	15–31	12–20	–

2.4.6 Mechanical properties

Cellulose is a natural polymer with high strength and stiffness per weight, and it is the building material of long fibrous cells. These groups of cells are "designed" for giving strength and stiffness to the plant.

However, the mechanical properties of plants are strongly influenced by the growing environment. Conditions such as temperature, humidity, the composition of the soil and the air affect the height of the plant and the strength of its fibres or its density. The way the plants are harvested and processed results in a variation of properties as well. Therefore, fibres of the same species may show deviated results after testings.

From the following table that compares different properties of glass fibres with other natural fibres, it becomes clear that the mechanical properties of natural fibres, especially of the ones that belong to the bast family (flax, hemp, and jute) are good and may successfully compete with glass fibre in specific strength and modulus. Natural fibres show higher elongation to break than glass or carbon fibres, which may enhance composite performance in case they are used as reinforcement.

Therefore, as flax, hemp and jute seem to be superior regarding their mechanical properties compared to all natural fibres, they are further researched and compared in the following subchapters.

Table 2.2 Physico-mechanical properties of natural, E-glass and basalt (mineral) fibre

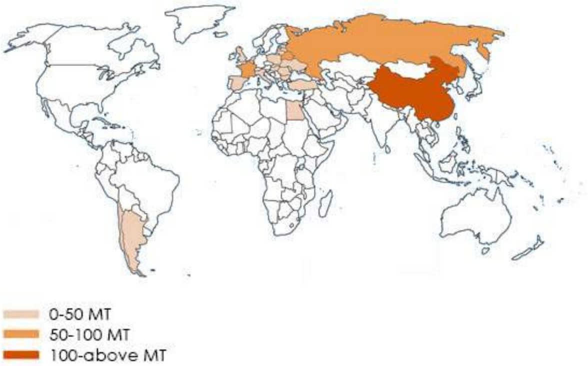
Fibre	Density (g/cm3)	Tensile strength (MPa)	E-modulus (GPa)	Elongation at failure (%)	Equilibrium moisture content (%)
Abaca	1.5	400	12	3 - 1	15
Bagasse	1.25	290	17	-	8.8
Bamboo	0.6 - 1.1	140 - 230	11 - 17	-	8.9
Basalt	2.67	1430 - 4900	71 - 110	3.1 - 3.3	< 0.5
Coir	1.25	220	6	2.5	10
Cotton	1.5 - 1.6	400	5.5 - 28	15 - 25	8 - 25
Curaua	1.4	500 - 1150	11.8	3.7 - 4.3	9 - 12
E-glass	2.55	2000 - 3500	73	2.5	0
Eleplant grass	0.82	185	11.3	3 - 10	11 - 13
Flax	1.5	800 - 1500	60 - 80	3	7
Hemp	1.48	550 - 900	70	1.2 - 1.6	9
Jute	1.3	400 - 800	10 - 30	1.8	12
Kenaf	1.2	220 - 930	53	1.6	8
Stinging Nettle	1.51	560 - 1600	24.5 - 87	2.2 - 2.5	
Sisal	1.4	500- 700	38	2 - 2.5	11
Ramie	1.5	560	61-128	2.5	9
Oil palm	0.7 - 1.55	248	3.2	25	
Pineapple	0.8 - 1.6	400 - 627	1.44	14.5	13

2.5 Flax

Flax, also known as linseed, is an upright annual plant growing to 1.2 m tall with slender stems. It consists a food and fibre crop that grows in cooler regions. The species is native to the region that extends from the eastern Mediterranean, through Western Asia and the Middle East, to India. However, the plant is cultivated also in other regions of the world including most Europe.

The life-cycle of the plant is divided into twelve growth stages, shown in the scheme 2.1, that are spread in three periods: a 45-60 day vegetative period, a 15-25 day flowering period and a 30-40 day maturation period.

Flax fibres are extracted from the bast or skin of the stem of the plant. They exist into bundles of 10–40 fibres bonded together by pectin as shown in Fig. 1 and they are separated individually in order to become functional. One general feature of all natural fibres is their non-uniform geometrical characteristics. Flax fibres exhibit a polygonal shape in cross-section with 5–7 sides and a non-constant longitudinal view. On average, a fibre is 19 mm in width and 33 mm in length, while the fibres are thicker near the root and become thinner nearer the tip. However, it is important to mention that due to the dispersal of the geometrical dimensions, the transverse and the longitudinal dimensions can vary between 5–76 mm and 4–77 mm, respectively.

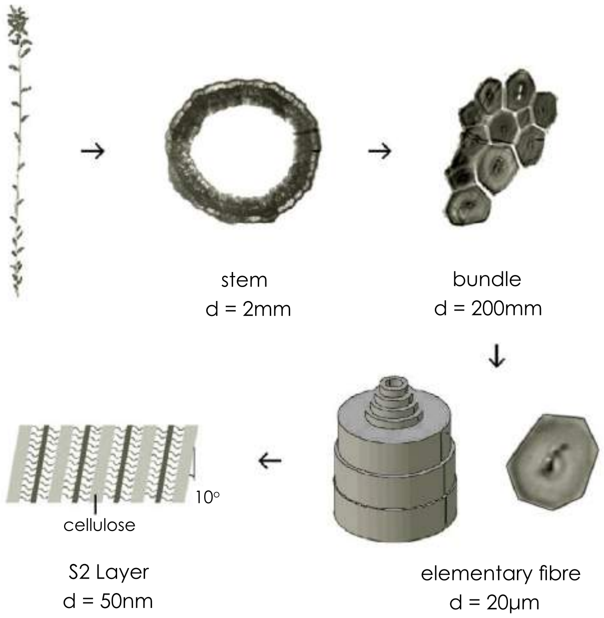


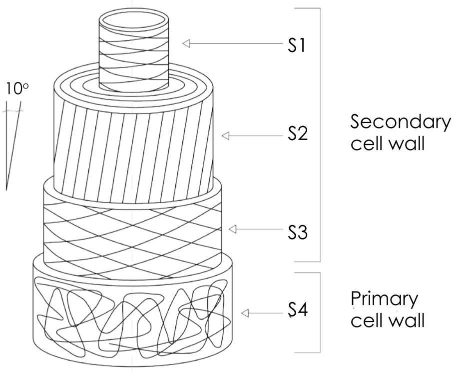
2.46 Distribution of flax global production (2005)
(http://www.jute.org)

2.47 Flax flowers
(http://www.csu.edu.au)

2.48 Harvested flax stalks
(http://www.bellavitabotanicals.com)

The microstructure of all natural fibres is extremely complicated due to their hierarchical organisation at different scales of observation and the different materials present in variable proportions. Under a mesoscopic scale, an individual fibre consists of two cell walls arranged as concentric cylinders with a small channel in the middle, which is called lumen and contributes to the water uptake. The outer cell wall designed as the primary cell wall is only 0.2 mm thick while the bulk of the fibre is essentially constituted by the layer S2 of the secondary wall cell. In this layer, highly crystalline cellulose fibrils are spirally wound, with a tilt angle of 10o, in a matrix of amorphous hemicellulose and lignin. These spiral fibrils give a unidirectional structure to the fibre, responsible for its tensile strength.





2.49 Flax structure from the stem to the cellulosic fibrils and structure of flax fibre cells

2.50 Flax harvesting 2.51 Decortication of hemp
(http://www.theguardian.com)
(http://en.wikipedia.org/wiki/Hemp)

2.5.1 From plant to fabric

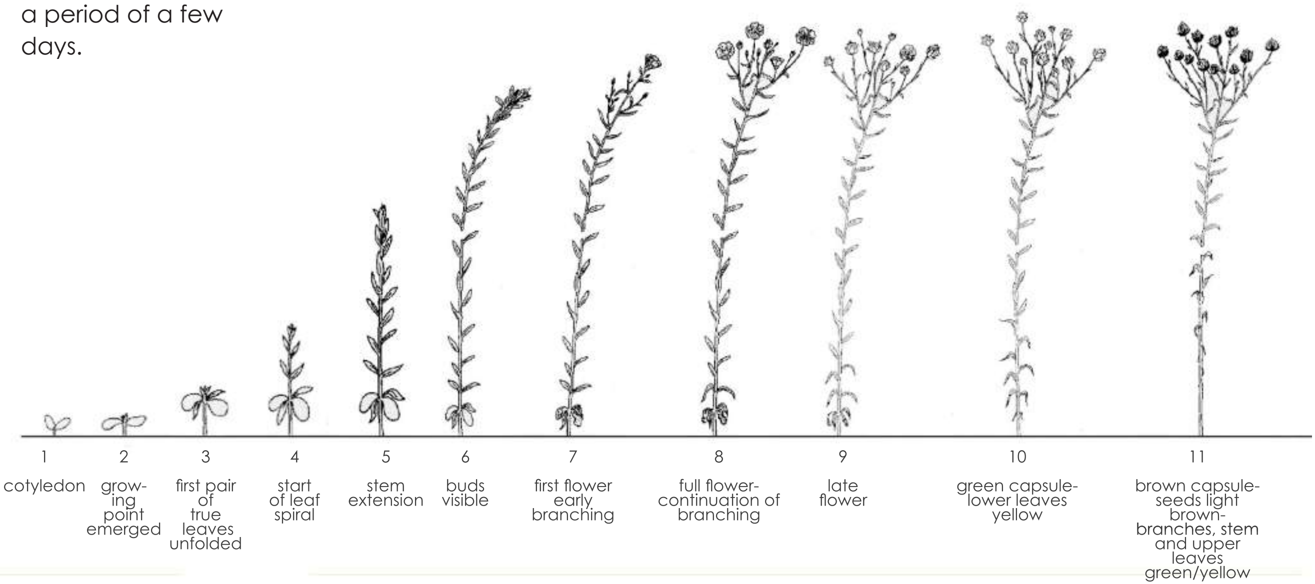
When the plant has grown 1m high and 30 days have passed from flowering, it is ready to be harvested. Harvest requires the use of simple processes based on pulling the plants and laying them on the ground, operated either manually by labour and animal power or by specific machinery. In general, harvest time affects the quality and thus the properties of natural fibres. The longer the plant is left, the coarser the fibre will be. Conversely, harvesting a few days after flowering, the result will be a fine flax fibre (Wildfibres, 2014).

After the crops have been harvested, retting of the fibres follows. Retting is a process using the action of moisture on plans in order to dissolve the "glue" that bonds the individual fibres, which consists of lignin and pectin, and so achieve separation of the fibre from the stem. There are three ways for retting fibres by using moisture, i.e. dew-, wet- and strand retting and one method based on exposure of the bundles of fibres to specific enzymes, such as pectinase, that break down pectin. The most widely used method is wet retting, which is a simple placement of the fibres into water for a period of a few days.

When the fibres have been retted and properly dried, the next step is the decortication. Decortication is the process of separation of the individual fibres from the core and is a basic common step for all bast fibre plants, such as flax, hemp and jute. Similarly with harvesting, the methods are divided into manual and mechanical. The two main mechanical approaches to decortication are with a roller breaker and hammer mill systems (Natural capital resources Inc., 2014).

The fibres are cleaned by removing the shive and then carding follows. Carding is a process operated either mechanically or by hand, that aligns and intermixes the fibres, by brushing and combing them with rollers, in order to produce a continuous web or sliver suitable for processing. Then the produced fibres are processed to spinning by getting twisted, to form yarns and tows. In that form, yarns are a preliminary product that can be subsequently used for making weaved, knitted and braided fabrics.

2.52 Carding rollers 2.53 Carded flax fibres
(http://fibercrush.wordpress.com)
(http://www.discovershropshire.org.uk)



2.54 Main growth stages of flax

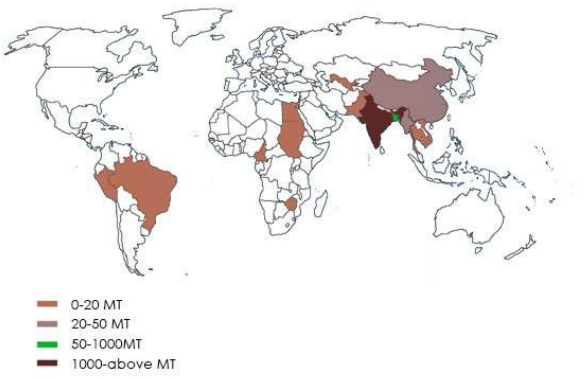
2.6 Jute

Jute is an annual crop of the bast family that reaches its maximum height at 2,5 – 4m. It could never grow in Europe, as the suitable climate for growing jute is the tropical (warm and wet), with temperatures from 20˚C to 40˚C and relative humidity of 70% -80%. To achieve successful cultivation jute requires 5–8 cm of rainfall weekly, and even more during the sowing time. Therefore the ideal conditions are created during the monsoon season. Originally grown for centuries in India and Bangladesh, global jute production is still concentrated in these two countries.

The plant is ready to harvest in four to six months, after the flowers are shed and the stems have reached their maximum height. Jute fields may be under water at the time of harvest and the workers often need to wade in the water to cut the stems at ground level or to uproot the plants. Usually, jute is planned close together so that the plants grow tall and straight. Unlike cotton, it has little need for pesticides or fertilizers.

2.56 Harvested jute stalks
(http://celadonathome.com/)

2.57 Hessian jute fabric
(http://asiajute.com/)



2.55 Distribution of jute global production
(http://www.jute.org)

Jute fibres are very long (1 to 4 metres), silky, soft, shiny and golden brown in colour, that can be spun into coarse, strong threads. The wide variety of uses that jute fibres have, makes them second, after cotton, most produced natural fibres.

Similarly with hemp, Jute can also have a beneficial effect to the soil that is cultivated. As it has little need for fertilisers and pesticides, jute plants enrich the soil with micronutrients that maintain soil fertility. This property of jute combined with its short growth cycle, makes the plant ideal for crop rotation, which is an old practise of alternating deep-rooted and shallow-rooted plants in order to improve soil structure and fertility.

Another important environmental impact of jute plants is their ability to clean the air. Studies show that during growth they assimilate several times more CO2 than the average tree, converting the CO2 into oxygen (Inagaki, 2000). Specifically, one hectare of jute plants can consume about 15 tons of CO2 from the atmosphere and release about 11 tons of oxygen in the 100 days of the growing season.

2.7 Basalt

Basalt is a variety of hard and dense igneous volcanic rock that originally was created in a molten state. Although 1/3 of Earth's crust is covered with basalt eruptive rocks and the availability from mines and open-air quarries is high, only specific locations contain basalt suitable for fibre processing because not all various chemical compositions satisfy the conditions for fibre preparation. Research, production and marketing efforts regarding basalt are based in the countries of the once aligned Soviet Union and China as within these regions the largest deposits are located.

2.58 Molten volcanic rock

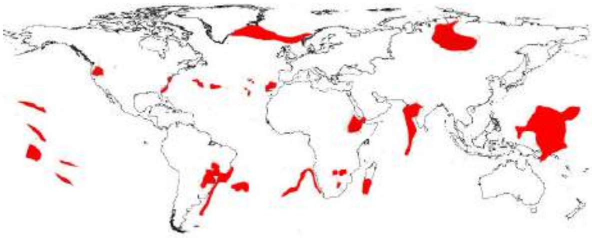
2.59 Basalt rocks

(http://www.physicalgeography.net/)

For many years, basalt has found application in the building industry in tiles, slabs or liner in steel tubing. For all these applications, manufacturing included casting processes while in crushed form basalt finds use as aggregate in concrete.

Only in the last decade, basalt has emerged as an alternative of fibre reinforcement in composites. Basalt fibre exhibits superior strength and stiffness, while its highly resistance to fire, moisture, UV radiation, alkaline and acid make it a good candidate for the use in fibre-reinforced composites.

Extraction of the raw material is achieved by typical mining operations (described in Chapter 3.4). Crushed basalt is then loaded in melting furnaces, from which thin filaments are extruded and processed to yarn and textile fabrication.



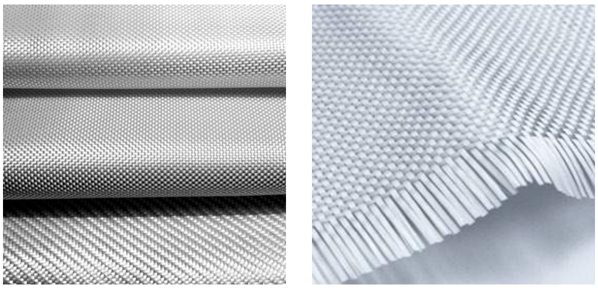
2.60 Global igneous provinces
(http://blogs.scientificamerican.com/)

2.8 Glass

Similar to basalt, glass fibre is an inorganic fibre produced from molten glass of specific composition of sand, limestone, kaolin, calcium fluoride (fluorspar), boric acid, natrium sulfate, and clay. Different variations of the consisting materials result in different types of glass can be produced. E-glass, C-glass and S-, R-, T-glass are the types used mainly for structural reinforcements, with E-glass being the most commonly used. The letter that characterises the various types, actually defines the specific field in which the fibre shows exceptional resistance and superiority. Thus, letter E (electrical) is used because E-glass was originally used for electrical applications, C-glass (chemical) due to its best resistance to chemical attack, A for alkali resistance and S for high stiffness.

In general, E-glass shows good tensile and compressive strength as well as stiffness, good electrical properties and relatively low cost. However, impact resistance is relatively poor. Concerning durability, E-glass has acceptable resistance in moisture, fire, ultra-violet radiation, acids and weak alkalis.

Due to the high availability of the consisting materials, glass fibres are largely used as reinforcement in FRP composites. The use of glass fibre products includes many applications from simple heat insulation up to high technologies and space industry, including also boats and ships, wings of wind turbines, automobile frames and floors, sports and medical equipment.



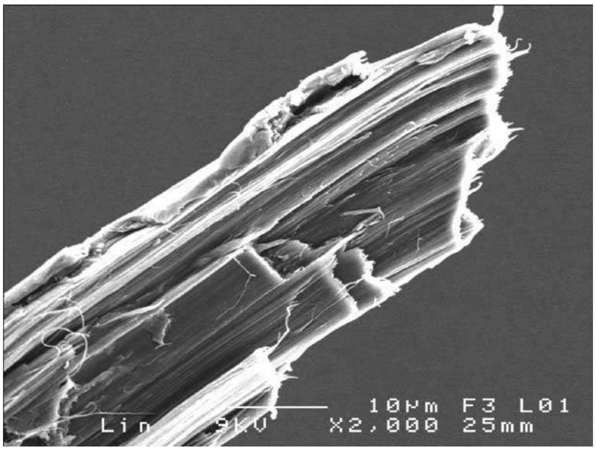
2.61 Glass fibre woven reinforcement
(http://www.bikeoff.org/)

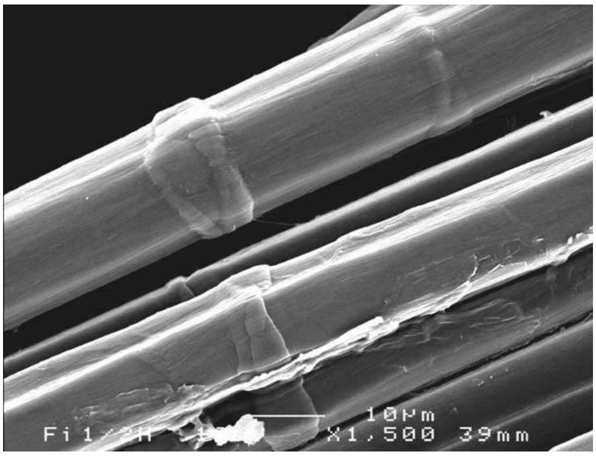
Production of glass fibre includes mixing of the consisting materials and import into the melting furnace. The procedure of melting, which is similar to basalt, produces molten glass which by extrusion forms the filaments.

2.9 Mechanical comparison

As it was also mentioned in the section Mechanical properties, one of the main drawbacks of naturally occurring fibres is that they show much higher variability of their various parameters compared to their synthetic counterparts. Chemical composition, crystallinity, surface properties, diameter, cross-sectional shape, length, strength, and stiffness vary from fibre to fibre as they depend on growth conditions, harvesting and processing. It is therefore very difficult to achieve precise quality characterization of these fibres as after repeated testings the results deviate.

Another important reason for the large spread in the mechanical properties of natural fibres is the defects on the structure of the fibre. It is a general rule in materials science that defects determine the mechanical properties of materials and so it turns out to be equally true in the case of natural bast fibres, such as flax, hemp and jute. Fig. 9 shows examples of cross-marks (deformed zones), called 'nodes' or 'dislocations'. During a tensile test, the break often occurs where the defect is situated. Defects in fibres are produced irreversibly either during plant growth or during the decortication process, thus they can be hardly controlled.





However, cellulosic fibres have an exceptional advantage over the conventional ones i.e. their low density and thus their low weight. Table 2.3 (Lilholt & Lawther, 2000) shows that the three researched bast fibres are almost 40% lighter than glass fibres. Therefore, although natural fibres' mechanical properties are much lower than those of glass, their specific properties, especially stiffness, are comparable to the values of glass fibres.

Specific stiffness also known as the stiffness to weight ratio or specific modulus is a materials property consisting of the elastic modulus per mass density of a material. High specific stiffness materials find wide application in structures where primary design limitation is deflection or physical deformation, rather than load at breaking and thus low structural weight is required. Such "stiffness-driven" structures include airplane wings, bridges, masts and bicycle frames. Therefore it is highly important that flax fibres almost 1,5 times higher specific stiffness from glass, hemp and jute.

Specific strength is a second important parameter after specific stiffness and is the strength of the material divided by its density. Also known as strength to weight ratio, high specific strength is needed in applications, that permanent deformation or failure has to be avoided at low weight. As shown in Table 2.3, natural fibres have lower specific strength compared to glass. Specifically, flax that shows again the highest values between the natural fibres has almost 3 times less specific strength than glass fibres.

Consequently, although flax fibres show the highest potential to substitute glass fibres as reinforcement in composite materials, they would not be suitable for applications that require high load-bearing capacity due to their lower strength. However, in the case of lightweight applications where the loads are sufficient for the structure, flax fibres would consist a more rigid reinforcement with higher resistance to deformation than glass fibres.

2.62 Example of defects on flax fibres
2.63 Break area of a flax fibre after a tensile test (http://sensiseeds.com)

Table 2.3 Mechanical properties of flax, hemp, jute, E-glass and basalt fibres

Properties Fibre	Modulus (GPa)	Strength (MPa)	Density (g/cm3)	Specific Modulus	Specific Strength
Basalt	90	1430-4900	2.67	33	~ 1185
E-glass	72	2000-3500	2.54	28	~ 1080
Flax	50-70	500-900	1.4-1.5	~ 41	~ 480
Hemp	30-60	300-800	1.48	~ 30	~ 370
Jute	20-55	200-500	1.3-1.5	~ 27	~ 250

2.10 Durability

2.10.1 Flammability

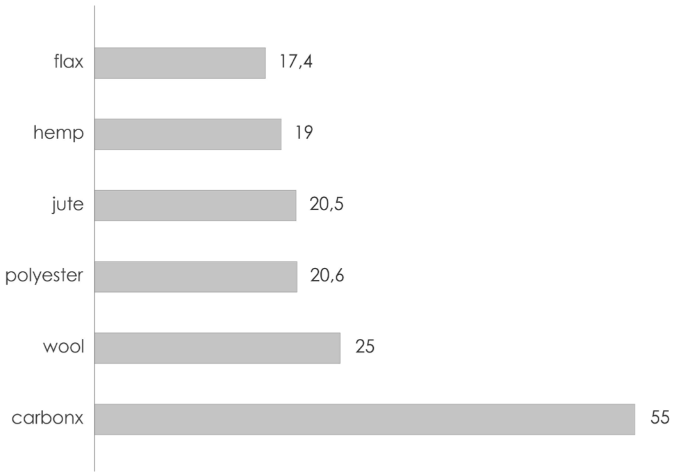
The flammability of the different types of fibres depends on their chemical composition and structure. Natural lignocellulosic fibres, being composed of carbon, hydrogen and oxygen are characterized for their high sensitivity to heat, as carbon is a main highly flammable element. Thus subjection of plant fibres to a constant temperature of 180°C can cause decrease of the mechanical properties while temperatures above 200oC destroy completely the fibres. For that reason, during production of natural fibre reinforced plastics, only short periods of exposure of the textiles to high temperatures are allowed, while composite production temperatures higher than 180oC have to be avoided in order to prevent degradation of fibres.

There are several ways to characterize the flammability degree of textiles. The most common method is the Limiting oxygen index (LOI), which is the percentage (%) of oxygen concentration required to maintain steady burning. The LOI value is measured by applying an oxygen/nitrogen-mix to the burning sample. If the sample burns for longer than 180s or the burning reaches a predefined mark, the oxygen level is gradually reduced. The LOI describes the minimum concentration of oxygen in the oxygen/nitrogen-mix which supports combustion. Thus, high LOI values mean good flame-retardancy. Specifically, fibres with LOI greater than 25 are said to be flame resistant.

As natural lignocellulosic fibres prove to be the most flammable, flame–retardant treatment has to be applied on the textile prior to incorporation in the matrix, in order to improve the fire resistance of the reinforcement. Flame retardants are generally classified in non-durable, semi-durable and durable. Non-durable flame retardants are usually

Table 2.4 Behavior in flame by fibres without flame-retardant treatment

Highly Flammable	Intermediate	Less Flammable	Flame Resistant (LOI greater than 25)	Non-flammable
■ Cellulosic fibers (flax, cotton, jute) Once alight, these burn easily and so can "propagate"	■ Acetate, triacetate These melt as they burn; ■ Nylon, polyester, olefin (polypropylene), acrylic. These do not ignite easily once ignited, burn and most melt; tend to drip (especially nylon); the drops tend to carry the flame away, so the fabric self-extinguishes in some situations	■ Protein (wool, silk) These do not ignite easily; burn slowly; tend to self-extinguish, except in very dry air or with very open fabric.	■ Modacrylic, saran, vinyon These melt; ■ Aramid These do not melt but char' tend to self-extinguish; give little smoke ■ Certain modifications Some MF fibres are given flame resistance by agents put in before the fibre is spun	■ Novoloid, polybenzimidazole (PBI) These will not burn; do not melt; char, but stay intact ■ Inorganic fibers (asbestos, glass, metal, etc.). These will not burn; can melt, but at temperatures so high they do not figure in textile fire safety



2.64 Limiting Oxygen Index (LOI) for different fibres

water-soluble inorganic salts which are inexpensive and can be easily removed by washing or exposure to water. Thus they are applied to fibres that are not going to be washed, such as batting for upholstered furniture and insulating fibres. The second type is semi-durable, and can be removed after repeated laundering. Finally, durable fire retardants are not affected by water.

There are several methods for applying flame-retardants on textiles, which are based on the four theories for fire retardant mechanisms. These include thermal (reducing the thermal build-up of a treated combustible), coating (via an insulating coating that can melt over the fibre), gas (in which non-flammable gases, like water or ammonia, are released), and chemical (in which fire retardance can be “grafted” to natural fibre or actually built into products). Common methods of treating materials would be by water-soluble salt impregnation, a purely physical method of depositing tiny crystals on the fibre surface. There is also vacuum or pressure impregnation and coating ways to treat materials.

Latest advances in genetic engineering have created the opportunity to obtain transgenic cellulose (flax, cotton, sisal, etc.) with built-in flame retardant groups inside the structure of cellulose or lignin. These substitute hydroxyl groups, making cellulose more flame resistant in its natural state.

2.10.2 Moisture absorption and fibre-matrix adhesion

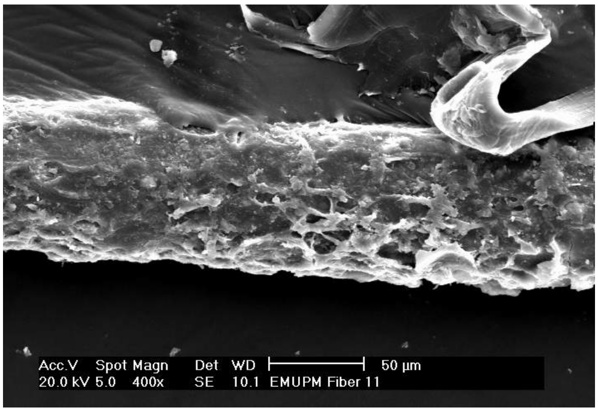
Major concern of utilizing natural fibres in biocomposites is their hydrophilic behavior due to their high content of cellulose which makes them susceptible to absorb water vapor from their environment. This hygroscopic characteristic of natural fibres affects the mechanical performance of the composites adversely. Water inside the fibres molecules behaves like a plasticizer. It allows cellulose molecules to move freely, which causes low elastic modulus and tensile strength. The decrease in mechanical property might be also because of fungus development due to internal moisture of fibre (Stamboulis et al., 2001).

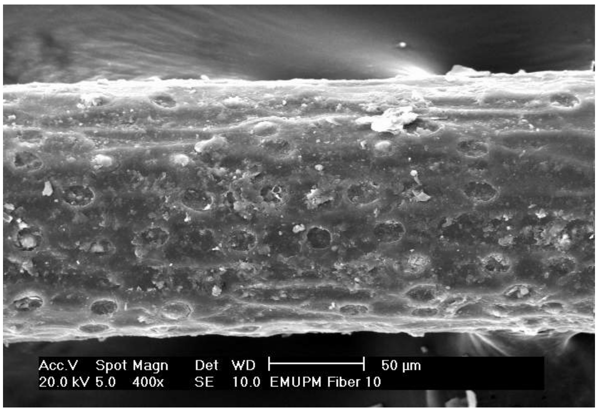
Additionally, the hydrophilic nature of untreated natural fibres results in insufficient compatibility between the fibres and the hydrophobic polymeric matrix. Due to this poor adhesion between the two materials, load transfer from matrix to fibres is not good, which may lead to a low quality product that can meet bonding failure with age. One the other hand, good adhesion usually reduces the moisture sensitivity. Therefore, an understanding of the hygroscopic properties of natural fibres is very important to improve the long-term performance of composites reinforced with these fibres.

Fibre surface treatment

To improve fibre-matrix adhesion chemical treatment of natural fibres is essential before they are used as reinforcement. Chemical treatments clean the fibre surface, modify the chemistry on the surface and reduce the moisture uptake. There are different chemical treatments available for producing a good quality fibre. Mercerization (alkali treatment), isocyanate treatment, acrylation, permanganate treatment, acetylation, silane treatment and peroxide treatment with various coupling agents and other pre-treatments are specific methods that have achieved various levels of success for improving fibre strength, fibre fitness and fibre-matrix adhesion(Cristaldi et al., 2010).

However, according to Cristaldi et al., (2010) it is found that most of the chemical treatments may decrease the fibre strength due to the extensive delignification and degradation of cellulosic chains during exposure to the chemical substances. Only silane and acrylation treatment does not break the bond structure, but creates strong covalent bonds, which consequently enhances the stiffness of the fibre. Another research on the effect of surface treatment on the mechanical properties of flax fibres showed that silane, benzoylation and peroxide pre-treatment improved the surface properties of the fibres and led to a higher tensile strength than that of untreated flax (Wang et al., 2007). On the contrary, it is proved that alkali treatment can pro-





2.65 SEM micrograph of the untreated sugar palm fibre (up)
2.66 SEM micrograph of the sea water treated sugar palm fibre (down)
(In: Ishak, M. R., Leman, Z., Sapuan, S. M., Salleh, M. Y., & Misri, S. (2009). The effect of sea water treatment on the impact and flexural strength of sugar palm fibre reinforced epoxy composites)

duce a drop in both tensile strength and Young's modulus of the fibres if a very high percentage treatment is adopted. This result is attributed to the damage induced in the cell walls and the excessive extraction of lignin and hemicellulose, which play a cementing role in the structure of the fibres.

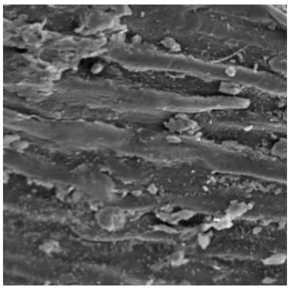
Chemical treatments have also raised concerns regarding their unsustainable and non-renewable nature, their toxicity and relatively high price. These reasons have forced scientists and engineers to search solutions through biological methods that substitute chemical treatment for fibre-matrix interfacial adhesion.

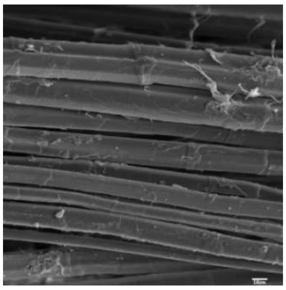
Ishak et al. introduce sea water treatment as a biologically based and sustainable low cost treatment that has minimum environmental impact and is safer than chemical methods. The research that investigates the effect of the treatment on the flexural and impact properties of palm fibre, proved that sea water improved the surface morphology of the fibres and thus the fibre-matrix interfacial bonding.

Drying phase

Fibres for further processing in biocomposites are washed under water after surface treatment and then dried, as moisture should be removed totally from the fibre. Drying processes used are based on removing moisture from the fibres through evaporation by means of heat. Temperatures should not be very high during drying in order to achieve better fibre quality. If the temperature is high, it can cause degradation of the material and reduction in quality (Tripathy, 2009).

Main drying methods for natural fibres are convection drying and microwave drying. Other drying methods, such as convection-microwave drying and microwave-vacuum drying consist combinations of the previous processes. However, drying is an energy consuming process which in addition with chemical surface treatment it increases the environmental impact and the cost of the natural fibres.





2.67 Untreated-undried flax fibres (right)
2.68 Silane treated- microwave oven dried flax fibres(left)
(In: Tripathy A. C. (2009) Characterization of Flax Fibres and the Effect of Different Drying Methods for Making Biocomposites)

2.10.3 UV-radiation resistance

Durability of natural fibres under exposure to ultraviolent light is of particular concern. Apart from moisture, lignocellulosic materials tend also to efficiently absorb sunlight which causes changes in the surface chemistry of the fibres and the resin, commonly known as photodegradation. According to Dence (1992), photodegradation of natural fibres is attributed to the degradation of its chemical structural components, and specifically lignin. Lignin degrades upon exposure to UV- by the formation of free radicals that cause oxidation of phenolic hydroxyls. Moreover, singlet oxygen (O2) that can be formed by oxygen quenching of photoexcited lignin allows degradation of lignocellulosic natural fibres. This happens because the formed singlet oxygen is a source of peroxides, compounds that contain oxygen, which can initiate the auto-oxidation of carbohydrates and fracture of lignin. The degradation ranges from mere surface discoloration (light-induced yellowing) which is mainly observed in indoor applications and can even reach loss of mechanical properties in outdoor conditions where the combination of light, moisture and temperature can destroy the lignocellulosic network.

To increase the ultraviolent resistance of natural fibres, various treatments, either based on biological processes or conventional chemical reactions, are available to be applied. Sparavigna (2008) suggests plasma polymerization methods as multi-purpose solutions for textile treatment. Characteristics that can be improved with plasma treatment include wettability, flame resistance, adhesive bonding, printability, electromagnetic radiation reflection, surface hardness, hydrophilic-hydrophobic tendency, dirt-repellent and antistatic properties.

Life cycle assesment

3.1 LCA approach

Life Cycle Assessment (LCA) is an environmental assessment technique with which, environmental aspects associated with the energy, materials and emissions of a product or process over its life cycle are assessed. The energy analysis includes four stages of a life cycle: material production phase, manufacturing phase, use phase, and end-of-life phase. The guidelines for an LCA study are defined by international ISO standards that suggest the subdivision of the study in four phases:

1. The goal definition and scoping
Establishment of the aim and scope of the study and clear definition of unit under examination and the method followed including boundary conditions, assumptions and limitations, chosen impact categories, type of information used and resources of data.

2. Life cycle inventory analysis (LCI)
Development of an Inventory that is including flows from and to nature (inputs, outputs) for a product system.

3. Life cycle impact assessment (LCIA)
Evaluation of the significance of potential environmental impacts over the eight impact categories listed in ISO/TR 14047:2003 (table 10).

4. Life cycle interpretation:
The results from the LCI and LCIA are summarized including the outcome of the study in a set of conclusions and recommendations.

3.1.1 Goal of the analysis

The subject of this study is a comparative qualitative life cycle assessment (LCA) on four fibres that can be used as reinforcement in fibre-reinforced composites: flax, jute, glass and basalt. The goal of the analysis is to draw conclusions in regards to the energy consumption and the environmental impact of the production of these fibres by evaluating their different production stages. As the fibres chosen are produced from renewable (flax, jute) and non-renewable (glass, basalt) resources, the study aims to prove whether this advantage of natural fibres is followed by efficiency in energy consumption and low environmental impact. Used information and data are based on published sources, such as researches and LCAs, whereas the Ecoinvent database provided significant data as well.

Table 3.1 The eight environmental impact classification factors (EICF) as outlined in ISO/TR 14047/2003 (2003).

Acidification	impact of acids that are emitted in the atmosphere and consequently deposited in soil and water
Aquatic toxicity/ Ecotoxicity	consequence of high concentrations of chemicals in air, soil and water which is responsible for contamination of eco-systems
Human toxicity	consequence of high concentrations of chemicals in air, soil and water on human health
Eutrophication	overfertilization of water and soil by excessive production of specific macronutrients (mainly Nitrogen and phosphorus)
Global warming/ Climate change	effect of increased reflected heat radiation by greenhouse gases (CO2, N2O, CH4 and volatile organic compounds: VOCs)
Depletion of resources	extensive consumption of abiotic non-renewable (mineral, fossil fuels and metal ores) and biotic renewable resources (deforestation, fishing, farming)
Ozone depletion	reduction of ozone in the stratosphere which results in more ultraviolent rays reaching Earth’s surface
Photochemical Oxidants	Excessive ozone formation by the degradation of VOCs in the presence of sunlight

3.2 Flax/Jute Fibre

3.2.1 Agricultural operations

As it was also mentioned in 2.1.2 From Plant to Fabric, flax fibre is the result of agricultural and fibre-processing process, which together with fertilizers and pesticides consist the primary energy consumption for fibre production. A typical production cycle of flax fibres includes the stages shown in the diagram 2.1. However, energy demand of some of these stages varies depending on different specific methods that can be employed. For instance, for ploughing (tillage) which prepares the land, conventional tillage (full tillage program), conservation tillage (reduced number of passes) or no-till can be used. Similarly, retting of the fibres includes a wide range of techniques such as warm-water retting, stand/de retting and bio-retting. Finally, the extensive use of agricultural machinery and fertilizers/pesticides adds to the production cost and the consumption of fuel. The table 1.1 shows the energy consumption of the agricultural operations of flax crop production.

Agricultural processes	1. Tillage 2. Drilling (planting) the seed 3. Weed control 4. Plant growth 5. Desiccation 6. Harvest
Fibre-processing processes	7. Rippling 8. Retting 9. Scutching/decortication 10. Hacking 11. Carding 12. Spinning

3.1 production stages for flax fibers (Turner 1987)

Table 3.2 Energy Consumption of Flax Crop Production

Garcia-Torres et al. 2002; Hood and Kidder 1992; Kastens 1997;
Lazarus and Selley 2005; Molenhuis 2001; Downs and Hansen 2006; Dhuyvetter and Kastens 2005)

Agricultural operation	No. of passes	Diesel consumption l/ha	Energy consumption GJ/tonne of yarn
Ploughing Moldboard	1	15.2	2.3
Ploughing—chiselFlax	1	9.0	1.4
No-till pass	1	0.9	0.2
Harrowing	1	5.9	0.9
Cultivating	1	4.9	0.7
Applying fertilizer	3	17.4	2.6
Spraying pesticides	3	3.9	0.6
Spraying desiccant	1	1.3	0.2
Harvesting	1	6.3	1.0
Swather	1	4.7	0.7
Baler	1	3.9	0.6

3.2.2 Fertilizers and pesticides

The use of fertilizers and pesticides is common and mechanized practice for most agricultural crop production. According to the Stern Review, fertilizer industry is the fifth most carbon- intensive industry and fourth in terms of energy intensity, consuming 13.31%, after electricity production (26.70%), gas distribution (42.90%) and refined petroleum (72.83%). Together with tillage operations, fertilizers and pesticides take about 70 % of the energy required for crop production whereas fertilizer alone accounts about 40 % (Gautam, 1979). Amongst fertilizers, nitrogen accounted for maximum energy input in crop production.

Nitrogen (N), phosphorus (P_2O_3), and potassium (K_2O) are the main fertilizers used for flax. Nitrogen-bearing fertilizers are the most energy-intensive input to modern agricultural production with values that vary from from 80 GJ/tonne to 130 GJ/tonne, whereas the energy required to manufacture phosphorus- or potassium-bearing materials is less per unit weight of nutrient than nitrogen fertilizers (table 2)(Dissanayake et al, 2009). However, these energy amounts could be reduced by the partial substitution of synthetic fertilizers by organic manure.

High nitrate and phosphate emissions contribute to increased eutrophication in local water-bodies and soil as nitrogen and phosphate are main nutrients for algae growth. Excessive production of such autotrophic microorganisms (algae, cyanobacteria) allows the increase of bacterial populations that subtract large amounts of oxygen. Low oxygen levels cause extensive deterioration of water quality which results in the loss of aquatic animals and hence disruption of the ecosystem. According to the LCA carried out by Turunen and van der Werf (2006, 2008), the nitrogen and phosphate emissions from the soil contributed about 90% of the global eutrophication with the remaining 10% coming from diesel combustion in field operations.

