Client: One Degree

State of art on sustainable boat building practices

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1 Preamble

One degree team is entered The Ocean Race campaign (2019-2022). Sustainability plays an essential role in this campaign and the team want to show exemplary leadership in the world of sport and team management.

One degree team has started designing a new boat the boat to sail the coming Ocean Race starting in 2021. The building of the new boat will start in 2020. The team wants to monitor the resource, waste, water and energy use and apply best practices all along the building process and during the race event.

In order to better understand the possibilities to reduce environmental impact in offshore racing, One degree asked Kairos to produce a state of art of practices and sustainable materials for boat building applications.

This document addresses sustainability resources, naval architects and boat builders to give them tools and general figures to help them introduce low impact materials and processes into sailing boats. It also gives initial consideration to better understand the potential and limitation of eco design in racing boats.

A product from renewable origin does not necessarily mean that its environmental performance is better when comparing it to traditional products in the market [1]. Therefore particular care must be taken and appropriate tools must be used to evaluate the environmental gain of a particular solution.

2 Introduction

Material properties have significantly driven the evolution of yacht design over the years. From wood plank construction to carbon/Epoxy composite, the increase in strength and stiffness associated to the diminution of material density led to build lighter boats. Hull shapes changed from being optimised for heavy displacements to planning and since a decade to "flying" modes.

The evolution of the mechanical properties of boat building materials has also been associated to an increase in their environmental impact. This is due both to the raw material and the production process.

3 Raw materials

3.1 Fibre type

Fibres are the solid part of the composites reinforced into the matrix. They determine the strength and stiffness of the composites. Most common reinforcements are fibres or particles. Fibre reinforcements are found in both natural and synthetic forms. Natural fibre composite was the very first form of composites. Straw was reinforced in clay to make bricks that were used for building.

3.1.1 Non renewable[1]

3.1.1.1 Carbon:

Carbon fibres were invented in 1878 by Thomas Alva Edison with cotton fibre and later on were made up of bamboo. Carbon fibres were used in high temperature missiles.

3.1.1.1.1 Production process:

Carbon fibre is made from acrylonitrile, a 100% petroleum based monomer resulting from the reaction of propene and ammoniac. Acrylonitrile is polymerised to produce poly-acrylonitrile (PAN). To obtain carbon fibre, the PAN is spun into fibres, which are then washed and stretched. The fibres are then stabilised by chemical alteration to stabilise the bonds. The fibres are carbonized carbonised by pyrolysis at 1200 / 1500 °C. The surface of the fibres is treated by oxidisation to improve bonding properties. Finally the fibres are coated with a sizing to help thermoset bonding for composite manufacturing.

3.1.1.1.2 Health and safety:

Acrylonitrile is corrosive, toxic, environmentally damaging and CMR (carcinogenic, mutagenic, reprotoxic). This health hazard concerns only the manufacturer of the carbon fibre and not the manufacturer of the composite part.

The principal health hazards of carbon fibre handling are due to mechanical irritation and abrasion similar to that of glass fibres. Carbon fibres are easily broken by stretching (by less than 2% elongation); the fibres can easily become a fine dust during cutting, machining or mechanical finishing and can then be released into the surrounding atmosphere. These micro fibres if uncontrolled have a potential to stick into human skin or the mucous membranes causing irritation.

3.1.1.2 Glass

Glass fibre reinforcements were produced for the first time in 1893. Now it is one of the most appealing reinforcements due to its high performance, good properties and low cost. Glass fibres are resistant to high temperatures and corrosive environments and they also have radar transparency. There are two main types of glass fibres: E-glass and S-glass.

3.1.1.2.1 Production process:

The basic component of glass fibres is silica (silicon dioxide SiO2) derived from ordinary sand. The addition of other oxides of metals such as sodium, calcium, aluminium, magnesium, etc., to silica serves to alter the network structure and the bonding, increase the production efficiency by reducing the viscosity, reduce the cost and modify the mechanical, electrical, chemical, optical, and thermal properties of the glass that fibres that are produced [2]. In the initial stage of glass manufacture, materials are mixed. More than half the mix is silica sand, the basic building block of any glass. From the batch house, pneumatic conveyor

[1] A renewable resource is a natural resource which will replenish to replace the portion depleted by usage and consumption, either through natural reproduction or other recurring processes in a finite amount of time in a human time scale; Wikipedia.

sends the mixture to a high temperature (≈1400ºC) furnace for melting. The molten glass then flows into the refiner, where its temperature is reduced to 1370ºC. Glass fibre formation, or fiberization, involves a combination of extrusion and attenuation (mechanical drawing of the extruded streams of molten glass into fibrous elements). Fibre sizes are ranging from 4 to 34 µm. In the final stage, a chemical coating, or size, is applied. Finally, the drawn, sized filaments are collected together into a bundle, forming a glass strand composed of 51 to 1,624 filaments.

3.1.1.2.2 Health and safety:

The dust created during the cutting, grinding and sanding of fibreglass can affect the skin, eyes, upper respiratory system and lungs. There may be immediate reaction to exposure, resulting in irritation to the eyes, nose and throat, while prolonged contact with the skin can lead to dermatitis. The long-term effects of the inhalation of fibreglass dust particles include breathing difficulties, asthma and decreased lung function.

3.1.1.3 Aramid

Aramid fibres were introduced in 1971. They are also known as Kevlar. Kevlar aramid is an aromatic organic compound of carbon, hydrogen, oxygen, and nitrogen. Kevlar fibres are produced by spinning long-chain polyamide polymers using standard textile techniques (Åstrom, 1997). The low-density, high-tensile strength produces tough, impact-resistant structures. One of the main disadvantages of aramid fibre due to its toughness is its difficulty to cut and grind with conventional tools from boat yards.

3.1.1.3.1 Production process:

Aramid fibres is forming substance is a long-chain synthetic polyamide in which at least 85% of the amide linkages are attached directly between two aromatic rings. Technically, aramid fibres are long-chain synthetic polyamides poly(p-phenylenediamine terephthalate) (PPTA). After production of the polymer, and similarly to carbon fibre, the aramid fibre is produced by spinning the solved polymer to a solid fibre from a liquid chemical blend. Polymer solvent for spinning is generally sulfuric acid (H2SO4). Then the fibres are washed and neutralized by heat treatment. Finally the fibres are coated with a sizing to help thermoset bonding for composite manufacturing.[3]

3.1.1.3.2 Health and safety:

Aramid Fibre is too big to inhale into the lungs, but fibre dust and fly from processing may be breathed into the nose and throat.

3.1.1.4 Basalt

Basalt fiber is made from a single material, crushed basalt, from a carefully chosen quarry source. Basalt of high acidity (over 46% silica content) and low iron content is considered desirable for fiber production. Unlike with other composites, such as glass fiber, essentially no materials are added during its production. The basalt is simply washed and then melted.

3.1.1.4.1 Production process:

The technology of production of BCF (Basalt Continuous Fiber) is a one-stage process: melting, homogenization of basalt and extraction of fibers. Basalt is heated only once. Further processing of BCF into materials is carried out using "cold technologies" with low energy costs. The manufacture of basalt fiber requires the melting of the crushed and washed basalt rock at about 1,500 °C (2,730 °F). The molten rock is then extruded through small nozzles to produce continuous filaments of basalt fiber.

3.1.1.4.2 Health and safety:

The basalt fibres typically have a filament diameter of between 10 and 20 µm which is far enough above the respiratory limit of 5 µm.

3.1.2 Renewable

All renewable fibres are coming from plants. Even if plant fibre were used in marine industry in the past for sails, ropes or caulking, they are nowadays mostly used in textile. Fabric production for textile industry is using twisted yarn. For composite application, twist lowers its mechanical properties. Most long fibre suppliers for composite application are developing semi-product[2] involving non twisted or low twist yarns. This lowers the strength of the yarn generating issues during the manufacturing process of the semi-product.

Natural fibres are widely used for various applications: jute bags, coco brushes, hemp and flax textile and composites. Figure 1 shows the world production of natural fibres [4].