Flax is a crop that does not compete well with weeds, making essential an adequate weed control in order to obtain high yields. Weed control is achieved through the application of herbicides. Glyphosate (N-(phosphonomethyl)glycine) is a broad-spectrum systemic herbicide used to kill weeds. Pesticides are also products with high embodied energy, applied to protect the crop from various insects-pests that may infest flax by the time of emergence to maturity.

Finally, agricultural lime ($CaCo_3$) is mainly used during land preparation in order to improve soil fertility and plant growth by controlling pH level of the soil. Adding the embodied energies of the mentioned agrochemicals, gives an energy input that covers more than 80% of the total energy in agricultural operations of producing 1 tonne of flax yarn. However, as it was mentioned before there are alternative methods (manure as fertilizer, biological pesticides) for reducing these high energy amounts.

Table 3.3 Amount of Fertilizers and Pesticides Used and Embodied Energy
Dissanayake and Summerscales (2009)

Input	Ammount used [kg/tonne of yarn]	Embodied energy in material [GJ/tonne]	Embodied energy in yarn [GJ/tonne]
Lime	2,45	1,44	3,52
Ammonium nitrate	445,0	66,0	29,37
Triple superphosphate	238,0	14,0	3,33
Potassium chloride	368,0	9,0	3,31
Pesticides	9,40	240,0	2,26
Total			41,79

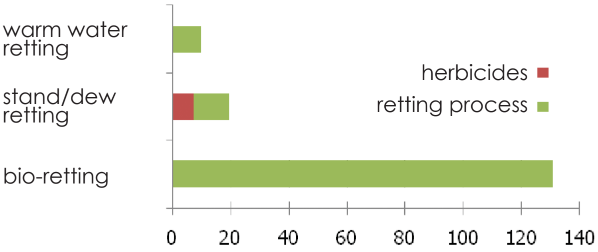
3.2.3 Fibre-Processing Operations

Harvesting of the plants is followed by rippling which is the removal of the flax seed capsules from the stalks. Nowadays, harvesters normally operate rippling during the harvest stage. After the crop is harvested retting is the first process at the fibre processing facility. There are different retting processes with varying energy consumptions. Warm water-retting, dew-retting and bio–retting are three commonly used methods. Enzymes may be also used to assist the retting process (Dissanayake and Summerscales, 2009).

Warm water-retting is the less energy consuming approach as the process is based on the establishment of good growth conditions for the development of natural micro-organisms, that are present on the plant from its growth stage and are responsible for retting the stalks by decomposing the pectin substances. However, the process generates a considerable amount of waste water (approximately94% of water used) which also contributes in water eutrophication. Turunen and van der Werf (2006, 2008) found that water-retting of hemp has contributed 13% of the total eutrophication, which is higher than other retting processes such as bio-retting and stand/dew retting.

3.2 Processing of water retting in a concrete retting pool. The bales of hemp sheaves are placed in the pool and secured with metal bars. The pool is filled with water and the stems are let in to ret for 5 days. (Van der Werf, H. M., & Turunen, L.,2008)

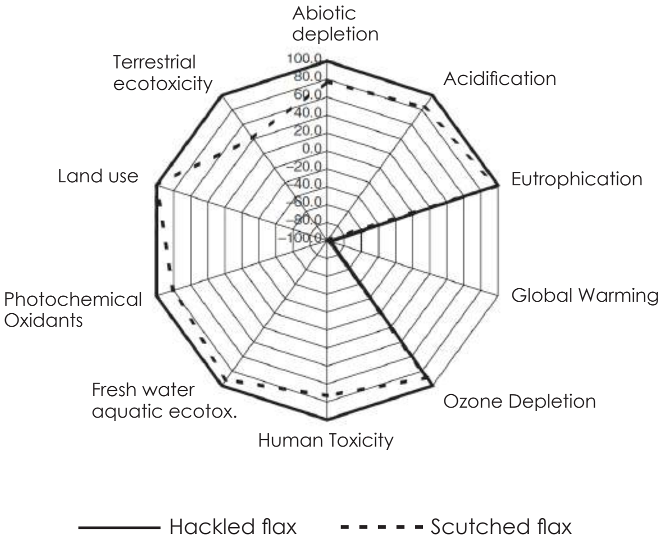
Bio-retting has the highest energy input in the fibre processing stage as it includes postharvest field operations, scutching, rinsing, drying, and mechanical softening in order to produce long fibers. Drying of the fibres after retting stands out as the most energy intensive part of the process. The values of energy consumption for retting followed by scutching are shown in diagram below.



3.3 Energy consumption in different retting and subsequent scutching processes
(Turunen and van der Werf 2006, 2008).

Retting is followed by scutching or decortication, a mechanical operation that breaks the woody core of the stems into small pieces (shives) without breaking the fibre and separates short tow fibres from long fibres by beating the broken stem with rotating blades (Turunen and van der Werf 2006, 2008).

Hackling or carding is the process that refines the raw fibre bundles that are in a form of coarse strands to produce sliver (see From plant to fabric). Textile sliver will be prepared for rove, bleached, and finally spun to produce yarn.



3.4 Influence of the hackling process on flax fibre environmental impacts
(Le Duigou, Davies and Baley, 2011)

Table 3.4 Comparison of environmental impacts for the production of hackled flax fibres and jute fibres.

Impact category	Hackled flax (Le Duigou et al.)	Jute fibre[1] (Ecoinvent data)
Acidification Potential [kg SO2 eq]	$2{,}20\ 10^{-2}$	$9{,}89\ 10^{-3}$
Aquatic Toxicity Potential [kg 1,4 DCB eq]	$5{,}90\ 10^{-2}$	$7{,}89\ 10^{-2}$
Eutrophication Potential [kg PO4 eq]	$1{,}40\ 10^{-3}$	$7{,}35\ 10^{-3}$
Global Warming Potential [kg CO2 eq]	1,40	$7{,}94\ 10^{-1}$
Human Toxicity Potential [kg 1,4 DCB eq]	$2{,}10\ 10^{-1}$	$1{,}10\ 10^{-1}$
Non-Renewable/Abiotic Resource Depletion [kg antimony eq]	11,70	$1{,}34\ 10^{-3}$
Ozone Depletion Potential [kg CFC 11 eq]	$2{,}40\ 10^{-8}$	$2{,}68\ 10^{-8}$
Photochemical Oxidants Creation Potential [kg formed ozone]	$7{,}30\ 10^{-5}$	$6{,}82\ 10^{-5}$
Land Use [m2/years/kg]	$8{,}40\ 10^{-1}$	1,98

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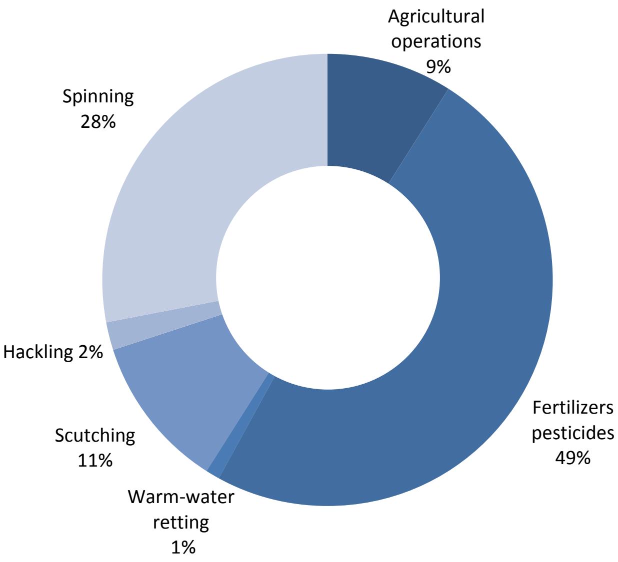
[1] Mainly manual cultivation of Jute from conventional production standards. Included steps are soil cultivation, pestizides fertilisation (mineral fertilizer), harvest, loading for transport and extraction of the fibres after retting process (hackling is not included)

Spinning is a major step in the fibre production process that produces filaments or yarns by twisting the slivers. The total environmental impact of a yarn increases significantly after spinning as the process requires large amounts of electric energy. Spinning techniques of bast fibres are generally classified into wet and dry spinning (Dissanayake and Summerscales, 2013). Nowadays, wet ring spinning is mainly operated rather than other techniques (open end rotor spinning and vortex spinning) due to the good quality of yarns, suitable for textile applications. (Turunen and van der Werf ,2006). 4

Table 3.5 Energy Consumption of Fibre-Processing Operations

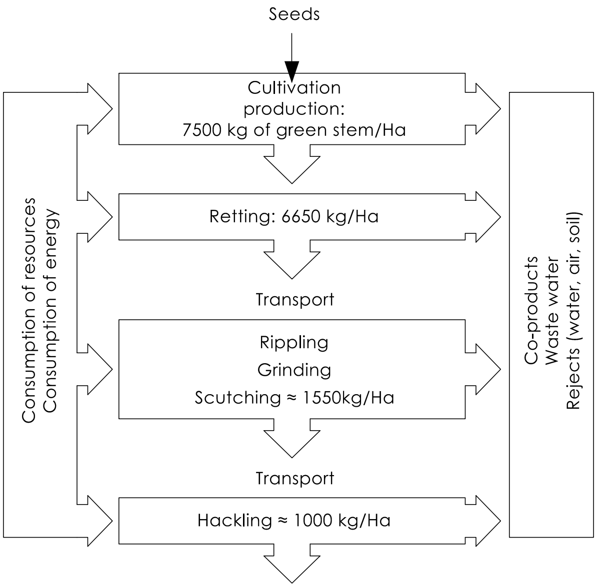
Turunen and van der Werf (2006, 2008)

Processes	Energy consumption [GJ/tonne of yarn]
Warm-water retting	0,59
Scutching	9,39
Hackling	2,23
Wet spinning	23,90



3.5 InTotal energy used in production of flax yarn

At the end of each process, total mass is reduced due to the production of co-products. As reported in the environmental impact analysis of the production of flax fibre by Dissanayake and Summerscales (2013), twenty-two tonnes of dry, green flax stems produce 1 tonne of flax yarn. Extensive loss of mass occurs by retting process in which the pectin substances are being decomposed. Co-products of bast fibre production are short fibre and shives, produced from scutching and hackling processes and used as animal bedding or in paper production. Dust that is also produced by these processes can be collected and consolidated as biomass fuel. The diagram below shows the mass reduction of flax fibre processing from cultivation until the step of hackling.



3.6 Diagram of flax fibre production, from the plant to the co-products, with yields (kg/ha)
(Le Duigou, Davies and Baley, 2011)

The main environmental impact of flax and jute fibre production is caused by the emission of greenhouse gasses during agricultural operations and fibre-production, the high nitrate and phosphate emissions by fertilizers and pesticides whereas extensive land use is also considered to have negative consequences to the environment. Primary sources of greenhouse gasses in the context of production of fibers include the following:

- Energy used to power agricultural equipment
- Energy used to produce and apply fertilizers and pesticides
- Releases of CO_2 from decomposition and oxidation of soil organic carbon (SOC) following soil disturbance
- CO_2 and CH_4 (methane) from retting
- Energy used in fibre-production processing
- Emissions resulting from transport for both types of fibre

Though, agricultural activity poses a positive environmental effect regarding global warming and climate change, which is the sequestration of CO_2

from the atmosphere by the process of photosynthesis. Photosynthesis allows plant growth by consuming CO_2 from the atmosphere and converting it by using solar energy to carbon in order to build the plant skeleton.

As previously stated eutrophication of local water bodies is a serious environmental impact of conventional agricultural activities that are supported by extensive synthetically-produced fertilizing (nitrogen, phosphorus, potasium-bearing fertilizers). Apart from the effect of fertilizing in water quality, soil pollution can be extensive, as well. In the study of Corbiere-Nicollier et al. (2001), cultivation of China reed, a bast-fibre crop cultivated for its fibre, had a dominant role effect to terrestrial ecotoxicity and human toxicity when cultivation of edible crops followed the reed in crop rotation system.

Tillage is another influential factor for soil quality. West and Marland (2002) stated that following notill method, the minimum tillage route, together with other practices such as efficient use of pesticides, irrigation, and heavy agricultural machinery, maintains the existing CO_2 storage in soil, enhances soil quality and decreases CO_2 emissions.

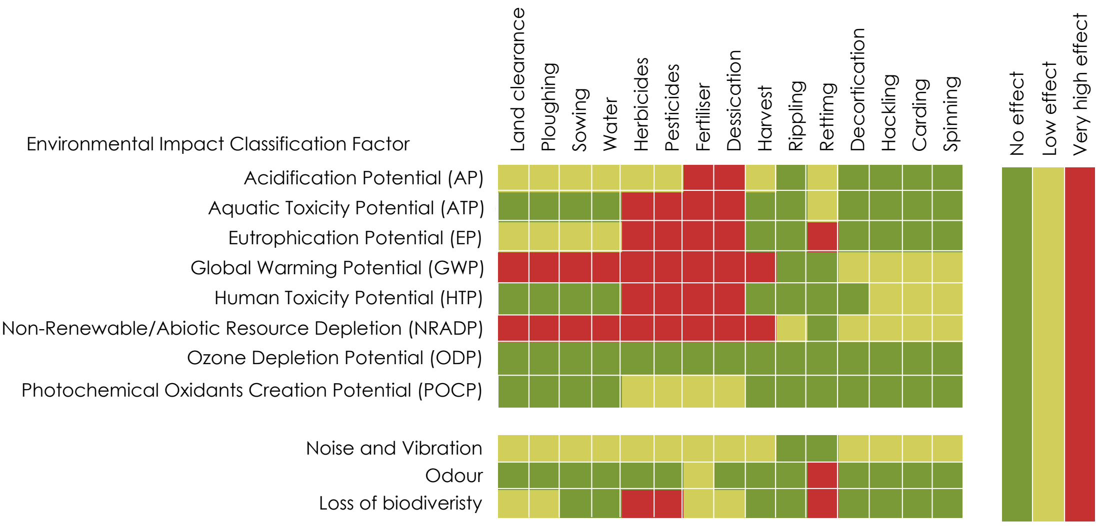
Land use (7 months per year for flax) is another inherent aspect of agricultural production that results in gradual reduction of habitats and biodiversity. Deforestation is a main consequence of increased on-land activity for agricultural or other activity. One solution that Le Duigou (2011) suggest for land use reduction is the improvement of production yields.

Finally, another crucial factor with significant environmental impact is transportation either as transfer of raw material and primary products during the production process or as shipping of final products. Optimization of transport distances between the different production units would reduce the embodied energy and CO_2 emissions. Yet, shipping which is a one of the largest sources of man-made CO_2, could be avoided by orienting textile or fibre-reinforced plastic production to locally available fibres or textiles. Environmental cost by extensive transportation is a main week point of jute fibre which grows only under the conditions of the tropical climate, in comparison with flax which is cultivated and processed in Europe.

3.2.4 Fabric production

Weaving and knitting are the two main methods for producing technical textiles and apparel fabrics from yarn. Weaving involves the interlacing of the yarns at right angles and in the technical textile industry it is used to create woven fabrics with different weaving patterns such as plain, twill or satin (see 2.3 Textiles). Knitting, which is based on looping the yarn around and through one another, is used for producing unidirectional and multiaxial textiles that are primarily used in fibre-reinforced polymes. In this knitting technique the yarns are maintained parallel and uncrimped by being knitted by a flexible stich.

As both weaving and knitting are mechanical processes, energy consumption is a significant parameter. Main factors that influence the energy intensity of these operations and result in different values are the energy requirements of the machinery or alter native techniques and the quality of the yarn. The table below shows different values of the energy intensity of weaving, whereas graph 2.65 shows the environmental impact of jute textile compared with jute yarn and jute fibre.



Environmental Impact Classification Factor	Land clearance	Ploughing	Sowing	Water	Herbicides	Pesticides	Fertiliser	Dessication	Harvest	Rippling	Rettimg	Decortication	Hackling	Carding	Spinning
Acidification Potential (AP)	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟩	🟨	🟩	🟩	🟩	🟩
Aquatic Toxicity Potential (ATP)	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Eutrophication Potential (EP)	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩
Global Warming Potential (GWP)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟨	🟨	🟨	🟨
Human Toxicity Potential (HTP)	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟨	🟨	🟨
Non-Renewable/Abiotic Resource Depletion (NRADP)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟨	🟨	🟨	🟨
Ozone Depletion Potential (ODP)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Photochemical Oxidants Creation Potential (POCP)	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Noise and Vibration	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨
Odour	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
Loss of biodiveristy	🟨	🟨	🟩	🟩	🟥	🟥	🟨	🟨	🟩	🟩	🟥	🟩	🟩	🟩	🟩

🟩 No effect
🟨 Low effect
🟥 Very high effect

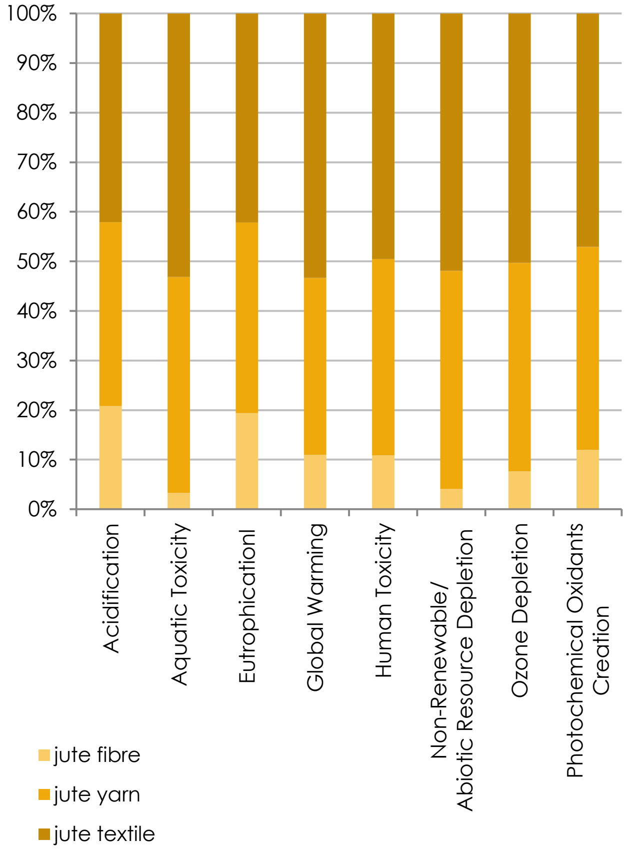
3.7 Trade off matrix of the environmental impact of the agricultural operations and fibre-production processes for flax fibre (Dissanayake and Summerscales, 2009)

However, apart from energy use, weaving involves another environmental concern: prior to the actual weaving the warp is treated by sizing agents that are applied in order to lubricate and protect the warp during weaving. These agents are removed by a finisher after the end of the operation. According to Turunen and van der Werf (2006), the environmental impact of this finishing step is associated with emissions to water by the employment of chemicals and auxiliaries (1kg per kg of processed textile).

It becomes clear that calculating the embodied energy and the environmental impact of a product is a complex procedure that requires detailed knowledge of all the energy inputs and co-product outputs. Alternative techniques, different energy resources (nuclear, fossil fuel, renewable), production of co-products and the analysis method followed are some of the parameters that create a significant deviation between the published values. Table 2.1 shows different published values of flax and jute products. It is noticeable that the results of Dissanayake et al. indicate much higher non-renewable energy consumption values, around 59 GJ/T for flax fibre. This difference can be attributed to the lower production yield used (6000 kg/ha compared with 7500 kg/ha used in the study of Turunen and van der Werf), the different energy source (for instance French energy has a high percentage of nuclear energy compared to United Kingdom) and the fact that the co-products are considered as waste products.

Table 3.6 Different published values of weaving energy consumption

Source	Energy consumption [GJ/tonne]
Koç & Çinçik	18
Pandita et. al.	30
Turunen & van der Werf	15-27

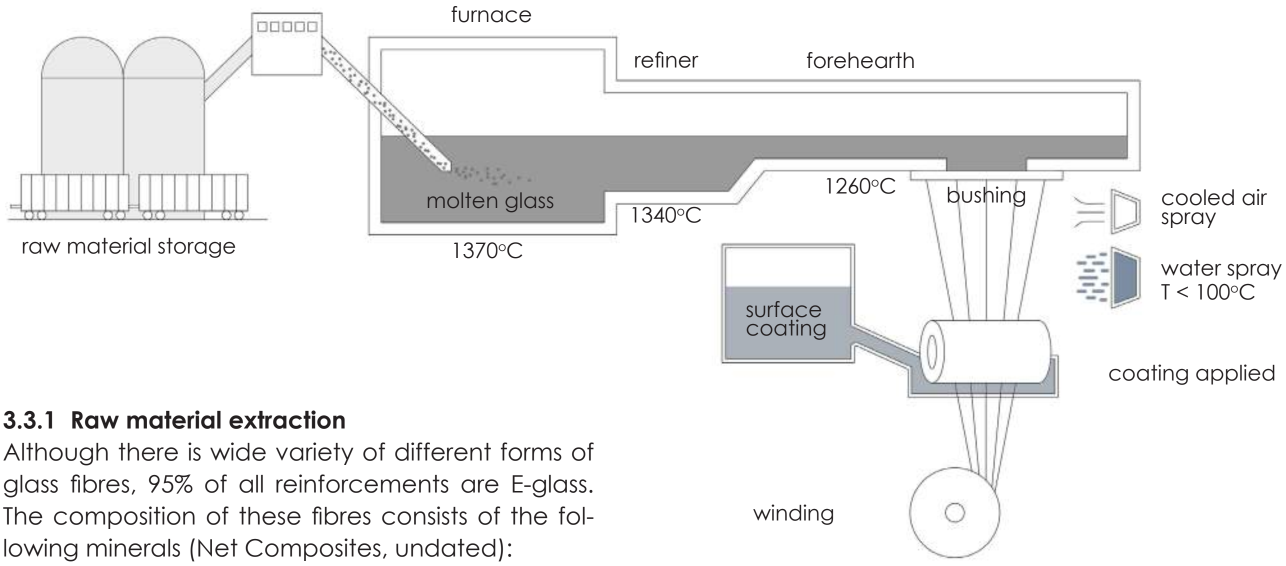


3.8 Comparison in environmental impact of jute fibre, yarn and textile production process (Ecoinvent database)
The values of each production step are added to the values of the following production step.

Table 3.7 Different published values of flax and jute products

Source	Product	Energy consumption [GJ/tonne]
Dissanayake & Summerscales	Flax fibre (sliver)	59,3
	Flax yarn	85,4
Turunen & van der Werf	Hackled flax fibres	11,7
González-García et. al.	Flax sliver	12,4
CES EduPack 2014 (Granta Ltd)	Flax sliver	10,5 - 11,6
	Jute yarn	30,3 - 33,5
Ecoinvent database	Jute sliver	2,83
	Jute yarn	24,9
	Jute textile	30,5

3.3 Glass fibre



3.9 Glass fibre production processes

3.3.1 Raw material extraction

Although there is wide variety of different forms of glass fibres, 95% of all reinforcements are E-glass. The composition of these fibres consists of the following minerals (Net Composites, undated):

- Sand - particles of minerals including quartz (silica: SiO2), mica (complex silicates usually with K, Na, Li, H, and Mg), and feldspar (aluminum silicates with varying amounts of K, Na, Ca, and Ba). Although sand used in glass fibre production is an abundant and naturally occurring raw material, it should be considered as a non-renewable resource and be conserved by reduced use (Waste & Resources Action Programme 2006).

- Kaolin - hydrated aluminum silicate (Al_2O_3•-$2SiO_2$•$2H_2O$)

- Limestone - mostly calcium carbonate ($CaCO_3$) with other oxides (Si, Al, Fe), carbonates (Fe, Mg), and calcium phosphate

- Colemanite - hydrated calcium borate (2CaO• $3B_2O_3$•$5H_2O$) (Tottle 1984).

After extraction, the raw materials are transported either by rail car and track or by drums and packaged, depending on the volume of the supply. The materials are unloaded by various methods, including drag shovels, vacuum or vibrator/gravity systems and conveyed to storage piles and silos by belts and bucket elevators. The next step is weighing of the material in order to achieve the exact quantities of the ingredients that the product recipe requires prior to mixing (batching). Batching is an automated process, using computerized weighing units and enclosed material transport systems. After well blending of the materials, they are processes into the melting unit. Weighing, mixing, and charging operations may be conducted in either batch or continuous mode.

3.3.2 Fibre processing operations

Melting of the raw material into high-temperature glass melting furnaces follows after mixing. Melting furnaces are normally large, shallow, and well-insulated vessels that are heated from above. Temperatures ranging from 1500 to 1700°C heat and transform the raw material through a sequence of chemical reactions into molten glass. In operation, raw materials are introduced continuously on top of a bed of molten glass, where they slowly mix and dissolve. Mixing is effected by natural convection, gases rising from chemical reactions, and, in some operations, by air injection into the bottom of the bed.

Table 3.8 Energy Consumption of glass fibre Glass fibre mat production

Diener and Siehler (1999)

Processes	Energy consumption [GJ/tonne]
Raw materials	1,70
Mixture	1,00
Transport	1,60
Melting	21,50
Spinning	5,90
Mat production	23,00
Total	54,70

There are four different types of glass melting furnaces, depending on their fuel source and heat application, known as: recuperative, regenerative, unit, and electric melter. The recuperative, regenerative, and unit furnaces can be fueled by either gas or oil. Recuperative furnaces use a steel heat exchanger, recovering heat from the exhaust gases by exchange with the combustion air. Regenerative furnaces use a lattice of brickwork to recover waste heat from exhaust gases, whereas electric furnaces melt glass by passing an electric current through the melt. Finally, unit melters are used only for melting glass by operating the "indirect" glass marble melting process, a process in which molten glass is sheared and rolled into marbles.

Molten glass in extruded through microfine bushings in order to produce filaments of 5–24 μm in diameter (Net Composites, undated). Bushing plates are heated electronically, and their temperature is precisely controlled to maintain a constant glass viscosity. As the filaments exit the bushing plate with a temperature of approximately 1204oC, they are cooled down by water jets, a process called attenuation. Then the molten streams are drawn by a high-speed winder which revolves them at a circumferential speed of ~2 miles/~3 km per minute. As this speed is much faster than the speed that molten glass exits the bushings, tension is applied by the winder, which is drawing molten glass into thin filaments.

The final stage of the fibre production includes surface treatment with the application of chemical coating. This coating or size is typically added at 0.5 to 2.0 percent by weight and may include lubri cants, binders and coupling agents. The lubricants are applied on fibres produced for technical textile used as reinforcement as they protect the filaments from abrading and breaking during collection and wounding into packages and, later, during weaving or other fabric production processes. Coupling agents are usually organofunctional silanes that make the fibre more compatible with particular resin chemistry, improve resin wet-out and promote fiber-matrix adhesion.

3.10 Cooling down of molten glass filaments by water jets (http://binaniindustries.com)

It is noticeable that production of glass fibre involves energy-consuming processes. Considering the environmental impact of the production of glass fibre the primary sources of greenhouse gases during the process include the following: (Dissanayake and Summerscales, 2009):

- Energy used in glass melting and spinning
- Energy used in fiber forming and curing
- Emissions from glass melting, VOCs, raw material particles, and small amounts of CO, NOx, SOx, and fluorides

Table 3.9 Different published values of glass fibre and glass fibre mat energy consumptions

Source	Product	Energy consumption [GJ/tonne]
Le Duigou et. al.	glass fibre mat	45
Diener & Siehler	glass fibre glass fibre mat	25,8 54,7
Corbiere-Nicollier et. al.	glass fibre	48,33
Song et. al.	glass fibre	13 – 32
CES EduPack 2014 (Granta Ltd)	glass fibre	62,2 - 68,8

Table 3.10 Comparison of environmental impacts of sand extraction and the production of glass fibres
Le Duigou, Davies & Baley (2011), Ecoinvent database

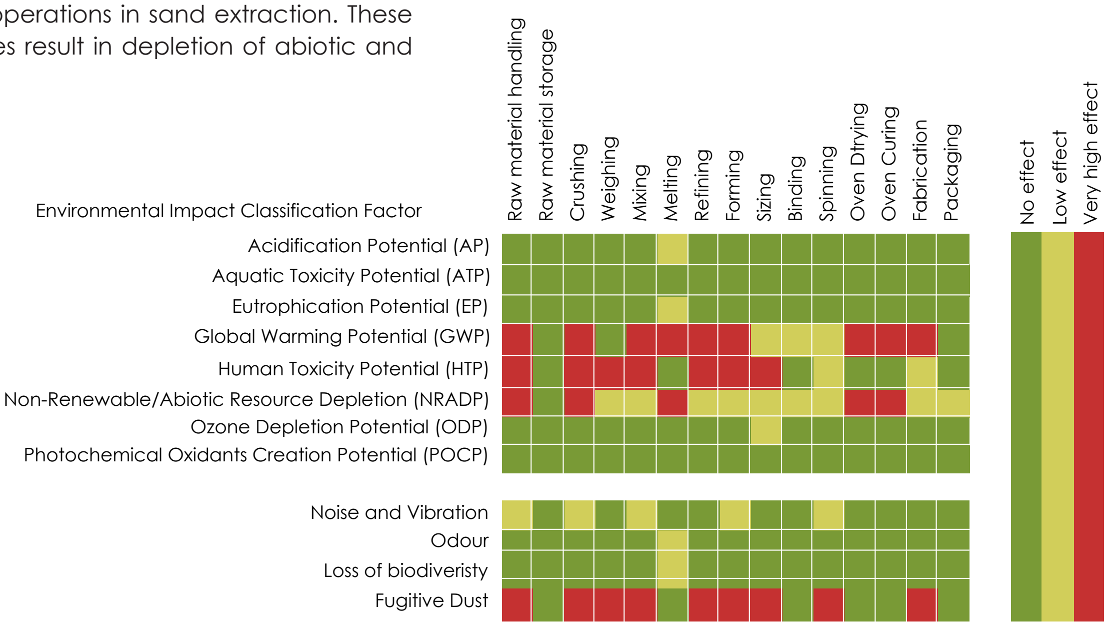
Impact category	Sand extraction[1]	Glass fibre
Acidification Potential [kg SO2 eq]	$1{,}51\ 10^{-5}$	$1{,}60\ 10^{-2}$
Aquatic Toxicity Potential [kg 1,4 DCB eq]	$6{,}79\ 10^{-4}$	$1{,}70\ 10^{-1}$
Eutrophication Potential [kg PO4 eq]	$2{,}34\ 10^{-5}$	$1{,}20\ 10^{-3}$
Global Warming Potential [kg CO2 eq]	$2{,}53\ 10^{-3}$	2,65
Human Toxicity Potential [kg 1,4 DCB eq]	$1{,}94\ 10^{-3}$	9,10
Non-Renewable/Abiotic Resource Depletion [kg antimony eq]	$1{,}62\ 10^{-5}$	45,00
Ozone Depletion Potential [kg CFC 11 eq]	$2{,}82\ 10^{-10}$	$2{,}00\ 10^{-7}$
Photochemical Oxidants Creation Potential [kg formed ozone]	$4{,}91\ 10^{-7}$	$6{,}0010^{-4}$
Land Use [m2/years/kg]	$4{,}89\ 10^{-4}$	$7{,}00\ 10^{-3}$

[1] Includes the whole manufacturing process for digging of gravel round and sand (crushing not included), internal processes (transport, etc.), and infrastructure for the operation (machinery)

Emissions, such as are fugitive dust and raw material particles, are also generated during raw materials handling phase at the transfer points. Such a point would be where sand pours from a conveyor belt into a storage silo. In order to control such emissions, wet or moist techniques and fabric filters are employed. Emissions during glass melting and refining include, volatile organic compounds from the melt, raw material particles entrained in the furnace flue gas, and, if furnaces are heated with fossil fuels, combustion products. Furnaces using electric energy generally have the lowest emission rates in comparison with other furnaces, due to the lack of combustion products. Variation in emission rates among furnaces is based on the operating temperatures, raw material compositions, fuels, and flue gas flow rates. Emission control for furnaces is primarily achieved by fabric filtration.

Soil erosion and compaction is an issue associated with dredging operations in sand extraction. These on-land activities result in depletion of abiotic and biotic resources. According to Van Oers et al. (2002) the relative contribution to the depletion of abiotic resources by the extraction of the consisting materials of glass fibre, is low due to the abundance of these elements. However, such on-land operations affect biotic resources through reduction of natural habitats and biodiversity.

Glass fibre production may involve significant transport distances between the raw materials source, the industrial-scale production unit and the customer. Diesel used in transportation and running machinery has potential contaminants of concern including carbon monoxide (CO), nitrogen dioxide (NO2), and sulfur dioxide (SO2). The direct impacts of these gases and pollutants include toxicity, global warming, acidification, human toxicity and ozone layer depletion.



Environmental Impact Classification Factor	Raw material handling	Raw material storage	Crushing	Weighing	Mixing	Melting	Refining	Forming	Sizing	Binding	Spinning	Oven Dtrying	Oven Curing	Fabrication	Packaging
Acidification Potential (AP)	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Aquatic Toxicity Potential (ATP)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Eutrophication Potential (EP)	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Global Warming Potential (GWP)	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟩
Human Toxicity Potential (HTP)	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟩	🟩	🟨	🟩
Non-Renewable/Abiotic Resource Depletion (NRADP)	🟥	🟩	🟥	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨
Ozone Depletion Potential (ODP)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Photochemical Oxidants Creation Potential (POCP)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Noise and Vibration	🟨	🟩	🟨	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Odour	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Loss of biodiveristy	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Fugitive Dust	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟥	🟩

No effect	Low effect	Very high effect
🟩	🟨	🟥

3.11 Trade off matrix of the environmental impact of the fibre-production processes of glass fibre (Dissanayake and Summerscales, 2009)

3.4 Basalt fibre

3.4.1 Raw material extraction

Due to its natural origin basalt is found in different compositions and classified according to the content of SiO2. Thus only compositions with SiO2 content about 46% (acidic basalts) are adequate for producing continuous filaments. After the rocks are extracted, quarried basalt is crushed on site into smaller particles (5-20 mm) by mobile crushing equipment.

Crushing is normally processed into two steps: primary and secondary. Quarried basalt is fed towards the jaw crusher by vibrating feeder in order to operate a primary crushing. Soon after the initial crush, the stones are transferred by belt conveyor to a cone crusher for the secondary crushing. Then the particles that meet the size requirements are washed, loaded and transported to be stored otherwise they are processed again to the cone crusher.

3.12 Basalt three-stage crushing line
(http://stonecrusherplantquote.com)

3.4.2 Fibre processing operations

Similar to glass, basalt fibre is produced in a continuous process. Crushed raw material is transported into the melting furnace by a loader. However, in contrast to glass fibre which consists of several elements that are mixed in the melting furnace, basalt has a simple composition that requires no secondary materials, thus the single feed line carries only crushed basalt. This contributes in shortening the entire process as prior preparation of various ingredients by weighting and mixing is not needed.

Inside the furnace basalt reaches its melting point at 1500oC (Ross, A., 2006). Molten basalt is non-homogeneous in nature and shows non-uniform temperature distribution during production stage. Additionally, unlike transparent glass, opaque basalt absorbs infrared energy rather than transmits. These properties make difficult the uniform heat distribution by conventional glass furnaces as the material has to stay in the furnace for extended periods of time in order to ensure uniformity. Therefore, basalt producers have developed several strategies including the immersion of electrodes in the bath or division of melting process into separate heating zones. According to Nefedov (2014) electroarc basalt melting furnaces have average power expenses 25,5 GJ/tonne.

After molten basalt is evenly heated, continuous filaments with diameter 9~15 microns are formed by passing through platinum alloy holes of bushing. The filaments are then drawn from the melt and lubricated with silane-based sizing agents for

Table 3.11 Environmental impact of basalt Mining Stage/Crushing/Washing/Classification
Ecoinvent database

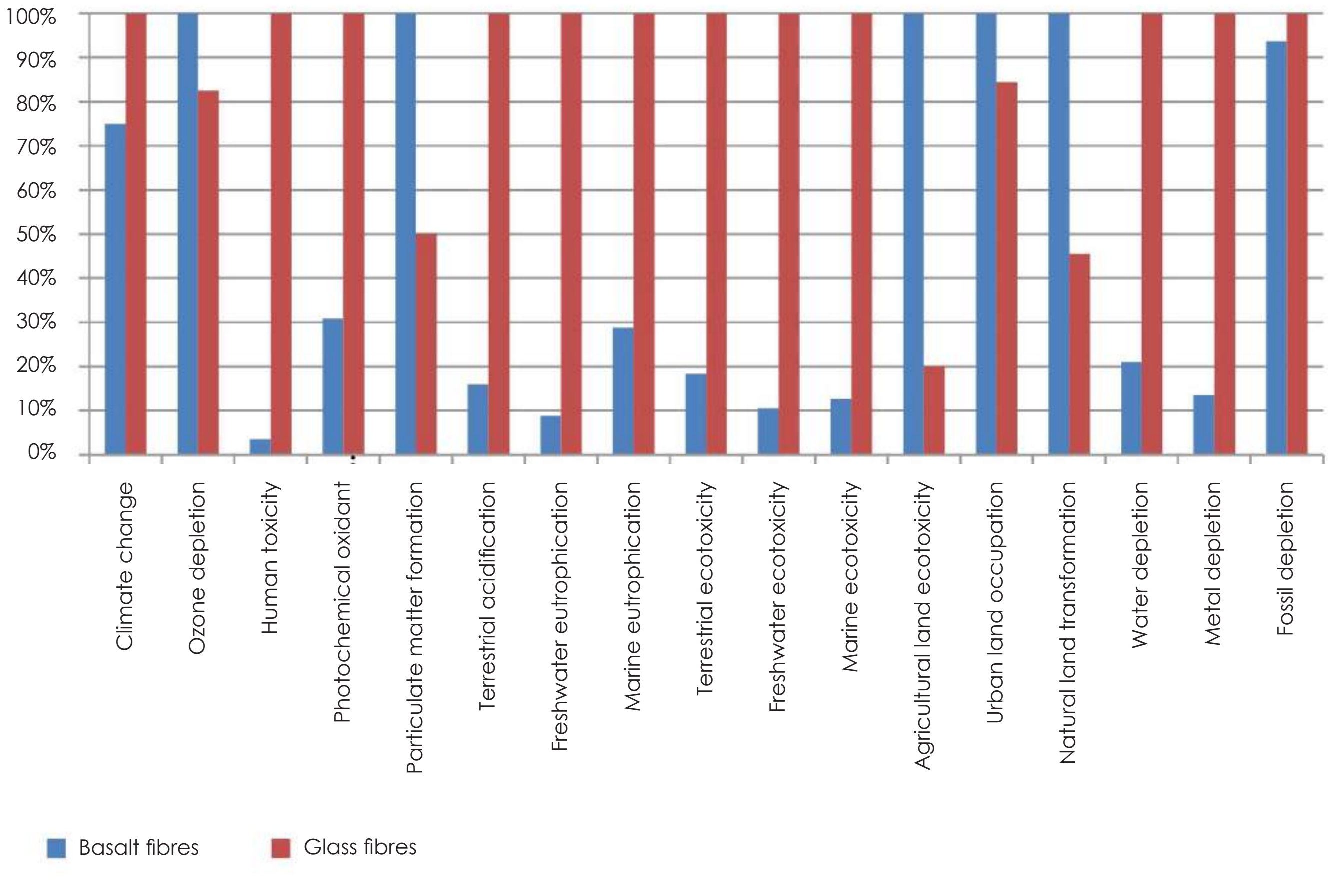
Impact category	Basalt
Acidification Potential [kg SO2 eq]	6,62 10^{-5}
Aquatic Toxicity Potential [kg 1,4 DCB eq]	2,14 10^{-3}
Eutrophication Potential [kg PO4 eq]	1,12 10^{-4}
Global Warming Potential [kg CO2 eq]	7,86 10^{-3}
Human Toxicity Potential [kg 1,4 DCB eq]	9,70 10^{-3}
Non-Renewable/Abiotic Resource Depletion [kg antimony eq]	5,26 10^{-5}
Ozone Depletion Potential [kg CFC 11 eq]	6,78 10^{-10}
Photochemical Oxidants Creation Potential [kg formed ozone]	1,13 10^{-6}
Land Use [m2/years/kg]	8,08 10^{-3}

lubricity, integrity and resin compatibility. Finally, filaments are taken by the winders, by which rovings of continuous basalt fibre are formed. As reported by the Italian national agency for new technologies energy and sustainable economic development (enea) in 2011, the total energy requirement for the production of basalt fibre is 17,85 GJ/tonne.

Concerning environmental impact, basalt fibre poses a strong characteristic compared to glass. Having a natural origin, basalt fibre is non-toxic, which consequently results in low values of human, terrestrial and aquatic toxicity. In contrast, glass fibre is linked with hazardous health effects. This is also proved in the life-cycle assessment performed by the Flemish Institute for Technological Research (VITO) in Belgium in collaboration with Basaltex, a Belgian company that produces technical basalt textiles. The result of this assessment, shown below, presents a significant difference between the impact of basalt and that of glass regarding factors that are linked with toxicity.

Easy recyclability is another dominant characteristic over glass fibres. Basalt fibres have excellent thermal properties compared to that of E-glass and can easily withstand the temperature of 1100oC – 1200oC for hours continuously without physical damage as the melting point is reached at about 1400°C. This exceptional resistance to fire allows for extraction of fully usable basalt after incineration of a composite material. In the contrary, a principal problem of glass fibre recycling is that they melt during incineration, sticking to the inside of the incineration chamber.