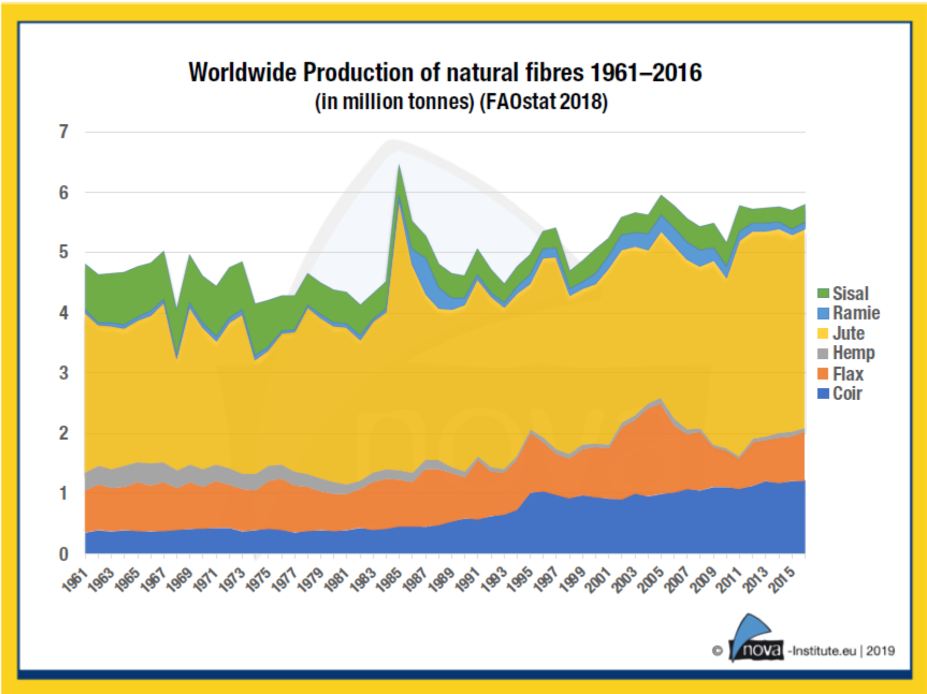

Figure 3: Development of worldwide natural fibre production 1961–2013 without cotton (nova 2019, based on FAOSTAT 2018)

Figure 1: Global natural fibre production

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[2] Semi-products in composites are woven, non-woven and non-crimp fabrics. They are commonly called woven rowing, Unidirectional, biaxial, mat, etc.

3.1.2.1 Flax

3.1.2.1.1 Production process:

Flax (Linum usitatissimum) is a bast fibre plant cultivated for the production of fibres. It is an annual plant. Normandy in France is the world leader region growing and scutching flax fibre. The cultivation stage last for 3 month. During this period the plants become straight, slender stalks from 60 to 120 cm in height, with tapering leaves and small blue, purple or white flowers. The plant with the blue flowers yields the finer fibre the others produce a coarser but strong fibre. When the plant reaches to height of 100 to 120 cm as consider full growth the plant is pulled up & cut down. Leaves and seeds are removed by a series of upright forks. The stems are then retted. It involves the decomposition of the woody matter enclosing the cellulose fibres. It is the first step of individualisation of the flax fibres. When the decomposed woody tissue is dry, it is crushed by being passed through fluted iron rollers. Fibres are going through a scutching process separating unwanted woody matter from fibres. The fibres are getting more individualised. The last step is heckling. This process is like the combing process of cotton fibres. The coarse bundles of fibres are separated from finer bundles and the fibres are also arranged parallel to one another the longer fine fibres. In most cases no sizing are used on flax fibres.

The quality of the fibre varies from one year to the other. Therefore, to control consistency, producers are blending harvests between different years.

3.1.2.1.2 Availability:

Flax fibres for semi-products for composite are available in various non-woven and woven fabrics. Flax exists in 0/90°, +/-45° and unidirectional fabrics. Flax fibre is also available as commingle fabrics. It consists in assemble of natural fibre and thermoplastic fibres.

3.1.2.1.3 Use in composites

Compared to other natural fibres, flax is the preferred fibre for mechanical application. This is mostly due to its high mechanical strength and stiffness and its availability in the form of semi-products applicable in the composite industry [5]. Flax is also used as non-woven in car industry [6].

3.1.2.1.4 Health and safety

Flax and other natural fibres do not irritate skin and has no specific health and safety risks identified.

3.1.2.2 Hemp

Hemp production process is similar to flax: seeding, flowering, cutting, retting, harvest, scutching, combing. France is the European leader of hemps production.

Hemp is mostly available as non-woven for car industry.

3.1.2.3 Jute

After cotton, jute fibre is the most cultivated fibre in the world with around 3 million tonnes harvested each year [7]. Jute is used for non-structural applications such like bags and for semi structural application in automotive industry.

3.1.2.4 Bamboo

Bamboo woven rowing for composite application is a recent product available on the market. The bamboo is split into thin strips and assembled together to create long bamboo rowings. Mechanical performances of these semi-products for composite are not well known so far and more research needs to be done to compare bamboo composite to other natural fibre composites. BAMCO is a consortium of companies who have come to together to design new biosourced technical composites based on bamboo [8].

3.2 Resin type

The two classes of resins are the thermoplastics and thermosets. A thermoplastic resin remains a solid at room temperature. It melts when heated and solidifies when cooled. The long-chain polymers do not form strong covalent bond. That is why they do not harden permanently and are undesirable for structural application. Conversely, a thermoset resin will harden permanently by irreversible cross-linking at elevated temperatures. This characteristic makes the thermoset resin composites very desirable for structural applications. The most common resins used in composites are the unsaturated polyesters, epoxies, and vinyl esters; the least common ones are the polyurethanes and phenolics.

3.2.1 Non renewable

3.2.1.1 Thermosets

Thermosets resins are found in a liquid state at ambient temperature. In composite industry they are used to impregnate the fibres via various processes. After reticulation the resin become hard and binds the fibres together.

3.2.1.1.1 Epoxy

The epoxies used in composites are mainly the glycidyl ethers and amines. The material properties and cure (hardening) rates can be formulated to meet the required performance. Epoxies are generally found in aeronautical, marine, automotive and electrical device applications. Although epoxies can be expensive, it may be worth the cost when high performance is required.

It also has some disadvantages, which are its toxicity and complex processing requirements. Most of the epoxy hardeners cause various diseases. Epoxy resin causes serious eye and skin irritation. It causes also skin irritation and it is corrosive. Bisphenol-A is responsible for epoxy resin being CMR (carcinogenic, mutagenic, reprotoxic). Suppliers have developed low toxicity resin such like Gurit Ampreg 36.

The global production of epoxy in 2011 was 2.2 million tonnes.

3.2.1.1.2 Vinyl ester

The vinyl ester resins were developed to take advantage of both the workability of the epoxy resins and the fast curing of the polyesters. The vinyl ester has better physical properties than polyesters but costs less than epoxies. A composite product containing a vinyl ester resin can withstand high toughness demand and offer excellent corrosion resistance. Its properties are considered the best compromise cost over performance and it can adhere to reinforcements very well.

3.2.1.1.3 Unsaturated polyester

The advantages of the unsaturated polyester are its dimensional stability and affordable cost as well as the ease of handling, processing, and fabricating. Some of their special properties are high corrosion resistance and fire retardants. These resins offer probably the best balance between performance and structural capabilities. They have low cost and good properties such as low viscosity.

Most polyester and vinylester resins contain styrene. Styrene can cause eye, skin and respiratory tract irritation. Styrene is a solvent and may be harmful if inhaled. Reports have associated repeated and prolonged occupational overexposure to solvents with permanent brain and nervous system damage. Extended exposure to styrene at concentrations above the recommended exposure limits may cause central nervous system depression causing dizziness, headaches or nausea and if overexposure is continued indefinitely, loss of consciousness, liver and kidney damage.

The global production of unsaturated polyester in 2011 was 76 million tonnes.

3.2.1.1.4 Methacrylate

Five years ago, Arkema released Elium resin made from a methacrylate base. It is presented to be thermoplastic and it can be thermoformed. Thermoforming is limited due to the presence of fibre. Elium is available for injection process such like infusion or RTM.

The polymerisation of Elium is inhibited by oxygen. Specific precaution must be taken to ensure a high degree of polymerisation and best mechanical performances.

Regarding recyclability, the viscosity obtained at high temperature does not allow to process it by injection moulding as a secondary raw material. This makes a significant difference compared to conventional thermoplastic resin such like polypropylene, polyamide or polylactic acid.

Arkema developed a depolymerisation process to separate the fibre and the matrix. The recycling of Elium resin is still under development and the recycled grades are not commercially available yet.

3.2.1.2 Thermoplastics

Thermoplastics offer significant advantages over thermosets: fast manufacturing process, low cost, and recyclable solution.

However the transformation of thermoplastic needs high temperature (i.e. 200°C for PP) and pressure (i.e. 7 bars). At the scale of a boat hull this could only be economically available for large volume of production. Small boats are manufactured with Twintex (commingle glass / PP semi-product): Twiner from Groupe Finot, twincat 13 commercialised by 2win.

Low cost thermoplastic composite is available for marine industry in the form of flat single skin and sandwich panels for structural applications[3]. Various fibre reinforcement are available such like carbon, glass and natural fibre.

The thermoplastics presented below are available in comingle woven and non-woven semi-products.

3.2.1.2.1 Polypropylene

Polypropylene is currently one of the fastest growing polymers. Much of this growth is attributed to polypropylene's cost/stiffness ratio. Polypropylene (PP) is a tough, rigid plastic and produced in a variety of molecular weights and crystallinities.

It is used in a variety of applications to include packaging for consumer products, plastic parts for various industries including the automotive industry, special devices like living hinges, and textiles.

3.2.1.2.2 Polyamide (PA)

Polyamides are semi-cristallines polymers offering good mechanical properties (especially PA6.6). Polyamides are suffering from hydrolysis in presence of water which lowers their mechanical properties. Polyamides are used in various industries such as automotive, electricity, house hold products, sports and goods.

[3] Kairos is equipped with thermocompression presses for thermoplastic panel manufacturing.

3.2.2 Biobased and Partly biobased

As shown on the diagram below, most conventional polymers can be manufactured from plant based raw materials. The Figure 2 below shows the origin of most biobased polymer [8].

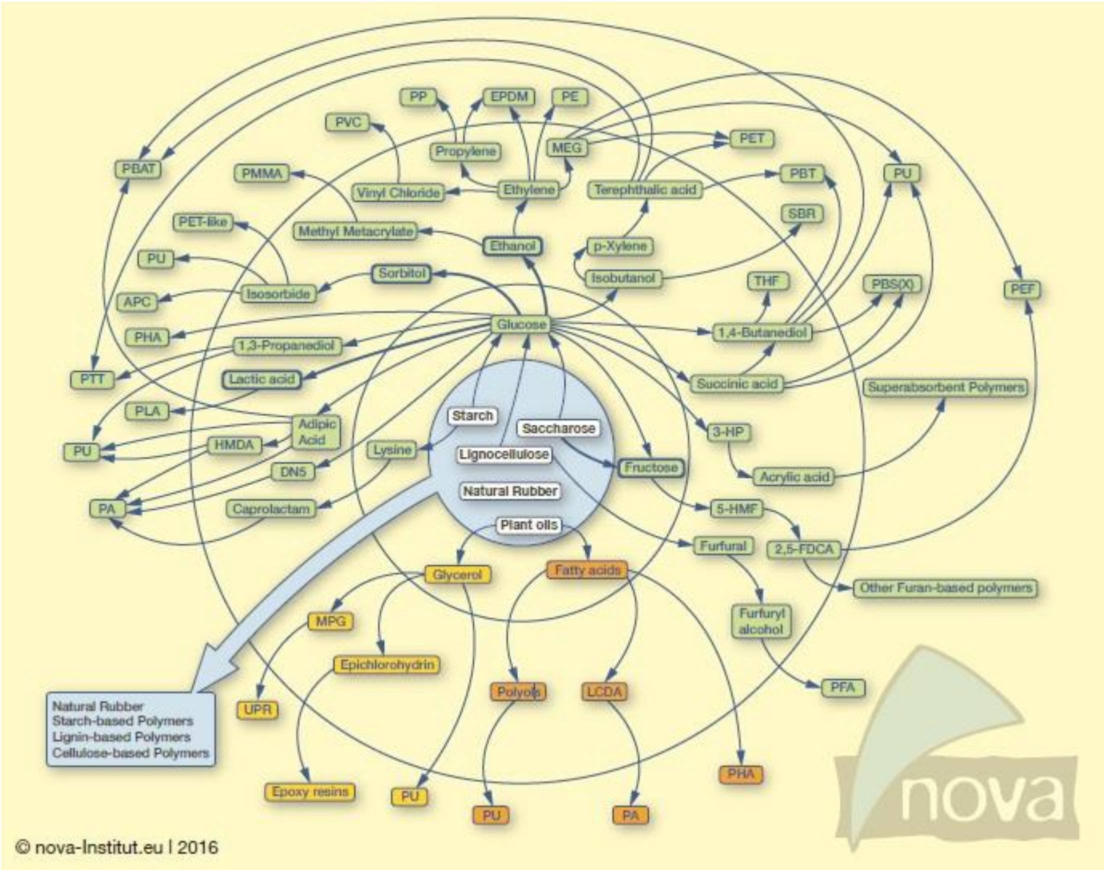

Figure 2: Origin of biobased polymer

3.2.2.1 Thermosets

Partly biobased polyester and Epoxy resins can be found from specific suppliers. They are partly from petroleum origin and partly from renewable resources. In order to determine the bio-based content of the polymer, the "new" carbon content must be measured according to standards detailed below in chapter 5.1.1.

3.2.2.1.1 Epoxy

The biobased content is coming from the epichlorohydrin part. Epichlorohydrin is produced from glycerine itself produced from colza and sunflower oil. Epoxy can be biobased up to 50%. Their mechanical properties are in the same range as standard epoxy resins. Partly biobased epoxy is neither recyclable nor biodegradable.

3.2.2.1.2 Polyester

The biobased content of polyester resins is coming glycerol. The biobased content of polyester resins can be up to 20%. Particular precaution must be taken when using partly biobased polyester resin with natural fibre as the humidity present inhibits the polymerisation. Partly biobased polyester is neither recyclable nor biodegradable.

3.2.2.1.3 Poly furfuryl alcohol (PFA)

PFA is 100% biobased made from sugar cane residues. When extracting the molasses from sugar cane, the remaining fibrous residue is called bagasse. PFA is obtained from this residue. PFA has good thermal and fire resistance. PFA is neither recyclable nor biodegradable.

3.2.2.2 Thermoplastics

3.2.2.2.1 Polylactic acid (PLA)

PLA is 100% biobased polyester from starch. PLA is recyclable and compostable in industrial compost. Due to its high strength and stiffness as well as its ability to be used in 3D printers, it is a commonly used biobased polymers.

3.2.2.2.2 Polyamide (PA11)

PA11 is 100% biobased. It is manufactured from castor oil. It is applied in the fields of oil and gas, aerospace, automotive, textiles, electronics and sports equipment, frequently in tubing, wire sheathing, and metal coatings. Its low water abortion makes it available for applications highly exposed to moisture. PA 11 is recyclable but not biodegradable.

3.3 Core materials

Most non-renewable core for sandwich construction such like PVC, Nomex or PP honeycomb are not developed in this document. However a few data are given here on PET foam.

PET foam can be manufactured from plastic bottle recycled PET. These foams can be competitive with conventional foam core. The principal mechanical properties of PET foams compared to PVC foam are presented in Table 1.

Mechanical property	Unit	Airex T92.100, PVC	Airex T10.100, PET
Nominal density	kg/m^3	100	100
Compressive strength	N/mm^2	1.75	1.4
Compressive modulus	N/mm^2	90	105
Tensile strength	N/mm^2	2.3	2
Tensile modulus	N/mm^2	110	150
Shear strength	N/mm^2	0.9	1
Shear modulus longitudinal	N/mm^2	26	34
Shear modulus transverse	N/mm^2	23	21
Shear elongation at break	%	20	20

Table 1: foam core comparison between PET and PVC.

3.3.1 End grain balsa wood

The origin of most balsa wood is Central America and more particularly Equator. End grain balsa wood has been used in boat industry for decades. Initially balsa core were simply glued under vacuum. Hence the balsa was not saturated with resin. This created severe damages of water absorption especially on decks and superstructures. With the development of infusion process as well as particular care taken to install chandlery on deck water absorption issues of balsa wood is well handled.

3.3.2 Cork

Most cork used in composite industry is coming from Portugal or France (Corsica and South West). Core itself has low mechanical properties on its own. Cork is however a good replacement of Soric® (a flexible core material used in large quantity for boat industry) as a thin core material.

4 Process

Processes are predominant in the construction of composite parts. The process defines the consolidation applied on the part during cure of the resin. Therefore it is affecting closely fibre fraction and porosity.

4.1 Hand layup

Hand layup is by far the most cost and environment effective process. Consumables are limited and the skills needed are moderate. It is mostly used for industrial application where weight has not a major impact.

However hand layup with vacuum consolidation is used a lot in boat building specially for assembling. This needs significantly more consumables and skills.

Additional cost and environmental impact in generated when the part is post cured.

Hand layup process tends to reduce due to the emission of volatile organic compound (VOC).

Hand layup is not suitable for natural fibre composite as the permeability of natural fabric is too high to be impregnated without additional pressure.

Hand layup is suitable for thermoset resins only.

4.2 Infusion

Infusion, also known as VARTM (Vacuum assisted resin transfer modelling) has been developed a lot for the past 15 years. It is appropriate for manufacturing large parts at low production rate and limits the emission of VOC compared to hand layup.

Infusion creates a lot of consumables because additional drainage is needed to help the resin flow. Grids (see chapter 6.3.2) are of particular interest for infusion. As well as their structural properties they help drainage and limit the use consumables.

Infusion is well appropriate for natural fibre composites.

Infusion is suitable only for thermoset resins.

4.3 Oven and autoclave

Oven and autoclave are mostly suitable for pre-pregs semi-products. These processes are used for high mechanical property composites. They need a lot of consumables and their processing energy is the greatest of all processes. Curing cycles are long and common temperatures around 120°C.

Pre pregs of flax associated with various resins are available on the market.

4.4 RTM

RTM and RTM light are mostly used for medium size parts and medium to high production rate. The fibre volume fraction is lower than infusion.