3.13 Comparative environmental impact of basalt roving fibres and glass fibre
(Flemish Institute for Technological Research (VITO) & Basaltex, 2011)



3.5 Conclusions of LCA

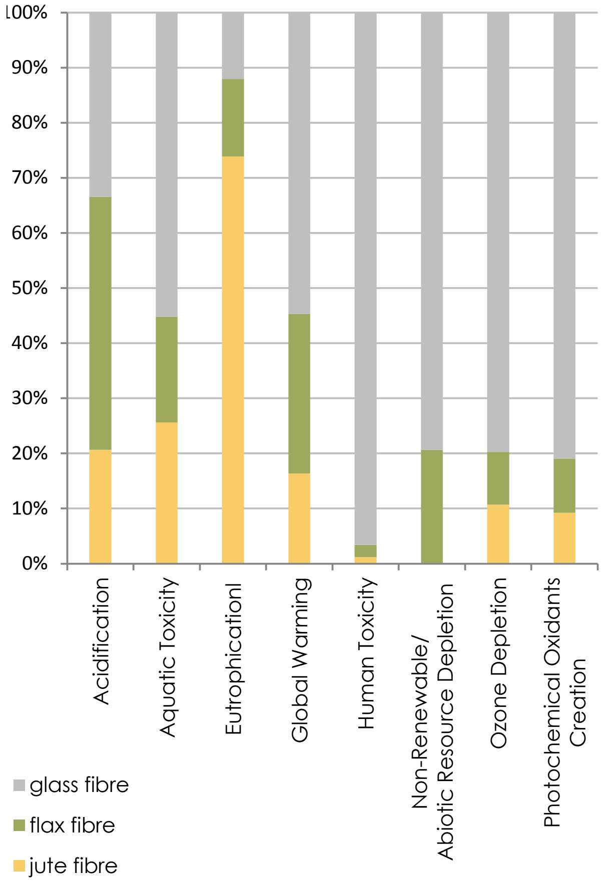
Analysing the steps of the fibre production operations for natural fibres and man-made resulted in the energy consumption and the environmental impact of the four examined fibres. These results were critical for the outcome of this project, mainly regarding the use of natural fibres as sustainable reinforcement in bio-composites. The LCA finally showed that production of textiles from natural fibres can also be an energy consuming process and reach or even exceed the embodied energy levels of artificial fibres.

Considering the environmental impact of natural fibres, fertilizing proved to be a serious contribution on climate change and eutrophication of water. Retting of the fibres was also linked with similar effects. Thus, it becomes clear that only under specific circumstances natural fibres can be considered as an essentially sustainable solution. Graph 2.66 shows a comparison of the environmental impact of glass, flax and jute fibres.

Environmentally orientated agriculture is the ideal way to reduce the potential environmental impact of natural fibres. Preserving and improving water quality and resources, controlling soil erosion/compaction, preserving physical/ chemical/ biological soil quality and air quality, preserving biodiversity and reducing energy consumption by using renewable energy sources are practices that sustainable agriculture should promote. Specifically, environmental credentials for flax fibre production could be improved by adopting no-till method for preparing the ground, using organic agrochemicals and achieving biological control of pests with traditional water retting.

Spinning of the sliver fibre in order to produce yarns is also an energy consuming process. Therefore, is more efficient to use natural fibre as reinforcement in the form of mats rather than woven or knitted fabrics. In conclusion the validity of the sustainability of natural fibres depends on the processes followed for production and the form of the chosen reinforcement.

Regarding artificial fibres, production of glass and basalt fibre is associated with high energy consumption due to melting the crushed materials. However, technological advancements focus on-improving the energy intensity of such processes.



3.14 Comparative environmental impact of glass, flax and jute fibre

Digital control of the process allows for measuring and managing the precise temperature of the glass as it moves through the furnace as well as the gas and oxygen flow rates. Control of oxygen flow rates is crucial advantage of newly developed furnaces because nearly pure oxygen is burned instead of air. This helps the natural gas fuel to burn cleaner and hotter, melting glass more efficiently. It also lowers operating costs by using less energy and reduces nitrogen oxide (NOx) emissions by 75% and carbon dioxide (CO_2) emissions by 40%.

Resins

4.1 The discovery and development of polymers

The demand for a long-lasting synthetic material, able to overcome the defects that natural materials show over the years, easy to be produced and available to everyone, was expressed centuries ago. The dream of the invention of such a material was becoming more realistic and feasible with the gradual evolution of practical alchemy into theoretical chemistry during the 17th and 18th centuries and the development of chemistry as one of the leading sciences of the Industrial Revolution in the 19th century. At the same time, the mass production as a result of the industrialization called for new materials that would replace the natural and thus expensive ones, as well as for new production technics.

In 1870 the American book printer John Wesley applied a patent for the technical process he had developed for producing celluloid. Being nowadays concerned as the first thermoplastic, celluloid was an easily molded and shaped polymer compound which consisted of nitrocellulose and camphor. However, two decades before Wesley had introduced his technical method, there was already a similar compound, called Parkesine, presented by Alexander Parkes at the 1862 World Exposition in London, which did not succeed due to its rapid crack formation.

By the end of the 19th century the French scientist Hilaire de Chardonnet set the beginning for the production of synthetic fibres by inventing artificial cellulose-based fibres that aimed at substituting the expensive natural silk. Though, as it was made from cellulose the product was characterized by a high degree of flammability, and therefore it was unsuccessful.

A few years later at the beginning of the 20th century another important step was done with the development of an ultrathin transparent foil by the Swiss chemist Jacques Brandenberger. Cellophane, as it was named by the word cellulose and diaphane (transparent) intended to become a cloth that would be able to repel liquids rather than absorb them. Finally, the product found a variety of applications and it is still used nowadays for packaging.

4.1 George Eastman, the founder of the Kodak company, started producing roll film made from celluloid in 1889 and thus made photography accessible to the masses (http://nice-cool-pics.com/)

4.2 Transparent flat cellophane sheets (http://www.asia.ru/)

During the same decade, in 1907, the Belgian chemist Leo Baekeland managed to develop the first completely man-made polymeric product based on synthetic raw materials: Bakelite. Bakelite is mostly consisted of phenol and is formed from an elimination reaction of phenol with formaldehyde. The product was used for its electrical non-conductivity and heat-resistant properties in electrical insulators, radio and telephone casings, and other products such as kitchenware, jewelry, pipe stems and children's toys.

In general, over the first decades of the 20th century research into chemistry was transforming gradually from individual experiments done by creative chemists, such as the previously mentioned ones, into scientific projects developed in large research departments. One product that was created in this way is nylon, the first completely synthetically pro

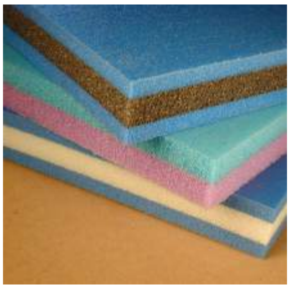
4.3 A 1949 Bakelite black and white television (http://i.dailymail.co.uk/)

4.4 Nylon filament yarn (http://img.diytrade.com/)

duced and commercially exploited synthetic fibre. Nylon is a thermoplastic material with polyamide structure (repeated amide bonds). It was first produced in 1935, by Wallace Carothers at the DuPont Experimental Station and it was the result of 11 years of research, while 230 other members involved in the research team. Nylon fibres were first used commercially in 1938 in a nylon-bristled toothbrush, followed more famously by women's stockings after being introduced as a fabric at the 1939 New York World's Fair.

At the same time, in 1939, another group of researchers in I.G.-Fraben industie AG plant in Berlin managed to produce a polyamide fibre with very similar structure, which they called "perlon". Although these synthetic fibres were developed originally for clothing, they found application as the main material for parachutes during the Second World War. One year later, in England (1940) polyester fibres were developed by J. R. Whinfield and J. T. Dickinson, which are still used today in membrane structures.

4.5 PVC tubes
(http://truewellpipes.com/)



4.6 Polyethylene foam panels
(http://www.8linx.com/)

4.7 Sliced polyurethane foam
(http://www.pasprayfoam.com/)

Another very influential polymer of the century, which is nowadays considered as the third-most widely produced plastic, is the polyvinyl chloride, or PVC. As early as 1912, chemists Ivan Ostromislensky and Fritz Klatte, researchers at the German chemical company Griesheim-Elektron, patented a method to produce PVC. However, difficulties in processing the rigid and sometimes brittle polymer blocked their plans to commercialize their product. Mass-production of the material happened only after Waldo Semon and the B. F. Goodrich Company developed a method in 1926 to plasticize PVC by mixing it with various additives. The result was a more flexible and more easily processed material that soon achieved widespread commercial use.

It becomes clear that during the 20th century polymer chemistry, as part of the field of the material science, saw great advance and changed our everyday life. Specifically, it was the middle of the century when the majority of the polymers we know nowadays, appeared and briefly, they are the following:

Polymethyl methacrylate (acrylic sheet), 1933

Polyethylene (PE), 1933

Polyurethane (PUR), 1937

Polyamide (PA), 1938

Unsaturated polyester (UP), 1941

Polytetrafluoroethylene (PTFE, Teflon), 1941

Silicone, 1943

Epoxy resin (EP), 1946

Polystyrene (PS), 1949

High-density polyethylene (PE-HD/HDPE), 1955

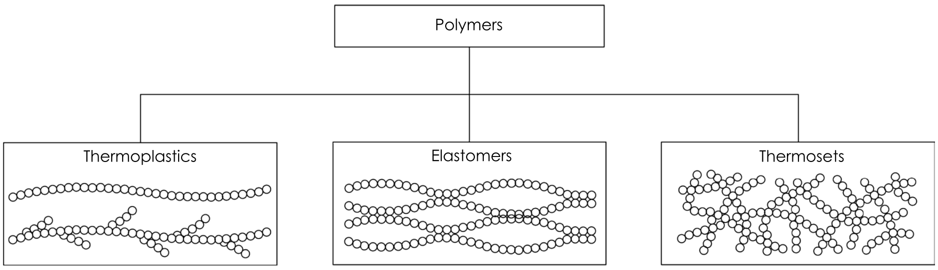
Polycarbonate (PC), 1956

Polypropylene (PP), 1957

Ethylene tetrafluoroethylene (ETFE), 1970

4.2 Classification of polymers (resins)

The polymers are normally categorized according to the way in which the organic molecules are bonded together, which affects their physical properties. Polymers are divided into three groups: Thermoplastics (or thermosoftening plastics), Thermosets (or thermosetting plastics) and Elastomers



4.8 Molecular structure of thermoplastics, elastomes and thermosets (Knippers et. al, 2011)

4.2.1 Thermoplastics

Thermoplastics are polymers that generally exhibit relatively low strength and low heat resistance as their molecules are not cross-linked. They become moldable when they reach a specific temperature and they can turn solid again when they are cooled down. This ability to be repeatedly remoulded without deterioration of the initial properties is a great advantage for industrial manufacturing and recycling. Therefore, the majority of our everyday plastic objects, including packaging, are made from thermoplastics. Common thermoplastic polymers include nylon, polyethylene, polypropylene, polystyrene, polyvinyl chloride and Teflon.

4.2.2 Elastomers

Elastomers are polymers with viscoelasticity (both viscous and elastic) and they cannot be melted again once they have been produced as the molecules of such polymers have cross-linked bonds. Each of the monomers which link to form the polymer is usually made of carbon, hydrogen, oxygen and/or silicon. The raw material for elastomers is tough crude rubber, which is made elastic by cross-linking. However, as they have low young's modulus they are inappropriate for structural applications and thus they are preferred to be used as seals in joints, adhesives or bearing pads in constructions. One main application is also in the automotive industry as common vehicle tires.

4.2.3 Thermosets

Thermosets are polymers with even denser cross-linked molecular bonds than elastomers. For that reason they present higher strength, better durability compared with other types of polymers while they can be highly heat resistant. However, they cannot be melted down again after curing. Before curing they are usually liquid and after they are heated up and reach a specific temperature they become permanently hard and can no longer be melted back to a liquid form. Consequently, they are bot recyclable. As they are generally harder and stronger than thermoplastics they are used in advanced composite materials for structural applications, such in aerospace engineering. Bismaleide resins (BMIs), Polyimide and Epoxies are some of the thermosets, but the epoxy resin is the most commonly used thermoset.

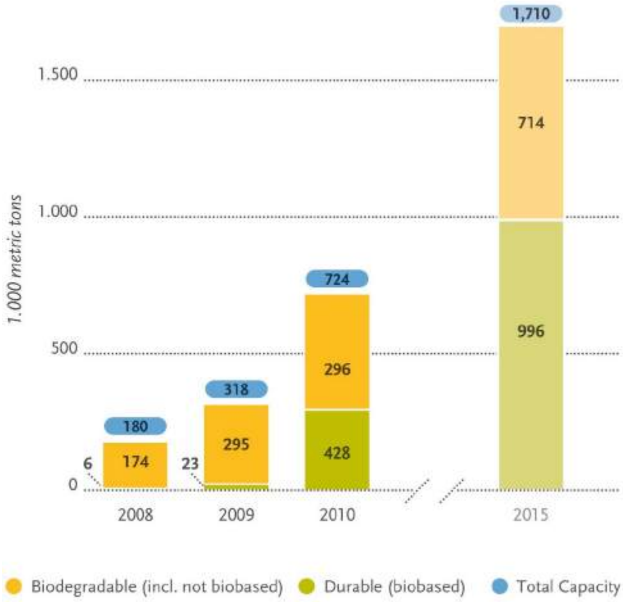
4.3 Biopolymers

As the use of fibre-reinforced polymers in the building industry is increasing rapidly, the users call not only the fibres, but also the matrix to be replaced by natural sustainable materials.

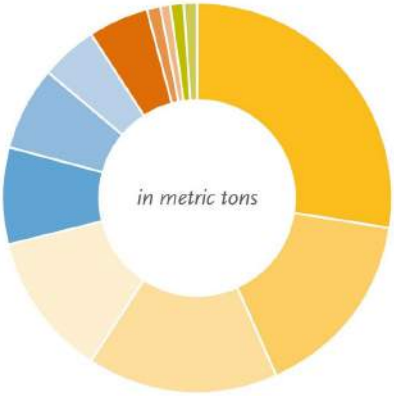
Biopolymers, known also as bio-based polymers or organic plastics, are synthetic materials that are produced from renewable raw material (RRM) such as starch and cellulose. Biopolymers are also known as biodegradable plastics when their compostability has been verified by the European Standard EN 13432. Bio-based plastics can be produced directly from natural biopolymers such as cellulose or starch through modification or they can also be composed by polymerized monomers of renewable raw materials. However, these polymers can be also produced from petroleum raw materials as long as the chemical structure of the polymer allows for biological degradability. Fig 3.10 shows different biopolymers and their production capacity for the year 2010. In the same way like conventional polymers, biopolymers are categorized in thermoplastics, elastomers and thermosets and they can be processed and machined with the same machinery.

Bio-based polymers are in fact not generally biodegradable. Compostable biopolymers made either from petroleum or renewable raw materials are preferred for temporary applications such as packaging or agricultural purposes. These types of polymers that can be composted are also known as second-generation biopolymers. In contrast, the third-generation biopolymers are maximizing the content of renewable raw materials and achieve a long-lasting functionality. These biopolymers compete conventional polymers in properties and allow for disposal after the end of their life cycle. Figure 3.9 shows the increased rate of use of biobased polymers with long-lasting properties in comparison with biodegradable polymers.

Recycling conventional polymers is associated with a downgrading in properties. With biopolymers this disadvantage is even more distinct due to their lower thermo-mechanical and chemical resistance. The disposal method that is used for these long-lasting biopolymers is incineration, which results in almost zero energy production.



4.9 Global production capacity of biodegradable and durable (biobased) bioplastics (European Bioplastics and University of Applied Scienced and Arts Hanover, 2011) (http://www.sustainableplant.com/)



●	Bio-PE	200.000	28 %
●	Biodegradable Starch Blends	117.800	16 %
●	PLA	112.500	15 %
●	PHA	88.100	12 %
●	Biodegradable Polyesters	56.500	8 %
●	Bio-PET	50.000	7 %
●	Regenerated Cellulose[2]	36.000	5 %
●	Bio-PA	35.000	5 %
●	Cellulose Derivatives[1]	8.000	1 %
●	PLA-Blends	8.000	1 %
●	Durable Starch-Blends	5.100	1 %
●	Others	7.500	1 %
	Total	**724.500**	100 %

4.10 Biopolymers global production capacity for 2010 (European Bioplastics and University of Applied Scienced and Arts Hanover, 2011) (http://www.sustainableplant.com/)

Under incineration the carbon dioxide (CO2) released is as much as the plant absorbed from the atmosphere during its growth. Finally, some biopolymers, especially polylactides (PLA), can be broken down into their monomers and then polymerized again and thus get recycled without any downgrading of their properties.

The most common biopolymers are briefly described below.

Thermoplastic starch (TPS)
TPS is the most common biopolymer today. Starch, which water-soluble is mixed with a water-repellent, petroleum-based polymer and the plasticizer glycerine. In the building industry it is used for insulation but in a limited scale because of the material's 4% moisture absorption.

Cellulose (tri)acetate (CA, CTA)
Cellulose acectate derives from the chemical reaction of natural cellulose with acetic acid. It is characterized by its shiny surface which allows light transmission and by its high resistance to scratches due to its high surface elasticity. Additives can reduce its flammability or make it weather resistant.

Polylactide (PLA)
PLA is a lactic acid synthetic polymer consisted of natural monomers and produced by bacteria from starch or sugar. This biotechnical method of production allows for developing the chemical structure of the polylactide and thus adjustment of its properties. Therefore, the properties of PLA are comparable with those of PP and PET. Polylactides are scratch-resistant, waterproof and transparent thermoplastics while they also show good mechanical properties. PLA can be processed by conventional methods such as injection moulding, blow moulding, extrusion and film forming operations.

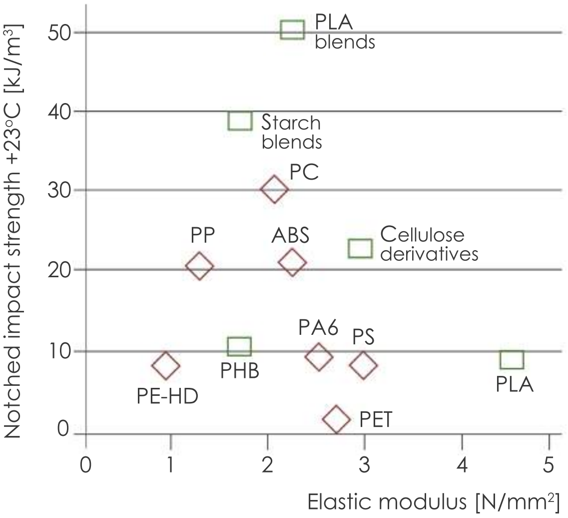
4.11 PLA containers for food packaging (http://projeto-pandora.blogspot.nl/)

Polyhydroxybutyrate (PHB)
PHB is a high-crystalline thermoplastic polymer with smooth, shiny and highly waterproof surface. It is resistant to UV radiation and in a temperature range from -30oC to +120oC it presents stable properties. However, because of its high production costs it is one of the most expensive biopolymers in the market.

4.4 Biopolymers vs. conventional polymers

Although thermoplastic biopolymers absorb more moisture than petroleum-based polymers, the percentage of this absorption, apart from the case of thermoplastic starch, remains below 1%.

Moreover, comparing the mechanical properties of both thermoplastic biopolymers and fossil fuel based polymers, and especially the modulus of elasticity and the stiffness of thermoplastic biopolymers it gets clear that both present approximately the same values. Analytically, the diagram 1.1 shows the notched impact strength in relation to the elastic modulus of different polymer types of both categories. The higher the value of the elastic modulus is, the less is the toughness of the polymer as it has a high tendency to get elastically deformed (non-permanently).



4.12 Comparative diagram of biopolymes (green) and conventional polymers regarding their mechanical properties (Knippers et. al, 2011)

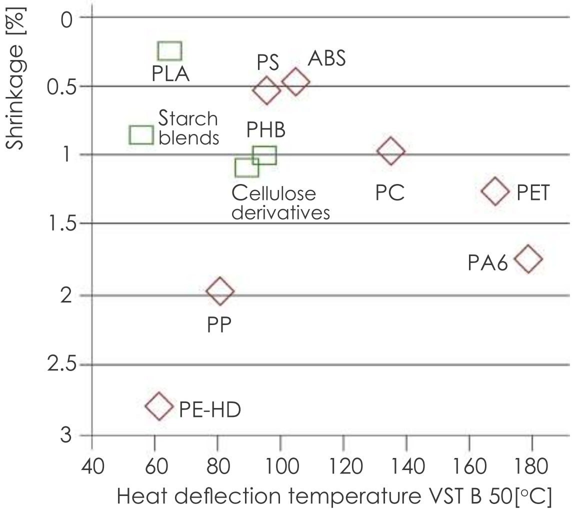
Table 4.1 Physical-mechanical properties of biopolymers and conventional polymers (Knippers et. al., 2011)

Properties	Tensile strength (MPa)	E-modulus (GPa)	Elongation at failure (%)	Moisture absorption (%) per 24h
PLA	48-60	3.45-3.85	2-6	0.5-1
PHB	40	1.8	4	3-5
CA	21-31	1.66-1.74	32.5-35.4	1.7-3.7
TPS	16-22	0.24-1.5	10-80	5-10
PP	19.7-80	1.5-2	52-232	0.01-0.09
PET	55-60	2-2.7	28-320	0.1-0.2
PC	43-66	1.5-2.6	92-200	0.13-0.15
PS	20-56	3-3.5	1,2-50	0.005-0.01

One of the advantages of thermoplastic biopolymers compared to conventional polymers is their lower rate of shrinkage, a fact which affects positively the high precision of the components during the production.

The diagram 1.2 presents the shrinkage rate and the heat deflection temperature of the same bio-based and petroleum-based polymers. The heat deflection temperature indicates the temperature at which a polymer deforms under a specified load.

However, long-lasting, durable biopolymers are just in the beginning of their development and so far little new findings, regarding their long-term properties such as fatigue behavior, UV resistance and creep, have been published.



4.13 Comparative diagram of biopolymes (green) and conventional polymers regarding heat deflection and shrinkage (Knippers et. al, 2011)

4.5 Durable bio-based polymers

Bioplastics were initially developed for short-lived applications such as packaging and consumer products that could easily biodegrade in contrast to conventional plastics. Soon, other industries, including the automotive and building sector showed their interest in employing bio-resins in durable applications. Thus, biodegrability was a drawback, rather than an advantage in such applications. To overcome low durability, cause by inherent brittleness, low heat resistance and moisture uptake, bioplastics were blended with conventional plastics and fortified with impact modifiers, reinforcing fillers and nano-additives.

Durable bio-based plastics that are used as resins in composites include modified polylactic acid (PLA), polyhydroxy alkanoates (PHBV), industrial starch and resins based on castor oils which is produced from agricultural waste, such as furan. Additionally, a big number of existing resins (PEBA, copolyester TPEs, TPUs and even acrylics) are modified to include a part of renewable content.

Therefore, blending PLA with polyethylene, copolyesters or other bio-resins such as PHBV reduces its brittleness. Mixing with PHBV improves also the heat resistance.

Additives are also important in improving durability of bio-resins. Nucleating agents speeds PLA's crystallization and reduce molding time, whereas calcium sulfate (dehydrated gypsum) improves heat resistance. Very fine-particle (0.05-micron) silica increases toughness and maintain clarity. Reinforcing PLA with a network of polymer-crosslinked carbon fibres adds thermal conductivity for use in electronic applications.

4.6 Furan

Furan also called polyfurfuryl alcohol has recently gained attention as a renewable alternative thermoset resin. Produced from pentose sugars, furfuryl alcohol or its prepolymers consist the raw materials of furan thermosets. Furfural, the raw material for furfuryl alcohol, is produced from the hemicellulosic part of agricultural wastes. A controlled, hightemperature digestion of this pentose-based fraction yields furfural. Thus, technically, furfural can be produced from any raw material which contains pentose, making it a renewable and CO2-neutral chemical. Corncobs and bagasse from sugar cane are the major industrial feedstocks for furfural production.

4.14 Furfuryl alcohol
(http://en.silvateam.com/)

Most of the furfural produced world-wide is converted into furfuryl alcohol (FA) by a low cost derivatization process. This latter furanic monomer can be easily polymerized into polyfurfuryl alcohol (PFA). PFA based-resins have found a range of useful applications in the foundry industry, wood adhesives and binders, polymers concretes and fibre-reinforced plastics.

Compatibility of furan with conventional and natural fibres is also good. However, as furan resins are generally cured by acid hardeners, natural fibres have to be protected. Plant fibres, being lignocellosic, can be degraded by both acid and alkaline chemicals through various pulping reactions. In order to compatibilize the acid curing mechanism of a furan resin with natural fibres, novel catalytic systems have been developed in order to protect the natural fibre from any degradation reaction.

4.7 Natural fibre-reinforced biopolymers

Natural fibre-reinforced biopolymers are composite polymers in which a bio-based polymer, such as the ones described previously, is used as a resin and natural fibres constitute the reinforcement. Incorporation of natural fillers into polymer matrices can optimize mechanical and thermal properties.
Two basic polymers of this category are described below.

Natural fibre-reinforced PLA (thermoplastic)
Although the mechanical properties of PLA are similar or even superior to petrochemical polymers, PLA shows low toughness because of its brittle nature, but also has much lower molecular weight compared to conventional polymers. In order to overcome the brittle nature of PLA, natural fibres are embedded into the polymer matrix. plasticizers can be used during processing.

Although PLA-natural fibre composites show increased tensile modulus they have lower tensile strength than PLA, and this has been attributed to factors such as the weak interfacial interaction between the hydrophobic PLA matrix and the hydrophilic natural fibers, and the lack of fiber dispersion due to a high degree of fiber concentration. However, various methods of modifying the surface of the cellulosic fibers have been explored in an effort to improve the interaction that occurs at the interface between the PLA matrix and natural fibres. Better development of processing technologies and improvements in natural fibre treatments will facilitate the production of PLA based composites with optimum mechanical and physical performance but also generate high cost competiveness and greater acceptance of these materials in the market.

One of the first applications on a real product was introduced by a Japanese electronics group which developed a virtually non-flammable mobile phone housing. Heat-absorbing metal hydroxides were added as flame retardants and short kenaf fibres were used as reinforcement. Another experimental approach was the “S-House” project carried out by the Vienna University of Technology in which a prototype for non-loadbearing partitions made from natural fibre-reinforced biopolymers was developed. Several layers of fleece made from straw, flax and polylactide fibres were laid on top of each other and pressed together giving a compression resistant sandwich panel with insulation properties.

Lignin-bonded natural fibre composites (thermoplastic)

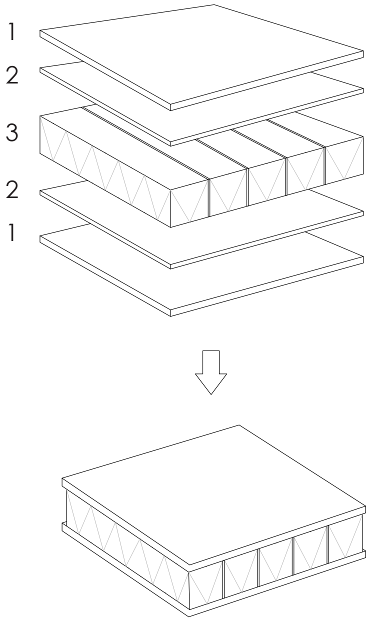
Lignin is one of the most common naturally occurring biopolymers and its function is to give stability between the cellulose fibres in all plants and wood. This biopolymer has a dark brown color, absorbs UV light almost totally and is difficult to be decomposed either biologically or chemically. It is also known as liquid wood as in combination with natural fibres it becomes a composite material with the positive properties of naturally grown wood and the unrestricted mouldability of a thermoplastic. Therefore, the composite shows similar mechanical and thermal properties to those of wood which makes it suitable as a connecting component in timber construction.

Cores

5.1 Sandwich construction

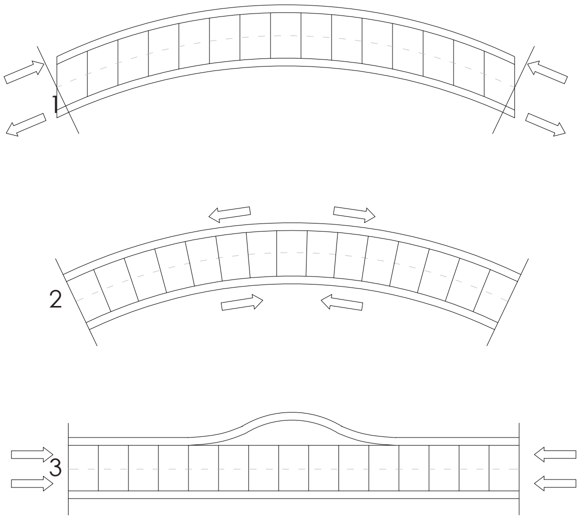
Structural members composed of two thin, stiff and strong skins separated by a lightweight and thick core are known as sandwich panels. The core is normally a low strength material as its main role is to maintain a distance between the two facings. This increases the moment of area of the panel, with little increase in weight and results is an efficient structure with an overall low density and good bending and buckling resistance.

Additionally, the role of the core is to take the shear forces of the structure, support the facings and maintain the proper distance between them. Therefore, the core should be a lightweight material with enough shear and axial stiffness. Otherwise, a weak core material in shear would result in bending of the facings and too low axial stiffness would cause buckling. But with the proper choice of materials for facings and core, constructions with high ratios of stiffness to weight can be achieved.



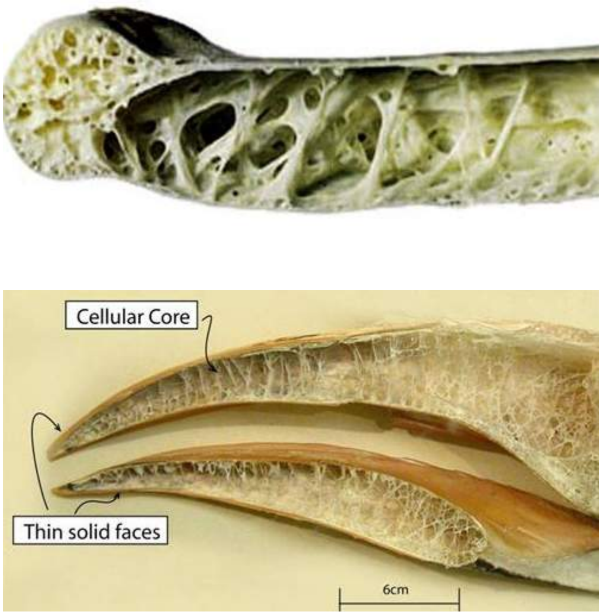
5.1 Structure of a sandwich composite
1. Facing 2. Adhesive 3. Core

Such structures exist originally in various forms in nature. Trees can support the bending loads applied by strong winds and our bones are able to support our weight due to the structural efficiency of shell sandwich structures based on strong and dense outer surfaces that enclose a low density and light material. Figure 6.3 shows examples of the structure of a Hornbill beak and an avian wing bone which demonstrate how well nature exploits these efficient design practices to create structures that can support high bending loads at minimal weight.



5.2 Reactions of core under bending and compression

1. Core weak in shear
2. Core strong in shear
3. Separation of core



5.3 Cross sections of (top) the beak of a Hornbill and (bottom) an avian wing bone
(http://www.virginia.edu/)

5.2 Core materials

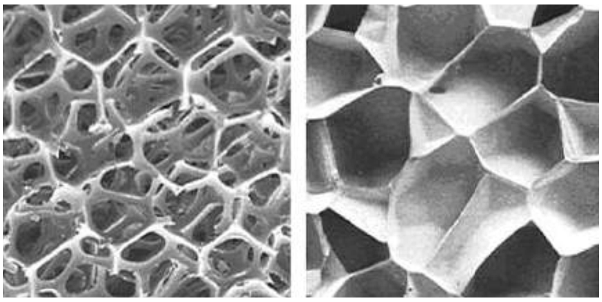
Many sandwich structures use synthetic polymer foams, honeycombs, aluminum but balsa wood has also been used for many years, and cork is also now available. Both balsa and cork are produced from renewable resources, may be partly recyclable and can be composted.

5.2.1 Polymer foams

Polymer foams are composed of a solid polymer and gas mixed together to form a foam. Polymer foams are known as either closed-cell or open-cell structure. In closed-cell foams, each cell is surrounded by connected faces. Partial cells, with cut faces and edges are visible only in the cross-section of the foam, whereas complete cells exist in the interior of the material. On the contrary, the structure of open-cell foams allows air to pass freely between the cells as all the cell edges are partly open. Closed-cell foams are generally more rigid, while open-cell foams are usually flexible.

Production of polymer foams can be achieved in a number of different processes including slab-stock by pouring, extrusion and different forms of molding. They can be divided into either thermoplastics or thermosets, which are further divided into rigid or flexible foams. The thermoplastics can usually be broken down and recycled, while thermosets are harder to recycle due to strong cross-linked bonds. Polymer foam industry faces environmental issues regarding waste disposal, recyclability, flammability and the effect of blowing agents on the environment.

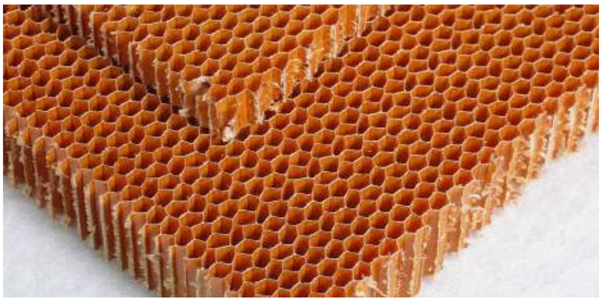
Foams that are commonly used as core elements in fibre-reinforced composites are polyurethane (PU), polystyrene (PS), polyethylene terephthalate (PET), PVC and others.



5.4 Open-cell (left) and closed-cell (right) foams.
(http://www.posterus.sk/)

5.2.2 Biodegradable polymer foams

Biodegradable polymer foams were developed as an environmental solution to the increasing non-disposable waste of traditional polymer foams, and as an alternative based on renewable raw resources and not on petroleum products. Similar to biodegradable resins and natural fibres, biodegradable foams are sensitive to humidity, while traditional petroleum-based foams are more inert to water. Thin sheets cannot be easily achieved with biodegradable foams as they have a different microcellular structure. There is also a wide range of bio-base materials that can be used for biodegradable foams, including ethylene vinyl alcohol, polyvinyl alcohol, polycaprolactone, polylactic acid and starch.



5.5 Honeycomb from aramid fibre paper
(http://www.acpsales.com/)

5.2.3 Honeycombs

Honeycomb cores are structures consisting of an array of hollow columnar cells, hexagonal in shape, formed between thin vertical walls. Having that geometry, honeycombs allow for minimization of the amount of used material, reach minimal weight and density while out-of-plane compression properties and out-of-plane shear properties are relatively high.

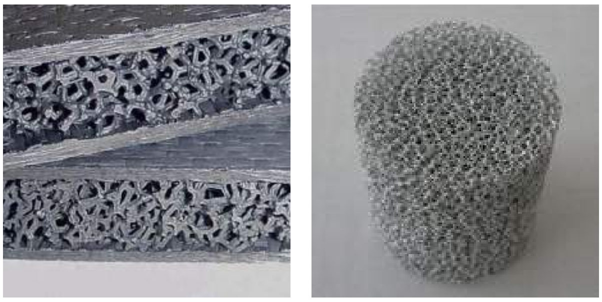
Materials used to produce such cores vary from paper to thermoplastics and depend on the intended application. In sandwich composites, aluminum, thermoplastic (polypropylene, polycarbonate, polyethylene) or fibre-reinforced plastic (glass, aramid) are preferred. Nowadays, honeycombs are manufactured by the continuous processes of expansion and corrugation, whereas extrusion is employed for production of thermoplastic honeycomb cores.

5.2.4 Aluminum foam (metal)

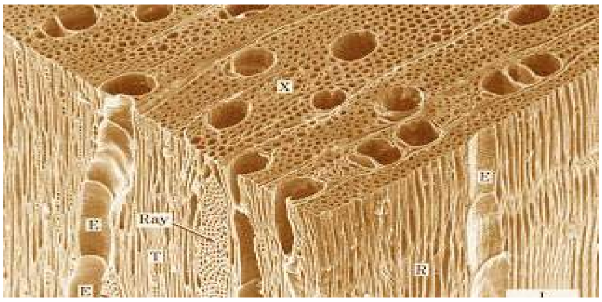
Aluminum foam is the most frequent variant of metal foams. Consisting of solid aluminum it shows a large volume fraction of gas-filled pores. The pores can be sealed (closed-cell foam), or they can form an interconnected network (open-cell foam). The defining characteristic of metal foams is their very high porosity as typically 75–95% of the volume contains void spaces making aluminum foams ultralight materials.

Similar to polymer foams, metallic foams are classified into open-cell and closed-cell. Open cell metal foams, also called metal sponges, can be manufactured by several ways, especially through foundry or powder metallurgy, whereas closed-metal foams are made by injecting a gas or mixing a foaming agent into molten metal. Under certain circumstances metallic melts can be foamed by creating gas bubbles in the liquid.

Closed-cell metal foams are primarily used as impact-absorbing materials for high impact loads. However, unlike polymer foams, metal foams remain deformed after impact and can therefore only be used once.



5.6 Aluminum foams
(http://www.ergaerospace.com/)

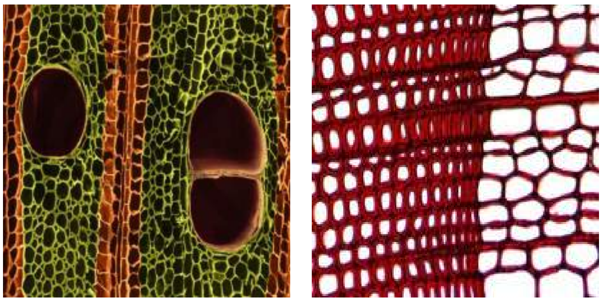


5.7 Microstructure of porous wood
(http://www.scielo.cl/)

5.2.5 Balsa wood

A more environmental alternative for core material is balsa wood. Being produced from balsa tree, a fast growing type of tree, balsa exhibits properties that make it suitable for use as core material in sandwich composites. The density of dry balsa is low, typically around 160 kg/m3, because it consists of large cells that contain water. After the tree is cut, moisture evaporates, leaving large areas within the resulting cells.

Balsa wood has also excellent stiffness-to-weight and strength-to-weight ratios as well as superior energy absorption characteristics. These properties are derived from the microstructure, which consists of long slender cells with approximately hexagonal cross-sections that are arranged axially, similar to honeycomb cores. Under compression in the axial direction the material exhibits a linearly elastic regime that terminates by the initiation of failure in the form of localized kinking. The material is less stiff and weaker in the tangential and radial directions.



5.8 Wood cell structure of Balsa wood
(http://www2.estrellamountain.edu/)

5.3 Environmental impact and embodied energy

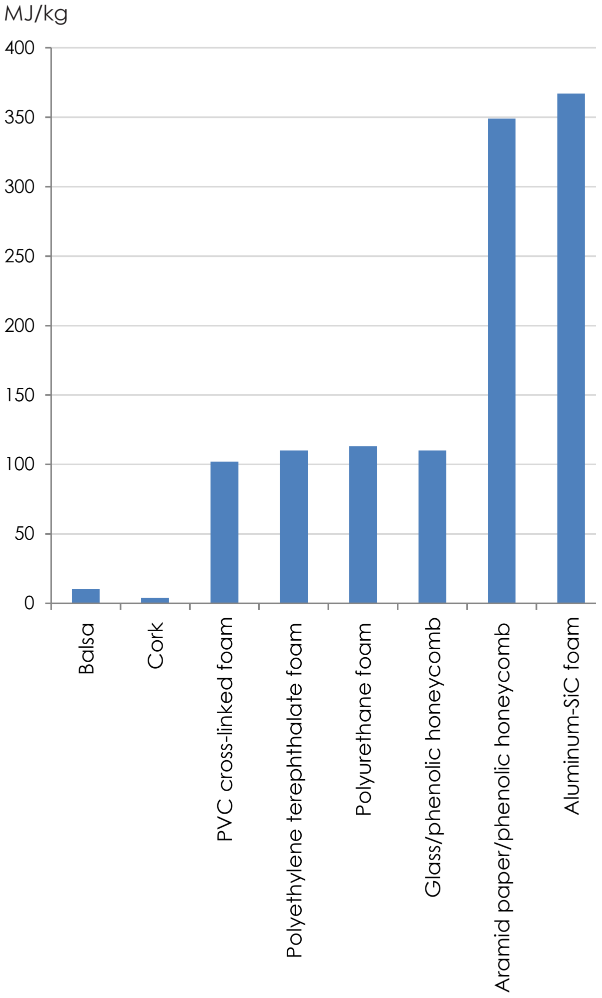
Considering the environmental impact of the described core materials, balsa wood offers an advantageous alternative. Conventional polymer foams, being based on non-renewable fossil fuel resources, have an increased environmental impact and energy intensity.

Production of polymer foams requires use of blowing agents, which are volatile liquids that evaporate, produce CO_2 and make the foam expand. The first generation of physical blowing agents, CFCs (chlorofluorocarbons) are mostly outruled nowadays due to their negative environmental impact on the ozone layer.

Hydrochlorofluorocarbons (HCFC) and hydrofluorocarbons (HFC) are blowing agents with lower impact on the ozone layer and with similar properties. However, the use of HCFC's is still linked with ozone depletion problems. On the other hand, HFC's have no contribution on ozone depletion, but on global warming potential.