The need in consumables is low and the emission of VOC is very low.

RTM is suitable for natural fibre composites

4.5 Thermo-compression

Thermo-compression for thermoset resins consists in curing the composite part with controlled temperature under a press. Flat panels are commonly built with thermo-compression. Local reinforcement of limited thickness can be integrated into the flat panels. 3D shape geometries can also be built.

Thermo-compression for thermoplastics makes high quality composites. It is widely used in automotive industry. It is well appropriated to natural fibre associated with comingled fabrics.

Thermo-compression needs low amount of consumables and emits low VOC.

5 Environmental impact

5.1 Norms and standards

5.1.1 Bio-based content

The biobased content of a polymer must be quantified using 14C content measurement. Standard have been developed in that sense:

- The European norm EN 16785-1 "Bio-based products – Bio-based content - Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis"
- The European standard, EN 16640, 2015. Bio-based products - Bio-based carbon content - Determination of the bio-based carbon content using the radiocarbon method
- The American standard ASTM D6866 “Standard Test Methods for Determining the Bio-based Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis”
- The ISO standard ISO 16620-4:2016 Plastics – Bio-based content - Part 4: Determination of bio-based mass content

5.1.2 LCA Standards

ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

ISO 14044:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies.

5.1.3 Biodegradability

Biodegradability of a material depends strongly on the conditions of degradation. Home composting and sea water degradation will have various effects on different materials. Labels exists such like Ok compost.

5.2 Fibre comparison

5.2.1 Energy needed for production process

Environmental impact of fibre is highly dependent on the resources needed for their productions. Figure 3 shows the energy needed, in mega Joules per tonne of fibre, for the production of various fibres. As an order of magnitude carbon fibres need 10 times more energy than glass to be produced. The manufacturing process of glass fibre needs also 10 times more energy than natural fibres to be produced.

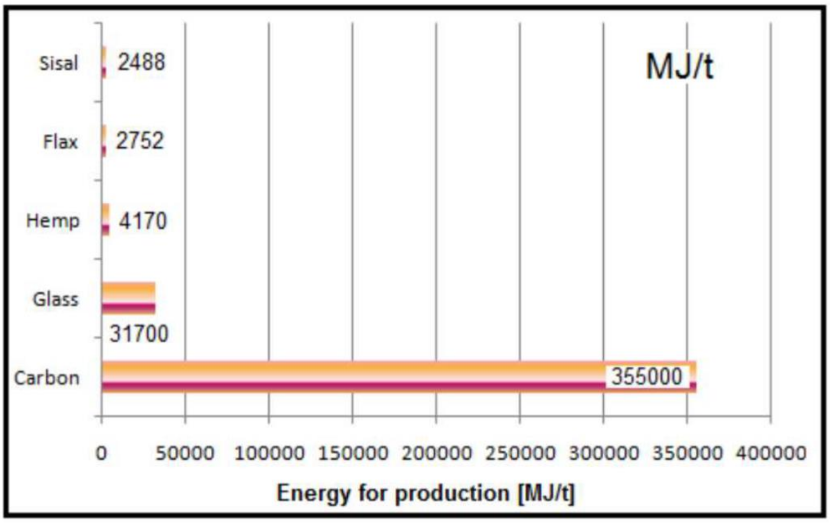

Figure 3: Energy for production of some fibre (sources: SachsenLeinen; Daimler 1999; BAFA; NOVA; AVB; CELC; REO)

Eco alternative to high impact carbon fibre exist for non-structural applications such like nonwoven mats from recycled carbon commercialized by CARBISO.

5.2.2 Life cycle analysis

Few studies have been conducted comparing the environmental impacts of the production of hackled flax fibres destined for reinforcement of composite materials and those for the production of glass fibres. The ecological advantages of flax fibres production over glass fibres are shown Figure 4. Most of the environmental indicators used (climate change, acidification, non-renewable energy consumption) are favourable to flax fibres. However the eutrophication indicator remains high, mainly due to the use and production of fertilizers. Globally, the production of flax fibres appears to be an environmentally attractive alternative to glass fibres [9].

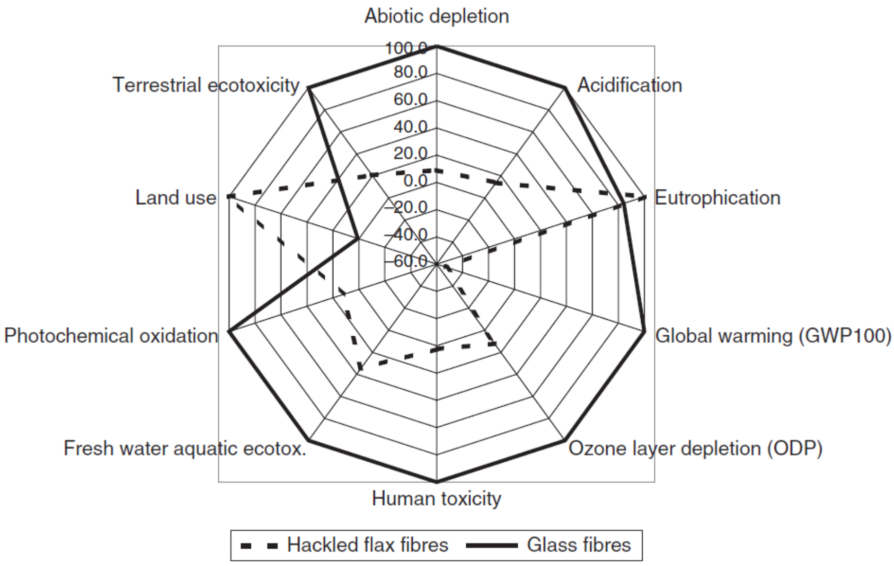

Figure 4: Environmental impacts during the production of hackled flax fibres compared to those for glass fibres

5.3 Resin comparison

Environmental impact of resins plays a major role in the LCA of composites. Although extensive studies have been conducted on the environmental impact of thermoplastics from renewable ressources, no results have been published yet for partly biobased thermoset resins.

Environmental impact of InfuGreen SR 810, a partly biobased Epoxy resin from Sicomin, is under study within the research program life-farbioty (https://www.life-farbioty.eu). Results should be shown by the end of 2019.

Regarding thermoplastics, as a general figure biobased polymer show lower impacts on abiotic depletion and greenhouse gaz emission whereas petroleum based polymer are advantageous regarding acidification and eutrophication.

5.4 Foam core comparison

The environmental impact of balsa wood in a ship superstructure has been compared to PVC foam core [10]. Even with a provenance from Central America, the use of balsa shows a significant decrease in abiotic depletion, global warming and acidification. The results are shown in Appendix 1.

5.5 Composite comparison

Figure 5 shows LCA comparison of flax and glass with various matrices. It can be seen that there is a significant interest of using flax over glass fibre at constant fibre volume fraction [11]. If the process used to manufacture the flax composite results in a lower fibre fraction than the glass composite, environmental gain is not so obvious.

Here the Eco-indicator considers the most relevant environmental impacts damaging ecosystems such as greenhouse effect, ozone layer depletion, acidification, etc.

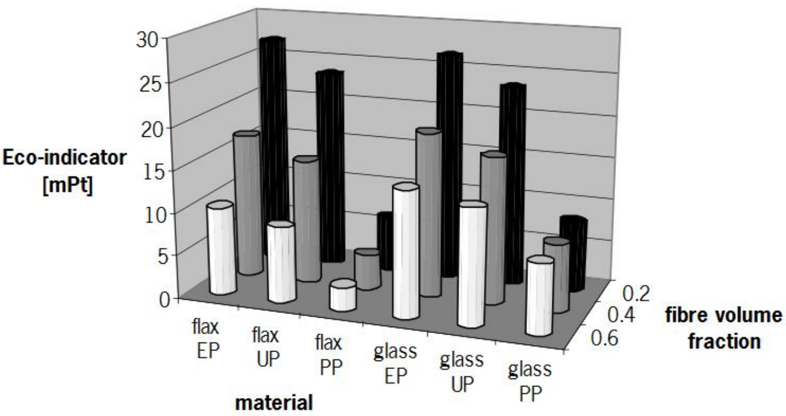

Figure 5: Eco-indicator of a deflection beam, width 100 mm and length 1 m, with variable thickness, designed to give a maximum deflection of 10 mm at a load of 1000 kN, as a function of fibre volume fraction, for the six material combinations. EP - epoxy; UP - Unsaturated Polyester; PP - Polypropylene

LCA analysis has been done comparing Flax/PLA to Glass/polyester composites. Figure 6 shows lower impact of biocomposite on most indicators [12].

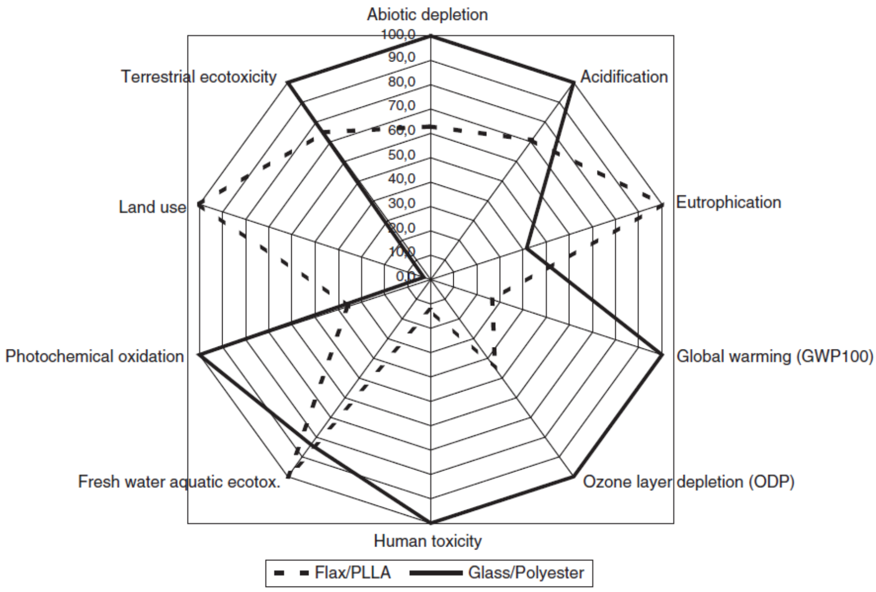

Figure 6: Comparison of the environmental impacts of the production of flax/PLA biocomposites and glass/unsaturated polyester composite

5.6 Land use

Natural fibres as well as biobased polymers are finding their origin from annual plants. It is therefore necessary to evaluate the available resources and a possible competition with alimentation. The French arable land available is about 29 million hectares. In 2030, ADEME (French agency for environment and energy control) estimates that the land use for flax and hemp will represent 290 000 hectares, about 1/100th of the arable land. It is also known that the loss of arable land in France is about 70 000 hectares every year due to housing [13].

5.7 End of life

5.7.1 Recycling

By 2020, annual global production of the widely used high performance carbon fibre reinforced polymers (CFRP) is expected to be over 140,000 tonnes. However, the resulting increased quantity of CFRP waste has highlighted the need for sustainable treatment options as carbon fibre manufacture has high-energy intensity. The environmental impacts of waste recycling and disposal pathways, comparing the current recycling techniques including mechanical, pyrolysis, fluidised bed and chemical recycling processes relative to conventional landfill and incineration have been quantified in [14].

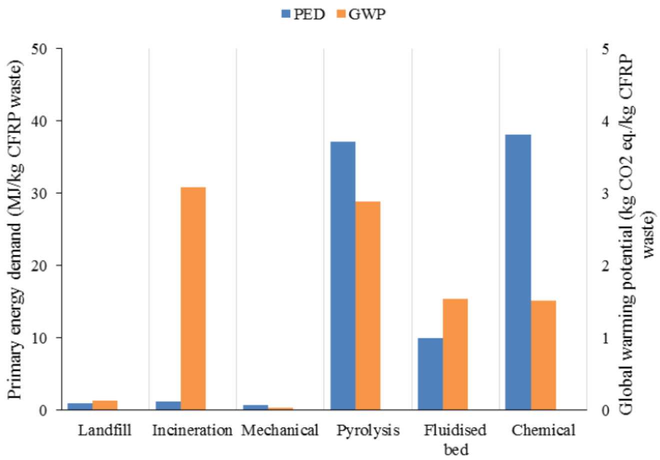

Figure 7: Primary Energy Demand and Global Warming Potential comparison of the carbon fibre recovery and conventional landfill and incineration without credits from the use of products of recycling processes.

A great advantage in using thermoplastic composite is their ability to be recycled at low cost. The entire composite (fibre and matrix) is crush and can be reintroduced either in a non-woven composite (RECYTAL project) or reintroduced as short fibre in a thermoplastic compound [15].

5.7.2 Incineration

The advantage of biocomposites over conventional composite is the high calorific value brought by the natural fibres. The calorific value of glass polyester (3380 kcal/kg) is below the threshold of 4000 kcal/kg expected by most city incinerator. However the calorific value of flax polyester (5255 kcal/kg) is above this threshold ensuring combustion without extra energy needed.

6 Physical properties

As presented above, within natural fibres, flax offers the best alternative to conventional fibres regarding mechanical properties. As with conventional composites, biocomposites mechanical properties are highly dependent on fibre fraction and porosity. These parameters are controlled partly by the compaction of the manufacturing process, partly by the permeability of the fibre and the viscosity of the resin.

The results shown below are general order of magnitude. It is recommended, to design with accurate mechanical properties, to run specific tests with a similar manufacturing process for the test specimen as the process used to manufacture the final part.

Mechanical properties of common resins and fibres are summarised in Appendix 2.

6.1 Traction

Traction is the most common initial test when comparing materials between each other. Even if at the macro scale traction is considered as being a pure solicitation without coupling, it is actually not the case at micro scale. Parameters like fibre length, fibre aspect ratio, fibre matrix adhesion or fibre individualisation have important effects [16].

In traction, the mechanical properties of unidirectional flax / Epoxy composite manufactured by infusion are the following:

- Young's modulus: 20 GPa
- Tensile strength: 200 MPa
- Fibre volume fraction: 35%

Comparison with glass fibre can be seen in Appendix 3. The graph shows that:

- to achieve an equivalent stiffness with flax compared to glass, flax laminate must be 50% thicker and 15% heavier
- to achieve an equivalent strength with flax compared to glass, flax laminate must be 2,9 times thicker and 2.2 times heavier.

If looking at pre-preg fabrics flax / epoxy, with a fibre mass fraction of 51% (corresponding to fibre volume fraction of 45%), cure in a oven, mechnical properties are rising to the following figures:

- Young's modulus: 35 GPa
- Tensile strength: 365 MPa

Studies have been conducted evaluating process parameters such like pressure, conditionning and cure cycle [17].

6.2 Compression

The compression behaviour of composites is predominant especially for flexural loading strength of sandwich parts. The skin in compression is often the weakest and particular care must be taken into consideration.

The tensile behaviour of biocomposite laminates has been widely studied to analyse the potential for reinforcement of flax fibres, but their compressive behaviour is still poorly understood. Indeed, these materials are still in the optimization phase and it is a complex task to carry out compressive tests. In addition, many parameters can influence the performances such as the fibre and resin properties, the interface bond strength, void content, fibre volume fraction and fibre misalignment, existence of kink band as well as the difference in Poisson ratio between fibre and matrix [18].

The results from [18] showing the mechanical properties of unidirectional flax for several polymers are on Table 2.

	Fibre volume fraction [%]	Compressive modulus (GPa)	Compressive strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)
Flax-PP	49.2	29.9 ± 1.0	74.9 ± 3.8	30.8 ± 3.2	193.0 ± 15.0
Flax-PP/MAPP	49.8	28.9 ± 3.1	110.1 ± 18.4	31.0 ± 1.8	234.0 ± 23.0
Flax-PA11	50.1	29.3 ± 1.4	133.9 ± 8.5	30.0 ± 2.3	257.9 ± 12.3
Flax-Acrylic	48	27.9 ± 2.1	101.3 ± 5.3	27.6 ± 1.6	243.8 ± 12.4
Flax-Epoxy	50.9	25.2 ± 1.9	115.4 ± 5.9	26.0 ± 2.0	408.0 ± 36.0

Table 2: mechanical properties of various flax composites

6.3 Flexion

6.3.1 Single skin

Due to the low density of flax fibres, equivalent rigidity of a single skin flax laminate compared to glass laminate can be obtained at a lower weight. The graph in Appendix 4 shows that:

- to achieve an equivalent bending stiffness with flax compared to glass, flax laminate must be 14% thicker conducting to a gain in weight of 14%.
- to achieve an equivalent bending strength with flax compared to glass, flax laminate must be 76% thicker and 33% heavier.

6.3.2 Grid

Grids made out of natural fibre such like the Power Ribs® one commercialised by the company Bomp are offering a significant increase in bending stiffness. They are applicable to stiffen in bending thin skin with no weight addition. The graph in Appendix 5 show that compared to a 600 g/m² single skin carbon the use of power ribs with 300 g/m² of flax skin increases the bending over weight ratio by 30%. When associated to carbon fibre single skin of 240 g/m² the bending over weight ratio increases three times compared to carbon single skin.

Particular care must be taken during the manufacturing process in order to manufacture high fibre content composites.

6.3.3 Sandwich

Sandwich biocomposites can be manufactured using cork and end grain balsa materials presented above. According to their mechanical properties cork is generally used on the bottom part of the hull and balsa on the sides the deck and the superstructures.

6.4 Shear

Shear is mostly driven by the adhesion between the fibre and the matrix. Pull-out tests can be done to ensure the adhesion [19]. Table 3 shows results of shear stress from pull-out tests for various fibre / matrix combination.