Polymer foams are also toxic and non-recyclable, creating problems regarding waste management. Manufacturing of such materials is also energy intensive. On the contrary, balsa wood is based on a renewable resource with the microstructure of the materials being naturally present. Graph 5.8 shows the embodied energy of different core materials.

5.9 Embodied energy of core materials
(CES EduPack 2014, Granta Ltd)



Production Techniques

6.1 Manual lay-up processes

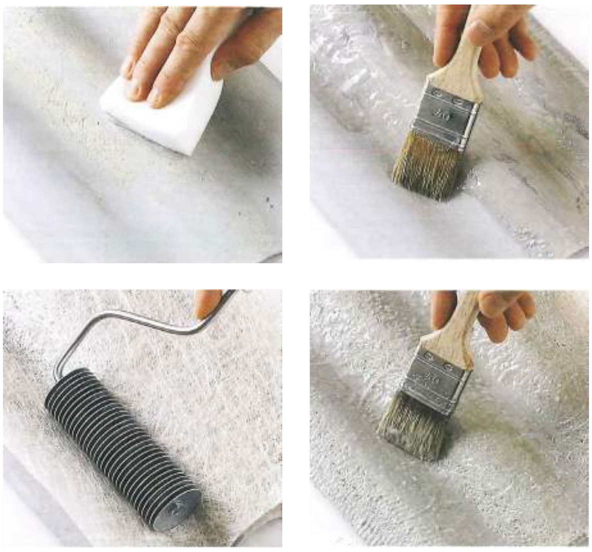
6.1.1 Hand lay-up

Hand lay-up or wet lay-up is the most widely used technique and one of the oldest for making composite parts. Being a simple process to perform, it allows for design flexibility and so it is more suitable for components with irregular shapes in small batches or for elements with large dimensions that cannot be produced with automated plant.

In hand lay-up process an one-part mold is used for shaping the component. Simple geometries and planar pieces can be produced by using metal sheet or wooden molds, but more complex one-off items normally can be achieved by molds made from rigid polyurethane foam. However, as the foam is often damaged during the first demolding operation such foam molds are not functional after a number of reuses. Molds made from glass fibre-reinforced polymers are suitable when more than 100 reuses are required as they are stronger and last much longer.

The surfaces of the mold are usually coated with a release agent that can ease demolding while for the case of a rigid foam mold it prevents the resin being absorbed into the foam. If the foam has to be integrated in the composite as a core material, then the application of a release agent would prevent a good bond between the foam and the first ply of material and so it is not applied.

The first stage of the process is the application of a gel-coat of less than 1mm thickness on the mold. This coat is a special non-fibrous pure resin with good hardness and impact resistance that is going to protect the surface of the laminate as a top coat after demolding. Once it has sufficiently cured, the reinforcement is laid on by hand and the liquid resin is applied and pressed by brush or roller to ensure good contact with the layer below and to remove all air bubbles. Additives such as flame retardants and inert fillers can be mixed in to reduce weight and improve mechanical and physical properties. The process is repeated layer by layer, until the desired laminate thickness is achieved.

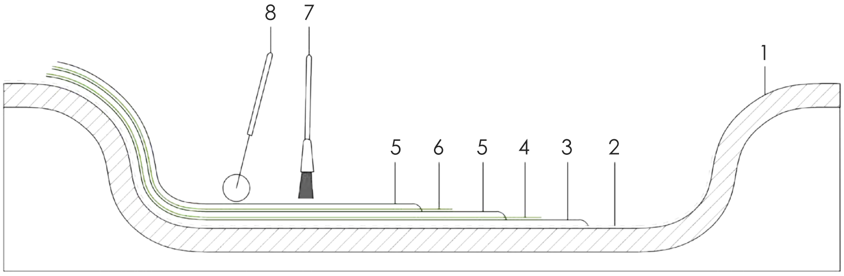


6.1 Basic steps of hand lay-up.
(In: Knippers, J,, Cremens, J., Gabler M., Lienhard J. *Construction manual for polymers + membranes*. Munich: Institut für international Architektur-Dokumentation)

In general, the application of hand lay-up method is limited to the thermosets as resins need to be low in viscosity to be workable by hand. Since most thermoplastic matrices have a high viscosity at room temperatures, impregnating the fibres with a thermoplastic resin becomes difficult. Due to the high flexural stiffness of thermoplastics it can be difficult to drape such prepregs in or over a mold.

Hand lay-up

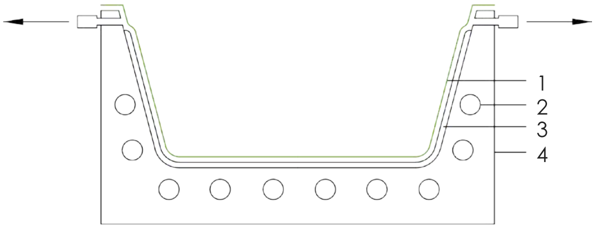
1 Mould
2 Release agent
3 Gelcoat
4 Layer of fleece
(surface layer)
5 Resin
6 Fibre reinforcement (textile)
7 Brush (resin application)
8 Deaerating roller



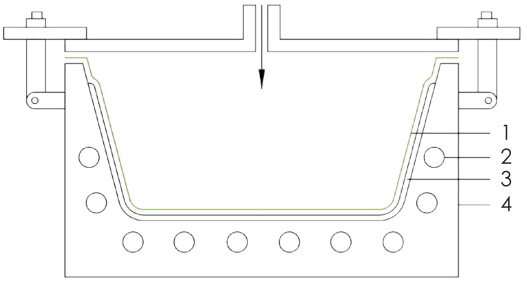
Hand lay-up is a relatively cheap process as equipment and tooling cost is low and as only one single mold is needed, which is usually simple in shape and thus is constructed out of cheap materials. However, it is a process that requires high labor intensity while the quality of the component heavily depends on the skill of the operators carrying out the work. Also, as the mold is a single piece, the face in contact with the mold has a smooth surface, whereas the inner face is rough. Finally, as the process is based on manual lamination longer cure times are required.

The nature of hand lay-up also has health and safety issues as it is an open mold process and because low viscosity resins can be harmful. The fumes from the curing process, especially with polyester resin requires appropriate ventilation systems that provide air extraction which complies with the high emission levels of styrene.

6.2 Operation of hand lay-up
(http://www.fassmer.de)



Vacuum bagging



Pressure bagging

6.1.2 Vacuum/pressure bagging

Vacuum and pressure bagging are basically an extension of the wet lay-up process described above with the difference that pressure is applied to the laminate in order to improve its consolidation and hold the resin-coated component in place until the polymer cures. The difference between vacuum and pressure bagging is the fact that in the first process pressure difference is created by air extraction inside the bag while in the latter, pressure difference is achieved by inserting air inside an airtight space above the bag. However, both processes require a single mold which can be made of glass fibre-reinforced polymer, epoxy, or metal. Components that are mainly produced by these two processes include shapes with high surface area to thickness ration and so they are preferred for large one-off components such as boats or racecars.

In vacuum bagging process the reinforcement and the resin are applied on the mold manually by hand or spray lay-up technics. Then the laminate is sealed within an airtight envelope that consists of an airtight mold on one side and an airtight bag on the other. When the bag is sealed to the mold, air is evacuated by a vacuum pump from the inside of the envelope, creating an air pressure difference between the inside and the outside of the envelope by reducing the air pressure inside. Atmospheric pressure forces the sides of the envelope and everything within the envelope together, putting equal and even pressure over the surface of the envelope.

To ensure consistent, high-quality composite parts it is necessary that proper components and materials, including specialized equipment and commonly available materials are used by specially trained operators. The materials usually used in preparing a lay-up for vacuum bagging are a peel ply, a release fabric, a perforated film, a breather material and the vacuum bag that encloses the laminate inside the envelope.

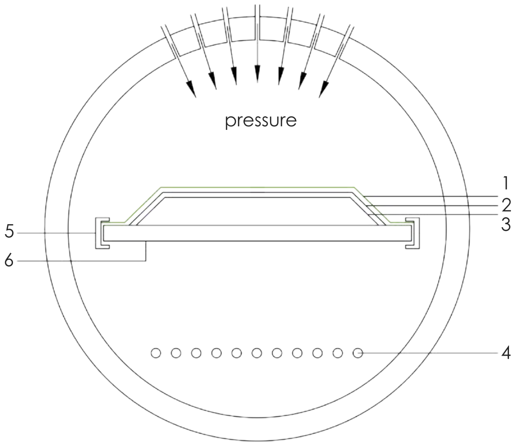
1 Flexible bag
2 Heating
3 Resin + fibre reinforcement
4 Mould

Vacuum bagging offers many advantages over conventional clamping, stapling or other techniques. Due to the continuous, firm and evenly distributed atmospheric pressure over the entire surface, it allows for a wide range of types and combinations of materials in laminates with a superior bond between them. Vacuum bagging's uniform clamping pressure across the laminate also results in thinner, more consistent glue lines and fewer voids.

Additionally, the ability to control excess adhesive in the laminate by the different bagging materials, results in higher fiber-to-resin ratios. This means that higher fibre-content laminates can be achieved than with other processes such as standard hand lay-up. High fibre-to-resin ratios are crucial as they are translated into high strength-to-weight ratios and cost advantages.

Another big advantage of vacuum bagging is in the simplicity and variety of the molds used. Since atmospheric pressure provides equal and even clamping pressure to the back of the mold, the mold only has to be strong enough to hold the laminate in its desired shape until the epoxy has cured. Therefore, most molds are relatively light weight, easy to build and cheap. Concerning health and safety issues, as vacuum bagging is a closed process the emission levels during the cure are low.

However, compared with hand lay-up process in vacuum bagging the extra process adds cost both in labor and in disposable bagging materials. Finally, the final quality of the composite is also determined by the level of the operators' skill.



Autoclave

1 Flexible bag
2 Resin + fibre reinforcement
3 Mould
4 Heating
5 Clamps
6 Table

6.1.3 Autoclave molding

Autoclave molding is a process similar to vacuum/ pressure bag with the difference that autoclave machinery is used for curing the composites. The autoclave machine is basically a large oven that subjects materials to high pressure, temperature and vacuum. Autoclaves can reach temperatures up to about 750 degrees Fahrenheit, and pressures up to 100 pounds per square inch.

6.3, 6.4 Autoclaves
(http://www.brebeckcomposite.com/)

In the same way with vacuum bagging, the reinforcement and the resin are applied on the mold by conventional hand or spray lay-up techniques. The laminate is again covered with a porous film and a layer of glass-fibre cloth or paper to absorb any excess resin and then it is covered with a flexible bag which is clamped on a table. The wet laminate and the mold are then placed inside the autoclave and subjected to high pressures of about 0.55 MPa and temperature which cause the back to be drawn on the laminate.

With the subjection of the material to elevated pressures and temperatures, higher fibre-to-resin ratios and removal of all voids (less than 2%) can be achieved, which leads in a maximization of the performance of the thermoset composites. Besides, inside an autoclave, three dimensional, uniform pressures can be achieved mainly due to the external pressure around the enclosed laminate. The pressure created by the vacuum inside the sealed bag that contains the laminate is not enough to achieve such evenly distributed forces around the bag. Therefore, autoclaves are used for the fabrication of high quality advanced components such as high strength aircraft and aerospace components.

Autoclave is a high labor intensive and time consuming process as it requires 1-12 hours for a curing cycle. At the same time, the high manufacturing cost makes autoclaving an expensive process which is used only for specialized high performance components.

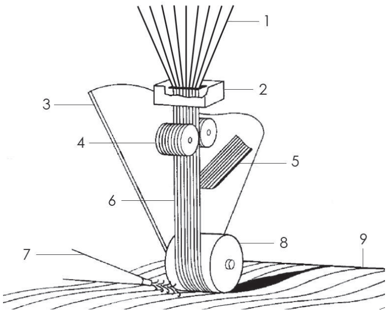
6.2 Automatic lay-up processes

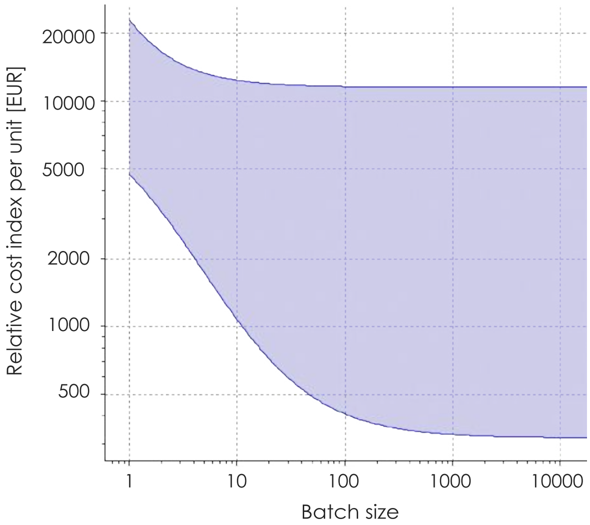
6.2.1 Automated tape placement (ATP)

Automated tape or tow placement (ATP) is a non-autoclave manufacturing process for advanced composites, based on lamination by layering pre-impregnated fibres in form of tape. During this process a pre-preg tape or tow is deposited by a laying head carried by a numerically-controlled multi-axis machine.

6.5 Robotic ATP machine
(http://www.investquebec.com)

1 Individual tow payout with controlled tension
2 Band collimator
3 Fibre placement head
4 Tow restart rollers
5 Tow cutters and clamp mechanism
6 Collimated fibre band
7 Controlled heat
8 Compaction roller
9 Mold surface





6.6 Diagram of cost per unit regarding batch size
(CES Edupack 2014, Granta Ltd)

The pre-preg tapes, stored in reels, are transported by rollers to the tape-laying head. Pre-preg tapes consist of reinforcement fibres in form of unidirectional strands that are impregnated with a resin. The matrix, which is usually an epoxy resin, is only partially cured and stored in cool conditions in order to avoid complete curing. Since heat accelerates complete polymerization, only during the process the tape is heated right on the moment is being applied on the surface.

ATP machines are normally large gantry style metal machines which can contain as many as ten independently controlled axes of movement in space (IHS GlobalSpec, 2006), such as head orientation, roller angle etc. As ATP machines require a considerable investment, the total capital cost of the process is high. However, compared to other manual processes, that require intensive labor by highly skilled personnel, such as hand lay-up, an automated tape-laying machine can provide up to 86% labor savings (Van Tooren, Sinke & Bersee, 1993).

ATP is a highly accurate process with very good repeatability and maximum utilization of the tape material. It delivers high quality composite components that have improved structural properties and thus it is primarily used in the aerospace industry. High quality is achieved as the tape-laying roller applies uniform pressure during the lay-up which gives compacted laminates with less entrapped air. Additionally, such machines allow for a variety on the shape, size and fibre orientation (0°, -45°, +45° or 90°).

The process is used for large scale productions of large, simple to moderately complex parts thatrequire excellent quality and strength. It is not efficient, also in terms of cost, to lay-up small, complex parts without structural requirements. Hollow and highly curved surfaces with radii of curvature less than that of the laying head cannot even be produced.

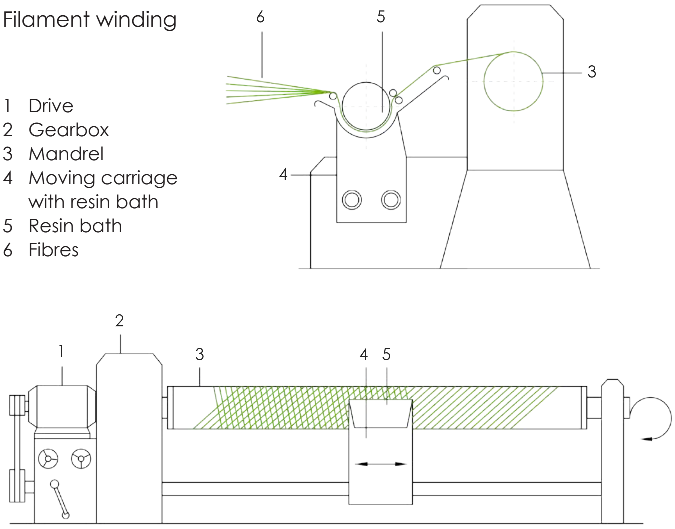
Although automated tape placement achieves exceptionally high quality and control of the lay-up, it is a slow process with low production rates. Besides, the high production cost limits the use of the process in specialized applications that require high performance. Finally, as ATP is an open process and thus toxic vapor is released during the cure, forced air extraction through ventilation systems is necessary.

6.2.2 Filament winding

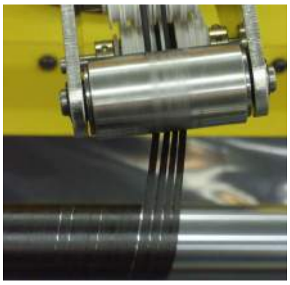
Also known as wrapping, this is a process in which continuous rovings, tows or tapes are wound over a rotating mandrel. These rovings or tapes can be pre-impregnated or impregnated during or after the winding process. When impregnation occurs during the process the fibre tows are passed through a resin bath, usually polyester or epoxy, before being wound on the mandrel.

The mandrel is made of steel, aluminum or plaster depending on the batch size and the geometry of the component. It usually has cylindrical, conical, round or any other shape without complex curvature that would not allow removal of the mandrel at the end of the cure cycle. The shape of mandrel should also have no bumps or undercuts that would not allow for entire wounding of the mold. Despite the shape limitations, with filament winding very large parts can be produced, larger that Thus, filament winding is ideal for producing axisymmetric hollow parts such as pipes, tubes, tanks and pressure vessels, turbine blades or rocket noses.

Filament winding



Filament winding is an accurate automated process with high level of mechanization. The produced components have high quality with excellent structural properties as high reinforcement content can be achieved. The machine has the ability to vary the winding angle, the resin content and the winding tension in each layer of reinforcement until the desired thickness, density, resin content and direction of strength of the composite has been obtained. Another important advantage of the process is the capacity to use continuous fibres, without joints, over the entire component surface that can be also oriented in the load direction.



6.7 Tude product by filament winding
(http://savercompositi.com/)

6.8 Filament winding
(http://www.cstcomposites.com/)

As a process it requires less capital investment, compared to other autoclave processes or automated tape lay-up. However, the cost of large mandrels can be high. In general it is an economic process with normal cost for large quantities as the material costs are relatively low. Fibres, for instance, are used in a primary form and not as fabrics which includes a secondary process that would increase the cost.

6.3 Resin transfer processes

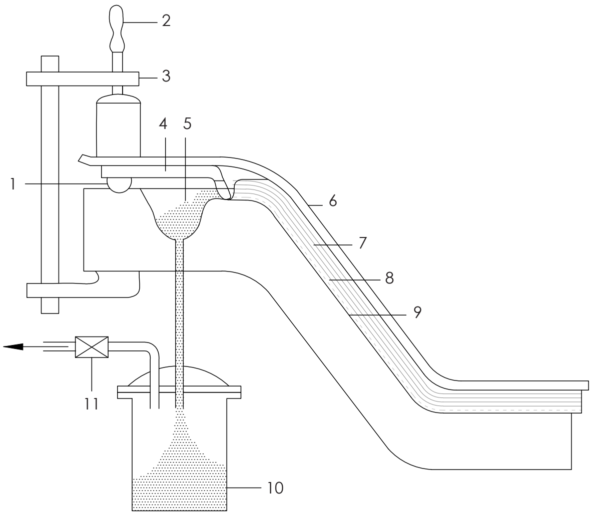
6.3.1 Resin transfer molding (RTM)

Resin transfer processes are a family of closed mold low-pressure processes in which the dry reinforcement and the resin are mixed within the closed mold.Such processes have a wide variety of products that range from simple, low-performance to complex, high performance components in terms of complexity and from small to very large in terms of size.

Resin transfer molding uses a double closed mold which is usually metal or a glass fibre-reinforced composite. Dry reinforcement in form of fibre mats is laid up on the first mold together with other fabric layers, such as a release fabric and a breather. Then a second mold is clamped over the first, and a low viscosity resin (usually epoxy or polyester) is injected into the airtight cavity between the two molds. The liquid resin is transferred through a tube that connects the cavity to the resin supply. During the injection, pressure difference is created inside the closed cavity which forces the resin to flow through the reinforcement. The mold also has vent points to allow air to escape from the cavity as the resin flows through under pressure. After the matrix has impregnated the reinforcement, the composite is allowed to cure at room temperature.

RTM is an easy process for manufacturing complex shapes without high cost tooling. Typical applications include car doors and side panels, propeller blades, boats, canoe paddles, water tanks, roof sections, airplane escape doors etc. Besides, as the process is closed-mold type styrene emission are reduced and thus exposure of the personnel to chemical environments is greatly reduced. Another advantage of double mold processes is the fact that both sides of the component have a smooth surface finish.

On the other hand, although the relative cost per unit is low, the fabrication of the two parts of the double mold can be expensive. Thus, the process is a cost-efficient option only for large mass productions in which the capital investment for the molds is balanced by the production profit.



Vacuum assisted resin transfer molding

1 Seal
2 Screw clamp
3 Tensioning frame
4 Perforated plate
5 Channel for excess resin
6 Vacuum bag
7. Layers of fibre reinforcement plus resin
8. Release agent
9. Mould
10. Vacuum vessel for excess resin
11. Vacuum pump valve

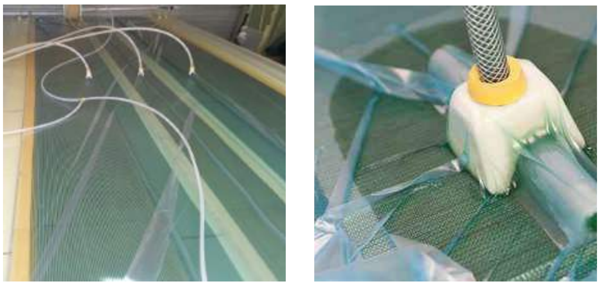
6.9 Double mold for resin transfer molding
(http://savercompositi.com/)

6.3.2 Vacuum assisted resin transfer molding (VARTM)

Another alternative process based also on resin transfer inside an airtight closed mold is the vacuum assisted resin transfer molding or vacuum assisted resin injection (VARI). The process is similar to typical resin transfer molding with the difference that the mold is a single part with a flexible bag clamped airtight on it, instead of a second solid mold. The pressure here is created by a vacuum pump that is connected with the cavity between the mold and the bag.

In a similar way to resin transfer molding the laminate is created by laying the fabrics of the dry reinforcement and the additional layers on the mold. Then the laminate is sealed airtight on the mold by the flexible bag that allows injection of the resin from a tube at the one side and extraction of air by the vacuum bag from the other side. The resin is released and sucked into the bag by the vacuum, flowing through and impregnating the fabric.

One of the major advantages of VARTM is that it is an economic process for small butch sizes and not mass productions while it retains the good quality of resin transfer processes. This basically lies in the fact that mold costs are lower than typical RTM, as molds here can be out of low-cost, disposable materials. However, due to the absence of a second mold only one good surface with smooth finish is obtained.

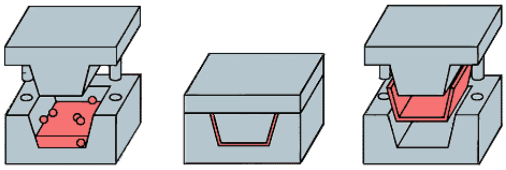


6.10, 6.11 Infusion of resin in VARTM
(http://www.ar-engineers.de/)

6.3.3 Resin film infusion (RFI)

Resin film infusion is a typical vacuum/pressure bag process. The reinforcement is again laid on the mold in form of dry, woven fabrics while the resin is applied on the laminate as semi-solid film which is supplied on a release paper. The entire laminate is again sealed with a flexible bag on the mold and then heated to allow the resin to melt and impregnate the air-free fabric reinforcement. At the same time, a vacuum pump extracts the air from the bag, compressing the dry fabrics on the resin.

6.4 Compression molding processes



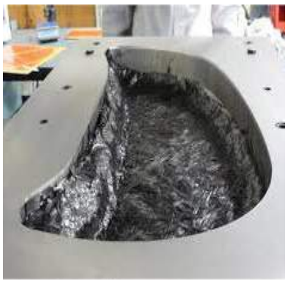
6.12 Compression molding technique
(http://www.gopixpic.com/)

Compression molding is a wide family of processes that includes several different technologies in which molding compounds are formed and cured in metal molds under heat and high pressure. Most compression mold processes consist of a two-part, negative and positive, double mold which is usually constructed either of aluminum, cast iron, steel or glass fibre-reinforced polymer. When the two parts of the mold are closed, their inner matching surfaces create a cavity which is the outline of the desired product.

The products of such processes have high strength, and can vary in size and in shape complexity. Besides, due to existence of a double closed mold, styrene emissions are reduced giving the process lower emission compared to other forming techniques. However, all compression molding processes require a high initial investment both for mold construction and tooling used, which makes them useful only for high volume productions.

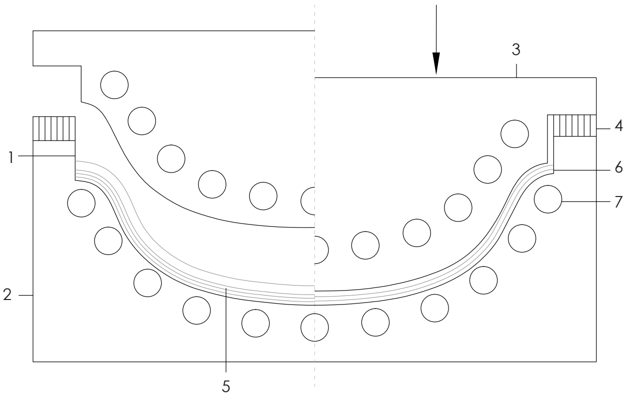
6.4.1 BMC molding

Bulk molding compound method is a compression mold process in which the molding compound is a sticky dough premixed material that includes the optimum portions of resin, fibre-reinforcement and additives. The compound is placed in the heated mold cavity and then pressed into the finished shape. Pressures applied vary between 0.5 and 15Mpa depending on the size requirements and the material being processed according to CES Edupack (2013). The mold reaches temperatures between 140-160oC through steam heating, electricity or hot oil.



6.13 BMC molding 6.14 Bulk molding compound
(http://www.tencate.com/)
(http://smccomposites.com/)

Resins that are commonly used for the bulk compound are thermosets, such as polyester, epoxy or vinyl ester or some thermoplastics like PP or nylon. The fibres used are normally short (25mm) glass or carbon fibres with random orientation inside the compound. As the fibres are not continuous, they cannot be oriented to certain load directions, and thus the composite products have low mechanical properties. Therefore, applications with high load bearing and durability requirements are restricted from the process. Common uses, include semi-structural applications such as electrical housings and car body parts.



Vacuum assisted resin transfer molding

1 Resin
2 Lower part of mould
3 Upper part of mould
4 Spacer
5 Layers of fibre-reinforcement
6 Finished laminate
7 Heating

6.4.2 SMC molding

Sheet molding compound method is a similar alternative of BMC. The only difference here is that the premixed compound is in the form of sheet, with the short fibre-reinforcement, the resin and the additives being again premixed in the optimum portions. After the sheet is cut to the desired dimensions it is placed on the mold. The mold then closes and applies pressure between 3-7MPa and constant heating (130oC-160oC) to the compound in order to initiate curing.

6.4.3 Thermoforming

Thermoforming is also known as thermoplastic composite molding as it is the base of all the thermoplastic forming processes. Being limited only in thermoplastic resins, the process is mainly based on heating and pressing the composite, not at the same time but in two different stages. First a premixed compound in form of sheet is cut to shape. The compound consists of fibrous fabric as reinforcement and a thermoplastic resin, such as PS, PE, PP etc. The laminate is first heated inside an infrared heater or hot air autoclave until it has reached the forming temperature. Then, it is transferred into the double compression mold were it is pressed to the desired shape. After forming, the laminate is cooled under the pressure of the matched press until is set.

6.15 Double compression mold
(http://wilbertinc.com/)

6.5 Continuous processes

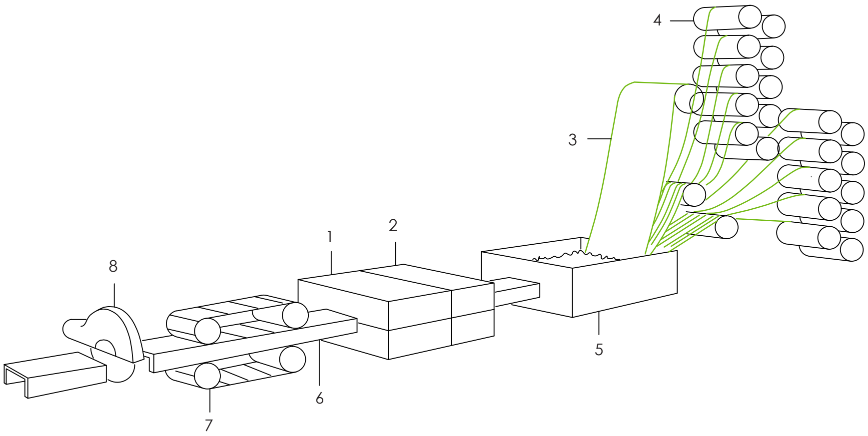
Continuous processes are manufacturing techniques for mass production of high-length components, in which the composite is continuously produced. Thus, with such processes there is no limit to the length of the fabricated parts. The fibre-reinforced components that are reinforced only in the length direction can be constant cross-sections, sheets or integrated panels. Continuous processes have a high degree of automation and are not as labor intensive as other production processes.

6.5.1 Pultrusion

Pultrusion is a well-known continuous manufacturing method for producing constant cross-sectional profiles. The dry fibres or fabrics are pulled from a series of creels and proceed through a resin bath before continuing to the forming dies. After passing the dies, the resin-impregnated fibres pass from a heated steel forming die that starts curing of the resin at high temperatures and shapes a rigid composite section. A special cutting device cuts the product to the desired length. The speed of the process is depended on the viscosity, thickness and curing of the resin.

The matrix that is typically used is a thermosetting resin, such as polyester, epoxy and the reinforcement mainly consists of glass fibres (60-75%), carbon or aramid in the form of continuous rovings or fabric mats (CES Edupack, 2013).

The cross-sections produced have thin walls and constant profile that gives a variety of shapes. Tubes, rods, channels, hollow rectangles, I-beams or angles are common extruded profiles. The process also allows for continuous encapsulation of core materials inside the composite, such as foam, wood or wire. Additionally, with pultrusion, high fibre content of 70% by vol. can be achieved (Knippers, Cremers, Gabler & Lienhard, 2011). However, as the unidirectional reinforcement is aligned in the longitudinal direction, the mechanical properties perpendicular to the pultruding direction are low.



Pultrusion

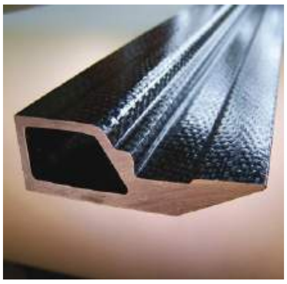
1 Heated mold
2 Pre-form
3 Textile reinforcement
4 Rolls of rovings
5 Resin bath
6 Molded section
7 Pull mechanism
8 Saw

Pultrusion is an automatic method with low labor intensity and high degree of mechanization. The equipment used includes the pultrusion machine that continuously pulls, consolidates and cuts the profiles and the steel forming die that heats and cures the composite in its' final shape. The capital cost for setting up a production unit whereas tooling is also expensive. Thus, pultrusion is worthwhile only for large quantities that exceed at least 1000 production meters.

6.5.2 Continuous lamination

In continuous laminating the reinforcement is mainly in form of fabrics or mats instead of fibre rovings. In the same way with pultrusion, the cloth sheets are pulled continuously from a series of creels and get impregnated with thermosetting liquid resin through resin baths. The wet fabrics are added one by one on top of each other and pressed together until they have reached the desired thickness. The resulting laminate is then cured by getting subjected to the high temperatures of a closed oven. After curing, the sheet is cut to the desired length.

The process which is limited to sheets, is used for producing flat and corrugated architectural panels that have a wide range of applications such as room separating light walls, composite doors and glazing, patio covers, greenhouse panels, skylights or electrical insulating materials.



6.16 Pultruded profile reinforced with carbon fibre (http://www.secar.at/)

6.17 Spay-up process (http://www.businessnc.com/)

6.6 Spraying processes

6.6.1 Spray-up

Spray-up is a simple and inexpensive method for large parts with complex geometries that is based on spraying a mixture of short chopped fibres and resin on the surface of the mold. The process requires a single mold that is usually made of GFRP or wood and the necessary equipment that includes a hand-held spray gun and rollers.

The reinforcement is installed in the spray gun as a continuous roving which is chopped in short fibres inside the gun. Prior to spraying the mixture on the surface, a gel coat is applied on the mold as in hand lay-up. Once this layer has cured, the fibres and the resin are sprayed on the mold. Air inserts are directly pressed out with a roller and then the wet laminate is left to cure in atmospheric room conditions. For thick laminates, the layering is processed in several stages, allowing the material to gel after every stage.

Spray-up is suitable for shapes with high surface area to thickness ratio while lamination of vertical surfaces or membranes is also possible. Typical applications include building panels, boat hulls or bathtubs. Another advantage is that the process is low labor intensive requiring only the minimum amount of work necessary.

However, the components produces are composites with low demands regarding their mechanical properties and load-bearing capacity due to the short length and random orientation of the fibres. Additionally, as the laminates tend to be rich in resin, the fibre-to-resin ratio is very low, resulting in heavier parts. Resins, also need to be low in viscosity (more in a liquid form) in order to be sprayable, which generally compromises their mechanical/thermal properties (NetComposites, 2014).

Regarding the environmental impact of the process, as spray-up is an open mold process the styrene emissions are high. Besides, the low viscosity resins that are used are typically more hazardous than other thicker resins. Thus a good ventilation system that provides constant air extraction is necessary.

6.7 Manufacturing cost calculation

Describing all the different processes showed that manufacturing a composite component consumes various types of resources, each of which has an associated cost. The summation of the costs of these resources results to the final cost of the product. These resources can be generally classified in the five following categories: materials, capital, time, energy, information (Ashby, Shercliff, Cebon, 2010).

6.7.1 Materials

Manufacturing a component that weights m (kg) includes the cost Cm ($/kg) of the materials and consumable feed-stocks from which it is made. Thus, the cost of the materials that primarily contributes to the final cost of the unit is mCm. However, processes usually do not use the right amount of material but create a scrap fraction f, such as machinery swarf and rejects. In order to include this lost material in the cost the material cost per unit has to be magnified by the factor 1/(1-f). Thus, the material cost per unit is:

$$C_1 = \frac{mC_m}{(1-f)}$$

6.7.2 Capital

The total capital investment is generally subdivided into the cost of tooling and the cost of equipment. The cost of tooling Ct ($), consists the cost of dies, molds, fixtures, and jigs and is also known as the dedicated cost because is entirely assigned only to the production run of a single component. Tooling has a certain lifespan, after the end of which it needs to be replaced. Tool life is defined by the number of units nt that a set of tooling can produce before being renewed. Every time tooling is replaced, the cost of the new tools is added to the total cost and spread over the whole batch size n of the production run, increasing the cost per unit. This increase in the total cost caused by the renewal of tooling is expressed by multiplying the cost of one tooling set Ct by (1+n/nt). Thus, the tooling cost per unit is:

$$C_2 = \frac{C_t}{n}(1+\frac{n}{n_t})$$

The capital cost of equipment Ct ($) is in contrast with the cost of tooling not dedicated only to one production. By installing different die-sets or tooling, the same equipment and machinery can be used to manufacture many different components. The overall capital cost of the equipment is converted into an overhead “rental” charge per hour by diving it by a capital write-off time, two, which is the years the machinery was used from the beginning of its function until the time it was recovered. Thus, in the exceptional case in which the equipment is used continuously during its lifespan, the charge per hour is Cc/two. However, as this is not the case, the write-off time is magnified with a load factor L, which is the fraction of time for which the equipment was productive. This hourly cost is then divided by the production rate/hour □ (units/hour) in order to get contribution of capital cost per unit.

$$C_3 = \frac{1}{\dot{n}}(\frac{C_c}{Lt_{wo}})$$

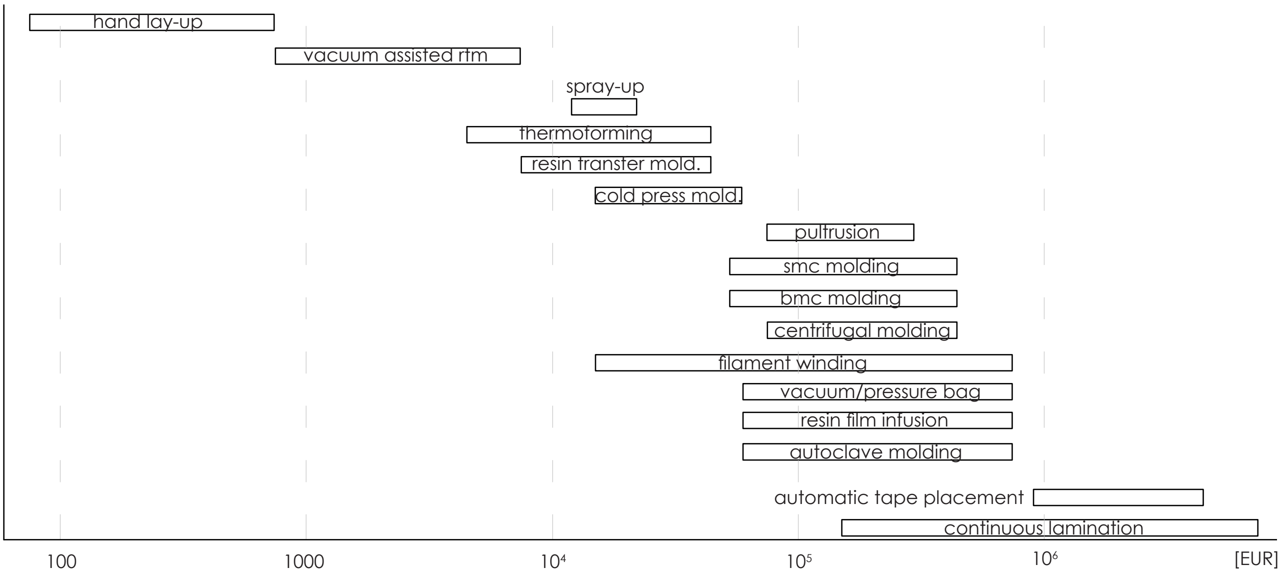


Table 6.1 Capital cost of composite manufacturng processes
(CES Edupack, Granta Ltd)

6.7.3 Time, energy and information

This category consists of costs of different resources that are included into the general hourly overhead rate Coh ($/h). The time required for the production of a series of components becomes chargeable by including the cost of labor, administration and general plant costs. Energy consumed for the process is also included in the Coh. Finally, there is also the cost of information in the sense of research and development done, royalty or license fees.

$$C_4 = \frac{C_{ch}}{\dot{n}}$$

The total shaping cost for one single unit, Cs is the sum of these four equotations, C1-C4, which can be simplified to the following (Ashby, Shercliff, Cebon, 2010):

$$C_s = C_{material} + \frac{C_{dedicated}}{n} + \frac{C_{capital} + C_{overhead}}{\dot{n}}$$

The equotation shows that the three main contributions to the cost of one product is the material cost per unit which is not depending on the production batch size or rate, the dedicated cost (tooling cost) per unit which depends on the production volume (1/n) and a general overhead per unit that is influenced by the production rate (1/□).

6.7.4 Cost comparisons between the processes

After having analyzed the costs of all the different resources consumed in order to manufacture composite components, the production techniques described previously are compared in the following tables in terms of these cost categories and other economic characteristics. All the tables were developed in the material science computer software CES Edupack 2013.

The tables of the capital and tooling cost show that processes that require either automated machinery (automated tape placement, continuous lamination) or complex, usually double and expensive molds (compression molding techniques, RTM), are the ones that have the higher values. On the other hand, manual processes that are based more on hand labor and make use of cheap molds (hand lay-up, vacuum assisted RTM, thermoforming) have a lower capital cost.

However, some manual processes, such as hand lay-up, even if they require low capital investment, they can be very labor intensive and thus have an increased cost per unit. Specifically, table 4.3 classifies 10 of the researched processes that require hand labor into three categories regarding their labor intensity: low, medium, high. Compared to hand lay-up, vacuum assisted resin transfer molding is a less labor intensive process that still can be operated within a low investment on equipment.