Material	Apparent shear stress (MPa)
PLLA (Naturworks)/Flax	16.4 ± 3.8
PLLA (Biomer)/Flax	15.3 ± 3.3
PP/Hemp	9
PP/Hemp	4.7
Epoxy/Flax	22.7 ± 0.8
Epoxy/Flax	23 ± 7
Unsatured polyester/Flax	14.2 ± 0.4
PP/glass	3.3
Epoxy/glass	29.3 ± 2.4

Table 3: Apparent shear stresses from debonding tests on single fibres [20]

6.5 Ageing

Natural fibres are hydrophilic and highly sensitive to water absorption, special care needs to be taken when natural fibre materials are exposed to moisture.

Similarly UV affects the fibres. Apart from whitening the fibre, the strength and stiffness of a flax/epoxy composite under UV lights are decreasing with exposure time and moisture as shown in Table 4.

Composites	Exposure conditions	Degradation
Glass/polyester	Exposure of 3000 h. One cycle consists of 4 h with UV radiation at 50 °C and 4 h without UV radiation at 60 °C.	21% and 33% reduction in tensile stress and modulus, 13% and 15% reduction in flexural stress and modulus
Carbon/epoxy	Exposure of 2000 h. Sequential exposure to UV radiation (1000 h) followed by condensation (1000 h)	21% reduction in tensile strength
Carbon/epoxy	Exposure of 1000 h. One cycle includes 6 h of UV radiation and followed by 6 h of condensation.	29% reduction in tensile strength
Glass/curaua/ polyester	Exposure of 2016 h. One cycle includes 18 h of UV rays and 6 h of steam-heated water.	22.4%, 1.3% and 16.9% reduction in tensile strength, modulus and elongation. 11.7%, 6.7% and 15% reduction in flexural strength, modulus and strain
Flax/epoxy	Exposure of 1500 h. One cycle includes: (1) 12 h of UV light exposure at 60 °C, (2) place at room temperature for 3 h, (3) spraying water to the exposed surface and exposed to UV light for 6 h at 60 °C, and (4) place at room temperature for 3 h	29.9%, 34.9% and 31.1% reduction in tensile strength, modulus and strain. 10.0%, 10.2% and 13.7% in flexural strength, modulus and strain

Table 4: Comparison between flax/epoxy composites with other composites [21]

To prevent such degradation solution exists and a particular care must be taken when designing with natural fibres. As an example the trimaran Gwalaz is in the water 6 month a year since 2013. Her ageing is evaluated each year by measuring her weight. She has not shown any significant increase so far.

6.6 Fatigue

While plant fibre type and quality, textile architecture and composite fibre content have a significant impact on the static properties, they have little impact on the material fatigue strength coefficient b (which dictates the slope of the S–N curve, see Appendix 6).

In essence, higher static properties are a sign of superior fatigue loading capacities throughout their lifetime. Increasing stress ratios lead to improved fatigue performance in natural fibre composites. Fracture mechanisms and modes are the same for composites made from three different bast fibres, but depend on fibre content, textile architecture and stress ratios. Although the absolute fatigue performance of glass fibre composites is far superior to natural fibre composites, fatigue strength degradation rates are lower in natural fibres composites than in glass fibre composites [22].

7 Obstacles of biocomposite development

Biocomposite and the use of natural fibres for structural application are under development. Many questions stills need to be answered to use the best out of these materials. C. Baley published in 2014 a study about the obstacles to optimise the performances and to develop the applications of biocomposites [13]. Ten obstacles have been identified in this study. The most relevant obstacles to marine application are presented below:

1) knowing why we are using biocomposites

The use of natural fibres is not simply about substitution. Natural fibres have specific properties that are interesting to valorise:

- Renewable origin
- Both durable and biodegradable
- High mechanical performance for certain fibres
- Low energy consumption to produce
- Their Incineration produces energy
- Lower the environmental impact
- Lower weight in some cases
- Various end of life scenarios
- Give a natural finish to parts
- Lower health hazards
- Answer coming environmental legislation
- Give strategic value to products

2) Learning eco-conception

A new material needs time to find its place. Habits need to be modified and new structures have to be imagined. Moreover the environmental impact must be evaluated during conception using LCA tool to ensure real gains compared to conventional materials.

3) Define a common language between all stakeholders

Communication between researchers, industrials and agricultural world must improve. Natural fibres are mostly used in textile and paper industry. Standards to characterise the properties of natural fibres in these fields exist. The use of natural fibres in composite still suffers from a lack of regulation. Nevertheless Afnor XP T 25-501 exists to characterise flax fibres in traction. The CELC (European confederation for flax and hemp) act in that direction to create technical data sheet and diffuse information

4) Appropriate choice of constituents

If the objective is to reduce environmental impact transportation must be limited and local resources should be preferred. Various parameters are driving the choice of the matrix: the provenance for a biobased polymer, the recycling scenarios for a thermoplastics and the end of life for a thermoset.

5) Adapt the process to respect the fibres

Thermal resistance of natural fibre is limited to 200 - 230°C for a short amount of time. Water content must be controlled in the fibres. Water evaporation during process generates porosity and a loss of mechanical properties.

6) Optimise the nature of semi-products

Most type of semi-products is available or under development: mat, biaxial, unidirectional, woven rowings. The cost of long fibre fabrics is a major obstacle for biocomposites. Fabric manufacturers are developing processes to reduce fabric cost. They are focusing on process speed optimisation and on simplification of weaving process.

7) Knowing and controlling the evolution of properties with time

Natural fibres are influenced by water absorption and UV. Specific precaution must be taken to protect the fibres from these environmental aggressions.

8) Run simulations with reliable data

The challenge is to understand the parameters influencing the behaviour of an elementary natural fibre. Plant fibres are polymers, therefore the issue of their service life required studying the viscoelastic behaviour of both the matrix and the fibres [23].

8 Examples of biocomposite in marine products

8.1 Built by KAIROS

Glaz board (2012) : flax surf board

S3 board (2012): biocomposite standup pladdle

Gwalaz (2013): a 100% natural fibre and partly biobased resin trimaran

Marlin (2014): Deck, coach roof and cockpit of a 10m cruising boat

Vachic (2014): Roofing and pilot house of a 10m passenger ferry

Oceanwings (2017): a reefable wing sail with VPLP

A-Ven (2018): a 100% biobased/compostable hull and structure

8.2 Other examples

Araldite: Mini 6.50 carbone structure, flax skins

Greens Boats: German flax fibre partly biobased epoxy dayboat

El Nino: Biocomposite dinghy

Navecomat: Biocomposite canoe

La gazelle des sables: Biocomposite day boat

Arkema 3: Mini 6.50 carbon, Elium resin

Twiner: twintex, glass PP

Gold of Bengal: Bangladeshi traditional boat in jute fibre

Loop 650, *GS4C*: Mini 650, Basalt fibre

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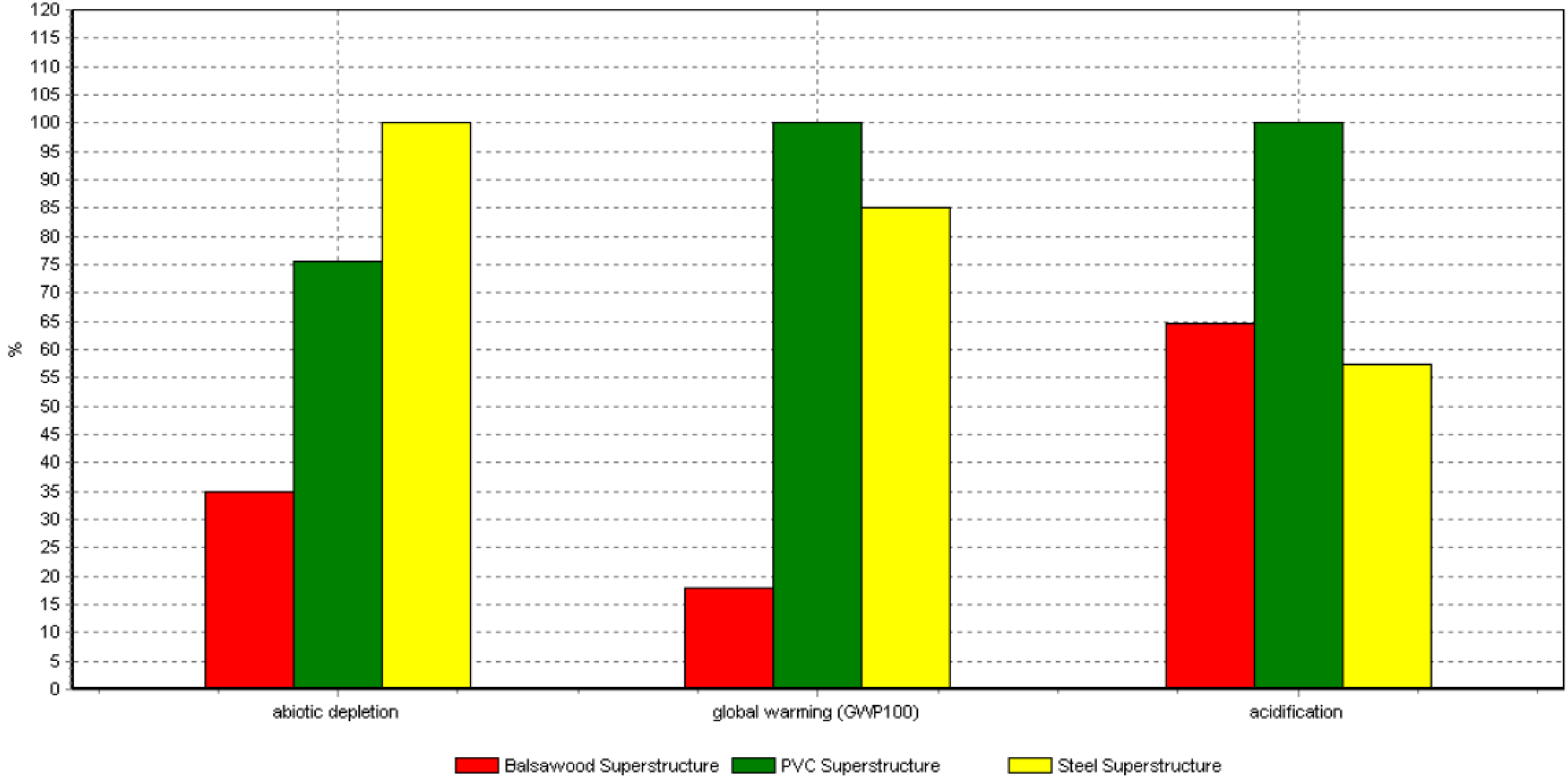
Appendix 1