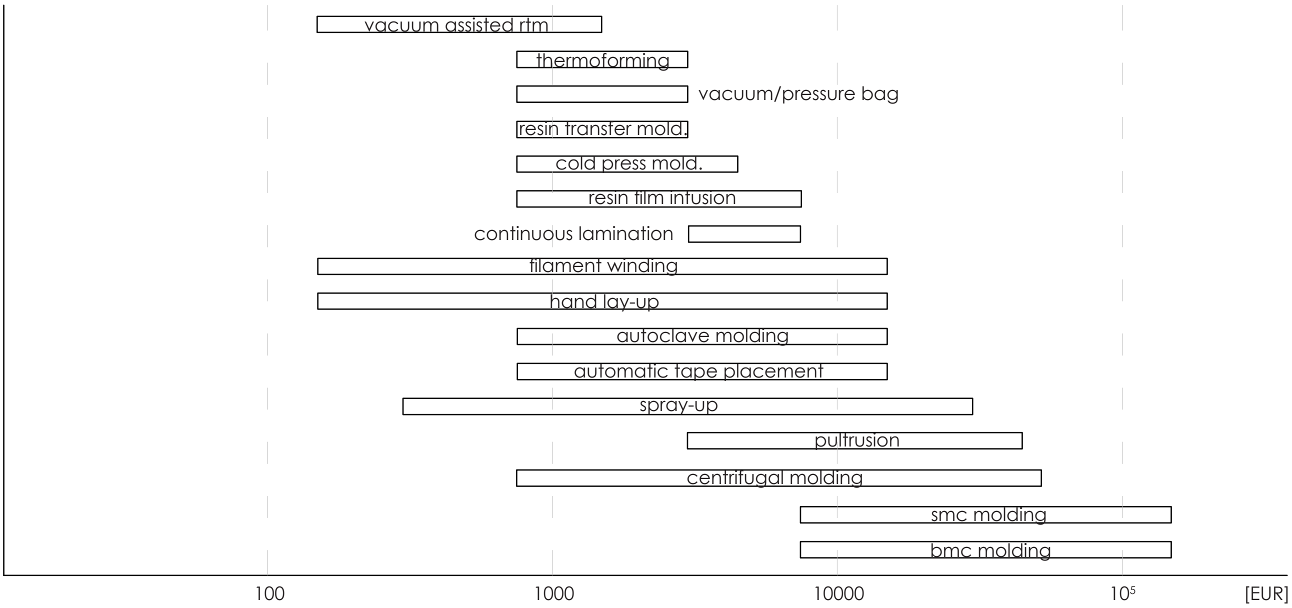


Table 6.2 Tooling cost of composite manufacturng processes
(CES Edupack, Granta Ltd)

Table 6.3 Labor intensity
(CES Edupack, Granta Ltd)

Low	Medium	High
Pultrusion	Vacuum assisted rtm	Autoclave molding
	Vacuum/pressure bag	Hand lay-up
	Filament winding	Resin tranfer molding
	SMC molding	
	BMC molding	
	Thermoforming	

Normally, processes that require high capital investment become economic only at large batch sizes and therefore are preferred for large production series. On the contrary, processes with low tooling cost are suitable for small batch sizes. Usually, such techniques use equipment with low tool life which needs to be replaced after a small quantity of units produced. Table 4.4 shows the economic batch size of the researched processes in units and Table 1.1 indicates the life of the equipment before it has to be renewed.

Finally, another important factor is the production rate. This output rate influences the time required for producing a series of composite components and is measured in number of units per hour or length per hour in the case of continuous processes. The production rate is associated with hourly costs of labor, charging of the machines and consummation of energy, while the rate becomes more important for large scale productions. As table 1.1 also confirms, automatic processes have higher production rates than their manual counterparts.

In conclusion, comparing the processes in terms of cost showed that for the case of a production with less than ten units batch size, such as a single bridge, the optimum methods are the typical manual ones, such as vacuum assisted resin transfer molding or hand lay-up. Nevertheless, the latter requires much more labor intensity.

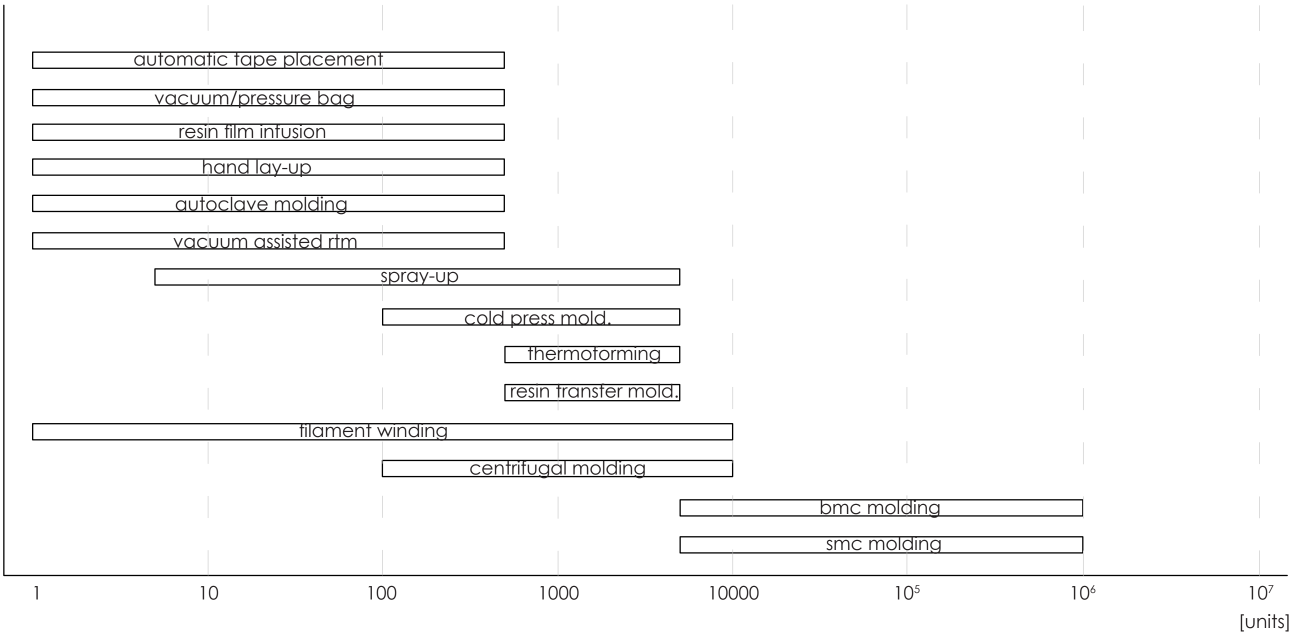


Table 6.4 Batch size capacity of composite manufacturng processes
(CES Edupack, Granta Ltd)

6.8 Moldmaking

Mold construction is an influential factor of the tooling cost. Molds are generally expensive in terms of their materials and production and in cases of complex shapes the cost of the mold can even exceed the cost of the actual component (Knippers, Cremers, Gabler & Lienhard, 2011).

The process of creating the mold is operated into two steps. The first step includes the production of the original or master mold. This first prototype is developed by means of adding or subtracting gradually material e.g by milling with CNC machine. The materials used are easy to work but normally they have short lifespan and thus are suitable only for a small number of reuses. Such materials include rigid foam, balsa wood, clay or gypsum.

The second step is the production of the negative mold by laminating or casting on the first original mold. Various materials such as fiber-reinforced polymers and metals can be used for the negative mold, depending on the size of the production run. In order to make easier the demolding of the negative mold, the surface of the original mold is coated with a release agent such as silicone oil or wax.

6.18 Foam shaped by a CNC router for a boat hull mold
(http://www.reinforcedplastics.com/)

Apart from the two-step process of moldmaking, the negative mold can be also created directly. For example, is possible to shape rigid foam with a CNC milling machine or place wooden boards in a way that they create a sealed mold hat can be used directly for producing the composite components. Finally, another special type of mold is the permanent formwork which remains as the core material inside a sandwich composite.

6.8.1 Mold materials

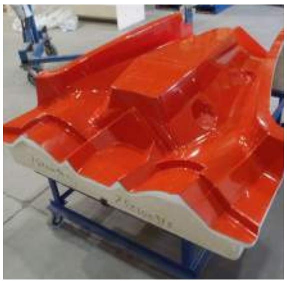
The selection of the proper material for a mold depends mainly on the dimensions of the component, e.g large components need strong materials, the desired surface quality and the number of reuses required. Strong materials are normally an option in cases of high batch sizes whereas cheaper materials allow only for a small number of reuses.

Gypsum is an inexpensive and easily formed material that is usually used both for negative or original molds. However, its low strength makes it fragile and thus the mold is frequently damaged during demolding. Clay is like gypsum another inexpensive easy to shape material suitable for small components and a few reuses.

Rigid foam (PVC, PUR, XPS) is a frequently used material that functions both as mold and core material. The cost of the material is relatively high and so the quantity of foam used must be reduced to minimum. Additionally, the computed-controlled shaping process by the CNC milling machine requires labor. Molds made from rigid foam have a short lifespan that makes them functional only for a few reuses.

Glass fibre-reinforced polymers consist a comparatively more expensive option used for constructing durable negative molds with a life span of more than 100 reuses. Polymers without reinforcement such as polyurethane resin are also an alternative. PUR has an excellent finish and is used where high-precision molds are needed. However, the mold itself is comparatively expensive and heavy.

Metal molds, normally from steel and aluminum are also durable and strong but expensive to produce and thus they require very large production runs. Wooden molds represent another reasonable alternative mainly for large components.



6.19 FRP composite mold 6.20 Steel mold
(http://www.pcminnovation.com/)
(http://www.emeraldinsight.com/)

Design

7.1 Case study

The selected site for designing the bridge is located in the municipality of Haarlemmermeer, in the province of North Holland in the Netherlands. Adjacent to the west border of the municipality at the south side of Schiphol Airport, the area is currently developed into a logistics park by Schiphol Area Development Company. Schiphol Logistics Park is 45 hectares in size and comprises a western section (24 hectare) and an eastern section (21 hectare).

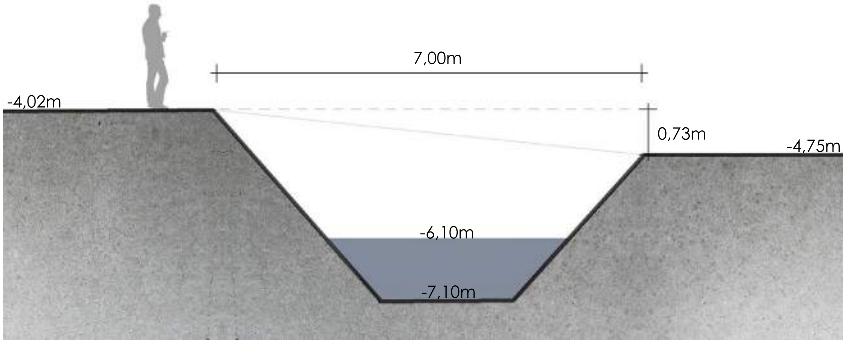
The eastern section is separated into two subareas as a small ditch runs the entire length of the area. From the one side of the ditch the area is programmed to become the business location offered for development and investment while the other smaller area is designed as a public park. The role of this almost 7 hectare green park, Ringdijkpark, is to stand as a buffer zone between the logistics area and a housing linear zone across Aalsmeerderdijk which is adjacent to the area. Thus, Ringdijkpark, will work as a refreshing intermediate zone given both to the employees of the logistic companies and the permanent inhabitants.

7.2 Site analysis

The ditch separating the Schiphol logistic park and the Ringdijkpark is the site that was chosen for designing the natural fibre-reinforced polymer bridge of this graduation. The width of the dike is 7 meters including the slopes from both sides while the ground from the side of the Ringdijkpark is 75cm lower than the other side.

The case study area, as well as the entire municipality of Haarlemmermeer is beneath sea level as for centuries Haarlemmermeer was a dangerously increasing 70 square mile lake which was transformed into land in the 19th century by using steam pumping machines that drained the water. Thus, the level of the ground of the logistic park is 4,02 meters beneath sea level, Ringdijkpark is at -4,75 meters whereas Schiphol airport is at -6 meters.

With the same technique of the polder system that was used in all lake draining examples in the Netherlands, a ring canal was opened first around the water surface while the excavated soil was used for building a dike between the canal and the lake. Then the water was pumped out from the lake by windmills or later by steam machines and thrown to the ring canal which was directing the water to rivers through outlet canals. (Dry feet. Flood mitigation in the low countries, 2010)



Drainage ditches, such as the one in Schiphol logistics park, were then dug on the reclaimed land in order to convey the remaining water to the perimeter of the lake bed. Once the land was dry, these ditches were usually used as borders for indicating and separating the properties. The drained lake required continuous maintenance for removing precipitation and groundwater seepage.

The water level of the ditch is at -6,10 meters with a seasonal level increase/decrease of 10 centimeters depending on winter/summer situation. The depth of the water is about one meter.

7.3 Design parameters

As this graduation project is a realistic scenario offered by SADC company as a request for designing and constructing a bio-based plastic bridge, cost- efficiency was from the beginning a very crucial parameter. The total cost of the construction should be kept within the limits of the budget offered by the company which was in this case the "client" of the project.

Apart from the budget limitations, the fact that the bridge would be a single product and not part of a large production run, orients the construction towards simple manufacturing techniques suitable for small batch sizes. Processes that require a high capital investment either in tooling, equipment or machinery could even double the cost of a single element.

According to the results of the research done on production methods, in terms of cost, moldmaking is a crucial factor. Not only is the cost of the chosen material for constructing the framework but also the labor required for shaping it, that increase considerably the actual cost of a product. Obviously, in the case of multiple reuses, the mold cost is spread over the butch size of the production and thus it is divided and added on the individual cost of each unit. However, as this is not the case for the bridge of this present project, moldmaking has to be reconsidered.

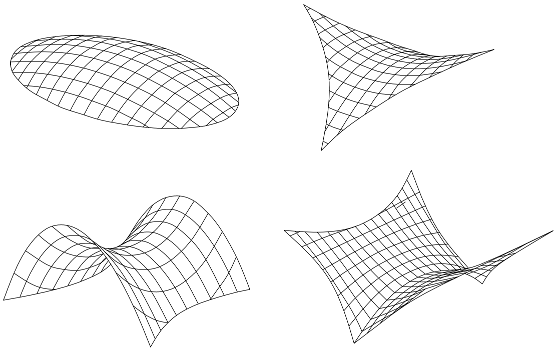
Consequently, the solution for minimizing the cost of making the mold seemed to be in using materials which can be easily found in most of the composite construction companies. Flat boards, simple molding tables and generally molds that were previously used in other productions and can be easily adjusted and reused or inexpensive new material are ideal elements for constructing efficiently and without much labor a mold that will be used only a few times.

Apart from the financial criteria, another parameter that is also considered as important for this project is the optimum structural design of the bridge. In that sense the chosen shape should be a result of comparison between a series of different possible solutions operated by a performance driven evaluation process. In order to achieve this optimized design result, a number of different digital simulations and tools have to be done on a parametric model that would allow for a continuous optimization of the chosen design based on its flexibility.

The last factor regarding the design is related with the aesthetical result and especially with the way that plastic material should influence the shape of a bridge. If a truss is connected with either steel or wood then what are the shaping potentials of plastic and how a plastic bridge should look like? Plasticity is a word used in plastic arts for describing the quality of being plastic and able to be molded. It is also characterizes the quality of a sculpture in terms of its three-dimensional appearance. So plasticity already including the word plastic, is an important element that should be reflected on a bridge that was not welded or drilled but molded.

7.4 Design evolution

The overall design phase can be generally divided into three different parts that follow a gradually narrowing course that starts from a general first approach and leads to the chosen design.



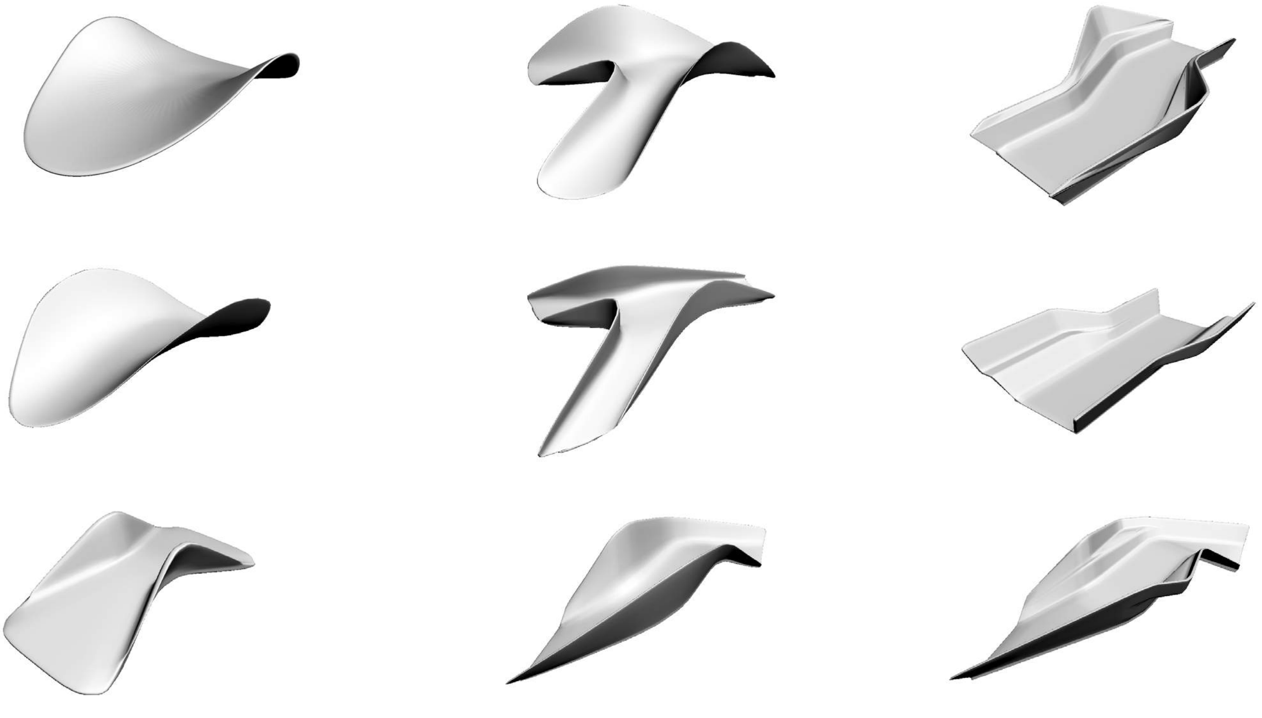
7.4.1 Stage 1. First design approach

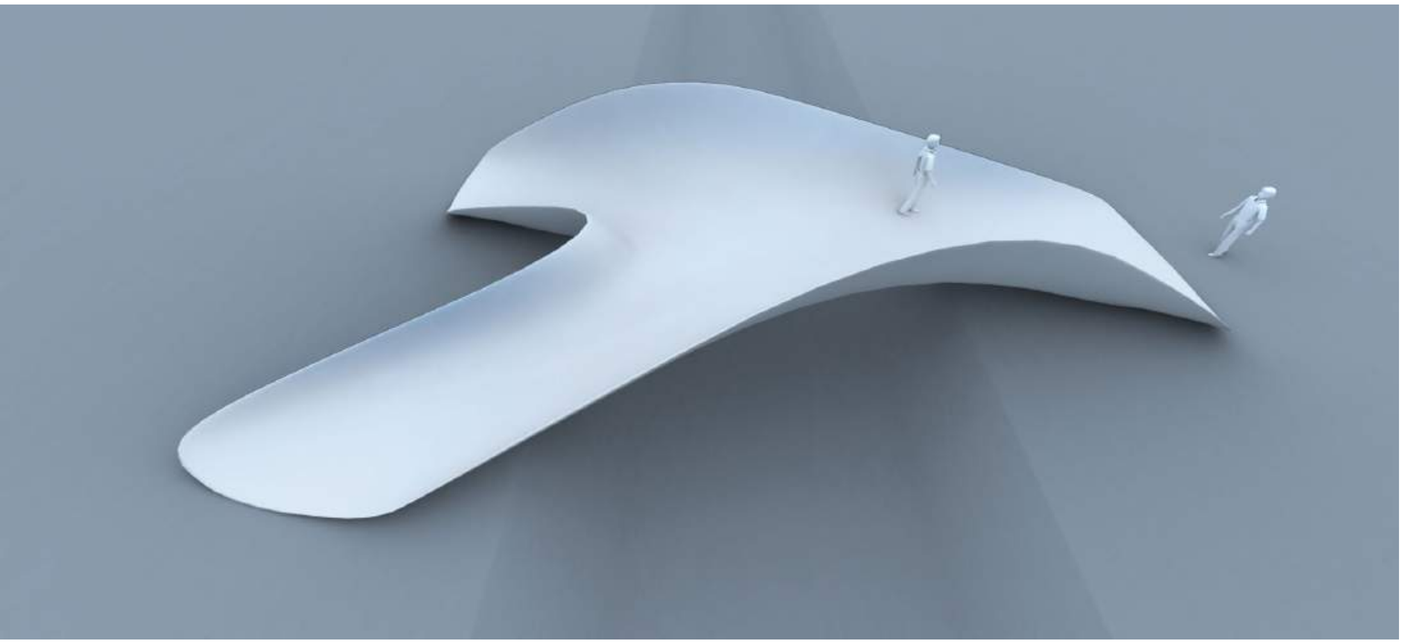
The first part of the design process is characterized by a freedom in form exploration as a result of a rough sense regarding production cost. Not only had these financial topics not been researched by that moment but also the project was still in a conceptual level and the real construction was only a possible but not verified scenario. The result of this phase is a series of design approaches that being released from cost limitations they explore the shaping potentials of molded plastic.

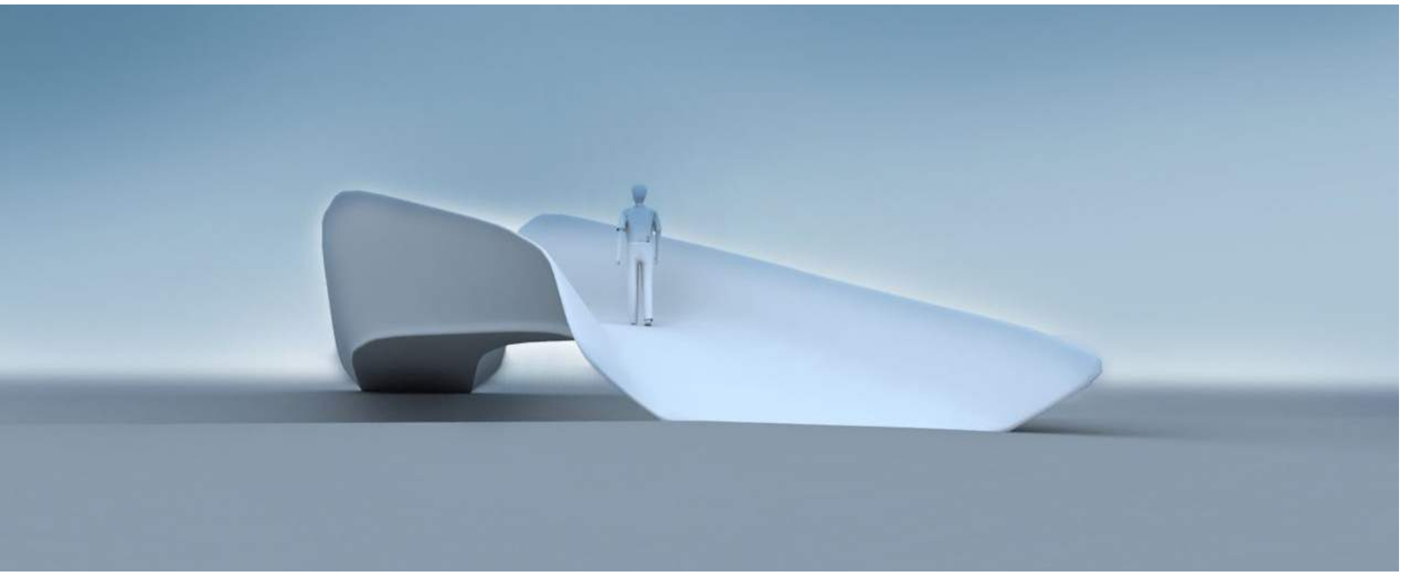
The main criteria for these preliminary designs were the structural efficiency of the shape itself and the reflection of plasticity. Considering that objects with surfaces that curve in two directions, such as domes and spheres, are much stronger compared to other structural systems, the forms try to translate these ideas in bridge design. Therefore, concerning a better structural performance the forms of this phase are all characterized by double curvature, smooth curved corners and a fluid plasticity.

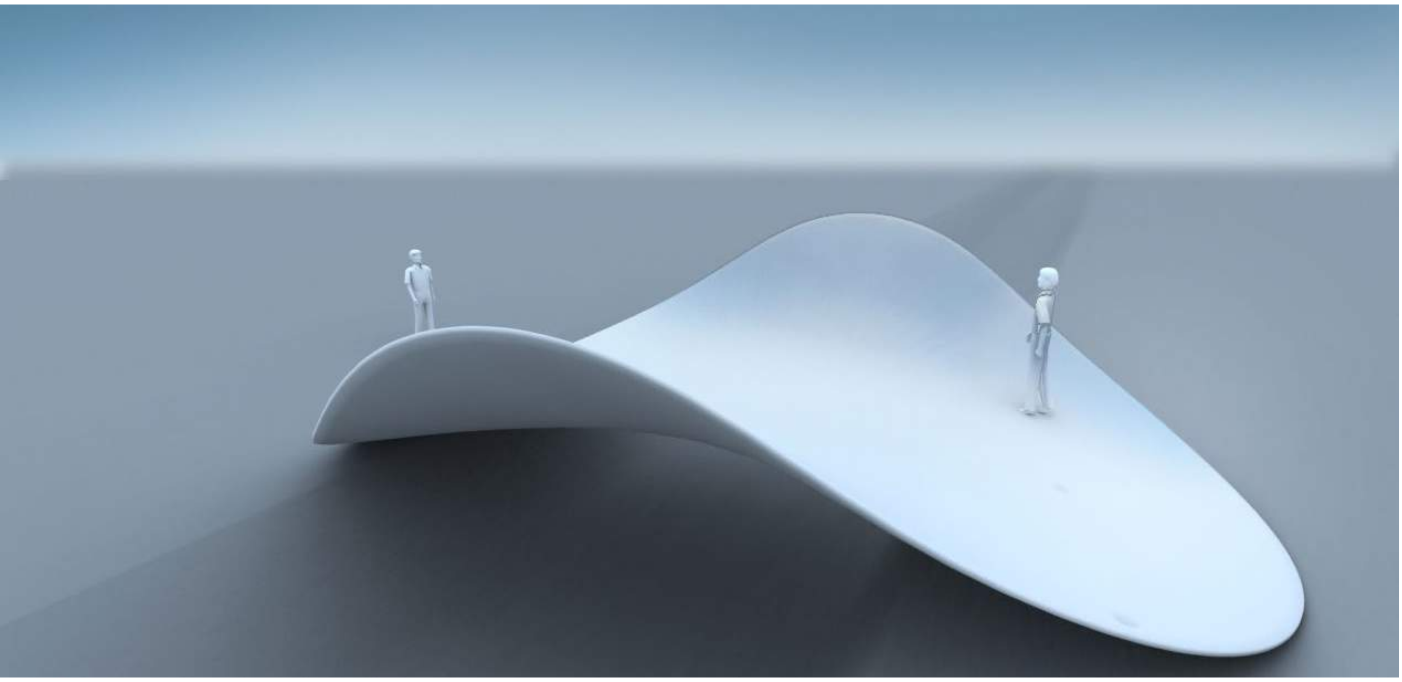
In conclusion, this phase shows interesting results on how a plastic bridge could look like under different financial and production circumstances. In a possible scenario where a larger number of bridges had to be delivered, the option of making a special mold would be more reasonable, as the cost of moldmaking would be distributed over the batch size. The research done on the production methods that could be used for achieving such shapes and on the financial issues proved that as the geometry becomes bigger and more complex, the cost of moldmaking increases because stronger and thus more expensive material are required and more labor is needed.

However, all this knowledge taken from this design part together with the research done was important in order to rethink issues of shaping and production and continue to more rational and cost-efficient solutions.









7.4.2 Stage 2. Second design approach

Design guidelines

Following the direction of having an inexpensive mold by reusing material that already exists in a composite company directly influences the design possibilities. Shapes that could be feasibly constructed without exceeding the given budget should be simple in geometry and consist mainly of flat or simply curved surfaces.

As it was previously mentioned in the chapter of the design parameters, a realistic solution towards low cost moldmaking would be to actually make use of already existing molds or in general materials that are easy to be found and do not require much labor to be used.

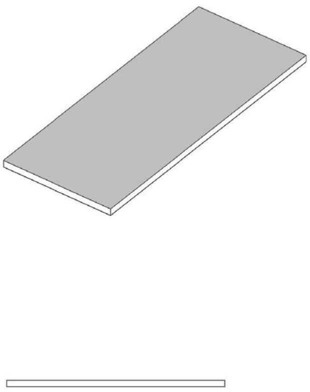
For instance, one object that is present in almost every composite company is a steel flat molding table mainly used for vacuum assisted resin transfer molding. This flat table has usually large dimensions, enough to fit the entire length of an 8 meter bridge. In some cases, especially in companies that produce composite bridges this flat steel plate is more flexible, allowing for bending as well.

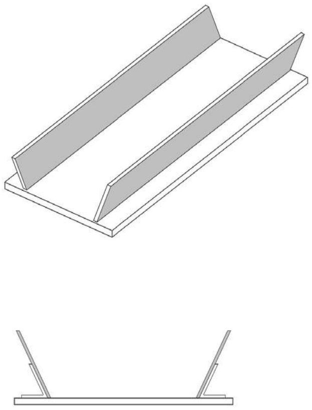
The design prepositions of this phase actually explore the potentials of using this flat plate either straight or slightly bended as the mold of the deck of the bridge. The plate will also be the base for adjusting vertical flat boards for shaping the parapets and making a single mold both for the dech and the parapets.

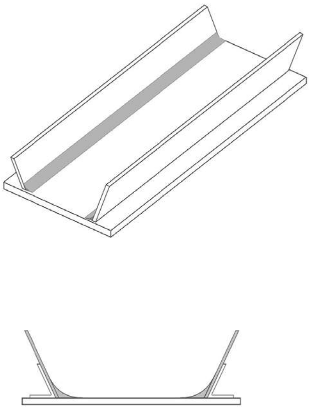
An important decision that is reflected in both design phases was to achieve a one-off uniform composite structure produced by the same production process from a single mold. The purpose of this intention is to use structurally the parapets as beam elements and have a coherent and complete structural system. Separating the structure in one deck element and two side parapets assembled together would cause discontinuity of the fibres and thus subdivision of the system. Additionally, the connection surfaces in the case of a separate structure would require special shaping of the joints that would add complexity to the mold, while in the final result the connection lines would be visible depriving the visual continuity and uniformity of the bridge.

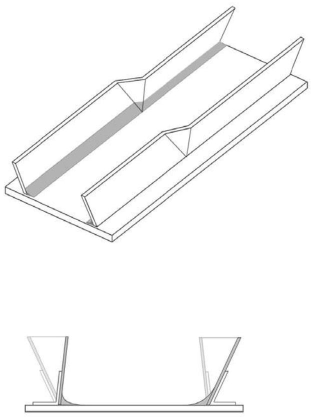
The design of the bridges is inspired by the Japanese paper folding art of the origami. The majority of these concept bridges consist of flat surfaces and gentle "folding" lines combined in clear geometries that resemble to origami structures. The results of this phase consist of 6 bridges, which although they follow the same "origami" design concept and they keep the same general dimension, they all have slight differences.

All the bridge geometries were created in a parametric design software in order to achieve a flexible and adaptable 3D model by controlling its basic parameters. The specific software that was used is Grasshopper for Rhino.

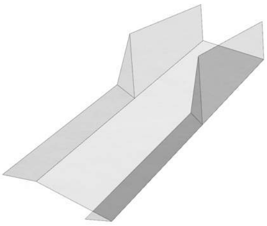

Vacuum table


Flat side boards out of wood, mdf etc

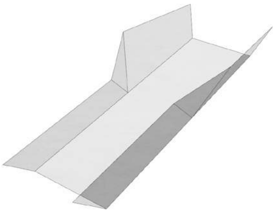

Curved corners


Flat side boards out of wood, mdf etc

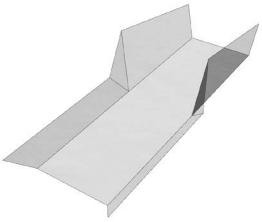
7.4.3 Design results



Bridge1
This bridge is characterized by a straight 2 meter in width deck and identically same parapets that have a slight shift in the middle of their length, which breaks the totally straight direction. This shifting in the geometry of the parapets results in an inwards turn and an outwards turn of the one and the other side accordingly. The minimum height of the parapets is 1 meter.



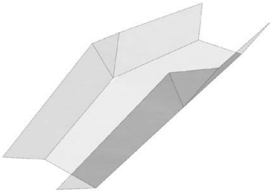
Bridge 2
The second design approach is similar to the previous bridge with the only difference that the side parapets are placed symmetrically to the horizontal axis of the deck giving an entire symmetry to the design. Both parapets keep an outward shifting resulting to more clear U-shaped crossections throughout the length of the bridge.

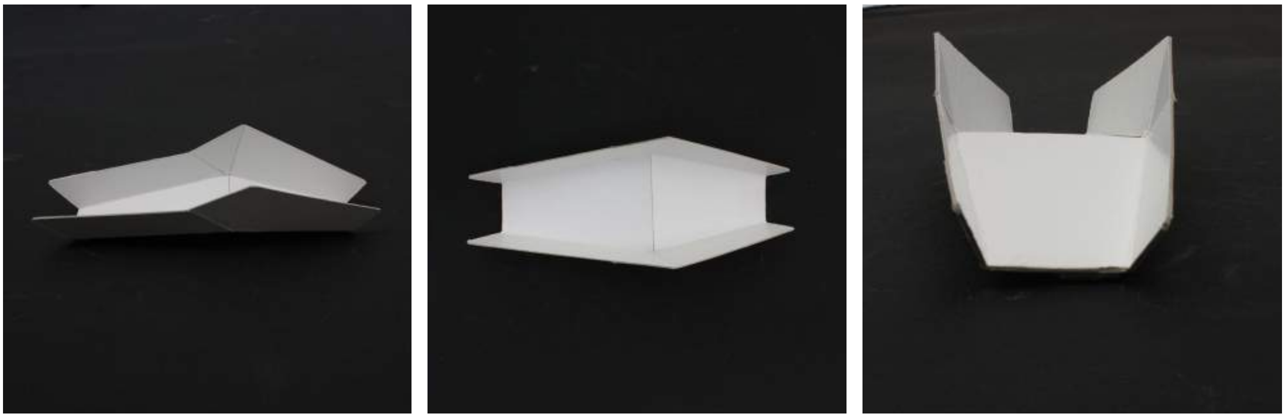


Bridge 3
Bridge 3 is also an alternative of bridge1 which retains the same general dimensions and asymmetry. The difference between the two designs is that in bridge3 the inward segments of the parapets are kept to a vertical straight position and are not turning towards the deck, whereas the outward parts keep the same position.

Bridge 4

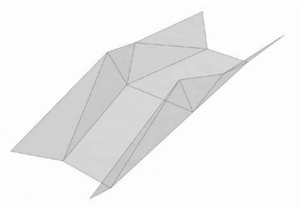
This design approach has a main difference from the previous examples as the deck is not straight in z-direction but consists of two planar angled segments that create a smooth curve at the point that they are joined. Additionally, the width of the deck increases respectively from both sides, starting from 1,8 meters of minimum width and reaching 2,6 meters at the highest point of the deck, where the two planar elements meet. The parapets keep a symmetrical order and both have segments that turn slightly outwards.

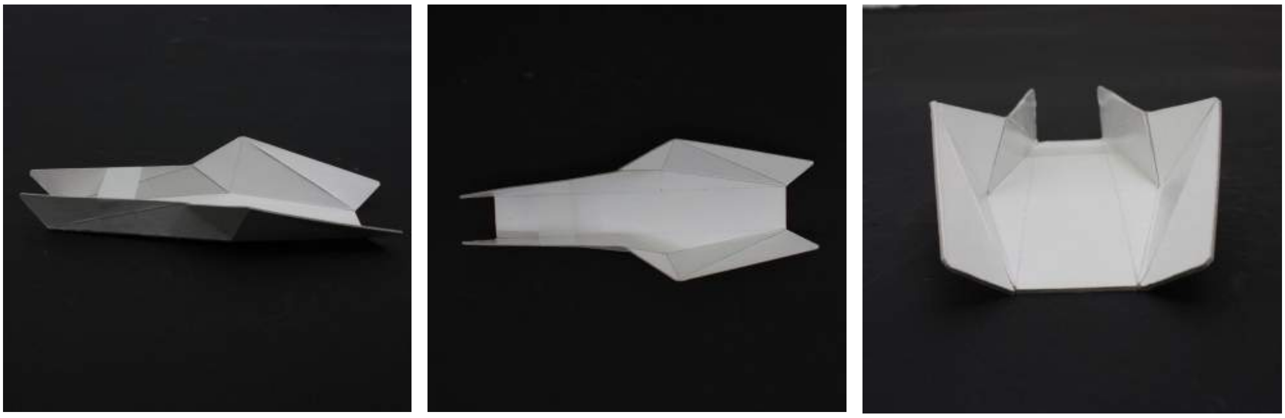


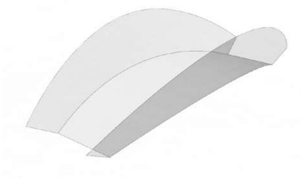


Bridge5

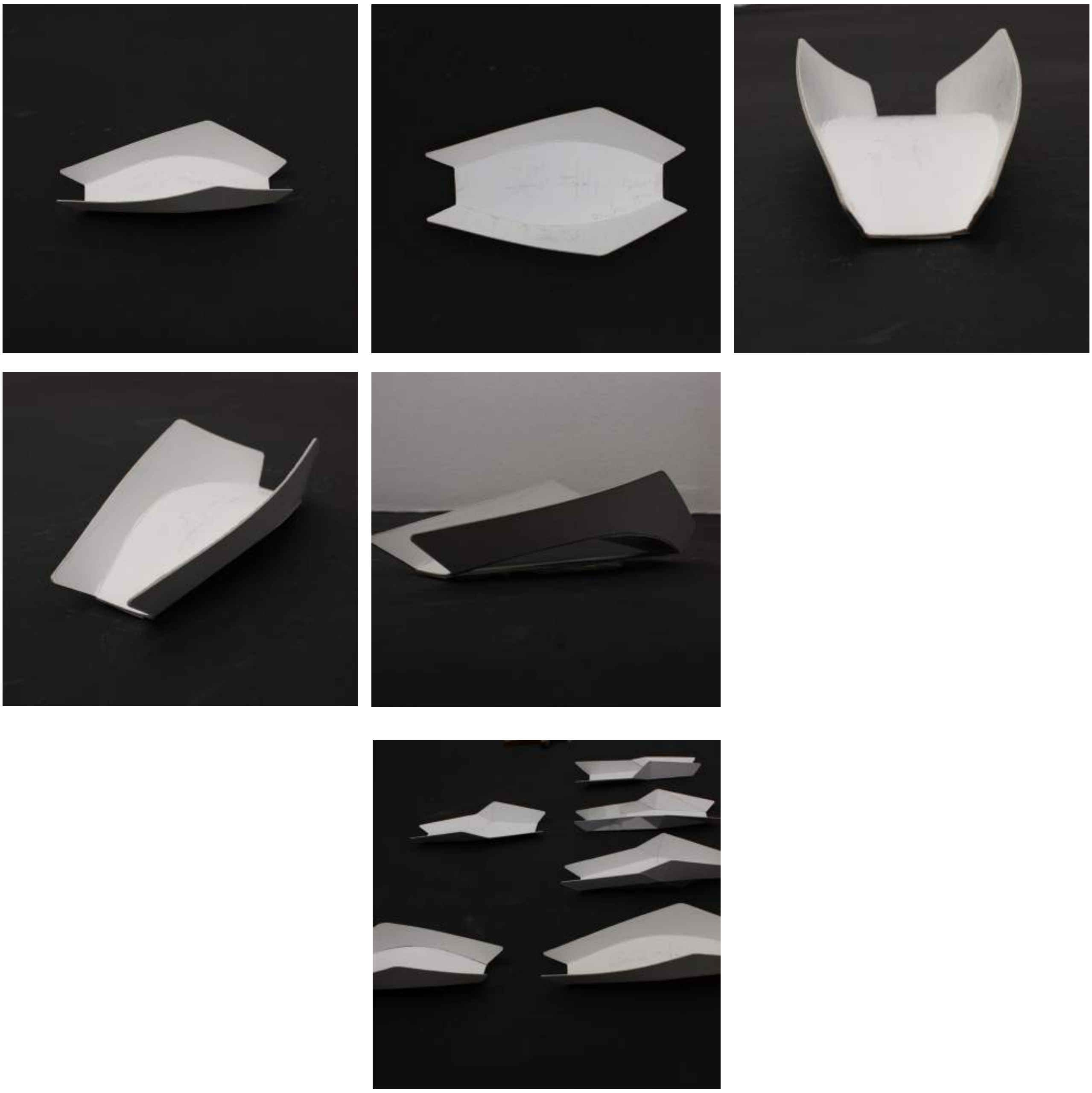
The 5th design is almost identical to the previous 4th design. Having the same deck, bridge5 and bridge4 are different only at the parapets. The only difference is that the parapets of this bridge are triangulated, meaning that they consist of triangular surfaces. Being closer to the origami structures, this bridge allows for more freedom in shifting the surfaces of the parapets.