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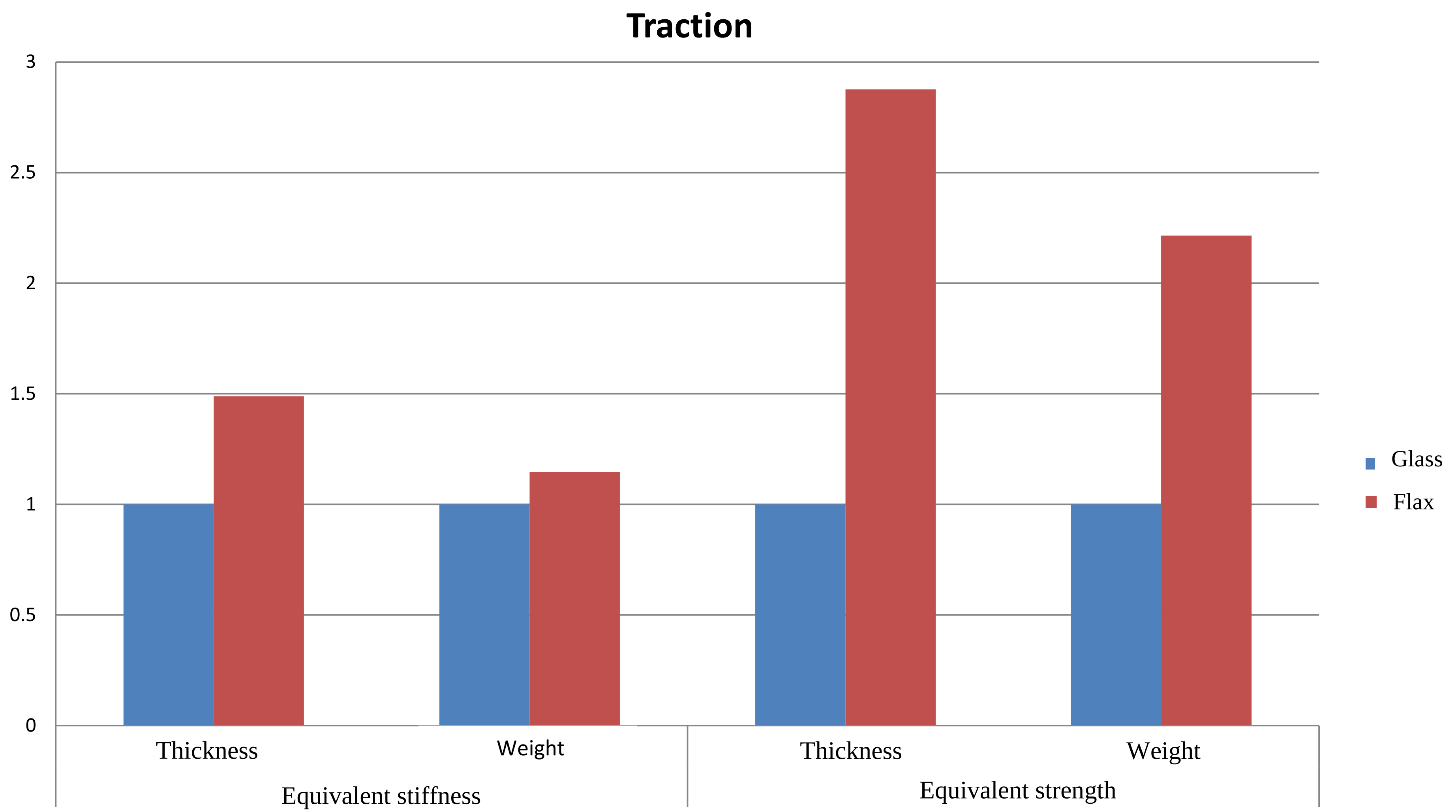
Appendix 2

Nature	Type	E_1 (Gpa)	ρ (g/cm3)	$σ_{max}$ tensile (Mpa)
Aramid	Kevlar 49	130	1.45	3500
Carbon HR	HR	230	1.7	4500
Basalt	Filava	100	2.6	2000
Glass E	E	78.7	2.6	2366
Glass R	R	86	2.5	3200
Flax		48	1.38	800
Hemp		45	1.47	700
Bomboo		30-50	0.9	500 - 740
Jute		42	1.23	610

Nature	Type	E (Gpa)	v12 (Gpa)	G12 (Gpa)	ρ (g/cm3)	σmax t (Mpa)	σmax c (Mpa)	τ max (Mpa)	Approx. cost (€/Kg)
Epoxy	SR 1700	3.5	0.4	1.6	1.2	90	90	75	12-18
Biobased Epoxy	SR810	3.2	0.4	n/a	1.2	70	70	47	12-18
Polyester ortho	Orthophthalic	4	0.4	1.4	1.1	80	80	46	2
Biobased Polyester		3.1	0.37	1.13	1.2	62	62	35	4.5
Polyamide	PA6.6	3.3	n/a	n/a	1.15	80	n/a	n/a	n/a
Polyamide	PA11	1.55	n/a	n/a	1.03	44	n/a	n/a	n/a
PLA	Polylactic acide	3.3	0.3	1.23	1.24	60	60	45	3.5
Elium	Methacrylate	3.3	0.3	1.27	1.19	76	130	45	14.5
Polypropylene		2	0.3	0.8	0.9	20	20	15	1