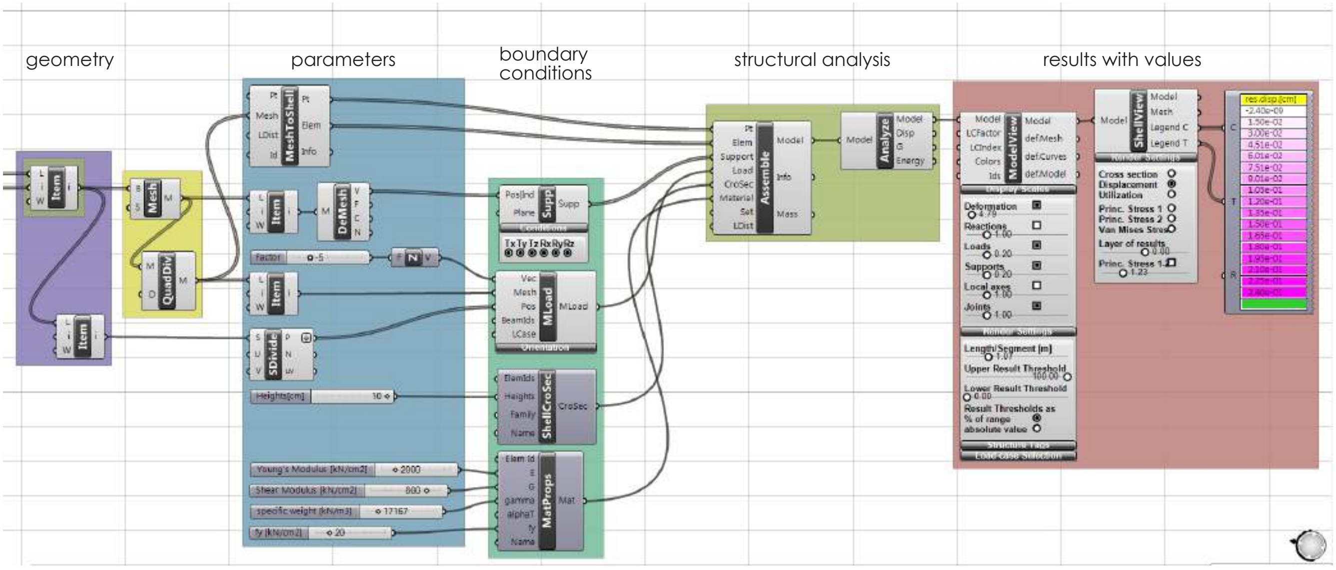


Bridge 6
The last bridge is an alternative of a bridge with a bended deck. In the same way like the two previous designs, bridge 6 keeps a curved increase of the width which reaches 3 meters maximum width and 1,8 meters minimum. The maximum height of the bend is 0,7 meters. The parapets here follow the bended character of the design and avoid having straight linear folds and geometry shifts.



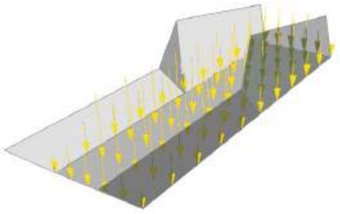
7.4.4 Stage 3. Structural testing

In the next phase, the previously presented design results had to be compared in terms of the structural behavior of their geometry. For that reason special software for structural analysis was used on the parametric models that were created in Grasshopper. Keeping the flexibility of the model allowed for optimization of the shapes by changing the dimensions of the geometry. The software that was used for the structural analysis and calculation is Karamba, a plug-in tool for Rhino that is fully embedded in the parametric environment of Grasshopper.

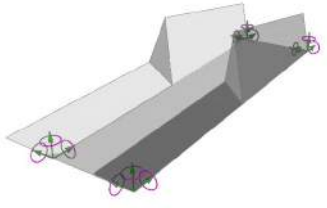


Boundary conditions

Running the analysis requires the construction of a finite model of the geometry composed by basic entities such as supports, loads, material properties and cross section that is applied to all 6 bridges in order to have an equal comparison based on the same boundary conditions.



Specifically, all the bridges are tested under a uniformly distributed load of 5.0 kN/m2 which is applied on the loading surface of the deck. Additionally, the support points are defined together with their degrees of freedom regarding translation in x-, y- and z- direction (Tx, Ty, Tz) and rotation (Rx, Ry, Rz).



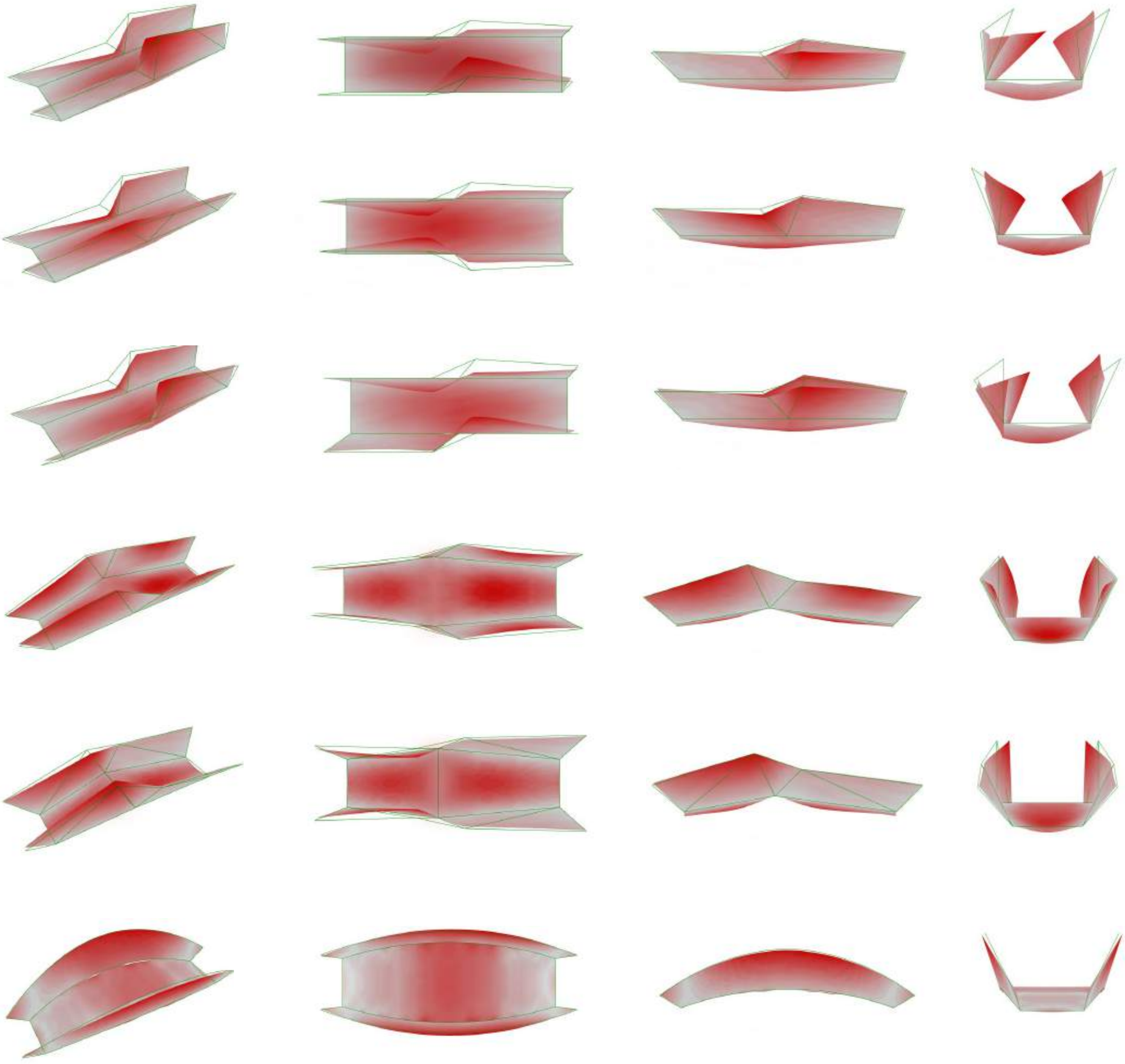
As the goal of the analysis is to compare the structural behavior of the geometries in terms of deformation and not to extract values or calculate the composite structure, an assumption was made in terms of the material selection of the bridges in order to simplify the process. Thus, the bridges are defined as 100mm thick structures with the mechanical properties of a composite that consists of an epoxy resin and E- glass fibres.

Results

The analysis regarding the structural efficiency of the shapes, which is expressed through the deflection of the geometries brought quite interesting results. First of all, the expectations of the superiority of the bridges with slightly bended decks over the straight ones obviously proved to be right as the deflection of the first was ten times less compared to the latter. Specifically, the bridge with the lower deflection was the bended one while the ones with the angled two-plate deck exhibited slightly higher values.

As the parapets of the given bridges are part of the structure their height and position also proved to be influential. Thus, the higher a parapet gets the more tends to get deformed inwards under uniform loading of the deck. This tendency also explains the high deflection values of the parapets that already designed to turn inwards to the deck (bridge1). Finally, the symmetry of the parapets in the longitudinal direction seemed to be a better option.

The following diagrams illustrate the deflection of the 6 bridges (vertically from bridge1 to bridge 6)



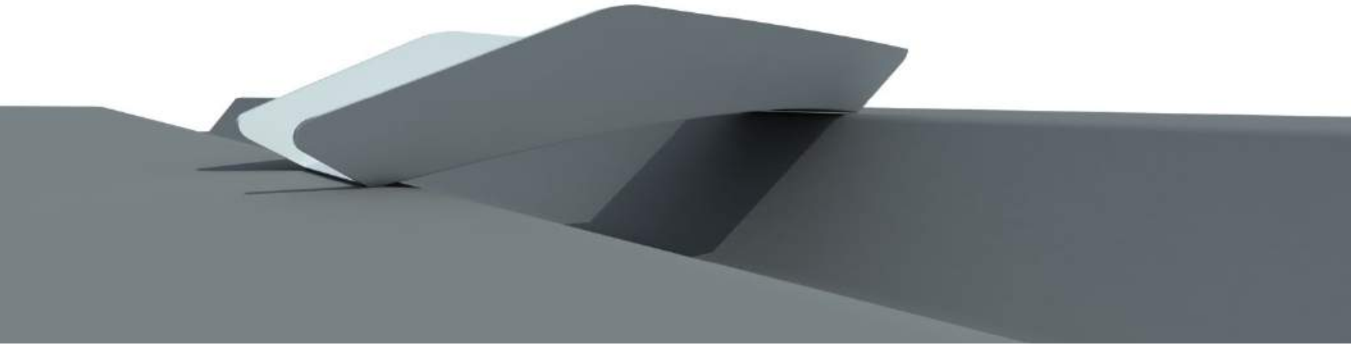
7.5 Final Design

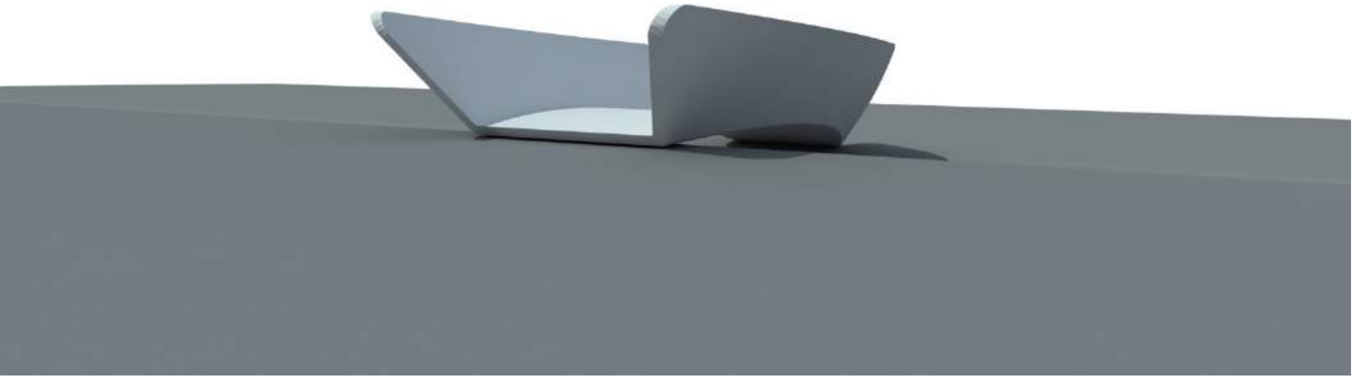
The final design is based on bended model that was chosen during the previous process. However, due to manufacturing limitations as well as reasons linked to functionality the deck could only slightly bended having a radius of 30 meters.

The parapets have a continuous height of 1 meter for most of the length of the bridge apart from the point where it smoothly turns downwards. At that point the height of the parapet is approximately 1,3 meters. Finally the parapets are placed with an inclination of 30o on the deck, while the deck-parapet connecting edges have a smooth turn.

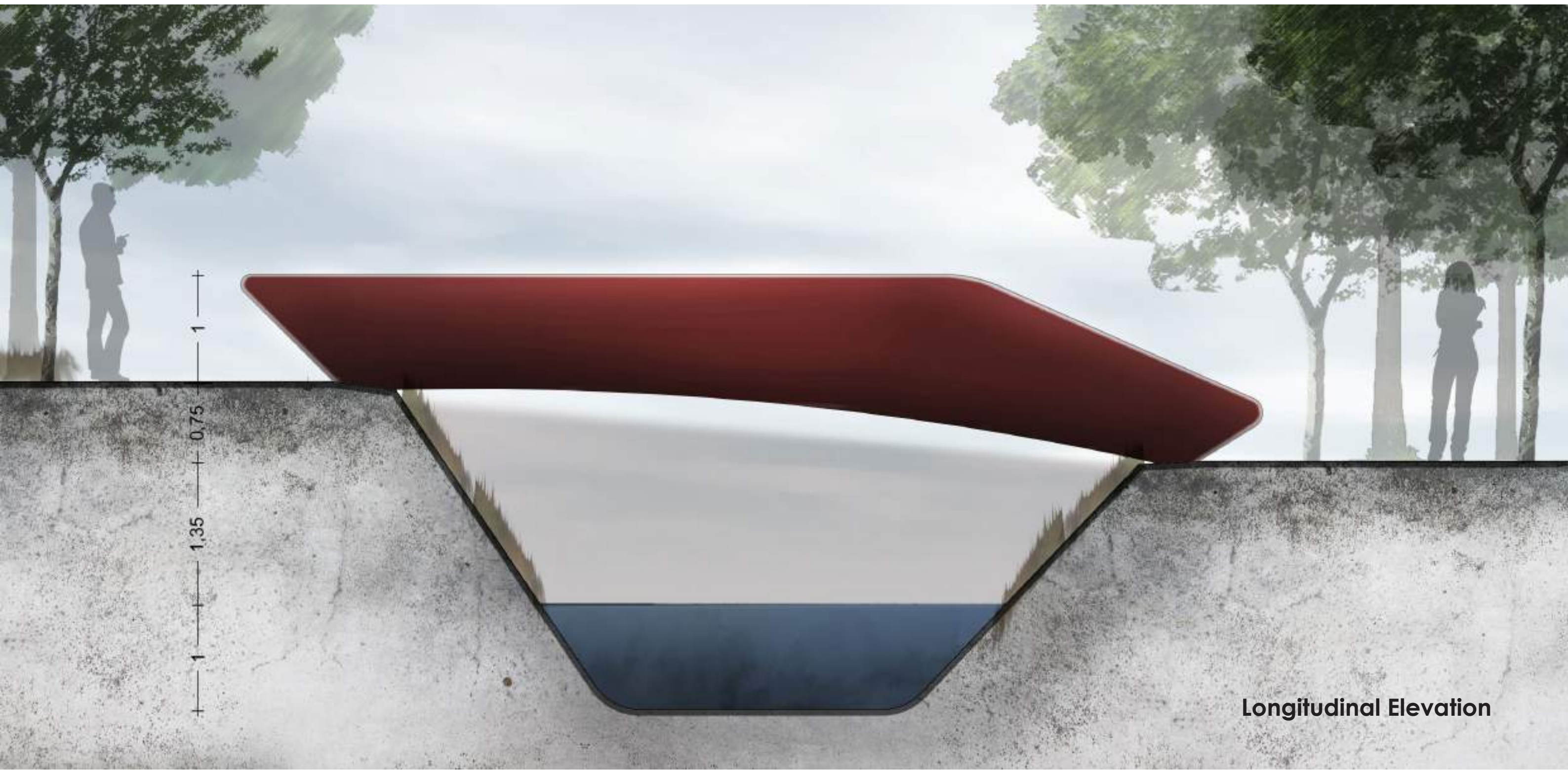
Similar to the bended tested model, the final design retains the elliptical shape on top view that creates a feeling of surrounding space to someone that stands in the middle of the bridge and give the sense of an entrance to the one entering the space from the two edges. The minimum width of the bridge at the two entrances is 2 meters and it reaches a maximum of 3 meters in the middle, while the span has a length of 8,2 meters. After performing the structural calculation, which consists the following chapter, the thickness of the structure was resulted to be 7 milimeters.

The bridge was chosen to be painted with two different colours, one from the outer surface and one from the inner. For the outer side a warm dark chestnut brown is suggested, while from the inside surface will be painted in light beige-grey.

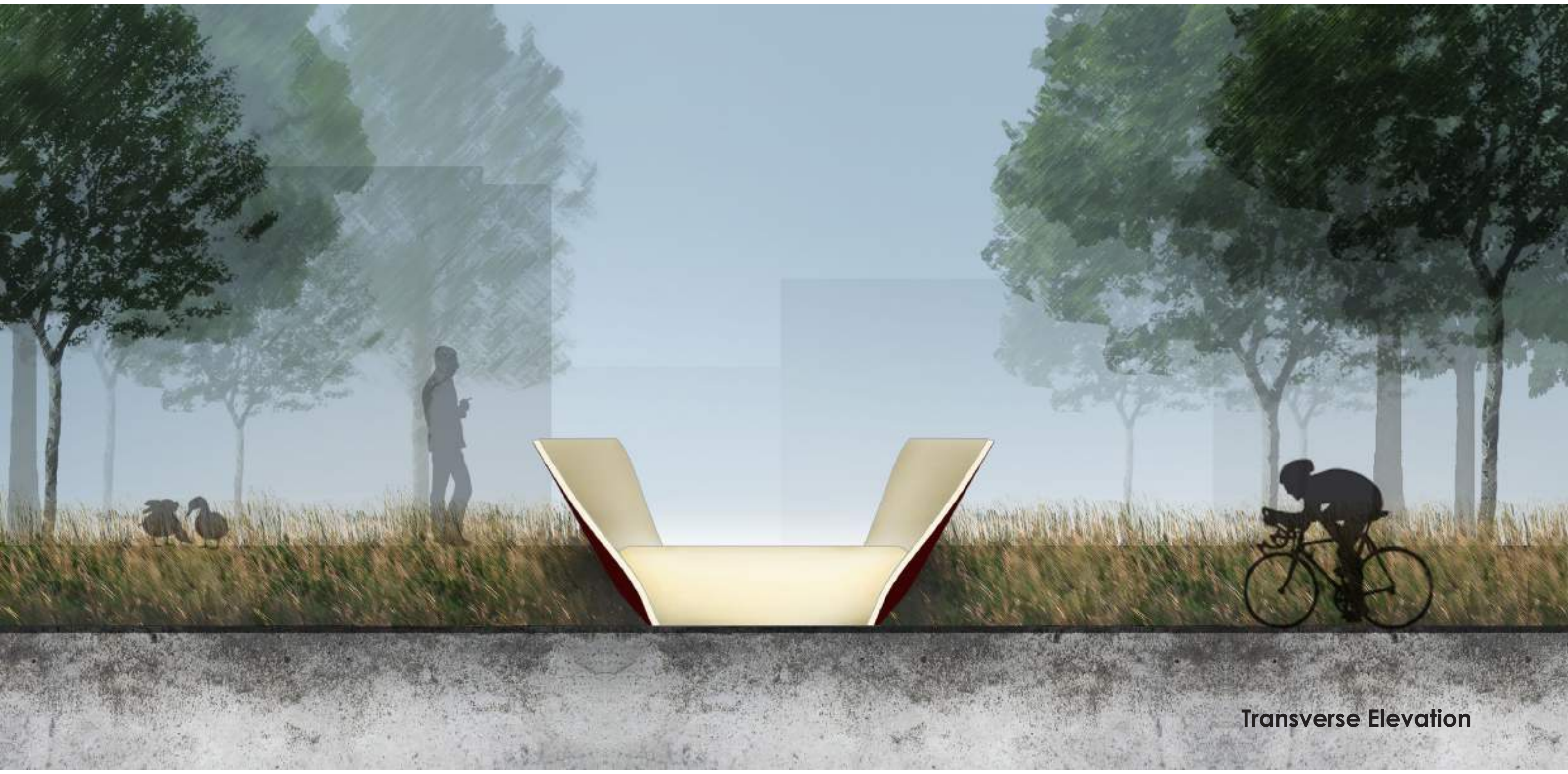




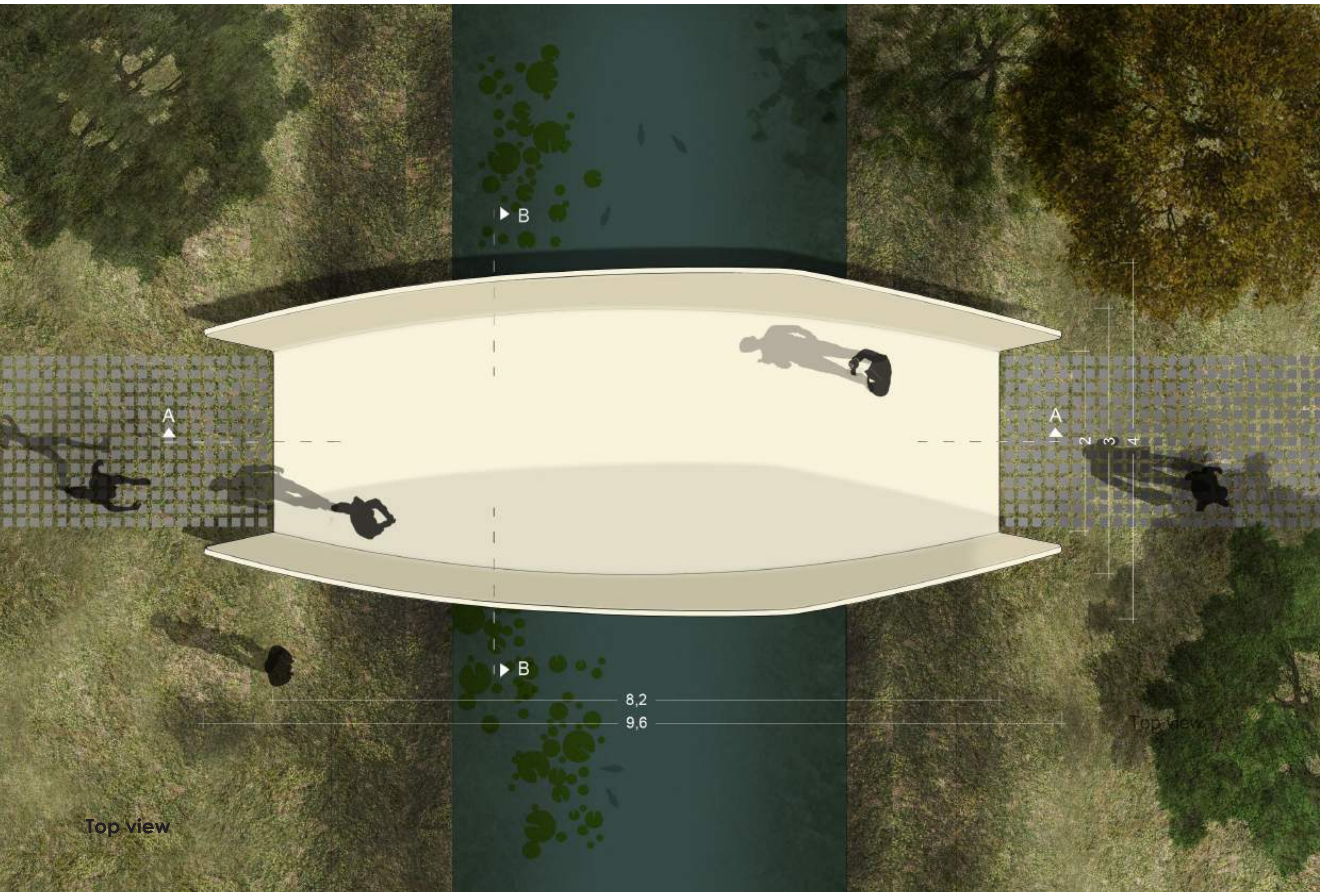
7.5.1 Architectural Drawings

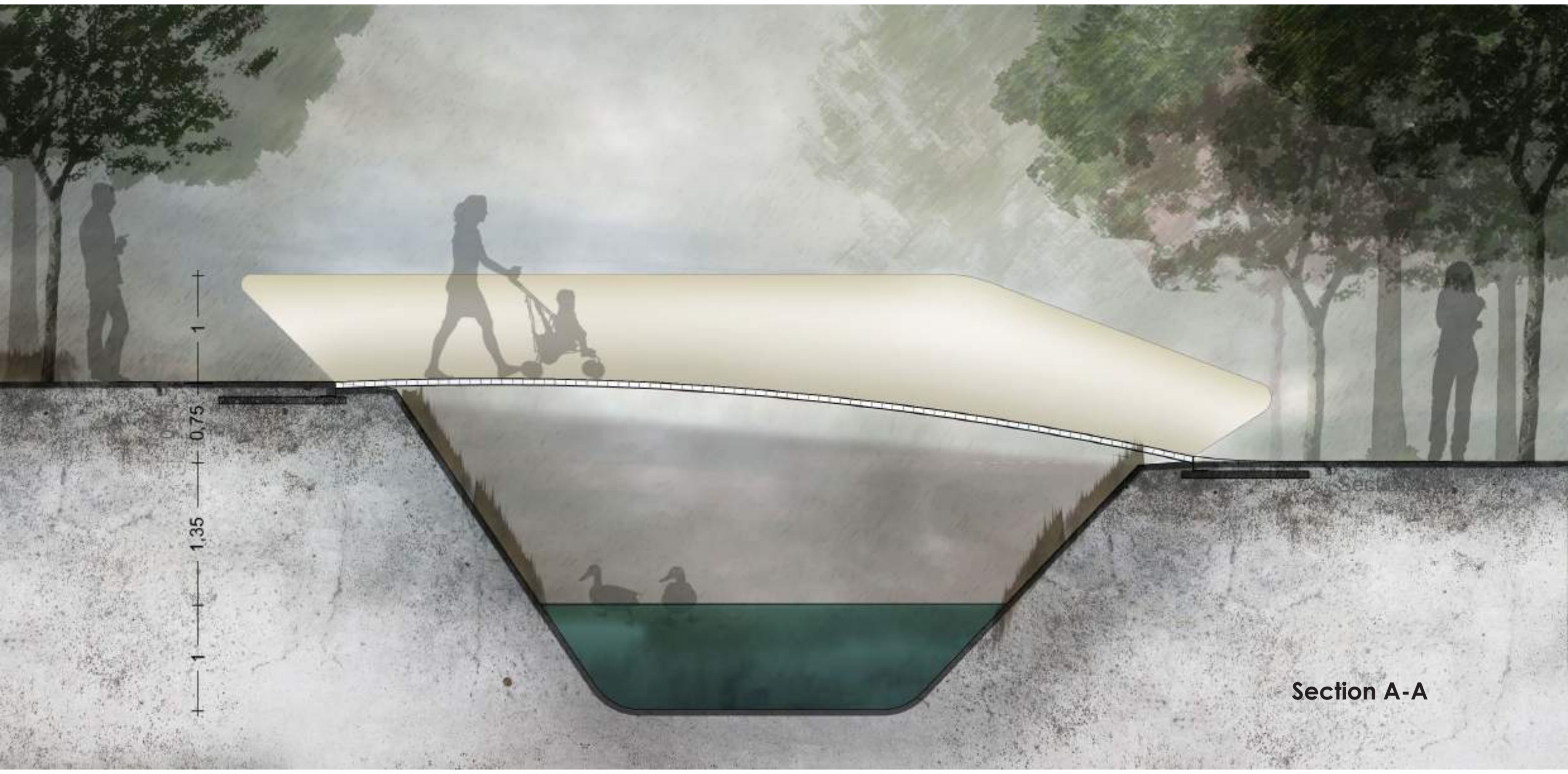


Longitudinal Elevation



Transverse Elevation

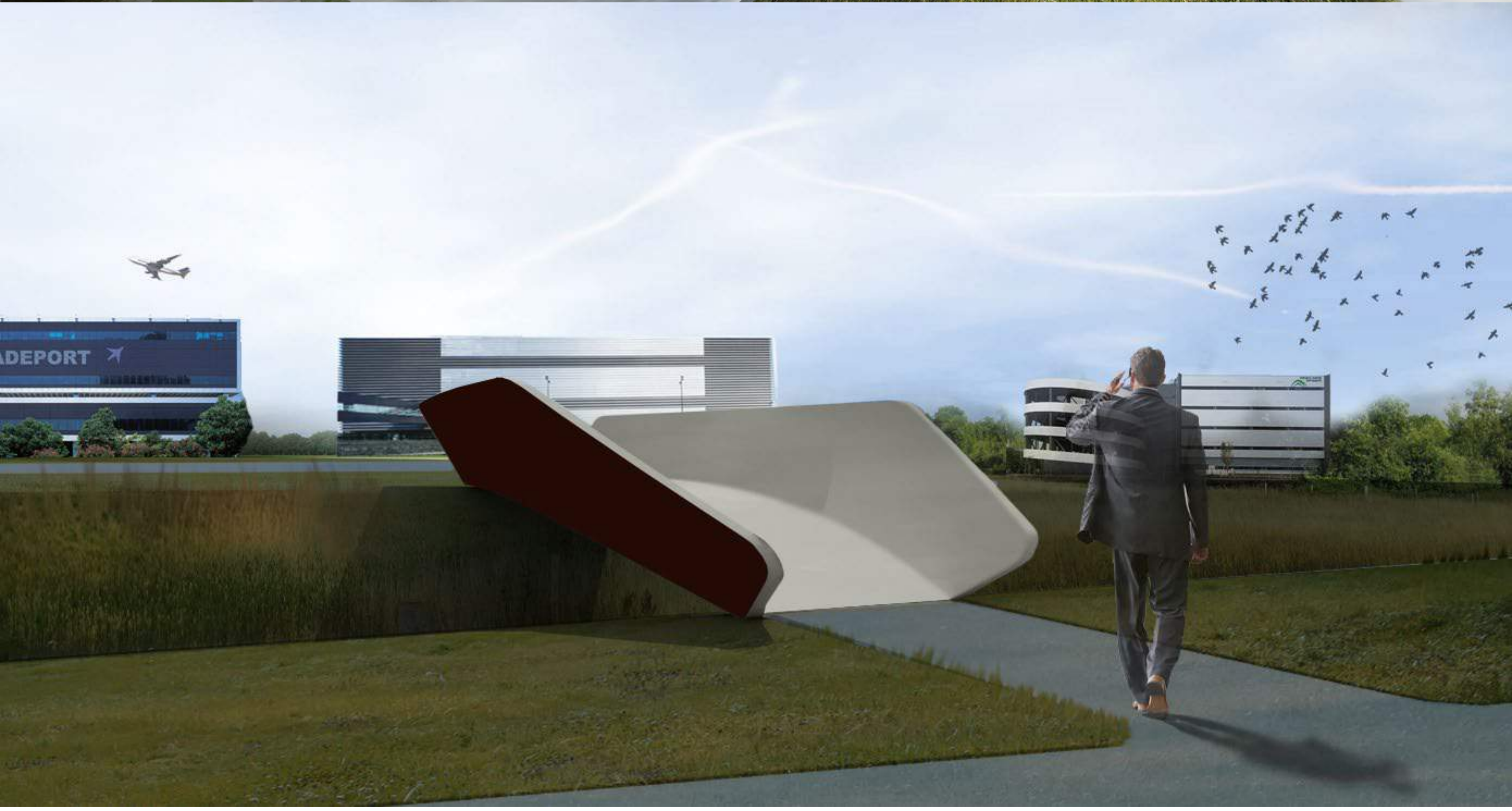

B
A
A
2
3
4
B
8,2
9,6
Top view
Top view



Section A-A

Section B-B

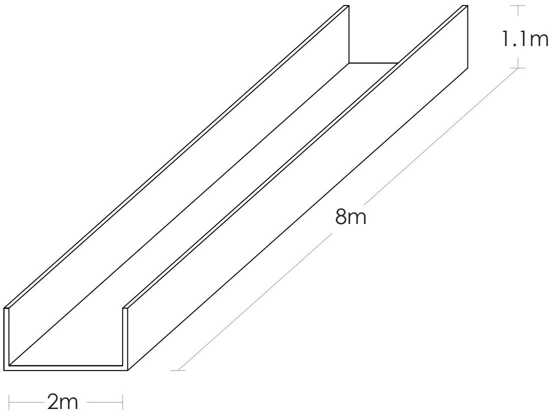
7.5.2 3D Impressions



Structural calculation

8.1 Structural simplification

In order to simplify the calculation of the structure, the geometry of the bridge was translated into a more rational shape, that of a straight U-beam. The general dimensions (width, span, parapet height) are retained, whereas curved lines are considered as straight. The parapets are positioned vertically to the deck while their height is constantly at 1,0m along the span. Figure shows the shape of the geometry that will be calculated.



8.1 Extruded view of the simplified structural model

8.2 Structural analysis approach

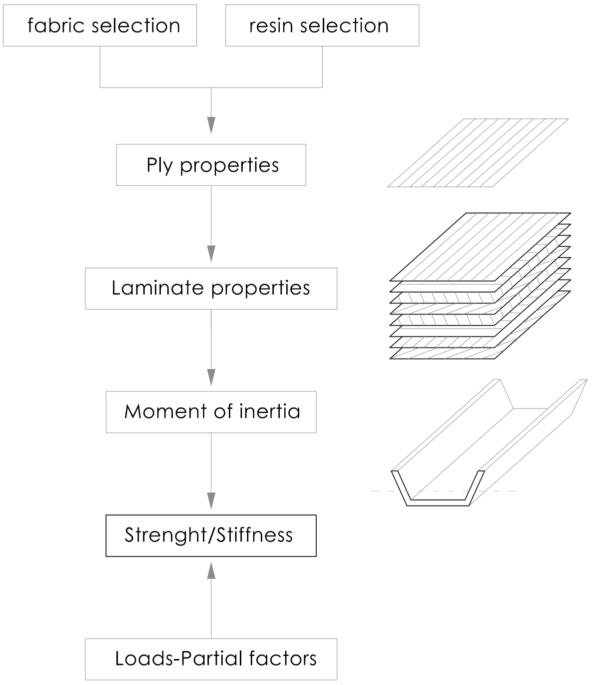
8.2.1 Calculation process

The structural analysis process of the simplified model is organized into the phases shown in figure. Starting from the fibre/resin properties, given by the supplier of the specific fabric and resin chosen, the properties of one ply with single orientation can be calculated by using the “Rule of Mixtures”.

Having the properties of a single ply, which consists resin and reinforcement in amounts according to the fibre volume fraction that the chosen manufacturing method can achieve, the properties of the laminate can be calculated. This is achieved by following a process based on the Classical laminate theory. At this phase, the computer software for laminate calculation, Kolibri, was used to evaluate validity of the manually found results. Important properties that result from this part of the calculation is the thickness, the Young’s modulus and the Shear modulus of the laminate.

After having calculated the properties of the composite, the U-beam bridge is analyzed. The first step includes the calculation of the moment of inertia for the cross-section of the geometry. The results of this part are used in the final part, which is the calculation of the ultimate and service limit state.

The entire structural calculation of the bridge was performed by repeating the described procedure in order to achieve a continuous optimization of the structure. The initial calculation assumed values such as thickness or ply orientation in order to draw and evaluate the first results. Then according to these results, input was adjusted and new values were calculated. In this way, optimum thicknesses for the composite were defined.



8.2 Flow of the output of the simplified structural caclulation

8.2.2 Aim of the analysis

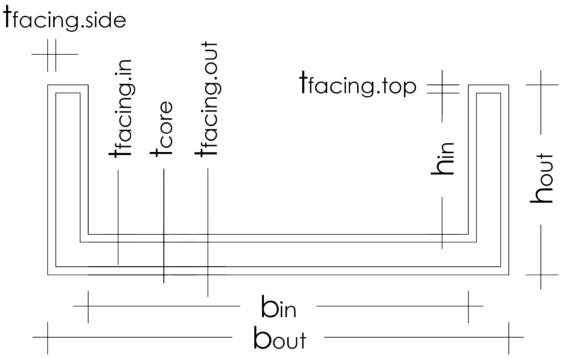
The structural analysis was performed for every of the four chosen fibres (flax, jute, glass and basalt). The aim of this analysis is to compare the structural performance of the four composites in regards to their optimum thicknesses. Through this comparison, the fibres are evaluated as for their environmental efficiency. Knowing the exact kilograms of required material for each composite allows for a comparison between their energy requirements and their financial cost. Thus this structural analysis combined with the Life Cycle Assessment will show which fibre is more suitable for the requirements of this project.

8.3 Dimensioning of the bridge

In order to proceed to the structural calculations of the bridge it is necessary to define the basic geometrical characteristics of the simplified model. The results of the first analysis are then evaluated and these first input data are reconsidered and changed according to the results.

Table 8.1 Dimensions of the structural analysis model

Top flange facing thickness	$t_{facing.top}$ = 7.2mm
Side parapet facing thickness	$t_{facing.in}$ = 7.2mm
Inner facing deck thickness	$t_{facing.out}$ = 7.2mm
Outer facing deck thickness	$t_{facing.side}$ = 7.2mm
Core thickness	t_{core} = 86mm
Parapet thickness	b_{top} = 116mm
Deck inner width	b_{in} = 1900mm
Deck outer width	b_{out} = 2000mm
Parapet inner width	h_{in} = 1000mm
Parapet outer width	h_{out} = 1200mm



8.4 Fibre-resin properties

The first of the fibres that was chosen to be calculated as reinforcement of the composite was the one with the highest mechanical properties, thus basalt. The specific textile used in the calculations is a unidirectional fabric with product name BAS UNI 600, supplied by Basaltex, a Belgian based company that produces basalt technical textiles. The resin that is used in all the calculations is a100% bio-based furan.

Table 8.2 Basalt-furan mechanical/physical properties

	Basalt fibre	Furan
Elastic modulus	E_f= 85 GPa	E_m= 2 GPa
Shear modulus	G_f= 35 GPa	G_m= 1.3 GPa
Poisson's ration	v_f= 0.26	v_m= 0.35
Volume fraction	V_f= 0.5	V_m= 0.5
Density	p_f= 2670 kg/m^3	p_m= 1100 kg/m^3
Weight	m_f= 600 gm/m^2	

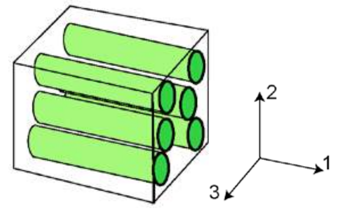
8.5 Calculation of ply properties

Calculation of the ply properties is based on the general Rule of Mixtures for composite materials, which is used to define values such as mass density, elastic modulus and shear modulus. Assumptions done by the rule of mixtures include the uniform distribution of the fibres in the matrix, ideal fibre-matrix adhesion, free of voids matrix, application of loads is either parallel or normal to the fibre direction, the lamina is initially in a stress-free state (no residual stresses) and the fact that fibre-matrix both behave as a linearly elastic material. Therefore, by using the rule of mixtures, the ply density, elastic longitudinal-transverse modulus, shear modulus and poisson's ratio are calculated:

Ply density

$$p_{FRP} = p_f \cdot V_f + p_m \cdot V_m = p_f \cdot V_f + p_m \cdot (1 - V_f) = (p_f - p_m) \cdot V_f + p_m$$

$$p_{FRP} := (p_f - p_m) \cdot V_f + p_m = 1885 \ \frac{\mathbf{kg}}{\mathbf{m}^3}$$

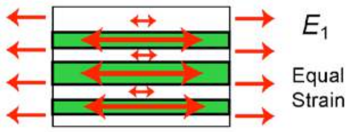


Longitudinal modulus (loading parallel to the fibres)

Equal strain assumption: $\varepsilon_c = \varepsilon_f = \varepsilon_m$

According to Hookes law we get,

Loading parallel to the fibres

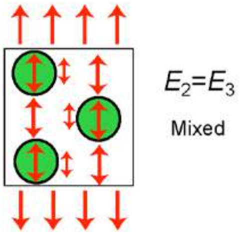


$$E_1 \cdot \varepsilon_{FRP} = E_f \cdot \varepsilon_f \cdot V_f + E_m \cdot \varepsilon_m \cdot V_m = E_f \cdot V_f + E_m \cdot V_m$$

$$E_1 := E_f \cdot V_f + E_m \cdot (1 - V_f) = 43.5 \ \mathbf{GPa}$$

Transverse modulus (loading perpendicular to the fibres)

Loading perpendicular to the fibres



$$E_2 = E_m \cdot \frac{1 + V_f \cdot \xi \cdot \eta}{1 - \eta \cdot V_f} \qquad \text{in which} \qquad \eta = \frac{\dfrac{E_f}{E_m} - 1}{\dfrac{E_f}{E_m} + \xi}$$

The term "ξ"is called the reinforcing factor and depends on:
1.fibre geometry
2.packing geometry
3.loading conditions

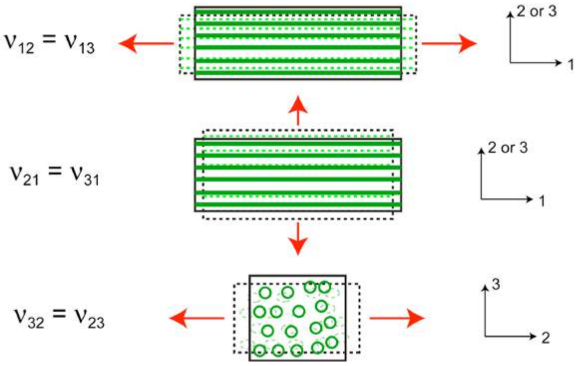
For our case $\xi := 2$

$$\eta := \frac{\dfrac{E_f}{E_m} - 1}{\dfrac{E_f}{E_m} + \xi} = 0.93 \qquad E_2 := E_m \cdot \frac{1 + V_f \cdot \xi \cdot \eta}{1 - \eta \cdot V_f} = 7.2 \ \mathbf{GPa}$$

Poisson's ratio

$$v_{12} := v_f \cdot V_f + v_m \cdot \left(1 - V_f\right) = 0.31$$

$$v_{21} := \frac{E_2}{E_1} \cdot v_{12} = 0.05$$

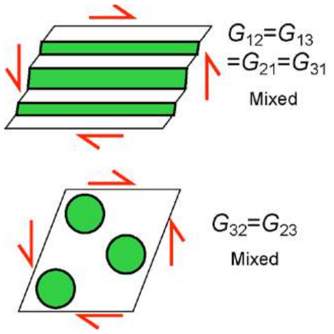


In-plane Shear modulus

The Halphin and Tsai equation for the in-plane shear Modulus G12 is :

$$G_{12} := G_m \cdot \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \qquad \text{in which} \qquad \xi := 1 \qquad \text{and} \qquad \eta := \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + \xi} = 0.95$$

$$G_{12} := G_m \cdot \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} = 3.7 \ \mathbf{GPa}$$

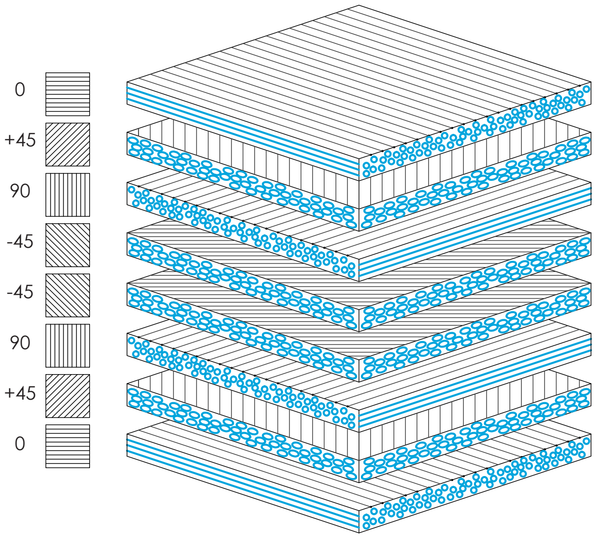


G_{12} is matrix dominated and is a series combination like E2.

8.6 Definition of the laminate

A laminate is an organized stack of unidirectional composite plies. Depending on the fibre orientation and the sequence of the individual plies the laminates are generally classified in isotropic and anisotropic. Isotropic laminates exhibit equal properties in all directions due to the uniform distribution of plies with different orientation. In the contrary anisotropic laminates, also called orthotropic, show different properties in each axis as fibre orientation is not equally arranged. In addition, laminates are characterised as balanced when for every +θ ply there is an equally thick –θ ply and symmetric when the plies of the laminate are stacked symmetrically about the geometrical mid-plane.

Considering a first simplified approach for the calculation of the structure an isotropic composite plate was chosen for all the parts of the structure. Specifically the laminate is Quasi isotropic, which means that it exhibits isotropic in-plane response but it is not restricted to show isotropic out-of-plane (bending) response. The suggested laminate is also balanced and symmetric and consists of 8 unidirectional plies, oriented in 0, +45, 90, -45 degree angles which are equally distributed each at a percentage of 25%. Scheme 1.5 shows the chosen arrangement of the laminate.



8.3 Chosen fibre orientation for the Quasi-isotropic laminate of the project

The laminate structure defined above consists a repeated module. Increasing the number (Nmod) of the module increase the thickness of the laminate but it will not influence its mechanical properties. For this simplified first calculation, equal thickness for all parts of the bridge was chosen, whereas the number of the modules is set to 2, thus 16 plies. Knowing the thickness of a single ply, the entire thickness of the laminate can be calculated as follows.

Thicness of fabric $t_{fabric} := \frac{m_f}{\rho_f} = 0.22\ \mathbf{mm}$

Thicness of ply $t_{ply} := \frac{t_{fabric}}{V_f} = 0.45\ \mathbf{mm}$

Thickness of QI laminate module (8 plies): $t_{QImod} := 8 \cdot t_{ply} = 3.596\ \mathbf{mm}$

Number of modules: $N_{mod} := 2$

$t_{lam} := N_{mod} \cdot t_{QImod} = 7.191\ \mathbf{mm}$

$n_{ply} := \frac{t_{lam}}{t_{ply}} = 16$

Calculation of laminate properties

After having defined the structure of the laminate, the calculation of the properties follows. To this point Classical laminate theory is employed in order to define the strains and the stresses for the entire thickness of the laminate by starting from the strains and stresses of a single ply that is loaded parallel to the fibres. By using the stresses and strains in the principal direction we can also calculate the force and moment resultants acting at that point and consequently the total forces and moments acting on the edges of the laminate.

8.6.1 Stress [σ] - Strain [ε] relations for principal directions

Coordinate axes (xyz)=subscripts (123)

The stress-strain relations on the principal axes can be expressed by the reduced stiffness constants S which form the stiffness matrix [S] such that

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

In which, by inspection of the individual equations, it can be seen that

$$Q_{11} := \frac{E_1}{(1 - \nu_{12} \cdot \nu_{21})} = 44.184\ \mathbf{GPa} \qquad Q_{12} := \frac{\nu_{12} \cdot E_2}{(1 - \nu_{12} \cdot \nu_{21})} = 2.244\ \mathbf{GPa}$$

$$Q_{22} := \frac{E_2}{(1 - \nu_{12} \cdot \nu_{21})} = 7.356\ \mathbf{GPa} \qquad Q_{66} := G_{12} = 3.671\ \mathbf{GPa}$$

The inverse version of the above matrix is expressed by the following compliance matrix and the constant Q

$$[\sigma]=[Q]\cdot[\varepsilon]$$

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix}=\begin{bmatrix}S_{11} & S_{12} & 0\\ S_{12} & S_{22} & 0\\ 0 & 0 & S_{66}\end{bmatrix}\cdot\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}$$

$$S_{11}:=\frac{1}{E_1}=0.023\ \frac{1}{\mathbf{GPa}} \qquad S_{12}:=\frac{-v_{12}}{E_1}=-0.007\ \frac{1}{\mathbf{GPa}}$$

$$S_{22}:=\frac{1}{E_2}=0.138\ \frac{1}{\mathbf{GPa}} \qquad S_{66}:=\frac{1}{G_{12}}=0.272\ \frac{1}{\mathbf{GPa}}$$

8.6.2 Stress [σ] - Strain [ε] relations for rotated axis

Rotation of axe (z) with angle φ of (xyz) gives (x'y'z')

The first step in establishing the lamina strains for off-axis loading is to find the stresses, referred to the fibre axis (σ_1, σ_2 and τ_{12}), in terms of the applied stress system (σ_x, σ_y and τ_{12}). This is done using the equation expressing any second rank tensor with respect to a new coordinate frame

$$\sigma_{ij}=a_{ik}\cdot a_{jl}\cdot \sigma'_{kl}$$

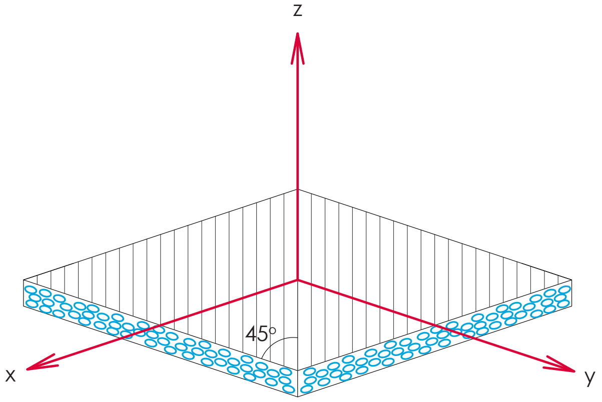
in which a_{ik} is the direction cosine of the (new) *i* direction referred to the (old) *k* direction. Obviously, the conversion will work in either direction provided the direction cosines are defined correctly. For example, the normal stress parallel to the fibre direction σ_{11}, sometimes written as σ_{11}, can be expressed in terms of the applied stresses σ'_{11} (= σ_x), σ'_{22} (= σ_y) and σ'_{12} (= τ_{xy})

$$\sigma_{11}=a_{11}a_{11}\cdot\sigma'_{11}+a_{11}\cdot a_{12}\cdot\sigma'_{12}+a_{12}\cdot a_{11}\cdot\sigma'_{21}+a_{12}\cdot a_{12}\cdot\sigma'_{22}$$

The angle φ is that between the fibre axis (1) and the stress axis (x). Referring to the figure, these direction cosines take the values

$$\phi:=45\ °$$

$$(a_{11}=c) \qquad c:=\cos(\phi)=0.71\ \mathbf{rad}$$
$$(a_{12}=s)$$
$$(a_{21}=-s) \qquad s:=\sin(\phi)=0.71\ \mathbf{rad}$$
$$(a_{22}=c)$$



Carrying out this operation for all three stresses and tensorial strains

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = [T] \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \qquad \text{and} \qquad \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_{12} \end{bmatrix} = [T] \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix}$$

where

$$[T] = \begin{bmatrix} c^2 & s^2 & 2\,c \cdot s \\ s^2 & c^2 & -2\,c \cdot s \\ -c \cdot s & c \cdot s & \left(c^2 - s^2\right) \end{bmatrix}$$

However, to use engineering strains ($\gamma_{xy} = 2\varepsilon_{xy}$ etc), |T| must be modified (by halving the elements t_{13} and t_{23} and doubling elements t_{31} and t_{32} of the matrix |T|), so as to give

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = [T'] \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \qquad \text{in which} \qquad [T'] = \begin{bmatrix} c^2 & s^2 & c \cdot s \\ s^2 & c^2 & -c \cdot s \\ -2\,c \cdot s & 2\,c \cdot s & \left(c^2 - s^2\right) \end{bmatrix}$$

The procedure is now a progression from the stress-strain relationship when the lamina is loaded along its fibre-related axes to a general axis involving a transformed compliance matrix, Q , which will depend on angle φ. The first step is to write the inverse of Eqn.(3.3), giving the strains relative to the loading direction, in terms of the strains relative to the fibre direction. This involves using the inverse of the matrix |T'| , written as $\left|T'^{-1}\right|$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [T']^{-1} \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \qquad \text{in which} \qquad [T']^{-1} = \begin{bmatrix} c^2 & s^2 & -c \cdot s \\ s^2 & c^2 & c \cdot s \\ 2\,c \cdot s & -2\,c \cdot s & \left(c^2 - s^2\right) \end{bmatrix}$$

Now, the strains relative to the fibre direction can be expressed in terms of the stresses in those directions via the on-axis stress-strain relationship for the lamina, Eqn.(3.1), giving

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [T']^{-1} \cdot [Q] \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}$$

Finally, the original transform matrix of Eqn.(3.2) can be used to express these stresses in terms of those being externally applied, to give the result

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [T']^{-1} \cdot [Q] \cdot [T] \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [Q'] \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

Therefore,

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} Q'_{11} & Q'_{12} & Q'_{16} \\ Q'_{12} & Q'_{22} & Q'_{26} \\ Q'_{16} & Q'_{26} & Q'_{66} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

Then, the following expressions are obtained

$$Q'_{11} := Q_{11} \cdot c^4 + Q_{22} \cdot s^4 + 2 \cdot (Q_{12} + 2\,Q_{66}) \cdot c^2 \cdot s^2 = 17.678\ \mathbf{GPa}$$

$$Q'_{12} := Q_{12} \cdot \left(c^4 + s^4\right) + (Q_{11} + Q_{22} - 4\,Q_{66}) \cdot c^2 \cdot s^2 = 10.335\ \mathbf{GPa}$$

$$Q'_{22} := Q_{11} \cdot s^4 + Q_{22} \cdot c^4 + 2\,(Q_{12} + 2\,Q_{66}) \cdot c^2 \cdot s^2 = 17.678\ \mathbf{GPa}$$

$$Q'_{16} := (Q_{11} - Q_{12} - 2\,Q_{66}) \cdot c^3 \cdot s - (Q_{22} - Q_{12} - 2\,Q_{66})\ c \cdot s^3 = 9.207\ \mathbf{GPa}$$

$$Q'_{26} := (Q_{11} - Q_{12} - 2\,Q_{66})\ c \cdot s^3 - (Q_{22} - Q_{12} - 2\,Q_{66})\ c^3\ s = 9.207\ \mathbf{GPa}$$

$$Q'_{66} := (Q_{11} + Q_{22} - 2\,Q_{12} - 2\,Q_{66})\ c^2 \cdot s^2 + Q_{66} \cdot \left(c^4 + s^4\right) = 11.763\ \mathbf{GPa}$$

In similar way we calculate the reduced stiffness constants Q' for all the different angles of the plies. By doing so, we create the following table

Table 8.3 Stiffness constants Q' for each fibre orientation of the laminate

ply	position from neutral axis [mm]	φ [deg]	thickness [mm]	Q_{11}	Q_{12}	Q_{22}	Q_{16}	Q_{26}	Q_{66}
1	1,8	0	0,45	44,184	2,244	7,356	0	0	3,671
2	1,35	45	0,45	17,678	10,335	17,678	9,207	9,207	11,763
3	0,9	90	0,45	7,356	2,244	44,184	0	0	3,671
4	0,45	-45	0,45	17,678	10,335	17,678	-9,207	-9,207	11,763
5	0,45	-45	0,45	17,678	10,335	17,678	-9,207	-9,207	11,763
6	0,9	90	0,45	7,356	2,244	44,184	0	0	3,671
7	1,35	45	0,45	17,678	10,335	17,678	9,207	9,207	11,763
8	1,8	0	0,45	44,184	2,244	7,356	0	0	3,671

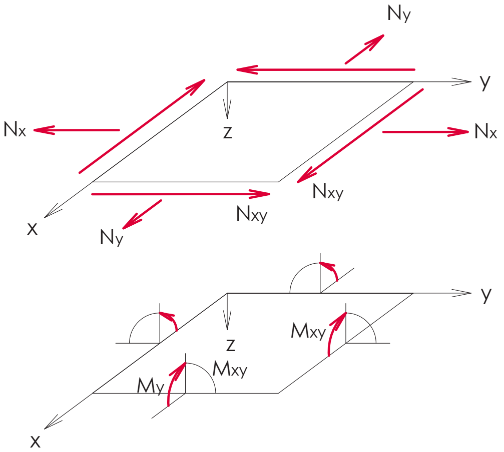
8.6.3 ABD Stiffness matrices

The inplane forces are denoted by Ni, (i = 1; 2; 6), for all component of the plane stress condition in i direction. The 3 moments per length are denoted Mi, (i = 1; 2; 6) for the i direction. Mxy is a twisting moment and can be associated to a distortion of the laminate in the bending mode due to shear stress gradient. Ni and Mi are sometimes called respectively stress resultants and moment resultants. The cross-sectional forces and moments can be determined by summation of the integrated stress components over each individual ply.

$$N_x = \int_{\frac{-h}{2}}^{\frac{h}{2}} \sigma_x \, dz \qquad M_x = \int_{\frac{-h}{2}}^{\frac{h}{2}} z\sigma_x \, dz$$

$$N_y = \int_{\frac{-h}{2}}^{\frac{h}{2}} \sigma_y \, dz \qquad M_y = \int_{\frac{-h}{2}}^{\frac{h}{2}} z\sigma_y \, dz$$

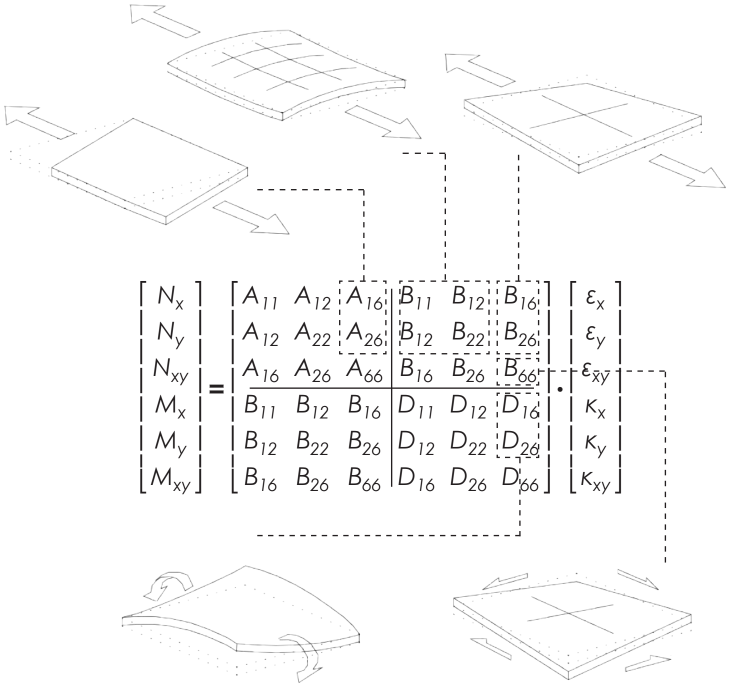
$$N_{xy} = \int_{\frac{-h}{2}}^{\frac{h}{2}} \sigma_{xy} \, dz \qquad M_{xy} = \int_{\frac{-h}{2}}^{\frac{h}{2}} z\sigma_{xy} \, dz$$



The result is the so-called ABD-matrix, also known as **laminate stiffness matrix**. The ABD matrix defines a relationship between the stress resultants (i.e., loads) applied to a laminate, and the reference surface strains and curvatures (i.e., deformations). Specifically, [A] is the extensional stiffness, [B] is called coupling stiffness, and [D] represents the bending stiffness of the laminate.

This form is a direct result of the Kirchhoff hypothesis, the plane-stress assumption, and the definition of the stress resultants. The laminate stiffness matrix involves everything that is used to define the laminate—layer material properties, fiber orientation, thickness, and location.

The figure below shows the influence of some components of the ABD-matrix.



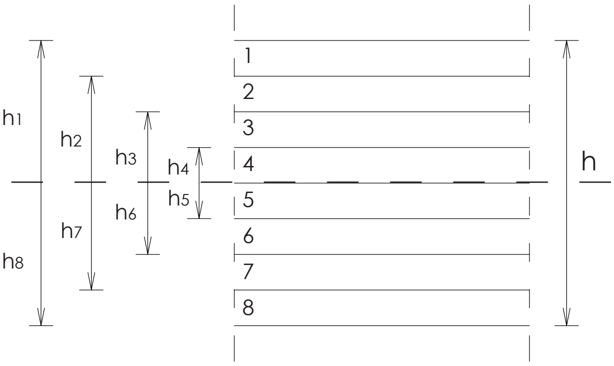
$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\begin{array}{ccc|ccc} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \hline B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{array}\right] \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

The components of these three stiffness matrices are defined as follows

$$A_{xy} = \sum_{k=1}^{n} Q_{xy} \cdot \left(h_k - h_{k-1}\right) \qquad h_k - h_{k-1} = t_k$$

$$B_{xy} = \frac{1}{2} \sum_{k=1}^{n} Q_{xy} \cdot \left(\left(h^2\right)_k - \left(h^2\right)_{k-1}\right)$$

$$D_{xy} = \frac{1}{3} \sum_{k=1}^{n} Q_{xy} \cdot \left(\left(h^3\right)_k - \left(h^3\right)_{k-1}\right)$$



Then, the following expressions are obtained

$$A_{xy} = Q_{xy_{(0)}} \cdot \left(h_1 - h_2\right) + Q_{xy_{(45)}} \cdot \left(h_2 - h_3\right) + Q_{xy_{(90)}} \cdot \left(h_3 - h_4\right) + Q_{xy_{(-45)}} \cdot \left(h_4\right) + Q_{xy_{(-45)}} \cdot \left(h_5\right) +$$
$$Q_{xy_{(90)}} \cdot \left(h_6 - h_5\right) + Q_{xy_{(45)}} \cdot \left(h_7 - h_6\right) + Q_{xy_{(0)}} \cdot \left(h_8 - h_7\right)$$

$$B_{xy} = \frac{1}{2}\, Q_{xy_{(0)}} \cdot \left({h_1}^2 - {h_2}^2\right) + Q_{xy_{(45)}} \cdot \left({h_2}^2 - {h_3}^2\right) + Q_{xy_{(90)}} \cdot \left({h_3}^2 - {h_4}^2\right) + Q_{xy_{(-45)}} \cdot \left({h_4}^2\right) + Q_{xy_{(-45)}} \cdot \left({h_5}^2\right) +$$
$$+ Q_{xy_{(90)}} \cdot \left({h_6}^2 - {h_5}^2\right) + Q_{xy_{(45)}} \cdot \left({h_7}^2 - {h_6}^2\right) + Q_{xy_{(0)}} \cdot \left({h_8}^2 - {h_7}^2\right)$$

$$D_{xy} = \frac{1}{3}\, Q_{xy_{(0)}} \cdot \left({h_1}^3 - {h_2}^3\right) + Q_{xy_{(45)}} \cdot \left({h_2}^3 - {h_3}^3\right) + Q_{xy_{(90)}} \cdot \left({h_3}^3 - {h_4}^3\right) + Q_{xy_{(-45)}} \cdot \left({h_4}^3\right) + Q_{xy_{(-45)}} \cdot \left({h_5}^3\right) +$$
$$+ Q_{xy_{(90)}} \cdot \left({h_6}^3 - {h_5}^3\right) + Q_{xy_{(45)}} \cdot \left({h_7}^3 - {h_6}^3\right) + Q_{xy_{(0)}} \cdot \left({h_8}^3 - {h_7}^3\right)$$

from which the ABD matrices below are created

$$[A] = \begin{bmatrix} 78.2064 & 22.6422 & 0 \\ 22.6422 & 78.2064 & 0 \\ 0 & 0 & 27.7812 \end{bmatrix} \qquad [B] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [D] = \begin{bmatrix} 123.9215 & 18.5552 & 10.0678 \\ 18.5552 & 56.8025 & 10.0678 \\ 10.0678 & 10.0678 & 24.1046 \end{bmatrix}$$

It derives that [B]=0, which it was expected as for symmetric laminates all the components of the B matrix are identically zero. A laminate is said to be symmetric if for every layer with a specific thickness, specific material properties, and specific fiber orientation to one side of the laminate reference surface, there is another layer with the identical distance on the opposite side of the reference surface with the identical thickness, material properties, and fiber orientation. Consequently, the full six-by-six set of equations of the [ABD] decouples into two three-by-three sets of equations, namely

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \cdot \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

Then the above relation can be inverted to give,

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & a_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} \cdot \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{16} \\ d_{12} & d_{22} & d_{26} \\ d_{16} & d_{26} & d_{66} \end{bmatrix} \cdot \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix}$$

where [a] and [d] are the inverted matrices of [A] and [D]

$$[a] = [A]^{-1} \quad \text{or} \quad \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & a_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix}^{-1}$$

$$[d] = [D]^{-1} \quad \text{or} \quad \begin{bmatrix} d_{11} & d_{12} & d_{16} \\ d_{12} & d_{22} & d_{26} \\ d_{16} & d_{26} & d_{66} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}^{-1}$$

The inverted [a] and [d] matrices are calculated as follows

$$[a] = \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & a_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} A_{22} & A_{26} \\ A_{26} & A_{66} \end{bmatrix} & \begin{bmatrix} A_{16} & A_{12} \\ A_{66} & A_{26} \end{bmatrix} & \begin{bmatrix} A_{12} & A_{16} \\ A_{22} & A_{26} \end{bmatrix} \\ \begin{bmatrix} A_{26} & A_{12} \\ A_{66} & A_{16} \end{bmatrix} & \begin{bmatrix} A_{11} & A_{16} \\ A_{16} & A_{66} \end{bmatrix} & \begin{bmatrix} A_{16} & A_{11} \\ A_{26} & A_{12} \end{bmatrix} \\ \begin{bmatrix} A_{12} & A_{22} \\ A_{16} & A_{26} \end{bmatrix} & \begin{bmatrix} A_{12} & A_{11} \\ A_{26} & A_{16} \end{bmatrix} & \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \end{bmatrix}$$

$$a_{11} = \frac{A_{22} \cdot A_{66} - A_{26}^{\ 2}}{det\,[A]} \qquad a_{12} = \frac{A_{26} \cdot A_{16} - A_{12} \cdot A_{66}}{det\,[A]} \qquad a_{16} = \frac{A_{12} \cdot A_{26} - A_{22} \cdot A_{16}}{det\,[A]}$$

$$a_{22} = \frac{A_{11} \cdot A_{66} - A_{16}^{\ 2}}{det\,[A]} \qquad a_{26} = \frac{A_{12} \cdot A_{16} - A_{11} \cdot A_{26}}{det\,[A]}$$

$$a_{66} = \frac{A_{11} \cdot A_{22} - A_{12}^{\ 2}}{det\,[A]}$$

in which det[A] is the determinant of A, given by the following equation

$$det\,[A] = A_{11}\left(A_{22} \cdot A_{66} - A_{26}^{\ 2}\right) - A_{12} \cdot \left(A_{12} \cdot A_{66} - A_{26} \cdot A_{16}\right) + A_{16} \cdot \left(A_{12} \cdot A_{26} - A_{22} \cdot A_{16}\right)$$

By calculating the above equations we get

$$[a] = \begin{bmatrix} 0.01395 & -0.00404 & 0 \\ -0.00404 & 0.01395 & 0 \\ 0 & 0 & 0.03599 \end{bmatrix}$$

Similarly, matrix [d] is calculated

$$[d] = \begin{bmatrix} 0.008635 & -0.002356 & -0.002622 \\ -0.002356 & 0.01965 & -0.0073 \\ -0.002622 & -0.0073 & 0.045599 \end{bmatrix}$$

After having calculated the inverted [a] and [d] matrices the Elastic modulus, Shear modulus and poisson’s ratio can be calculated by the following equations. The results were also checked by the computer software Kolibri which is used for designing and calculating laminates.

$$E_{xFRP} := \frac{1}{a_{11} \cdot t_{lam}} = 19.93\ \mathbf{GPa}$$

$$E_{yFRP} := \frac{1}{a_{22} \cdot t_{lam}} = 19.93\ \mathbf{GPa}$$

$$v_{xyFRP} := \frac{-a_{12}}{a_{11}} = 0.29$$

$$G_{xyFRP} := \frac{1}{a_{66} \cdot t_{lam}} = 7.73\ \mathbf{GPa}$$

8.7 Partial factors

8.7.1 Conversion factors

The behavior of polymers and fibres, either there are natural or synthetic, varies over time as deformation increases (creep) and relaxation occurs under long-term loads. In addition, polymers are characterized by lower strengths for permanent loads than they are for brief loads. Another aspect is also their temperature –depended behavior as both the elastic modulus and the strength of a polymer drop as the ambient temperature rises. Besides, in the case of natural fibres, moisture is a very crucial element as natural substances show high moisture absorption.

Therefore, these ambient conditions and the period of use must be taken into account in the design procedure. These criteria are incorporated directly in the calculations by way of reduction factors. In order to define the specific safety factors for composites, a research was done in relevant composite design codes. At present in The Netherlands the codes used for composites are the following:

- Eurocode EN 1991 (1) Loads on structures and load factors
- CUR Recommendation 96 (2) Composite properties and material factors

The CUR Recommendation 96 has been recently revised and translated into English. It is written in a Eurocode form and will be proposed in the task committee TC250, working group WG 4 for the realization of a Eurocode for composite materials.

For the current analysis the relevant factors where the load and conversion factors. Load combinations and load factors are based on the European Standard EN1990 EN1991-2 and. Conversion factors are reduction factors to the rigidity with which environmental conditions (humidity, temperature, creep and fatigue) will be charged on the material properties.

Table 8.4 Conversion factors

Temperature	$\gamma_{ct} = 1.1$
Humidity	$\gamma_{cm} = 1.1$
Creep	$\gamma_{ck} = 1.14$
Fatigue	$\gamma_{cf} = 1.1$

8.7.2 Material factors

The material factor has to be derived from the following formula [CUR96]:

$$\gamma_m = \gamma_{m1} * \gamma_{m2}$$

Where, $\gamma_{m1} = 1.35$ which is the partial material factor, taking into account the uncertainties in deriving the correct material properties. γ_{m2} is the partial material factor, which takes into account the uncertainties in the production method. γ_{m2} can be derived from the following table.

Table 8.5 Partial material factors [CUR96]

Production method	Fully post-cured laminate	Not fully post-cured laminate
Spray-up	1.6	1.9
Hand lay-up	1.4	1.7
VARTM or RTM	1.2	1.4
Filament winding	1.1	1.3
Pre-preg lay up	1.1	1.3
Pultrusion	1.1	1.3

Table 8.6 Application of different conversion factors for different applications [CUR]

	Ultimate limit state			Serviceability limit state		
	strength	stability	fatigue	strength	stability	fatigue
Temperature	x	x	x	x	x	x
Humidity	x	x	x	x	x	x
Creep	x	x	-	x	-	x
Fatigue	-	x	-	x	x	x

8.7.3 Load factors

The load factor for FRP composites is the same as for structures made of other materials. It has to be calculated according to the following quideline, derived from Eurocode 0, Basis of structural Design [NEN-EN 1990:2002, table A1.2(B),p59] and the National Annex to NEN-EN 1990.

For the ultimate limit state

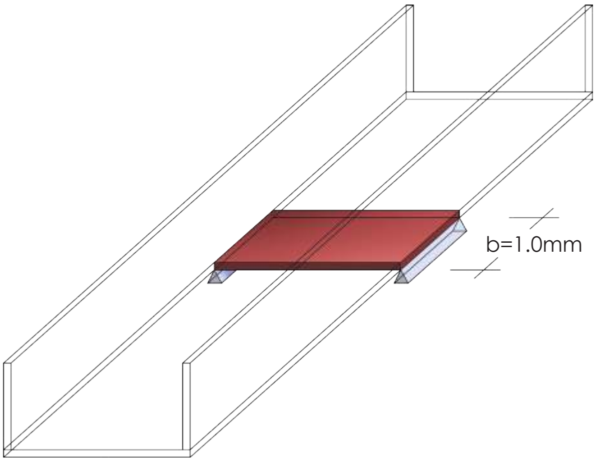
For the serviceability limit state

	(NEN-EN 1990)	(National Annex to NEN-EN 1990)	(NEN-EN 1990)
$\gamma_G = K_{FI} * \gamma_G$	$\gamma_G = 1.35$	$\boxed{\gamma_G = 1.2}$	$\gamma_G = 1.0$
	(NEN-EN 1990)	(consequence class CC2)	(NEN-EN 1990)
$\gamma_Q = K_{FI} * \gamma_Q$	$\boxed{\gamma_Q = 1.5}$	$K_{FI} = 1.0$	$\gamma_Q = 1.0$

8.8 Parapet to parapet (deck) calculation

Neutral axis definition

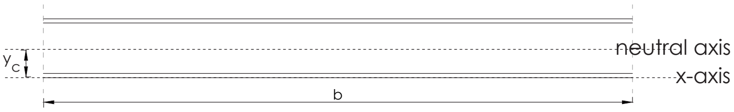
Distances from base axis x



$$y_1 := \frac{t_{facing.in}}{2} + t_{core} + t_{facing.out} = 0.097\ \mathbf{m}$$

$$y_2 := \frac{t_{facing.out}}{2} = 0.004\ \mathbf{m}$$

$$y_c = \frac{\sum (y_i \cdot A_i)}{\sum A_i}$$



$$y_c := \frac{y_1 \cdot b \cdot t_{facing.in} + y_2 \cdot b \cdot t_{facing.out}}{b \cdot t_{facing.in} + b \cdot t_{facing.out}} = 0.05\ \mathbf{m}$$

8.8.1 Moment of Inertia about centroidal (neutral) axis

$$I_{xci} = I_i + dy_i^{\,2} \cdot A_i$$

$$I_{xc1} := \frac{b \cdot t_{facing.in}^{\ 3}}{12} + (y_1 - y_c)^2 \cdot b \cdot t_{facing.in} = \left(1.567 \cdot 10^{-5}\right) \mathbf{m}^4$$

$$I_{xc2} := \frac{b \cdot t_{facing.out}^{\ 3}}{12} + (y_2 - y_c)^2 \cdot b \cdot t_{facing.out} = \left(1.567 \cdot 10^{-5}\right) \mathbf{m}^4$$

$$I_{xctot} := I_{xc1} + I_{xc2} = \left(3.133 \cdot 10^{-5}\right) \mathbf{m}^4$$

8.8.2 Ultimate limit state

$$q_{tot} = \gamma_G \cdot q_G + \gamma_Q \cdot q_Q$$

Dead load

$$q_G = A_{FRP} \cdot p_{FRP} + A_{core} \cdot p_{core}$$

$$A_{FRP} := b \cdot t_{facing.in} + b \cdot t_{facing.out} = 0.014\ \mathbf{m}^2$$

$$A_{core} := b \cdot t_{core} = 0.086\ \mathbf{m}^2$$

$$p_{FRP} = p_f \cdot V_f + p_m \cdot V_m \qquad \text{but} \qquad V_f + V_m = 1$$

$$p_{FRP} = p_f \cdot V_f + p_m \cdot (1 - V_f) = (p_f - p_m) \cdot V_f + p_m$$

$$q_G := (A_{FRP} \cdot p_{FRP} + A_{core} \cdot p_{core}) \cdot \mathbf{g} = 0.395\ \frac{\mathbf{kN}}{\mathbf{m}}$$

Imposed load

Traffic load (NEN-EN 1991-2)

$$q_{ped} := 5\ \frac{\mathbf{kN}}{\mathbf{m}^2}$$

$$q_Q := q_{ped} \cdot b = 5\ \frac{\mathbf{kN}}{\mathbf{m}}$$

$$q_{tot} := \gamma_G \cdot q_G + \gamma_Q \cdot q_Q = 7.974\ \frac{\mathbf{kN}}{\mathbf{m}}$$

Bending moment

$$M_{max} := \frac{1}{8}\, q_{tot} \cdot L_2^{\ 2} = 4\ \mathbf{kN} \cdot \mathbf{m}$$

Stress

$$\sigma_{max} = \frac{M_{max}}{W} \qquad W = \frac{I_y}{h_{tot} - y_c}$$

(first moment of area)

$$W := \frac{I_{xctot}}{t_{facing.in} + t_{core} + t_{facing.out} - y_c} = \left(6.242 \cdot 10^{-4}\right)\ \mathbf{m}^3$$

$$\sigma_{max} := \frac{M_{max}}{W} = 6.388\ \mathbf{MPa}$$

$$\sigma_{max.allowable} := \frac{0.012 \cdot E_x}{\gamma_m \cdot \gamma_c} = 122.008\ \mathbf{MPa}$$

CUR 96 ;2003 recommends a stress criterion which limits the maximum stress in the laminate according to the following formula:

$$\frac{\sigma_{max}}{\sigma_{max.allowable}} \le 1$$

$$\frac{\sigma_{max}}{\sigma_{max.allowable}} = 0.052 < 1$$

8.8.3 Service limit state

Deflection

$$q_{rep} := q_G + q_Q = 5.395\ \frac{\mathbf{kN}}{\mathbf{m}}$$

(The loads without partial factors)

$$A_{core.deck} := b \cdot t_{core} = 0.086\ \mathbf{m}^2$$

$$G_{core} := 183\ \mathbf{MPa}$$

$$w_2 := \frac{5 \cdot q_{rep} \cdot L_2^{\ 4}}{385 \cdot E_x \cdot I_{xctot}} + \frac{\eta \cdot q_{rep} \cdot L_2^{\ 2}}{8 \cdot G_{core} \cdot A_{core.deck}} = 1.962\ \mathbf{mm}$$

$$w_{allowable} := \frac{1}{300 \cdot \gamma_c} \cdot L_2 = 5.51\ \mathbf{mm}$$

8.9 Abutment to abutment calculation

Neutral axis definition

Distances from base axis x

$$y_1 := \frac{t_{facing.top}}{2} + h_{in} + t_{facing.in} + t_{core} + t_{facing.out} = 1.104\ \mathbf{m}$$

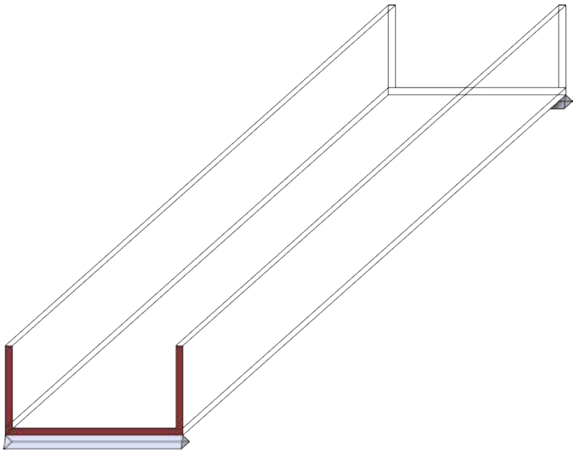
$$y_2 := \frac{h_{in}}{2} + t_{facing.in} + t_{core} + t_{facing.out} = 0.6\ \mathbf{m}$$

$$y_3 := \frac{t_{facing.in}}{2} + t_{core} + t_{facing.out} = 0.097\ \mathbf{m}$$

$$y_4 := \frac{t_{core}}{2} + t_{facing.out} = 0.05\ \mathbf{m}$$

$$y_5 := \frac{t_{facing.out}}{2} = 0.004\ \mathbf{m}$$

$$y_c = \frac{\sum (y_i \cdot A_i)}{\sum A_i}$$



$$y_c := \frac{y_1 \cdot 2\ b_{top} \cdot t_{facing.top} + y_2 \cdot h_{in} \cdot 4\ t_{facing.side} + y_3 \cdot b_{in} \cdot t_{facing.in} + y_4 \cdot t_{core} \cdot 2\ t_{facing.side} + y_5 \cdot b_{out} \cdot t_{facing.out}}{2\ b_{top} \cdot t_{facing.top} + h_{in} \cdot 4\ t_{facing.side} + b_{in} \cdot t_{facing.in} + t_{core} \cdot 2\ t_{facing.side} + b_{out} \cdot t_{facing.out}} = 0.337\ \mathbf{m}$$

8.9.1 Moment of Inertia about centroidal (neutral) axis

$$I_{xc1} := \frac{2\ b_{top} \cdot t_{facing.top}^{\ 3}}{12} + (y_1 - y_c)^2 \cdot 2\ b_{top} \cdot t_{facing.top} = 0.00098\ \mathbf{m}^4$$

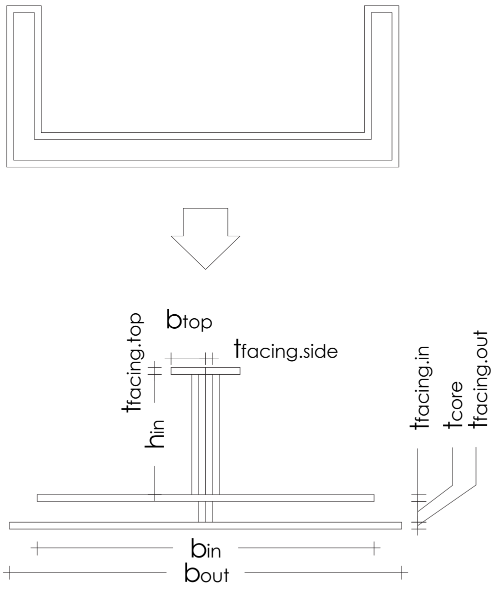
$$I_{xc2} := \frac{4\ t_{facing.side} \cdot h_{in}^{\ 3}}{12} + (y_2 - y_c)^2 \cdot 4\ t_{facing.side} \cdot h_{in} = 0.004\ \mathbf{m}^4$$

$$I_{xc3} := \frac{b_{in} \cdot t_{facing.in}^{\ 3}}{12} + (y_3 - y_c)^2 \cdot b_{in} \cdot t_{facing.in} = 0.00083\ \mathbf{m}^4$$

$$I_{xc4} := \frac{2\ t_{facing.side} \cdot t_{core}^{\ 3}}{12} + (y_4 - y_c)^2 \cdot 2\ t_{facing.side} \cdot t_{core} = 0.0001\ \mathbf{m}^4$$

$$I_{xc5} := \frac{b_{out} \cdot t_{facing.out}^{\ 3}}{12} + (y_5 - y_c)^2 \cdot b_{out} \cdot t_{facing.out} = 0.002\ \mathbf{m}^4$$

$$I_{xctot} := I_{xc1} + I_{xc2} + I_{xc3} + I_{xc4} + I_{xc5} = 0.008\ \mathbf{m}^4$$



8.9.2 Ultimate limit state

$$q_{tot} = \gamma_G \cdot q_G + \gamma_Q \cdot q_Q$$

Dead load

$$q_G = A_{FRP} \cdot \rho_{FRP} + A_{core} \cdot \rho_{core}$$

$$A_{FRP} := 2\ b_{top} \cdot t_{facing.top} + h_{in} \cdot 4\ t_{facing.side} + b_{in} \cdot t_{facing.in} + t_{core} \cdot 2\ t_{facing.side} + b_{out} \cdot t_{facing.out} = 0.061$$

$$A_{core} := b_{out} \cdot t_{core} + 2\ h_{in} \cdot t_{core} = 0.353\ \mathbf{m}^2$$

$$\rho_{FRP} = \rho_f \cdot V_f + \rho_m \cdot V_m$$

but $\quad V_f + V_m = 1$

$$\rho_{FRP} = \rho_f \cdot V_f + \rho_m \cdot (1 - V_f) = (\rho_f - \rho_m) \cdot V_f + \rho_m$$

$$q_G := (A_{FRP} \cdot \rho_{FRP} + A_{core} \cdot \rho_{core}) \cdot \mathbf{g} = 1.661\ \frac{\mathbf{kN}}{\mathbf{m}}$$

Traffic load (NEN-EN 1991-2) $\quad q_{ped} := 5\ \frac{\mathbf{kN}}{\mathbf{m}^2}$

Imposed load $\quad q_Q := q_{ped} \cdot b_{out} = 10\ \frac{\mathbf{kN}}{\mathbf{m}}$

$$q_{tot} := \gamma_G \cdot q_G + \gamma_Q \cdot q_Q = 16.946\ \frac{\mathbf{kN}}{\mathbf{m}}$$

Bending moment

$$M_{max} := \frac{1}{8}\ q_{tot} \cdot L_1^{\ 2} = 135.6\ \mathbf{kN} \cdot \mathbf{m}$$

Stress

$$\sigma_{max} = \frac{M_{max}}{W} \qquad W = \frac{I_y}{h_{out} - y_c}$$

(first moment of area)

$$W := \frac{I_{xctot}}{h_{out} - y_c} = 0.009\ \mathbf{m}^3$$

CUR 96 ;2003 recommends a stress criterion which limits the maximum stress in the laminate according to the following:

$$\frac{\sigma_{max}}{\sigma_{max.allowable}} \le 1$$

$$\sigma_{max} := \frac{M_{max}}{W} = 14.742\ \mathbf{MPa}$$

$$\sigma_{max.allowable} := \frac{0.012 \cdot E_x}{\gamma_m \cdot \gamma_c} = 122.008\ \mathbf{MPa}$$

$$\frac{\sigma_{max}}{\sigma_{max.allowable}} = 0.121\ < 1$$

$$\frac{1}{\gamma_m \cdot \gamma_c} = 0.51$$

8.9.3 Service limit state

Deflection

$q_{rep} := q_G + q_Q = 12.161\ \frac{kN}{m}$ (The loads without partial factors)

$A_{FRP.parapet} := 4 \cdot t_{facing.side} \cdot h_{in} = 0.029\ m^2$

$$w_1 := \frac{5 \cdot q_{rep} \cdot L_1^{\ 4}}{385 \cdot E_x \cdot I_{xctot}} + \frac{\eta \cdot q_{rep} \cdot L_1^{\ 2}}{8 \cdot G_x \cdot A_{FRP.parapet}} = 4.483\ mm$$

$$w_{allowable} := \frac{1}{300 \cdot \gamma_c} \cdot L_1 = 22.039\ mm$$

So w1 < w_u

8.10 Optimization of the structure

The resulting stresses and deflections both from the parapet to parapet and the abutment to abutment check proved to be much lower than the allowable values. Consequently, the structure is unreasonably over-dimensioned, making excessive material use which leads to increased material costs. In order to reduce the margin between the design and the allowable values the thickness of the laminate and the core are reduced. The following table shows the influence of dimensional changes on the mechanical performance of the structure. The first data in the table are the results from the calculations that have been already performed, while the next two are results from calculations based on difference dimensions.