Appendix 3



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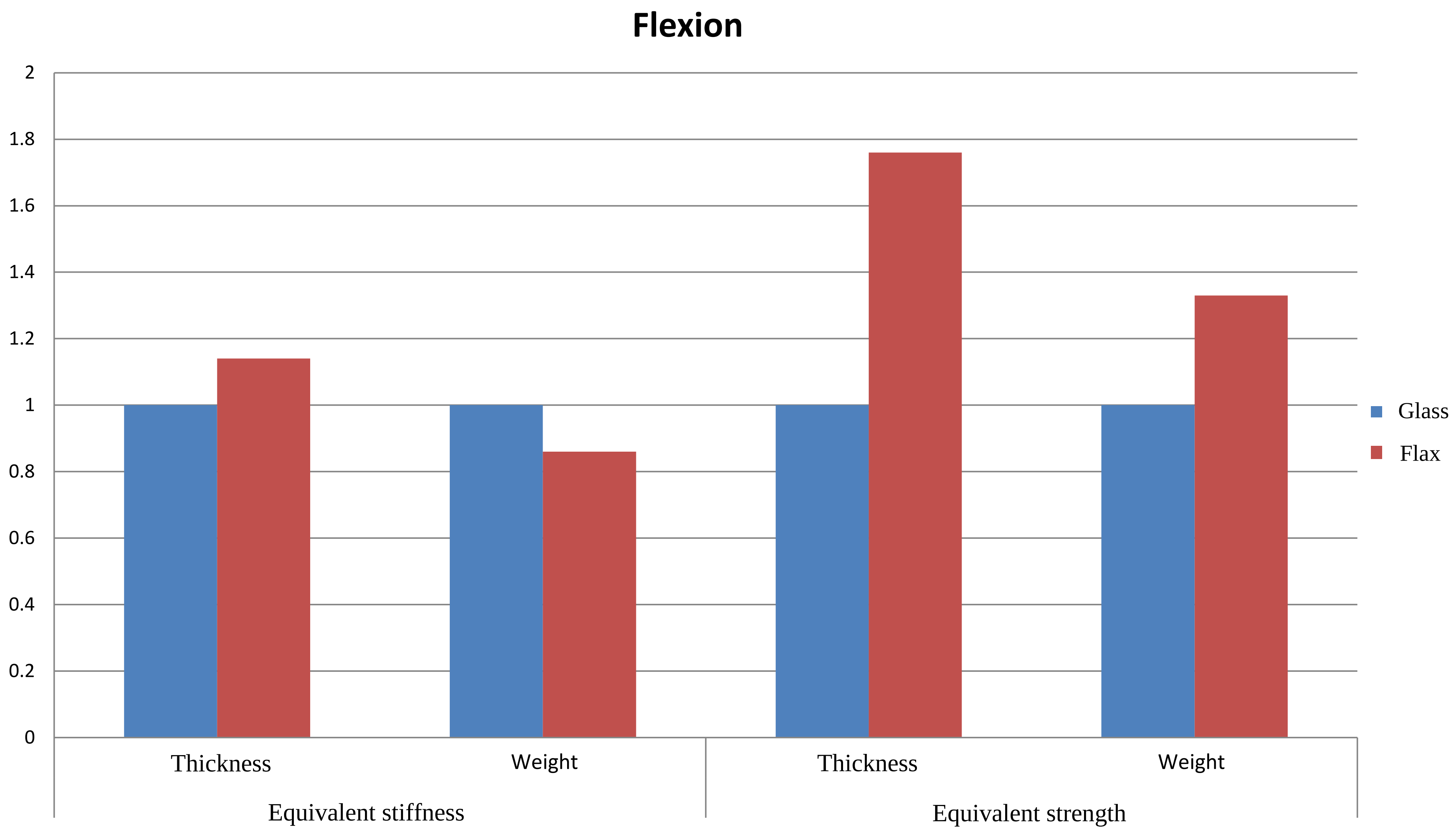
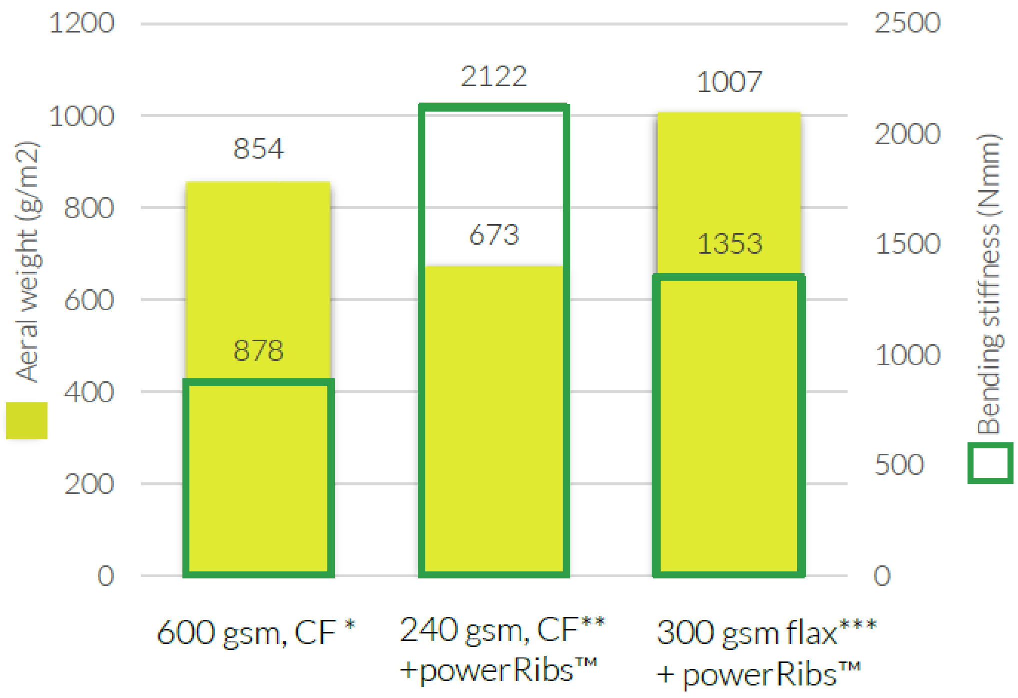
Appendix 4


Flexion
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Thickness
Weight
Thickness
Weight
Equivalent stiffness
Equivalent strength
Glass
Flax

Appendix 5



*Carbon fiber Fabric Aero Tenax HTA 3K plain 200g/m² (CF200)
**Carbon fiber Fabric Aero Tenax HTA 3K plain 240g/m² (CF240)
***Bcomp ampliTex™ 5040 twill 300g/m²
Bcomp powerRibs™ 5020, Flax Yarn 3000 tex, grid 28x28mm

http://www.bcomp.ch/

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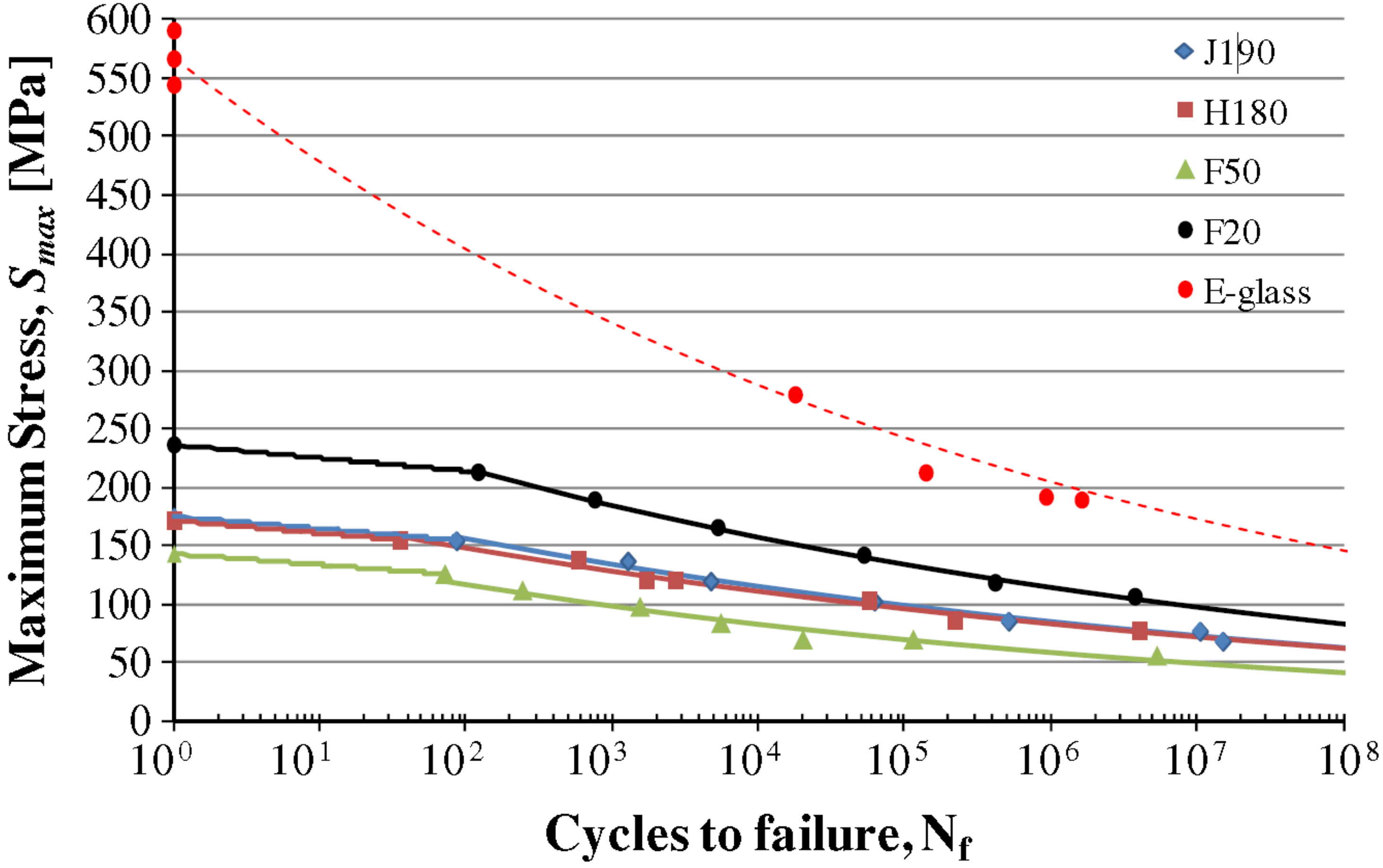
Appendix 6 : Fatigue loading



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