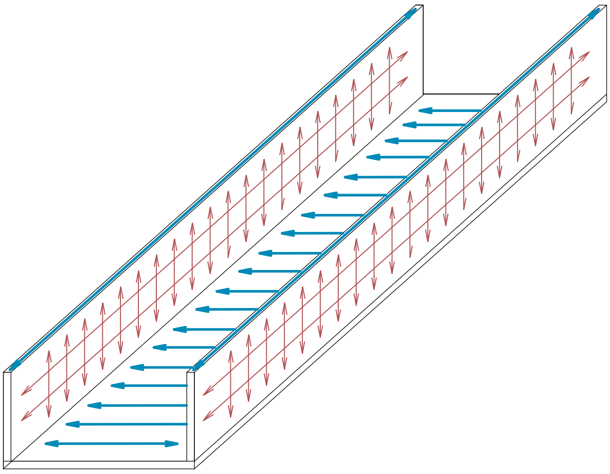
Table 8.7 Optimization of laminate and core thickness

Thickness [mm]	Parapet to parapet $\sigma_{max}/\sigma_{allow} < 1$	Parapet to parapet $w_{max} < w_{allow} = 5.51mm$	Abutment to abutment $\sigma_{max}/\sigma_{allow} < 1$	Abutment to abutment $w_{max} < w_{allow} = 22.04mm$
laminate= 7.2 core= 86	0,05	1,96	0,12	4,48
− laminate= 3.6 − core= 56	0,15	8,75	0,26	9,30
laminate= 3.6 + core= 78	0,11	4,74	0,25	8,94

It becomes clear that the most critical result is the deflection of the deck on the width of the bridge between the parapets and not the deflection in the length (span) direction. However, the thickness of the laminate is reduced successfully to half of the original dimension. The 3.6mm laminate consists of the single 8-ply quasi isotropic module that was used for the original laminate calculation.

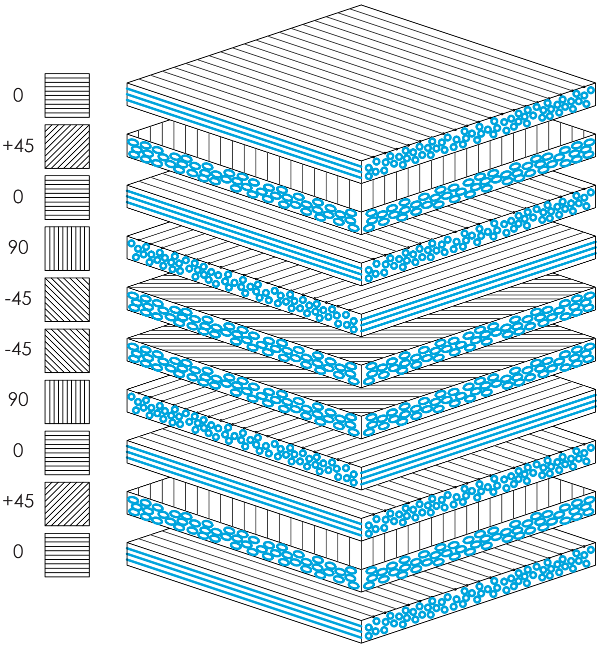
Nevertheless, the structure could be further improved by optimising the properties of the laminate in critical parts. As it was mentioned previously, a quasi-isotropic laminate behaves structurally in a similar way in all principal directions as the fibre reinforcement is equally distributed within the structure of the laminate. On the contrast an orthotropic laminate shows higher properties in specific directions that are reinforced with more unidirectional plies. Thus, orthotropic laminates are preferred in structures that demand better performance in one main direction.

With deflection closely under the allowable for the ''parapet to parapet'' structural check and a big margin between the maximum and the allowable value in the ''abutment to abutment'' check it is obvious that the structure would benefit in terms of efficient material use, with the application of a laminate with orthotropic properties on the deck of the structure. As diagram 6.6 shows, the orthotropic laminate will have its highest mechanical properties oriented to the width direction.



8.4 Optimum arrangement of fibre orientation in the laminates

Other critical areas are the two top edges of the parapets. Being the most distant areas from the neutral axis they show the highest stress consentrations. Although, in terms of stress the values are much below the allowables, this stress could be reduced by increasing the thickness of these top flanges and orienting the fibres to the longitudinal direction so that maximum stability is achieved.



8.5 Chosen fibre orientation for the Orthotropic laminate of the deck

For the orthotropic laminate of the deck, the existing quasi isotropic structure was modified by adding two extra layers with orientation angle of 0 degrees. Thus the thickness of the laminate was increased from 3,6mm to 4,5mm. With the new layers the percentages of fibre orientation change to 40% 0o, 20% 45o, 20% -45o and 20% 90o. The suggested structure is illustrated in the scheme.

The properties of the laminate were calculated again by the classical laminate theory while digital software Kolibri was a useful and efficient tool that was used in order to avoid repeating the procedure manually during the optimization process. The new resulted values for the orthotropic laminate are shown in the table below.

Table 8.8 Orthotropic laminate properties

E-modulus longitudinal	25,9 GPa
E-modulus transverse	19,8 Gpa
Shear modulus	7,08 GPa
Poisson's ratio longitudinal	0,33
Poisson's ratio transverse	0,25

Table 8.9 Optimization of laminate and core thickness

Thickness [mm]	Parapet to parapet $\sigma_{max}/\sigma_{allow} < 1$	Parapet to parapet w_{max} $< w_{allow} = 5.51mm$	Abutment to abutment $\sigma_{max}/\sigma_{allow} < 1/$	Abutment to abutment w_{max} $< w_{allow} = 22.04mm$
deck/flange= 3.6 parapet= 3.6 core= 78	0,11	4,746	0,25	8,94
deck/flange= 4.5 parapet= 3.6 core= 78	0,07	2,94	0,18	8,37
deck/flange= 4.5 parapet= 3.6 core= 56	0,097	5,35	0,194	8,73

8.11 Evaluation of flax, jute, glass and basalt fibre reinforced laminate

After having calculated the optimum thicknesses for the basalt fibre reinforced composite, the same optimized structure with orthotropic laminate for the deck and the top flanges and quasi isotropic for the parapets will be calculated again with flax, jute and glass fibres as reinforcement instead of basalt. Table 6.10 shows the laminate properties for an orthotropic and Quasi-isotropic laminate structure.

Table 8.10 Mechanical properties of Orthotropic and Quasi isotropic laminates

	Basalt		Flax		Jute		Glass	
	Ortho	Q-Iso	Ortho	Q-Iso	Ortho	Q-Iso	Ortho	Q-Iso
E-modulus longitudinal [GPa]	25,9	21,3	18,3	15,3	13,8	12,0	21,4	17,6
E-modulus transverse [GPa]	19,8	21,3	13,8	15,3	11,0	12,0	15,7	17,6
Shear modulus [GPa]	7,08	7,98	5,51	5,98	4,43	4,68	6,22	6,87
Poisson's ratio longitudinal	0,33	0,33	0,28	0,27	0,29	0,28	0,28	0,28
Poisson's ratio transverse	0,25	0,33	0,21	0,27	0,23	0,28	0,20	0,28

As was also concluded from the research on natural fibres, the hydrophilic nature of lignocellulosic fibres allows for extensive moisture uptake while compatibility with conventional resins in most of the cases problematic. Moisture results in dimensional changes (swelling), mechanical performance changes (plasticisation and hence higher strains to failure but lower moduli) and higher susceptibility to microbiological attack (Searle et al, 1999). Fibre treatment methods that have been researched during the previous years, improve at a certain degree the performance of the fibre but they also increase its cost and environmental impact. The result is a higher degree of reduction in mechanical performance compared to glass and basalt.

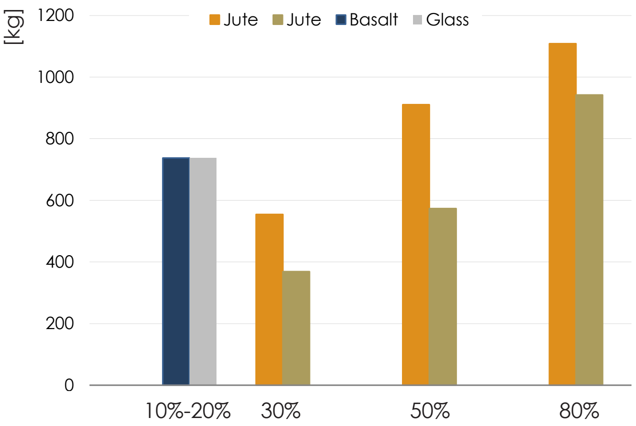
According to Shahzad, hemp fibre reinforced composited showed a reduction of 40% in strength and stiffness under accelerated weathering conditions. Another research (Joseph et. al) proved that sisal fibre-reinforced polypropylene composites showed almost 20% reduction in tensile strength only after 3day immersion into 28o C warm water. Experiments done on untreated jute fibre-reinforced composites resulted even in 90% reduction of their initial properties.

Taking into consideration these results, calculating the structure with natural fibre reinforced laminates requires higher levels of safety by increased factors regarding moisture and temperature. Increasing the conversion factors reduces the allowable values for strength and stiffness, resulting in increased thicknesses. Graph 6.8 shows the increase of the weight of the structure according to 30%, 50% and 80% end of life reduction of the properties of jute and flax. With reduction above 50%, natural fibres "lose" their benefit of being lightweight as their composites start to weight more than glass and basalt fibre-reinforced composites.

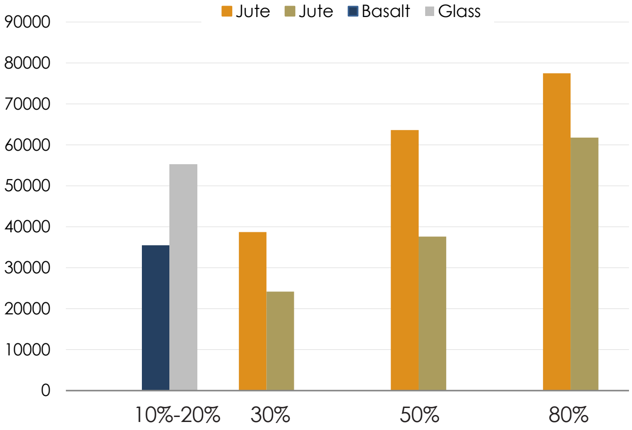
Knowing the weight of the material needed, the embodied energy of the total fibre amount can be calculated by taking average values from the findings of the LCA. Graph 6.9 shows that basalt is the most competitive among all other fibres. Even with a minimum reduction of 30% in the performance of natural fibres, jute has similar embodied energy with basalt while in the same category flax is the most efficient option.

However, cost was from the beginning another critical factor for this project. Research of the previous years, done on natural fibres, recognizes them for their lower cost in comparison with conventional fibres. Nevertheless, approaching suppliers and requesting prices for specific products, such as unidirectional technical textiles, proved that some fibres could not be considered as a cost efficient solution. Flax, for instance turned out to be the less economic solution as its UD textiles had an almost four times higher cost than glass-fibre textiles. Glass fibre showed the lowest price, closely lower from basalt. Diagram 6.10 compares the four fibres in terms of cost.

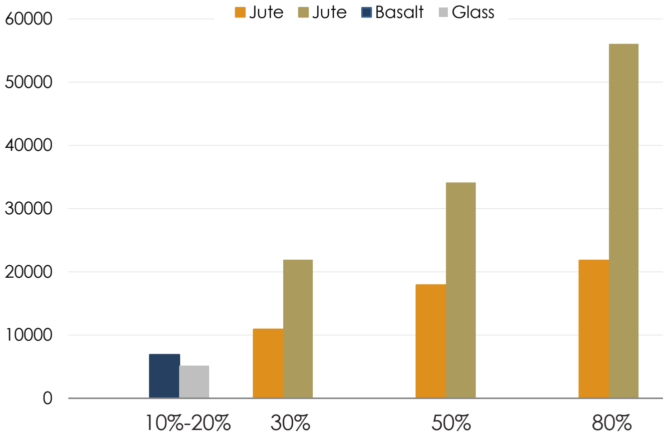
In conclusion, considering the reasons above, basalt proves to be the best option for fibre reinforcement compared to glass, flax and jute.



8.6 Weight of fibre required for the bridge in relation with reduction of mechanical properties



8.7 Energy consumption of the required fibre in relation with reduction of mechanical properties



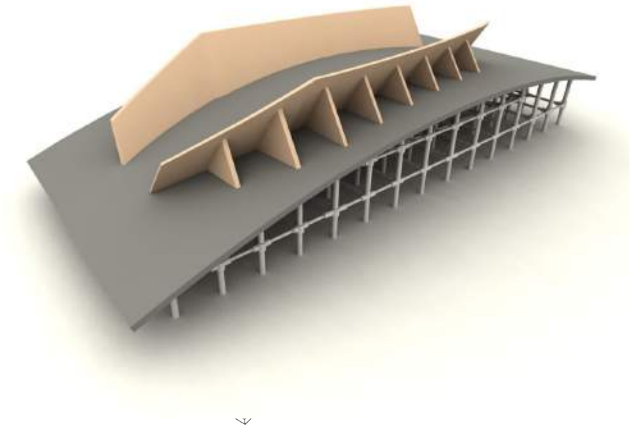
8.8 Cost of the required fibre in relation with reduction of mechanical properties

Manufacture
&
Installation

9.1 Moldmaking and lamination

According to the research done on composite shaping processes, the most appropriate production method for this bridge proved to be the vacuum assisted resin transfer molding, widely known as resin infusion or resin injection. The reasons that led to that technique were mainly the low butch size, as the bridge would be a single product and the budget limitations that directed the design to inexpensive mold solutions.

The structure of the mold will consist of a bended steel plate and two side molds out of wood, connected on the plate. After the mold is constructed the inner surfaces may be coated with a release agent that eases demolding. The first stage in laminating is the application of a gel coat over the inner surfaces of the mold that protects the laminate. This coat is a non-fibrous pure resin with less than 1mm thickness. Special resins, with good hardness and impact resistance are used for this coat.



9.1 Mold diagram. Bended steel plate and wooden side parts for parapets

After the gel coat has been applied, the reinforcement fabrics of the laminate are laid, with the first layer being usually a fine fleece that ensures a good surface finish. The process of layering the plies is repeated until the desired thickness is achieved.

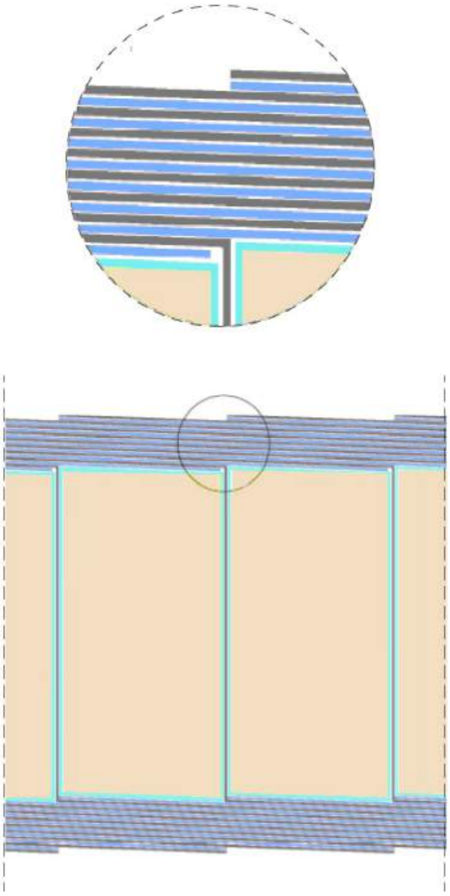
Arrangement of the individual unidirectional plies is based on the outcome of the structural calculation. For the deck an orthotropic laminate that consists of 10 plies was chosen. The plies are laid symmetrically with a different angle on top of each other, according to the following sequence [0,+45,0,90,-45,-45,90,0,+45,0]. The dominant direction (0o) is oriented to the width direction as this part proved to be the most critical by the calculation of the structure. For the parapets, the quasi-isotropic laminate chosen consists of 8 plies symmetrically arranged according to the following sequence [0,+45,90,-45,-45,90,+45,0].

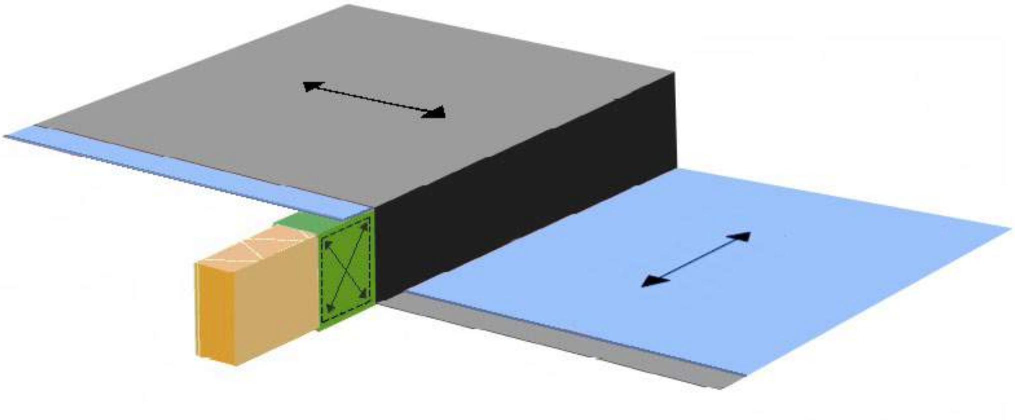
9.2, 9.3, 9.4 Mold constuction of a 21meter fibre-reinforced composite bridge. Similar to the bio-based brige of this project, the process followed in that example is also vacuum assisted resin injection.

9.2 Construction of shear web

After finishing with the lay-up of the reinforcement of the lower facing, the core is placed over the fibre plies. In the case of making a shear web in order to ensure a good bond between the core and the facing, which is the case of this bridge, the core obviously is not a continuous single unit. The core is separated in linear pieces that are placed repeatedly the one next to the other with a ply of fabric in between them. In that way, during resin injection, the liquid matrix will flow from the plies of the facings to the fabric between the shear web plates, making them part of both the lower and upper skin.

The detailed way the rectangular core beams are arranged side by side together with the separating fabric is clearly shown in the following schemes. The plies are repeatedly arranged with one (gray) taking a Z turn, starting from the upper facing, turning down attached to the side of the core and then continuing as a ply of the down facing. Then the next fabric (blue) is laid waiting for the next piece of core. The core pieces can also wrapped all around their surfaces usually with a ply of a +45o, – 45o non-crimp fabric (green) before there are placed in the mold. With this technique, both facings are connected through these fabrics that after curing they consist a compact shear web within the sandwich structure.

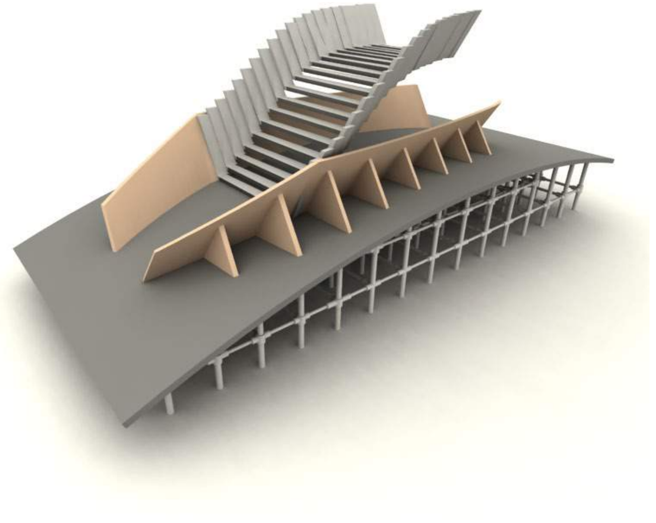

9.5 Detail of the shear web in the structure


9.6 Arrangement of unidirectional plies around the core pieces in order to build a shear web whithin the structure

9.3 Direction of the web plates

In web-core structures, the web plates run only in one direction. In a similar way as spanning a rectangular concrete slab with beams, these plates are normally arranged vertically to the span direction. By doing so, both the core beams and the web plates have higher stiffness as due to their short length (3.0m) deformation is less than if spanning was in the long direction (8.0m).

In order to achieve a good concentration of web plates that prevents separation between the two facings the plates are usually spaced at a distance 10–100 times the thickness of the facing. Thus, the distance of the web plates was chosen to be 100mm, which means that core blocks of this thickness have to be produced.

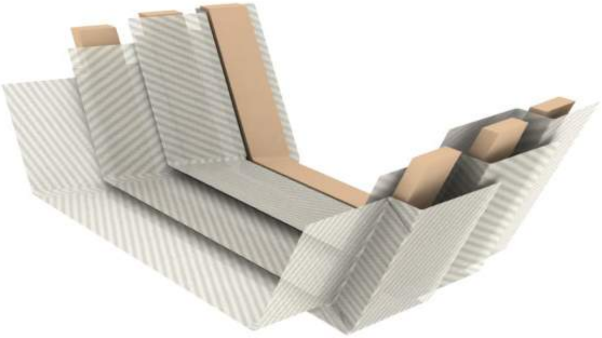


9.7 Arrangement of core elements for the achievement of the shear web

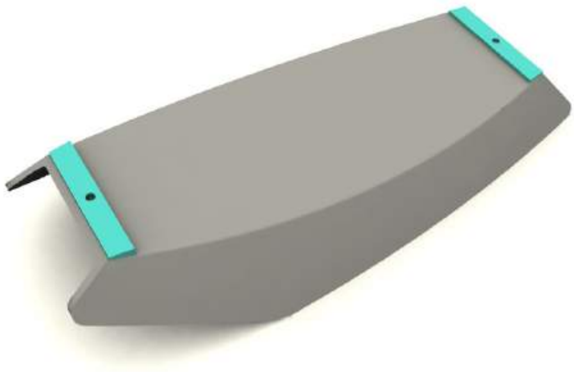
9.4 Injection and final operations

After injection and curing of the product the panel is released from the mold and the edges are trimmed to the desired shape. Sawing the composite at the cutting edges removes the facing plates from the cut sections leaving their surfaces uncovered with the core visible and exposed. Thus, layers of pure resin, preferably the same used for the entire structure, are applied manually afterwards over these surfaces in order to enclose again the core and achieve a smooth and aesthetically better finish at the cut corners.

The final process in the manufacturing unit, before the bridge is transported to the site, is the adjustment of the two cradles at the edges c the deck. The role of the cradles is to prevent c rect contact of the structure with the foundatio system. The cradle consists of a rubber materi that is placed on the structure and is hand lam inated with the same combination of fibre an resin used in the structure. After the addition hc cured the holes that will connect the structur with the foundation are drilled.



9.8 Construction method of the laminate



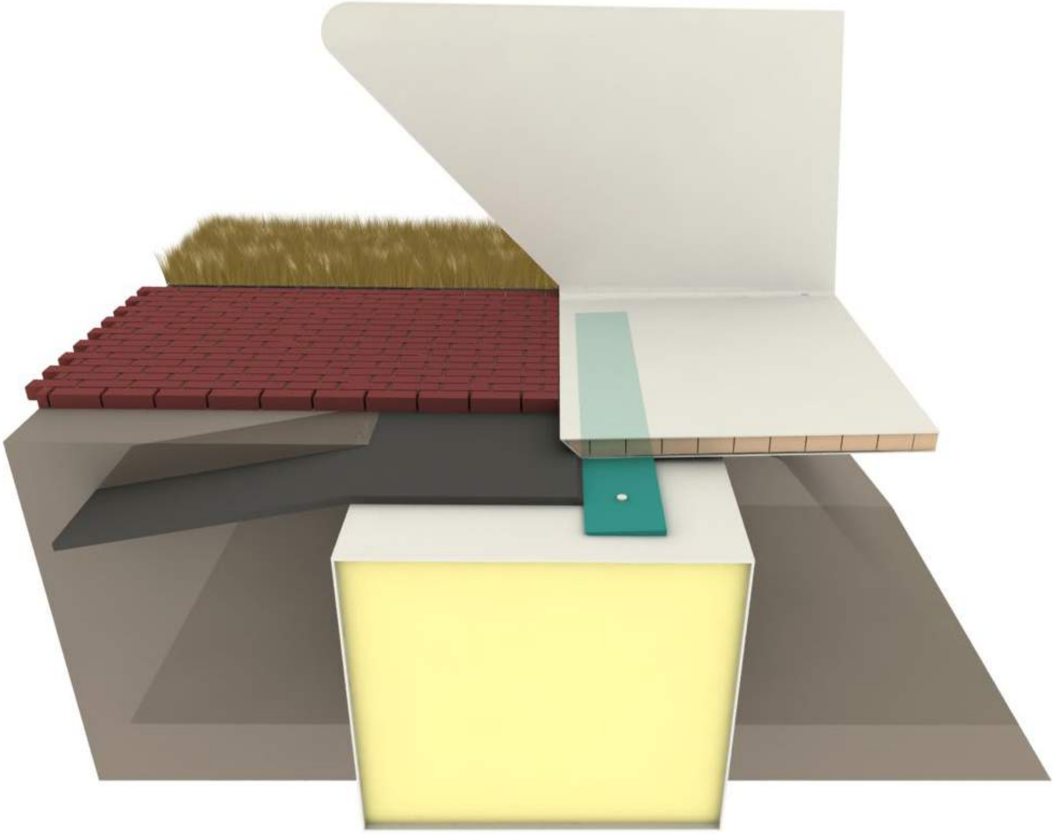
9.9 Plastic cradles at the edges of the deck

9.5 Installation on site

Prior to the transportation of the structure on site, the foundation is constructed. Due to the light weight of the structure the foundation can be a simple system. A common solution in such cases is the use of concrete blocks as a foundation system with poles would be excesive. However, it is suggested for the bridge of this projected the concrete blocks to be replaced by glass-fibre reinforced blocks that are used in FRP manufacturing companies as testing models. These blocks normally have cubic shape with a volume of 1m^3 and while their sturctural performance is still after the test good, these cubes costist a waste material for all these companies. Thus, reusing this elements, avoids the added envionmental impact and financial cost of a concrete supporting structure.

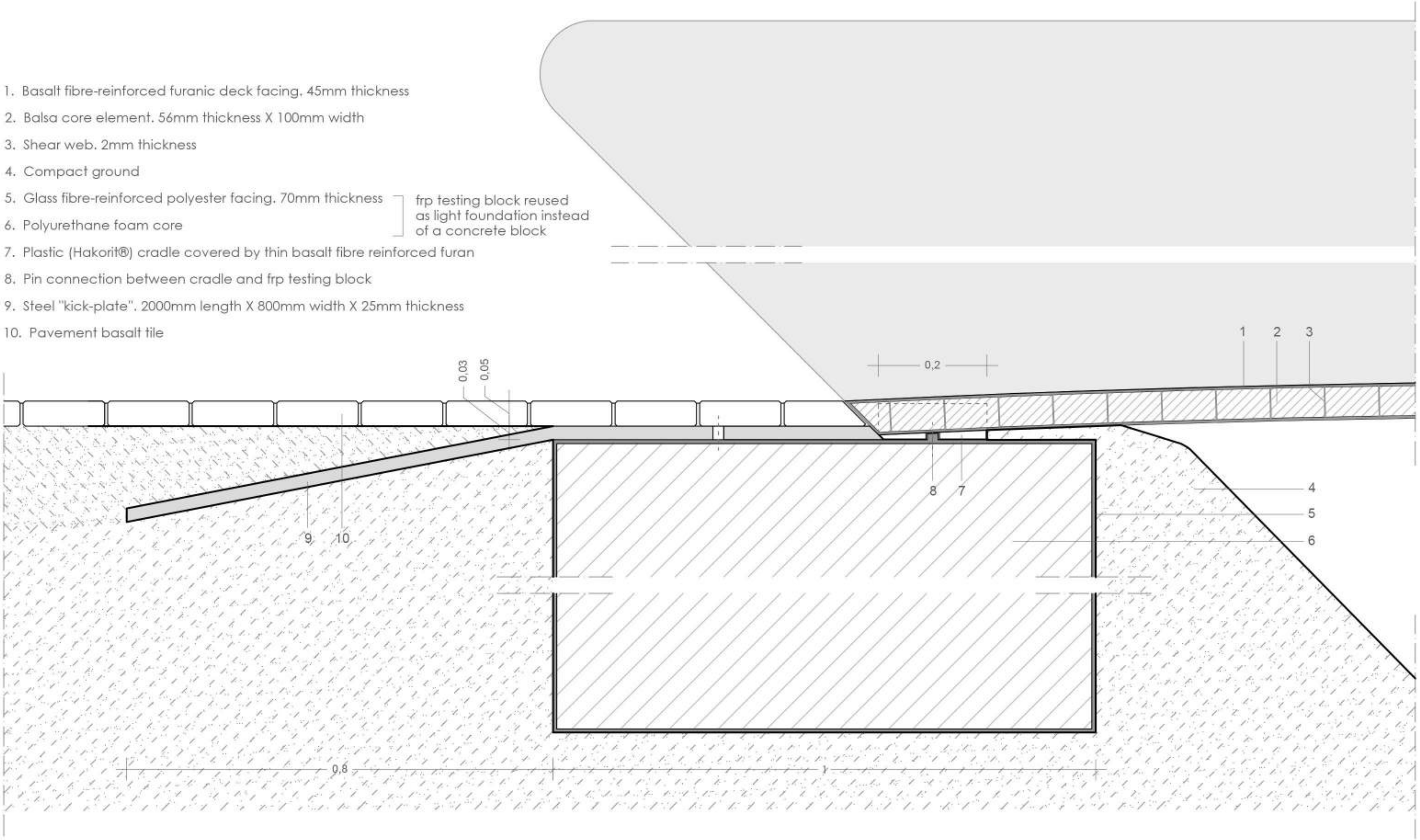
9.10 Soil compaction next to the foundation (concrete block solution)

A problem that occurs in most bridges that use a foundation system similar to the concrete blocks is the soil compaction through time. The ground that gradually moves causes the pavement to slide vertically together with the ground resulting in a small step. To solve this, a steel plate is adjusted on the top surface of the concrete block and extendts under an algle into the ground. The soil that is placing compact soil above the steel plate ensures that the pavement will remain straight and no slide will appear above the plate.



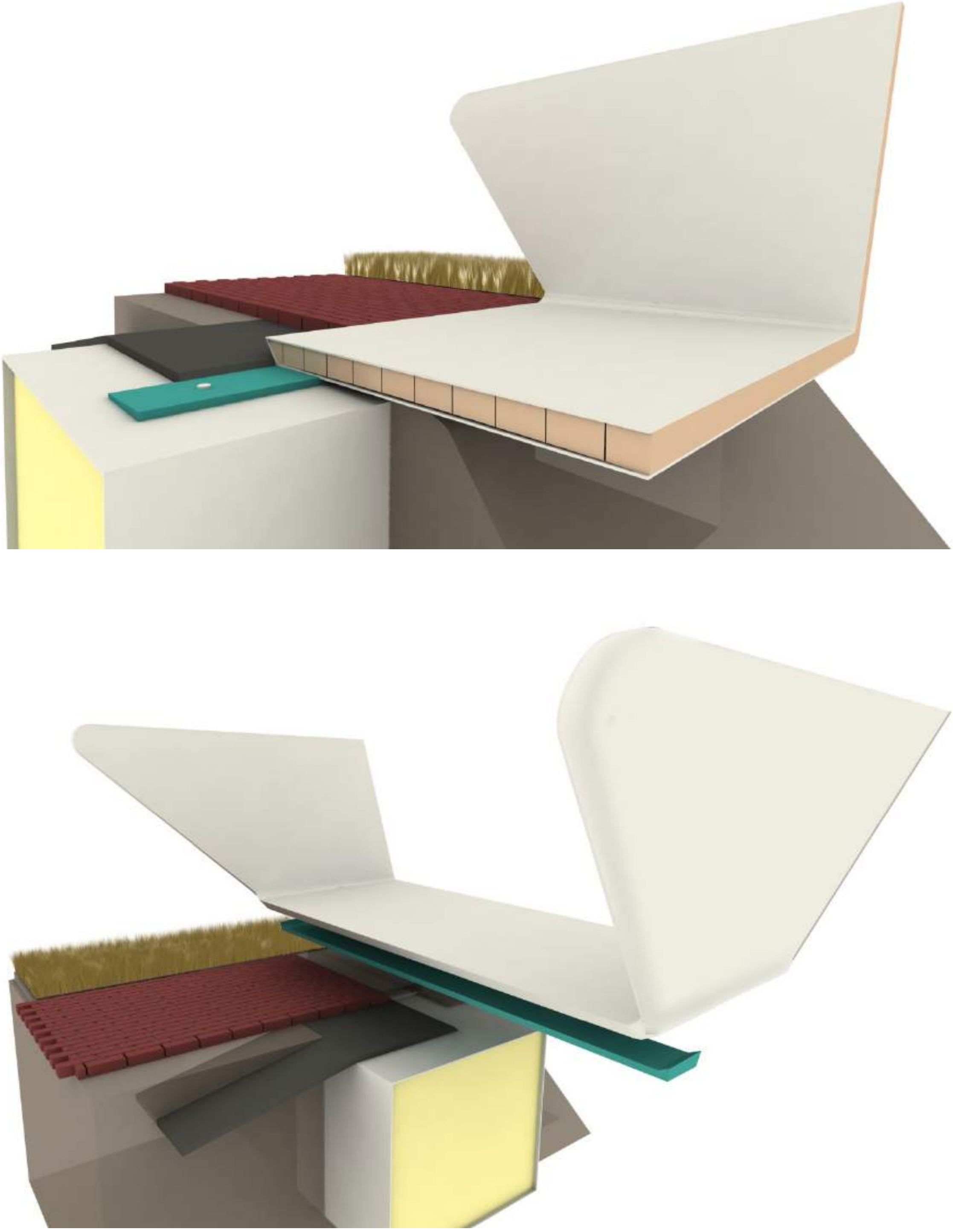
9.11 Foundation solution with glass-fibre reinforced plastic testing block and steel plate

Detail of the foundation



1. Basalt fibre-reinforced furanic deck facing. 45mm thickness
2. Balsa core element. 56mm thickness X 100mm width
3. Shear web. 2mm thickness
4. Compact ground
5. Glass fibre-reinforced polyester facing. 70mm thickness
6. Polyurethane foam core
7. Plastic (Hakorit®) cradle covered by thin basalt fibre reinforced furan
8. Pin connection between cradle and frp testing block
9. Steel "kick-plate". 2000mm length X 800mm width X 25mm thickness
10. Pavement basalt tile

frp testing block reused as light foundation instead of a concrete block



9.12, 9.13 Foundation solution with glass-fibre reinforced plastic testing block and steel plate

Conclusions
&
Recommendations

10.1 Conclusions

Considering the results from the LCA and the structural calculation we can conclude that sustainability can be approached by many different ways. It is finally the way a material is used or the chosen application and not only its natural origin that makes a product or structure sustainable. Reducing extensively the end of life of a structure such as a bridge by using a non-durable but sustainable material proves to be less efficient in terms of sustainability than using a conventional durable material.

Main drawback of natural fibre is their low durability due to various reasons, such as moisture absorption, temperature and fibre-resin low compatibility. Resulting in bigger dimensions, more material is required, which increases the environmental impact and embodied energy of the structure. Development of sustainable fibre treatment methods that would be applied during textile manufacturing could become a future solution. Yet, more research and testing results are required in order to be able to use natural fibres in load-bearing applications without considering serious mechanical performance reduction.

For the present level of development of natural fibres as reinforcement in composites, their use in non-loadbearing and less durability-demanding applications with lower life-span is a more efficient practice. For that reason, the automotive industry was the ideal sector to introduce such bio-based materials, test them and use to the maximum all their advantages. It is no wonder that this sector has high percentage in use of bio-plastics.

Another disadvantage of the two examined natural fibres was their high price that raised together the increase in material requirement. So even if the environmental benefit by using natural fibres in a load-bearing application was of significant importance, the cost of the structure would be a few times higher than it would be by using conventional fibres. All the above show that for this specific project, in which durability is linked with sustainability and cost is an influential factor, conventional fibres prove to be a more sustainable and efficient solution.

Comparing glass fibre and basalt, as mentioned in the LCA, the latter shows advantages in terms environmental impact and embodied energy compared to glass fibre. Easier recyclability, pure consistency, non-toxicity and use of alternative sources for the production of basalt are some factors that reduce the impact of basalt. In addition, basalts higher durability and mechanical performance compared to glass allows for less material use. Specifically, from the calculation it was found that having the minimum laminate thickness of 4,5mm, basalt reinforcement allowed for reduction of the core material to 56mm, as the margin was still considerable. In contrast, the 4,5mm glass fibre reinforced laminate could not achieve core thickness lower than 76mm.

Due to the reasons explained above, basalt fibre was considered as the most efficient solution for the bridge of this project in terms of sustainability, cost and feasibility of the real construction. In any respect, opting for reinforcement with non-renewable resource does not influence the bio-based character of the bridge as for the core a natural material (balsa wood) was chosen and the matrix is the bio-based furan.

10.2 Recommendations and points of improvement

Research regarding the durability of natural fibres and their use as reinforcement in fibre-reinforced composites, used in load-bearing application is still at an early stage of development. Through the present research, it became clear that accelerated reduction of the mechanical properties of plant fibres due to low durability is the main reason prohibiting their use in such applications. Thus, future research should be directed on exploring solutions for improving the durability of these fibres either by fibre treatment methods or long-lasting protection within the composite. In any case, such an investigation requires material testings and experimentations on real testing samples in order to draw conclusions.

Apart from the fibre, significant is also the contribution of the resin for the durability, environmental impact and strength of a composite. However, in this graduation project most of the research is dedicated on natural fibre, rather than the resin and the core material, which creates topics for further development on these two elements.

Finally, the life-cycle analysis done on natural fibres was an important step with interesting results regarding the embodied energy and the environmental impact of the fibres. However, the LCA focuses mainly on the production phase of the fibre rather than on the use phase (maintenance, repair) and the end of life treatment (recycle, disposal, etc.). A complete extensive LCA that would consider all phases could consist an individual topic of research on the environmental impact of load-bearing natural fibre-reinforced plastics.

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